# A comparison between high airflow drying and adsorption assisted drying for the dewatering of fine coal

**MJ van Rensburg**

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Thesis submitted for the degree Doctor of Philosophy in Consumer Science at the North-West University

| | |
|---|---|
| Promoter: | Prof M le Roux |
| Co-promoter: | Prof QP Campbell |

Graduation: July 2019

Student number: 21089906

# Preface

## Overview of document

This manuscript is prepared for examination and submitted in completion of the author's Doctoral studies at the North-West University. The preface contains an overview of the thesis submitted for examination. A list is given of the key rules and guidelines as specified by North-West University. Personal comments are forwarded regarding the formatting as well as the numbering and referencing style used throughout the document. The preface includes signed statements and consent to publish from each co-author. The deliverables arising from this study are discussed and an abstract of the thesis is given.

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# Rules and guidelines

### *Academic rules of the North-West University*

This manuscript adheres to the General Academic Rules as outlined by the North-West University. The rules were approved on 21 September 2017 and an electronic copy can be found at http://www.nwu.ac.za/content/policy_rules. Academic rules regarding doctoral degrees are specified in Section 5. This doctoral thesis, which includes peer reviewed journal and conference papers, adheres to these rules.

- Rule 5.10.3 states that:

"A thesis, mini-thesis or other research product of a doctoral study must comply with the technical requirements provided for in the Manual for Master's and Doctoral Studies and in faculty rules." An electronic copy of the Manual can be found at http://library.nwu.ac.za/ under Guides and Training.

- Rule 5.10.4 states that:

"Where faculty rules require that a research article must be submitted to an accredited journal as part of the requirements for the degree, the candidate must provide evidence of such submission."

- Rule 5.10.5 states that:

"Where a candidate is allowed to submit the research product in the form of research articles, such research product must be presented for examination purposes as an integrated unit, supplemented with a problem statement, an introduction and a synoptic conclusion as prescribed by faculty rules and the manuscript submission guidelines, or the url link to the manuscript guidelines of the journal or journals concerned."

- Rule 5.12.5 states that:

"A doctoral candidate who is in terms of these rules required to, or otherwise wishes to submit a publication based on a research product of the study, must obtain the advice of the promoter concerned regarding the scholarly quality of the research product, the selection of a suitable publication or publication medium, possible considerations of confidential classification, and the requirements and implications of rules 5.12.7 and 5.12.8."

- Rule 5.12.6 states that:

"The promoter concerned must record compliance with rule 5.12.5 in the report contemplated in rule 1.15.4."

- Rule 5.12.7 states that:

"In a publication referred to in rule 5.12.5 its foundation upon the doctoral study at the university must be acknowledged and the promoter or promoters must be cited."

- Rule 5.12.8 states that:

"A doctoral degree graduate is deemed to be the sole author of a research product of the study unless another person, including the promoter, makes a substantial contribution to the production of the publication, as distinguished from the supervised research product, to warrant co-authorship taking the conventions of the discipline concerned into account, or where another person takes the primary responsibility for the writing of the publication to the extent that it justifies the first authorship of such other person."

### *Formatting, numbering and referencing*

General details regarding the published papers are given along with the papers in this thesis. Title pages from each of the published papers are included in the Annexure.

The papers included in this thesis were published in various journals and conference proceedings, each specifying its own formatting and style. These papers were formatted to have a similar structure, numbering and referencing style. Even though the published papers were edited to have a consistent style, it should be noted that no major changes were made to the content thereof. Changes made included the correction of minor typographical and language errors.

This thesis was submitted for language editing to Prof. Gerhardus Jacobus van Jaarsveld as declared in the certificate on page iv.

***Formal declaration: Language editing***

# Hestia Promosies

**Formal Declaration**

I hereby formally declare that I

Gerhardus Jacobus van Jaarsveld

read and edited the following thesis by

Martha Johanna van Rensburg

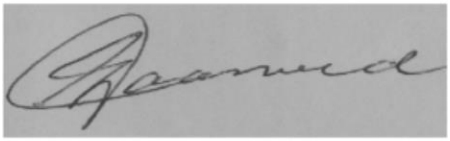
entitled

*A comparison between high airflow drying and adsorption assisted drying for the dewatering of fine coal*

submitted in completion of the author's degree

Philosophiae Doctor in Chemical Engineering

at the Potchefstroom Campus of the North-West University



PROF. G J VAN JAARSVELD D.LITT.

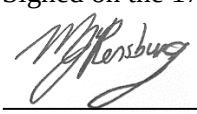
# Declaration

I, **Martha Johanna van Rensburg**, hereby declare that this thesis entitled:

***A comparison between high airflow drying and adsorption drying for the dewatering of fine coal***

is my own work and has not been submitted to any other university before. Where publications involving co-authors were used, the necessary permission from these authors had been obtained in writing. The relative contributions by the co-authors are acknowledged in the associated chapters.

Signed on the 17th day of November 2018.



Martha Johanna van Rensburg

# Statements from co-authors

The following co-authors, listed below, made contributions to this study. Their contributions are disclosed in the various chapters of the thesis along with the corresponding paper. Their contributions are acknowledged and a signed letter of consent of each is given in this section.

### *Statement of consent: Prof. M le Roux*

To whom it may concern,

I, **Marco le Roux**, give my consent to **Martha Johanna van Rensburg**, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in her thesis entitled: "**A comparison between high airflow drying and adsorption drying for the dewatering of fine coal**" the following publications, of which I am a co-author:

- **Le Roux, M**., Campbell, Q.P. & Van Rensburg, M.J. 2014. Fine coal dewatering using high airflow. *International Journal of Coal Preparation and Utilization*, 34:220-227.
- **Le Roux, M**., Campbell, Q.P. & Van Rensburg, M.J. 2014. Drying of fine coal using air in a fluidized bed. (*In* Yianatos, J., *eds*. XXVII International Mineral Processing Congress, Santiago, Chile. Chile: Gecamin.
- **Le Roux, M**., Campbell, Q.P., Van Rensburg, M.J., Peters, E.S. & Stiglingh, C. 2015. Air drying of fine coal in a fluidized bed. *Journal of the Southern African Institute of Mining and Metallurgy*, 115: 335-338.
- Van Rensburg, M.J., **Le Roux, M**., Campbell, Q.P. & Peters, E.S. 2015. Drying of fine coal using warm air in a fluidized bed. Paper presented at the Southern African Coal Processing Society's conference, Secunda, South Africa.
- Van Rensburg, M.J., **Le Roux, M**. & Campbell, Q.P. 2016. Drying of coal fines assisted by ceramic sorbents. (*In* Litvinenko, V., *eds*. XVIII International Coal Preparation Congress, Saint-Petersburg, Russia. Switzerland: Springer.
- Peters, E.S., **Le Roux, M**., Campbell, Q.P. & Van Rensburg, M.J. 2017. Adsorbent assisted drying of fine coal. Paper presented at the Southern African Coal Processing Society's conference, Secunda, South Africa.
- Van Rensburg, M.J., **Le Roux, M**., Campbell, Q.P. & Peters, E.S. 2018. Contact sorption: A method to reduce the moisture content of coal fines. *International Journal of Coal Preparation and Utilization*, 1-15.
- Van Rensburg, M.J., **Le Roux, M**., Campbell, Q.P. & Peters, E.S. 2018. Moisture transport during contact sorption drying of coal fines. *International Journal of Coal Preparation and Utilization*, 1-16.

Signed on the 29th day of October 2018.

Marco le Roux

### *Statement of consent: Prof. Quentin P. Campbell*

To whom it may concern,

I, **Quentin Peter Campbell**, give my consent to **Martha Johanna van Rensburg**, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in her thesis entitled: "**A comparison between high airflow drying and adsorption drying for the dewatering of fine coal**" the following publications, of which I am a co-author:

- Le Roux, M., **Campbell, Q.P**. & Van Rensburg, M.J. 2014. Fine coal dewatering using high airflow. *International Journal of Coal Preparation and Utilization*, 34:220-227.
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- Van Rensburg, M.J., Le Roux, M. & **Campbell, Q.P**. 2016. Drying of coal fines assisted by ceramic sorbents. (*In* Litvinenko, V., *eds*. XVIII International Coal Preparation Congress, Saint-Petersburg, Russia. Switzerland: Springer.
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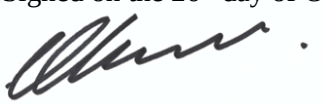
- Van Rensburg, M.J., Le Roux, M., **Campbell, Q.P**. & Peters, E.S. 2018. Moisture transport during contact sorption drying of coal fines. *International Journal of Coal Preparation and Utilization*, 1-16.

Signed on the 26th day of October 2018.



Quentin Peter Campbell

***Statement of consent: Miss. Elmarie S. Peters***

To whom it may concern,

I, **Elmarie Sunette Peters**, give my consent to **Martha Johanna van Rensburg**, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in her thesis entitled: "**A comparison between high airflow drying and adsorption drying for the dewatering of fine coal**" the following publications, of which I am a co-author:

- Le Roux, M., Campbell, Q.P., Van Rensburg, M.J., **Peters, E.S**. & Stiglingh, C. 2015. Air drying of fine coal in a fluidized bed. *Journal of the Southern African Institute of Mining and Metallurgy*, 115: 335-338.
- Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & **Peters, E.S**. 2015. Drying of fine coal using warm air in a fluidized bed. Paper presented at the Southern African Coal Processing Society's conference, Secunda, South Africa.
- **Peters, E.S**., Le Roux, M., Campbell, Q.P. & Van Rensburg, M.J. 2017. Adsorbent assisted drying of fine coal. Paper presented at the Southern African Coal Processing Society's conference, Secunda, South Africa.
- Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & **Peters, E.S**. 2018. Contact sorption: A method to reduce the moisture content of coal fines. *International Journal of Coal Preparation and Utilization*, 1-15.
- Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & **Peters, E.S.** 2018. Moisture transport during contact sorption drying of coal fines. *International Journal of Coal Preparation and Utilization*, 1-16.

Signed on the 26th day of October 2018.

Elmarie Sunette Peters

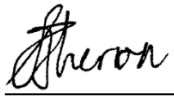
***Statement of consent: Mrs. Christel Theron (neè Stiglingh)***

To whom it may concern,

I, **Christel Theron (neè Stiglingh)**, give my consent to **Martha Johanna van Rensburg**, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in her thesis entitled: "**A comparison between high airflow drying and adsorption drying for the dewatering of fine coal**" the following publications, of which I am a co-author:

- Le Roux, M., Campbell, Q.P., Van Rensburg, M.J., Peters, E.S. & **Stiglingh, C**. 2015. Air drying of fine coal in a fluidized bed. *Journal of the Southern African Institute of Mining and Metallurgy*, 115: 335-338.

Signed on the 12th day of November 2018.



Christel Theron

# Deliverables from study

1. The following papers were published in peer reviewed journals:

| Category | Information |
|---|---|
| Paper name | Fine coal dewatering using high airflow |
| Authors | Le Roux, M., Campbell, Q.P. & Van Rensburg, M.J. |
| Journal | International Journal of Coal Preparation and Utilization, 34:220–227 |
| Year | 2014 |
| Copyright | ©Taylor & Francis Group, LLC |
| ISSN | 1939-2702 (Online) & 1939-2699 (Print) |
| DOI | 10.1080/19392699.2014.869939 |

| Category | Information |
|---|---|
| Paper name | Air drying of fine coal in a fluidized bed |
| Authors | Le Roux, M., Campbell, Q.P., Van Rensburg, M.J., Peters, E.S. & Stiglingh, C. |
| Journal | Journal of the Southern African Institute of Mining and Metallurgy, 115: 335-338 |
| Year | 2015 |
| Copyright | © The Southern African Institute of Mining and Metallurgy |
| ISSN | 2411-9717 (Online) & 2225-6253 (Print) |
| Web address | http://www.saimm.co.za |

| Category | Information |
|---|---|
| Paper name | Contact sorption: A method to reduce the moisture content of coal fines |
| Authors | Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & Peters, E.S. |
| Journal | International Journal of Coal Preparation and Utilization, 1-15 |
| Year | 2018 |
| Copyright | ©Taylor & Francis Group, LLC |
| ISSN | 1939-2702 (Online) & 1939-2699 (Print) |
| DOI | 10.1080/19392699.2018.1541895 |

| Category | Information |
|---|---|
| Paper name | Moisture transport during contact sorption drying of coal fines |
| Authors | Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & Peters, E.S. |
| Journal | International Journal of Coal Preparation and Utilization, 1-16 |
| Year | 2018 |
| Copyright | ©Taylor & Francis Group, LLC |
| ISSN | 1939-2702 (Online) & 1939-2699 (Print) |
| DOI | 10.1080/19392699.2018.1541895 |

2. The following papers were presented at conferences and published in the conference proceedings:

| Category | Information |
|---|---|
| Paper name | Drying of fine coal using air in a fluidized bed |
| Authors | Le Roux, M., Campbell, Q.P. & Van Rensburg, M.J. |
| Journal | Proceedings of the XXVII International Mineral Processing Congress |
| Year | 2014 |
| Copyright | © Gecamin, Chile All rights reserved gecamin@gecamin.com |
| Web address | http://www.impc2014.org/english/proceedings |

| Category | Information |
|---|---|
| Paper name | Drying of fine coal using warm air in a fluidized bed |
| Authors | Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & Peters, E.S. |
| Journal | Proceedings of the Southern African Coal Processing Society's conference |
| Year | 2015 |
| Web address | http://www.sacoalprep.co.za/ |

| Category | Information |
|---|---|
| Paper name | Drying of coal fines assisted by ceramic sorbents |
| Authors | Van Rensburg, M.J., Le Roux, M. & Campbell, Q.P. |
| Journal | Proceedings of the XVIII International Coal Preparation Congress, 741-746 |
| Year | 2016 |
| Copyright | © Springer International Publishing Switzerland |
| ISBN | 978-3-319-40943-6 (Online) & 978-3-319-40942-9 (Print) |
| DOI | 10.1007/978-3-319-40943-6_114 |

| Category | Information |
|---|---|
| Paper name | Adsorbent assisted drying of fine coal |
| Authors | Peters, E.S., Le Roux, M., Campbell, Q.P. & Van Rensburg, M.J. |
| Journal | Proceedings of the Southern African Coal Processing Society's conference |
| Year | 2017 |
| Web address | http://www.sacoalprep.co.za/ |

3. The following awards were conferred on work resulting from this study:

- A study and presentation on high airflow drying was awarded first place for the Outotec 'Sustainability in the Minerals Industry' prize given for research presented at the Southern African Mineral Beneficiation and Metallurgy conference in 2014.
- A team consisting of Miss Jana van Rensburg, Prof. Marco le Roux and Prof. Quentin Campbell, were chosen as semi-finalists in a competition held by the Global Cleantech Innovation Programme in 2017. The adsorbent assisted drying technology was presented in the waste beneficiation category. "The Global Cleantech Innovation Programme (GCIP-SA) is part of a global initiative that aims to address the most pressing energy, environmental and economic challenges of our time through promoting clean technology innovation and supporting Small and Medium-size Enterprises (SMEs) and start-ups. Specific areas of focus are energy efficiency, renewable energy, waste beneficiation, water efficiency and green buildings and transportation. The GCIP-SA combines an annual competition and a business accelerator programme where SMEs and start-ups are continuously trained, mentored and assessed on their business models, investor pitches, communication and financial skills for the development of a more marketable and investor-attractive product and business. The competition and program were held in 2017 by the Global Environment Facility (gef), United Nations Industrial Development Organization (UNIDO), Clean tech open and Technology Innovation Agency (TIA)."
- Miss Jana van Rensburg presented a business idea and adsorption assisted drying technology at the North-West University's Leopards Lair competition held in 2017. The project pitch was awarded 2$^{nd}$ place and received money to invest into the project and innovation.

  "The finalists underwent training offered by the TTIS Office to improve their pitching and presentation skills. They also formed part of the NWU SETHI Explosions event where they could exhibit their ideas to the public and industry partners. The final pitches were delivered on 23 August 2017 at the Roots in Potchefstroom"

# Acknowledgements

I hereby want to offer my appreciation towards the following people:

- Firstly, I want to thank my heavenly Father for giving me love and guidance throughout the whole process. All the work that was completed wouldn't be possible without my God and my Provider. Daniel 2: "Praise the name of God forever and ever, for He has all wisdom and power. He gives wisdom to the wise and knowledge to the scholars."
- I want to give a heartfelt thank you to my parents, brother and close friends. You all have played such a pivotal role throughout my studies. I greatly appreciate your support, encouragement and valuable advice.
- A special thanks to my two promotors, Prof. Marco le Roux and Prof. Quentin Campbell. Your guidance, help and vision has encouraged and motivated me throughout the duration of my post-graduate studies. I have learned valuable professional and personal skills, that I will carry with me for the rest of my life.
- I would also like to thank the personnel of the North-West University, School of Chemical and Minerals Engineering and the students in our Coal Beneficiation Group, for all their support, help and ideas.

I would like to acknowledge the following institutions for their contribution towards this project:

- Coaltech
- NRF (National Research Foundation).

This work is based on research supported by the South African Research Chairs' Initiative of the Department of Science and Technology and the National Research Foundation of South Africa. Any opinion, finding, or conclusion, or recommendation expressed in this material is that of the authors and the NRF does not accept any liability in this regard.

"*What you get by achieving your goals is not as important as what you become by achieving them*"

# Abstract

Development in the fossil fuel sector should be an on-going process to promote sustainability, while reducing the environmental footprint. It is important to improve operations in the mining sector to ensure that coal is being used sensibly to extend the lifespan thereof. It is generally accepted that coal will remain an industry player in the foreseeable future as South Africa relies primarily on this cheap and abundant fossil fuel for electricity generation, whilst local petrochemical and metallurgical industries also require substantial coal resources. One part of the mining industry that undeniably needs attention is the considerable wastage of valuable fine and ultra-fine coal. Even after dewatering, these coal fines carry around 15-30%$_{wt}$ moisture and is subsequently discarded in an effort to supply a coal product with specified moisture requirements. In South Africa, this practise has led to the accumulation of approximately 1 billion tons of discarded fines and an estimated 53 million tons are added annually.

Studies have shown that coal fines, when upgraded, have similar calorific values compared to the coarser fraction of coal. Therefore, effective removal of the mineral matter and high moisture content from these coal fines, would directly increase the heating value thereof. While coarser coal can easily be dewatered, fine and ultra-fine coal tend to retain a large percentage of water. Beneficiating and dewatering these fines to a valuable resource that can supplement the saleable coal fraction, will not only increase revenue, but reduce environmental problems as well. Conventional mechanical dewatering technologies prove to deliver poor dewatering results and effective thermal drying technologies are too costly to warrant the upgrading of this discarded fraction of coal. The industry critically requires feasible, practical and economically viable dewatering technologies for the fine and ultra-fine coal to recover this valuable wasted resource and to improve current operations in the coal mining sector.

The aim of this thesis is to propose possible dewatering technologies focussed specifically on the dewatering of the finer particle size distributions. High airflow drying and adsorption assisted drying were investigated. Laboratory scale equipment made it possible to examine these techniques while finding the best operating conditions. With these, finding the key advantages and limitations of each technique could be determined to make an informed decision regarding the most suitable option for implementation on a larger scale.

This thesis contributes to the field of fine coal dewatering and the following key findings resulted from this study:

- When compared to high airflow drying, adsorption assisted drying resulted in lower energy consumption. An added benefit is that sorbent material could be regenerated to its original state; showing no degradation. The regenerated sorbent could be reused to obtain similar drying rates and final coal product moisture targets.
- The loaded sorbent material could successfully be regenerated with air at ambient conditions instead of applying thermal techniques. It required less than 10 minutes to dry the sorbent material with airflow

in a packed bed. Leaving the sorbent material in atmospheric conditions also indicated that the sorbent material could reach its initial inherent moisture content. The possibility of regenerating the sorbent material ensures that adsorption assisted drying is an energy positive and financially viable option for implementation on a larger scale.

- It was proven that moisture transport occurred in the liquid phase, requiring direct contact between the coal and sorbent particles to initiate and sustain the movement of moisture. The moisture transport mechanism could be described by determining the capillary resistance against liquid flow. The moisture transport mechanism indicated that increasing sorbent surface area available for contact led to a decrease in capillary resistance, which allowed for added liquid moisture flow.

These findings led to the conclusion that dewatering of coal fines by means of adsorption assisted drying is feasible and proved to be a practical approach for handling and the dewatering thereof. This approach is specifically beneficial for drying the finer fraction as transport of moisture is increased with optimised contact between the large surface area of the sorbent material and coal particles. Therefore, adsorption assisted drying, relying on optimised contact between the wet coal fines and sorbent material, proved to be specifically beneficial for drying the finer coal fraction.

*Keywords*: Adsorption assisted drying, Alumina-rich sorbent, Capillary resistance, Contact sorption, Dewatering, Fine coal, Fluidized bed, High airflow drying, Moisture transport, Rotary bed, Silica-rich sorbent, Ultra-fine coal

# Table of contents

# Chapter 1

## Introduction

This chapter provides an overview of the background and motivation for this thesis. The introduction focuses specifically on the problems found in the mining industry related to the fine and ultra-fine coal fractions containing high moisture content and the consequential wastage of this valuable resource. The financial and environmental implications arising from fine coal waste form the basis for the development of improved dewatering technologies. This study aims at evaluating the performance of two new dewatering operations for possible implementation on fine coal drying. The solutions and value proposition originating from this thesis are summarised in this chapter. In conclusion, the hypothesis and a list of objectives for this thesis are highlighted.

## 1.1. Background and motivation for study

> "*Each energy source has a very clear and definite advantage as well as disadvantages. By combining these energy sources, they could complement each other, rather than 'waging war'. There should be no winner, no loser and certainly no war or any industry being crushed when it comes to electricity in South Africa.*" (Cilliers, 2017)

South Africa mainly relies on mined coal for electricity generation as it currently provides a total of 77% of the national electricity grid (Department of Energy, 2017). However, in the debates around energy sources, coal mining is often seen as an industry that should be shut down to make way for nuclear energy or renewable energy sources. It is, however, recommended that these industries need to work together instead to achieve and maintain climate targets, energy security, grid stability and in return economic growth within South Africa (Cilliers, 2017). Coal is still an abundant and cheap fossil fuel and with the current electricity generation infrastructure, it will be an industry player for years to come (Jangam *et al*., 2011; Cilliers, 2017). Furthermore, coal is used in local petrochemical and metallurgical industries while a large quantity of high-quality coal is exported (Department of Energy, 2017). Even if coal as an energy resource is phased out, it will still be a reliable and cost effective reducing agent (Cilliers, 2017).

It is important to improve operations in the mining sector to ensure that coal is used sensibly as it is a non-renewable resource (World Coal Association, 2012; Fourie *et al*., 1980). One segment that definitely needs attention is the wastage of valuable fine and ultra-fine coal produced during mining operations. The fine and ultra-fine coal production as a result of mechanised mining methods adds up to an estimated 11% of the total mined coal in South Africa (SANEDI, 2011). It has become a common practice to discard this substantial portion of the mined coal while upgrading the remainder of the coal produced in order to meet the quality requirements of the various industries it supply to (Department of Energy, 2017). Coal fines and ultra-fines contain a moisture content between 15-30%$_{wt}$ (even after dewatering) depending on the particle size distribution and in return elevates the moisture content of the total product stream to an undesirable level that would inevitably result in moisture penalties (Bourgeois & Barton, 1998; Hand, 2000). According to SRK Consulting (2016) the coal mining industry has produced and discarded around 1 billion tons of coal fines, located either on heaps or in slurry dumps. Annual production of discard and slurry formation of coal fines account to approximately 11 million ton and 42 million ton respectively (SRK Consulting, 2016). This said, it was shown that the heating value of the fine coal fractions compares favourably to that of its coarser counterparts, and these fractions, therefore, are a valuable resource to recover and beneficiate to improve current operations in the coal mining sector (Reddick *et al*., 2007).

While coarse material can easily be dewatered with mechanical dewatering options, the finer fraction proves to be more challenging (Campbell, 2006; Bourgeois *et al*., 2000). Mechanical dewatering methods can remove moisture up to a final fraction of 15%wt for fine (-0.5mm) coals. When applying mechanical dewatering methods on ultra-fine coal (-0.1mm), the product moisture can only be reduced to about 25%$_{wt.}$

(De Korte & Mangena, 2004). Le Roux & Campbell (2003) reported moisture levels even higher than 25%$_{wt}$ when subjecting these particle sizes to vacuum filtration. Mechanical dewatering options are useful to remove the initial bulk of free moisture from the fines, but require costly thermal drying to eliminate the remainder of the moisture (Campbell, 2006; De Korte & Mangena, 2004). While working on vacuum filtration of coal fines, Le Roux & Campbell (2003) showed that an increase in airflow through a filter cake, even at the expense of the applied pressure differential, resulted in an increase in the dewatering capabilities of the filter, resulting in a dryer final filter cake product.

## 1.2. Problem statement

While coarser coal can easily be dewatered, fine and ultra-fine coal retains a large fraction of moisture due to their physical properties. Smaller particles have a greater surface area making adhesion of more moisture possible. The surface tension ensures that moisture adheres to this larger coal surface. These fine particles form lumps in a filter cake with small intra-particle radii between the particles. The increased capillary pressure ensures that the moisture is trapped in the filter cake which increases the total product moisture (Toa *et al*., 2003). The finer coal size distribution exhibits higher surface- and capillary forces compared to the coarser fraction. Fine coal and ultra-fine coal can therefore attract and retain much larger portions of water (Van der Merwe & Campbell, 2002). The high moisture content of the finer fractions contributes to difficulties in handling and consequently increases transportation costs and added moisture penalties when blending the wet finer fraction with the coarser fraction (Hand, 2000).

Although discarding the finer coal might avoid the immediate difficulties, this method of fines handling has added up to a number of environmental problems (Reddick *et al*., 2007). The discarded fraction can be found on heaps, dumps or in slurry dams (SRK Consulting, 2016). There is a total of 142 disposal facilities in South Africa, which amounts to an estimated 4,011 hectares of occupied land (Department of Energy, 2017). The fines found on dumps or heaps contribute to coal particulate pollution and can cause potential fire hazards (Reddick *et al*., 2007). These discards become weathered over time and develops a higher inherent moisture content as the coal surface becomes more oxidised. It is therefore important to recover these fines timeously to get an economically viable yield and usage out of the coal before it reaches this stage (SRK Consulting, 2016). Another environmental concern is the formation of acid mine drainage from the dissolution of sulphur containing minerals found in coal. The acid seeps into the surrounding water sources and can contaminate the immediate water table (Reddick *et al*., 2007; Hand, 2000). Additionally, these slurry dams need to be supervised to prevent breaking and flooding (Hand, 2000).

According to Hand (2000) a significant amount of money is spent to build these disposal facilities and transport material to them, while these sites needs to be managed and maintained. The added disposal costs could have been prevented if the totality of mined coal, including the fines, were processed on the plant to the point where it could be economically utilised in the product stream. It does seem wasteful not to process

the entire mined coal fraction as money has already been spent to mine and transport the finer fraction as well. Previously environmental laws allowed for cheap waste disposable and the overall mining costs were lower. However, it is not currently the case and it is sensible to process the fines formed during production and to recover discarded coal instead of following the status quo. Studies completed by Hand (2000) showed revenue can still be made on a plant when dewatering the fines rather than discarding this fraction of coal, depending on the material matter of the fines and sufficient beneficiation processes completed.

A further problem is a suitable technology to dewater coal fines to a satisfactory level. Technology found on plants can be divided into two categories: mechanical dewatering methods and thermal drying methods which will be elaborated on in Chapter 2. The limitations of these technologies have prompted investigation into improved dewatering and drying methods, specifically suited for finer coal.

In conclusion, the fine and ultra-fine coal production and thereafter the disposal thereof contributes to the wastage of a valuable resource that can supplement the marketable coal fraction of a mine and in return increase revenue if dried economically. While fine coal processing has been proven and implemented with great success on modern plants, the dewatering of fines is still playing catch-up. Therefore, fine coal circuits can only operate efficiently when feasible dewatering methods are developed and implemented.

## 1.3. Aim and objectives

The aim of this thesis is to evaluate the performance of two new dewatering operations for possible implementation on fine coal drying. The two proposed methods are high airflow drying and adsorption assisted drying. A laboratory study will be conducted on both these operations; describing and comparing the key advantages and limitations of each, as well as determining the energy efficiency thereof. The chosen dewatering operation will be studied in more detail to optimise the operability and understand the drying mechanism applicable to this technique.

The objectives of this thesis were to:

1. Lay out the problems related to fine and ultra-fine coal in the industry and complete a literature study to determine the benefits of recovering, dewatering and beneficiating the fine coal fraction for inclusion in the saleable coal product stream. This will include an investigation on the current technologies utilised in the industry to dewater coarse and finer coal fractions in order to propose possible dewatering techniques that can be introduced into the South African coal mining industry.
2. Build a laboratory scale drying unit and complete test work to investigate the possibility to dry coal fines with high airflow in operation 1. Determine the best operating conditions and difficulties during operation in order to improve and develop this technology. To establish whether operation 1 can be optimised in such a way to dry wet coal fines without utilising costly high temperatures.

3. Build a laboratory scale unit to determine whether it is possible to dewater coal fines by means of adsorption in operation 2 where moisture transport is initiated with porous sorbent spheres. Determine the operating parameters required to reach the desired coal product moisture. Determine whether it is possible to regenerate the loaded sorbent material used in operation 2 and establish whether the sorbent material can be re-used to efficiently dry wet coal fines.
4. Compare the drying efficiency of operation 1 and operation 2 by measuring the drying rate and coal product moisture. Compare the energy efficiency of both laboratory setups to determine which technique would consume the least amount of energy to upgrade coal fines to a marketable product. Complete an evaluation between operation 1 and operation 2 to choose the most feasible and practical option that can be used as a basis for further development.
5. Define a moisture transport mechanism to describe the dewatering process taking place as a result of the operation of choice. The mechanism should describe the type of moisture transfer and the operating conditions improving or limiting the moisture transfer.

## 1.4. Hypothesis

It is hypothesised that two moisture transport operations will be identified to be implemented for fine coal drying at ambient conditions. Due to the relatively low drying temperature, a liquid phase transport mechanism will dominate and will be found the more pliable one of the two operations.

## 1.5. Solution and value proposition

This thesis addresses the problems related to fine coal dewatering by contributing to the solution in the following ways:

### *1.5.1. Literature*

- A desktop study concerning the fine coal fraction and challenges regarding moisture retention and dewatering. Point out the need for improved dewatering and drying methods for fine and ultra-fine coal. (Chapter 1)
- Acomprehensive literature study to investigate the moisture retention of coal and specifically the finer fraction. Description of the moisture removal when operating with high airflow and adsorption drying methods. (Chapter 2)
- An evaluation study between high airflow drying and adsorption drying (investigated in Chapter 3 and Chapter 4). The aim is to describe, evaluate and determine the most effective technology process, suitable for industrial application. (Chapter 5)
- An in-depth study of the moisture transport mechanism during contact sorption drying that will lead to a contribution of the current literature. (Chapter 6)

### *1.5.2. Technology development*

- Improve a high airflow drying technology by investigating the operational difficulties and establishing the best operating conditions on a laboratory scale unit. (Chapter 3)
- A study on adsorption assisted drying by building a laboratory scale unit and completing comprehensive experimental test work to understand and optimise this technology. (Chapter 4)

## 1.6. Scope and layout of thesis

Each chapter of the thesis is written to elaborate on a specific subdivision of the study. The layout and arrangement of these chapters are illustrated in Figure 1.1.

### *Chapter 1: Introduction*

The first chapter serves as a background and motivation behind the initiative for this thesis. The chapter defines and discusses the problems related to the fine and ultra-fine coal in industry and highlights the mining industry's need for improved and cost-efficient drying technologies. The solution and value proposition arising from this study are discussed in this chapter and the objectives that will be addressed in the remainder of the thesis are pointed out.

### *Chapter 2: Literature review*

The aim of Chapter 2 is to discuss the moisture related to fine and ultra-fine coal as it leads to an understanding of moisture transport during drying processes. The literature review will also focus on the drying technologies currently used in the mining and related industries. The thesis will specifically investigate high airflow drying and adsorption assisted drying and for that reason Chapter 2 will serve as a background study into the operation and technology behind these drying techniques.

### *Chapter 3: High airflow drying*

Chapter 3 aims to investigate the possibility to dry fine and ultra-fine coal with high airflow techniques. The chapter addresses the laboratory set-up, experimental procedures, results and energy considerations when operating with high airflow in order to dry coal fines. This chapter is dedicated to determine the influence of a range of experimental parameters on the operation, drying results and efficiency of the technique. The information is given in the form of two papers published in peer reviewed journals and two papers published in conference proceedings.

### *Chapter 4: Adsorption drying*

The aim of Chapter 4 is to examine the use of sorbent material combined with coal fines to initiate moisture transfer. A laboratory set-up was built and this chapter focuses on the experimental procedures, results and energy considerations of adsorption drying. The aim was to investigate a range of parameters to make suggestions regarding the main driving forces required for improved dewatering. Solutions to regenerated and re-use sorbent material are also considered and discussed in this chapter. One paper submitted to a peer reviewed journal and two conference papers are presented in Chapter 4.

### *Chapter 5: Comparison between high airflow drying and adsorption drying*

The aim of Chapter 5 is to complete a comparison between high airflow drying and adsorption assisted drying. The focus is to firstly compare the operating parameters and results of both drying techniques tested on laboratory scale. Furthermore, the energy consumption and efficiency of these two technologies are compared focussing on the upgrading of coal. This chapter lays out the key advantages and limitations of both technologies, specifically looking at laboratory results and practicable industrial application.

### *Chapter 6: Moisture transport during adsorption drying*

Adsorption drying was chosen as the most suitable and efficient method to dry fine and ultra-fine coal. The moisture transport during adsorption drying was investigated and the transport mechanism was isolated and discussed. Operating conditions inhibiting or promoting moisture transport were investigated and considered as well. The primary finding is summarised in one paper submitted to a peer reviewed journal.

### *Chapter 7: Conclusions and recommendations*

The most prominent conclusions arising from Chapter 1 to Chapter 6 are summarised in Chapter 7 and therefore serves as a final overview of this thesis. The contribution this study has made to the research field and the coal industry are also highlighted. This chapter concludes with a list containing a number of suggestions to improve and further research in this field.

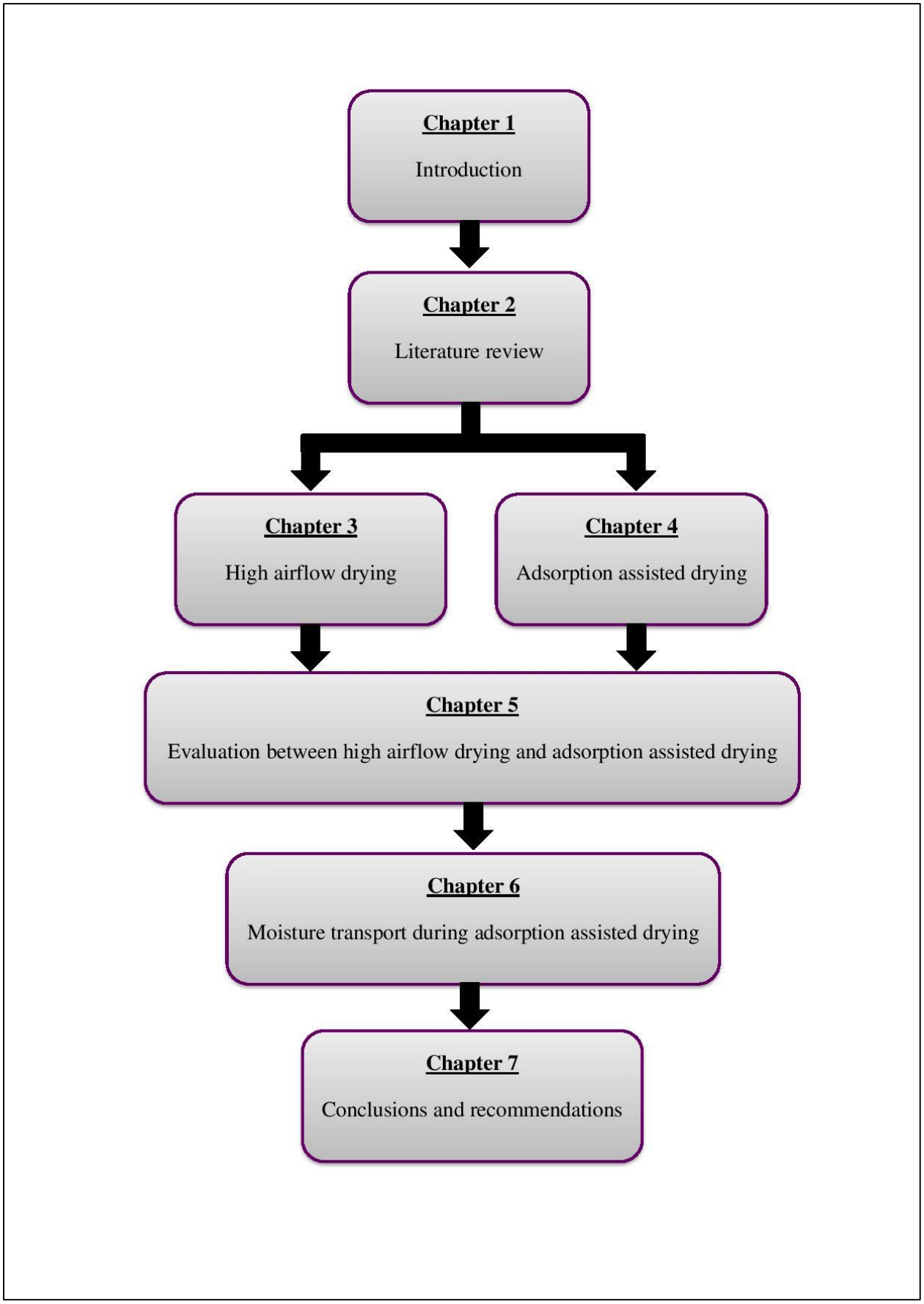



*Figure 1.1. Layout of thesis*

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# Chapter 2

## Literature review

This chapter provides an overview of coal formation as well as the coal constitutes and properties leading to moisture retention in coal. The different types of moisture associated with coal are classified and the accumulation thereof is discussed. A summary is given of commonly used dewatering and drying methods and the related moisture transfer mechanisms. The formation of the fine and ultra-fine coal fraction and the intrinsic properties leading to its high moisture retention is discussed. In conclusion, the removal of moisture by means of high airflow drying and adsorption drying is discussed as these methods are investigated in this thesis.

## 2.1. Overview of coal and associated moisture

Coal originated from an array of transformed plant and animal remains buried within the crust of the earth. The physical and chemical changes of these remains resulted in a fossilised rock containing a high carbon content (Falcon & Ham, 1988). The properties and composition of this fossil fuel vary considerably from one region to another (Osborne, 1988). The environment, climate, historic geological events and the type of remains all contribute to the heterogeneous nature of coal (Falcon & Ham, 1988). Coal can be classified according to three main categories: macerals, minerals and associated moisture. Section 2.1.1 and Section 2.1.2 discusses the maceral and mineral content, respectively. The moisture content associated with the maceral and mineral content is discussed in Section 2.1.3.

### *2.1.1. Macerals*

Macerals refers to the array of organic components present in the coal structure (Miller, 2011). The organic material within the coal points to the type of animal or plant material the coal originated from (Falcon & Ham, 1988). Categorisation of these macerals constitutes a challenge as these macerals usually have a cross-section smaller than 100μm and are difficult to separate. Therefore, in situ petrographic methods are used to classify the type of macerals (Crelling, 1989).

- *Vitrinite*: This maceral was formed from the decaying of plant cell substances like wood, roots and bark (University of Kentucky, 2006). The chemical constitutes of vitrinite include polymers, lignin and cellulose found in these cell walls of the buried vegetation (Dow, 1977). Vitrinite is known for having a high oxygen content (Falcon & Ham, 1988).
- *Liptinite*: This maceral was formed from leaf cuticles, spores, pollens as well as resins. These materials contribute to the high hydrogen-rich hydrocarbons present in the liptinite (University of Kentucky, 2006). Liptinite is more often associated with coals with high volatility and disintegrates as coal matures. This maceral can easily be identified in the coal structure as it is present in the form of plant fossils that keep their original form (Falcon & Ham, 1988).
- *Inertinite*: This maceral consists predominately out of woody material, spores and fungal remains that were moulded by charring caused by thermal or biochemical oxidation. Fusinite and semifusinite both fall under this category and is identified as fossil charcoal (Crelling, 1989; Falcon & Ham, th them1988). Inertinite is the product of oxidation of other macerals and therefore contains a higher carbon and a lower hydrogen and oxygen content in comparison with them (University of Kentucky, 2006; Falcon & Ham, 1988).

Figure 2.1.2 shows shows a photomicrograph of two coal samples with a scale of 1cm = 100μm for each photomicrograph with petrographic analysis of inertinite and vitrinite rich coal samples. Vitrinite (V) appears as a medium or light grey; liptinite (L) as a dark grey. The inertinite including reactive semifusinite (RSF) and semifusinite (ISF) reflect as bright white (University of Kentucky, 2006).

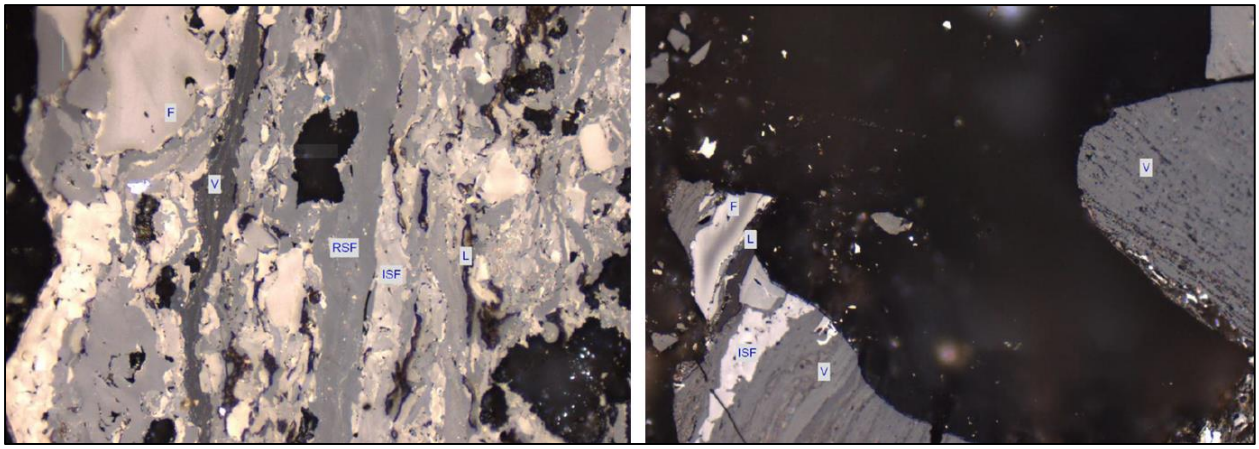


*Figure 2.1.2. Petrographic analysis of an inertinite-rich sample (left) and vitrinite-rich sample (right)*

The categorisation of the type of maceral in conjunction with the coal rank is used to determine the maturity of a coal sample (Crelling, 1989). Figure 2.1.2. illustrates the levels of coal maturity.

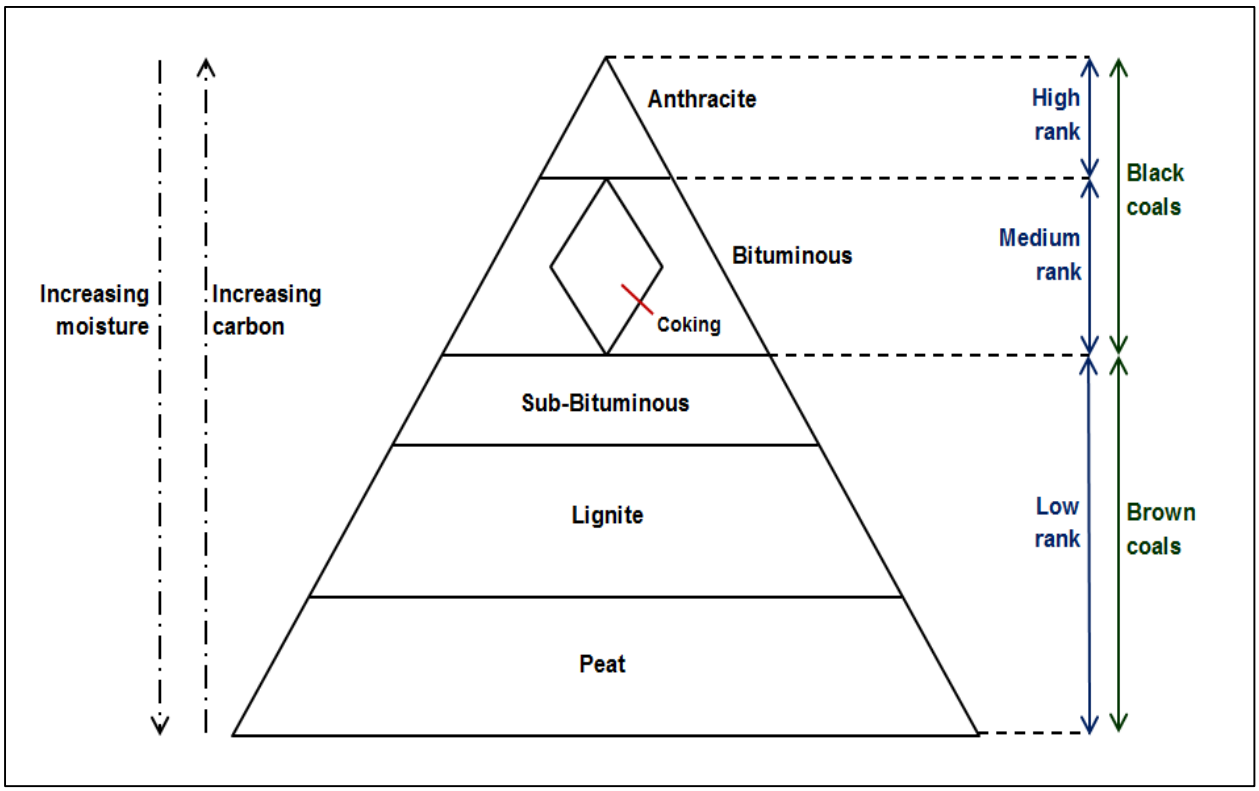


*Figure 2.1.2. Levels of coalification process, adapted from Osborne (1998)*

Coalification refers to the process where animal and plant remains are altered with time, pressure and temperature to form an increasingly carbon rich substance. These remains form peat can mature into lignite, sub-bituminous coal, bituminous coal or anthracite. An increase in the coal rank means an increase in the carbon or organic content of the coal with a more dense coal structure that is less porous (Falcon & Ham, 1988).

### *2.1.2. Minerals*

The coal structurally also contains inorganic material, which is referred to as the mineral matter content (Osborne, 1988). The typical minerals found in the structure can be classified as clay minerals, quartz as well as components containing oxides, nitrates, sulphides and carbonates (Harvey *et al*., 1983). Table 2.1.1 gives a summary of the properties of coal at different stages during the coalification process. The data were completed on a moisture and ash free (maf) basis.

*Table 2.1.1. Coal properties, adapted from Higman & Van der Burgt (2008) and NIST Chemistry WebBook (2017)*

| Type of coal | Ultimate analysis ($\%_{wt}$) | | | | Volatile matter ($\%_{wt}$) | Moisture ($\%_{wt}$) | Calorific value (kJ/kg) |
|---|---|---|---|---|---|---|---|
| | Carbon | Hydrogen | Oxygen | Nitrogen | | | |
| Wood  | 40-50 | 5-6 | 20-40 | 0-0.5 | - | 70-90 | < 15 |
| Peat  | 45-60 | 3.5-6.5 | 20-45 | 0.75-3 | 45-75 | 70-90 | ± 15 |
| Lignite  | 60-75 | 4.5-5.5 | 17-35 | 0.75-2 | 45-60 | 30-50 | ± 26.7 |
| Bituminous coal  | 75-90 | 4.0-5.5 | 20-30 | 0.75-2 | 11-50 | 10-20 | ± 36.1 |
| Anthracite  | 90-95 | 3-4 | 2-3 | 0.5-2 | 3.8-10 | 1.5-3.5 | ± 36.2 |

An increase in the rank and carbon content correlates with an increased calorific value of the fossil fuel. The ultimate analysis gives an indication that the volatile and array of mineral matter will decrease with an increase in the carbon content of a coal sample (Higman & Van der Burgt, 2008). Mineral matter can either be crystalline mineral particles included in the maceral or be found as dissolved salts in the pore water of the coal sample. As the coal rank increases, these dissolved salts will be removed along with the moisture that is pushed from the maceral (Ward, 2002). More mature coal will as a result contain less dissolved mineral salts and less of an overall inorganic constitutes (Higman & Van der Burgt, 2008). Higher ranked coal will therefore rather contain solid mineral constitutes (Ward, 2002).

Solid mineral matter can be classified either as intrinsic or extrinsic deposits. Intrinsic mineral matter was existent in the original plant and animal remains and was moulded within the carbon rich matrix (Ward, 2002). Extrinsic mineral matter is additional mineral matter that ends up in the coal sample during mining procedures. These minerals come from the floor and roof of the coal seam (Van Alphen, 2005). The mineral content determines the hardness and abrasiveness of the coal and results in pollution when coal is burned. Consequently, the mineral matter causes a decrease in the calorific value of coal and needs to be removed with beneficiation processes (Falcon & Ham, 1988).

### *2.1.3. Moisture*

An inherent fraction of moisture originated during the formation of coal and remains an integral part of the coal even after extraction from the ground (Hatt, 2003). The use of water for beneficiation processes on mines, also adds to the overall moisture content of the mined coal (Nkolele, 2004; Hatt, 2003). The moisture associated with coal can be interrelated to the macerals and minerals (Harvey *et al*., 1983).

- *Maceral associated moisture*: According to Osborne (1998) an increase in carbon content leads to a reduced moisture content. However, the moisture content cannot be directly linked to the organic maceral (Unsworth *et al*., 1988). It was established that it is rather the porosity in the coal structure that makes way for moisture adsorption (Rong & Hitchins, 1994). Capillary pressure and surface tension ensure that the moisture is locked in the pore network (Asmatulu & Yoon, 2012). The development of the coal structure brings forth a decrease in the moisture content as moisture is pushed away to form a more carbon-rich deposit (Hatt, 2003; Rong & Hitchins, 1994). As a result, the lower rank coal has a more porous structure with a tendency to adsorb more moisture (Falcon & Ham, 1988). The coal surface also has oxygen containing functional groups that makes way for water molecules to bind unto the surface of the coal macerals. (Allardice & Evans, 1971; Kaji *et al.*, 1986).
- *Mineral associated moisture*: The mineral matter acts as a hydrophilic site and retains moisture in the coal structure (Falcon & Ham, 1988; Van der Merwe & Campbell, 2002). A higher mineral matter content will therefore make provision for more moisture to be adsorbed (Van der Merwe & Campbell, 2002). According to McCutcheon & Barton (1999) the moisture adsorption capacity of mineral matter are 2.3 to 2.8 times higher compared to porous organic materials. The presence and quantity of mineral matter in a coal sample dictates the moisture levels in more mature coal. Clay is the biggest contributor to the total moisture content as it can contain a large amount of water in its lattice structure (Spears, 2000). Some clay material like the montmorillonite group has the ability to absorb water and swell to retain the water fraction. These swelling clay types have the ability to retain even more than twice the amount of moisture compared to non-swelling clay like illite and kaolinite (McCutcheon & Barton,1999).

## 2.2. Classification of moisture

The quantity and type of moisture associated with coal is dictated by the properties and constitutes of heterogeneous coal deposits (Petrick, 1969). The moisture can be classified according to the manner in which it is associated or bound to the coal particles (Karthikeyan *et al*., 2009). Figure 2.2.1 illustrates where the different types of moisture is located in and around the coal particles. The moisture is either classified as chemically bound to the coal particle, part of the inherent moisture content or moisture that moves freely.

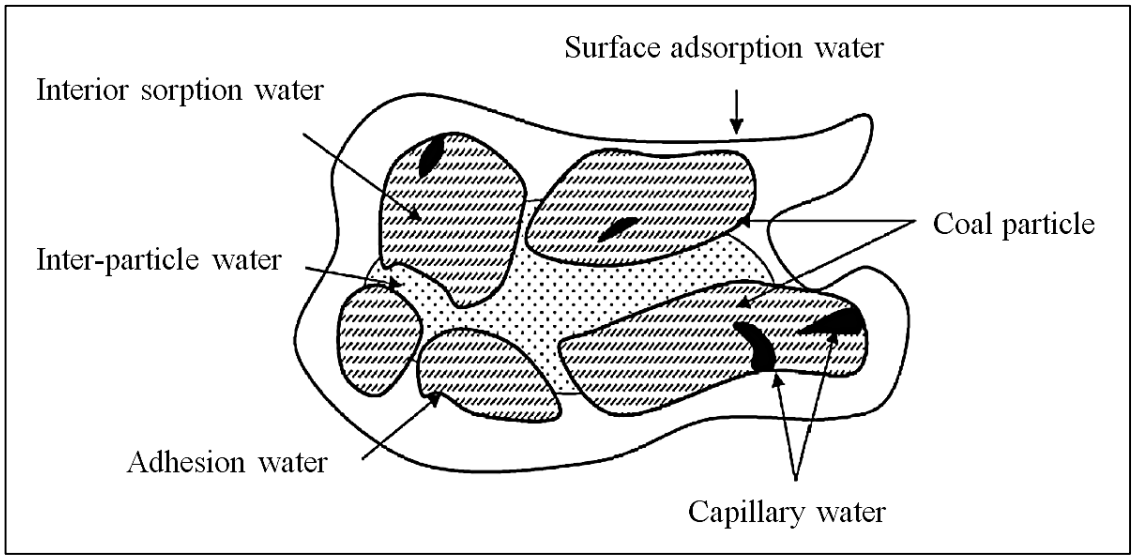


*Figure 2.2.1. Classification of moisture; adapted from Karthikeyan et al. (2009)*

### *2.2.1. Chemically bound moisture*

The interior sorption water forms part of the coal structure which is imbedded in the crystalline structure during formation (Karthikeyan *et al.*, 2009). Mechanical dewatering, thermal drying or advanced drying methods can't reduce this portion of water. Chemically bound moisture forms a part of the coal structure and is only removable by means of pyrolysis. For this reason, the chemically bound moisture is not included when determining the total coal moisture content (Buckley & Nicol, 1995; Campbell, 2006). The quantity of the chemically bound moisture content is influenced by the maceral and mineral content of the coal seam (Harvey *et al*., 1983).

### *2.2.2. Inherent moisture*

Inherent moisture is associated with a coal particle either by being bound internally (capillary water) or externally (adhesion water), as showed in Figure 2.1.1 (The Southern African Coal Processing Society, 2015; England, 1980). Inherent moisture is also referred to as capillary moisture or deemed as part of the moisture holding capacity of a coal particle (Wang, 2007). The internally bound moisture is found within

the pore network and cracks related to the coal particles (England, 1980). Capillary forces ensure that the internally bound moisture is entrained within the pore network (Asmatulu & Yoon, 2012). Surface tension and adhesion forces ensure that moisture adheres to the external surface of a coal particle and the internal surface of the pore network (The Southern African Coal Processing Society, 2015). This adhesion water forms a moisture film on the surface by binding unto the oxygenated surface functional groups (Strydom *et al*., 2015, Asmatulu & Yoon, 2012).

### *2.2.3. Free moisture*

Cohesion forces ensure that additional moisture can bind to the inherent moisture content of the coal particles (The Southern African Coal Processing Society, 2015). Hydrogen bonding makes it possible for additional layers of moisture to bind unto one another resulting in more moisture to accumulate (Du Preez *et al*., 2012). This accumulation of multilayers occurs in and around the coal particles and is relatively free to move. The surface adsorption water and interparticle water, showed in Figure 2.2.1, forms a part of the free moisture content (Karthikeyan *et al.*, 2009; Asmatulu & Yoon, 2012). Free moisture particularly accumulates in the voids found between coal particles in a heap (England, 2011).

## 2.3. Accumulation of moisture

A moisture gradient is created when dry coal particles are placed within an environment containing more moisture which will prompt the transfer of moisture to the coal particles (Petrick, 1969). The stages of accumulation of moisture are illustrated in Figure 2.3.1.

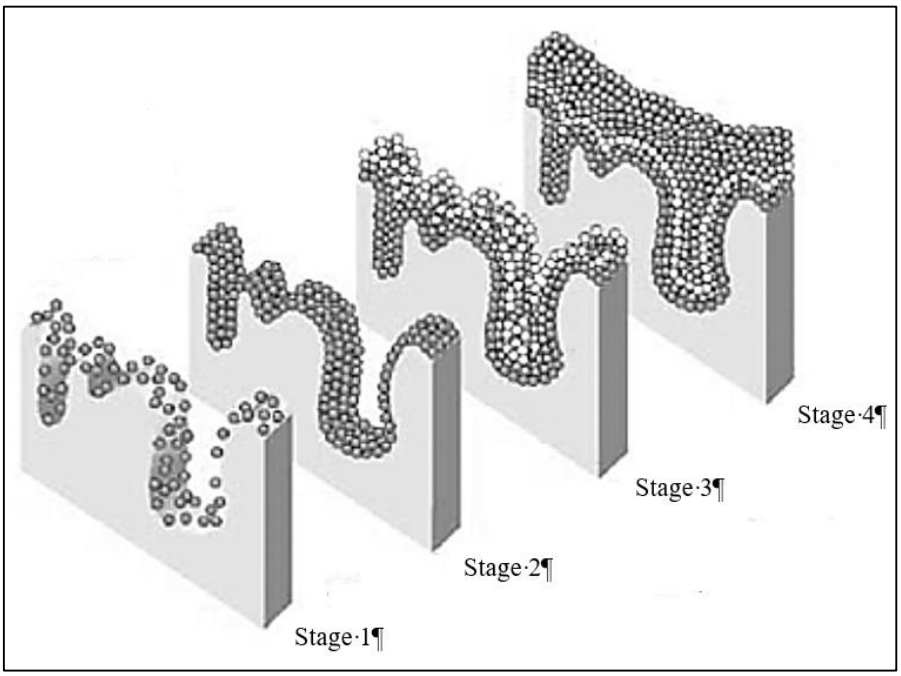


*Figure 2.3.1. Accumulation of moisture; adapted from Jasińska (2011)*

Moisture firstly binds unto isolated sites on the exposed coal surface. Water molecules with a polar nature have the tendency to bind to the oxygenated functional groups on the coal surface (Gregg & Sing, 1982; Rutherford & Coons, 2004). This portion of moisture is depicted as inherent moisture as indicated by stage 1 in Figure 2.3.1. The first stage makes it possible for more moisture from the environment to be transferred to the coal particle as the moisture on the isolated sites will allow for hydrogen bonding. This part of the moisture created by hydrogen bonds is classified as part of the free moisture. Hydrogen bonding will firstly cause a monolayer (stage 2) and subsequently a multilayer (stage 3) of moisture accumulating on the coal surface as seen in Figure 2.3.1. With a higher level of environmental moisture, the accumulated moisture will cover the particles and fill the porous network, as seen in stage 4 (Kaji *et al*. 1986; Charrière & Behra, 2010; Švábová *et al*., 2011). At this stage the moisture will also be retained in the voids between the coal particles in a heap (Condie & Veal, 1998). Table 2.3.1 illustrates different quantities of moisture in relation to coal particles in a heap.

*Table 2.3.1. Moisture related to coal particles in a heap; adapted from Université de Liège (2013)*

| Liquid content | State | Diagram |
|---|---|---|
| No | Dry |  |
| Small | Pendular |  |
| Middle | Funicular |  |
| Almost saturated | Capillary |  |
| More | Slurry |  |

When a small amount of water is added to dry particles, the particles will be in a pendular state. At these low moisture levels, lens-shaped liquid rings develop between the particles as a result of surface tension. As moisture accumulates, the air is displaced and the particles will be in a funicular state. Capillary state means that all the voids between the particles in a heap are filled with water. When all the air is displaced, the particles in a heap are depicted as almost saturated (Université de Liège, 2013, Jalil *et al*., 2013). Accumulation of moisture beyond the saturation capacity of particles in a heap, would lead to the formation of a slurry (Université de Liège, 2013).

## 2.4. Removing moisture from coal

The free and inherent moisture associated with coal samples can be removed by means of standard drying techniques, as discussed in Section 2.4.2 and Section 2.4.3. This can be achieved either by transporting the moisture away from the wet coal samples in the form of liquid or vapour.

### *2.4.1. Transfer mechanism*

The transfer of moisture can occur in the form of liquid, vapour or a combination thereof (Bianchi Janetti, 2012). Table 2.4.1 shows the driving forces initiating and causing moisture transfer.

*Table 2.4.1. Moisture transfer in porous material; adapted from Bianchi Janetti (2012)*

| Moisture type | Driving potentials | Transport phenomena |
|---|---|---|
| Liquid | Total pressure | Hydraulic flow |
| | Curvature pressure | Capillary suction |
| | Concentration | Surface diffusion |
| Vapour | Partial pressure | Vapour diffusion |
| | Temperature | Evaporation |
| | Total pressure | Convective flow |

- *Liquid*: Moisture in liquid form can be transported as a result of three possible transport phenomena: hydraulic flow, capillary suction or surface tension (Bianchi Janetti, 2012). The transport of liquid moisture is referred to as dewatering (Bennamoun *et al*., 2013). Applying a pressure gradient across a wet coal particle, will result in hydraulic flow as well as capillary suction in the internal pore network (Bianchi Janetti, 2012; Wakeman, 1984). A concentration gradient at the surface of coal particle will result in the transport of moisture from the higher to the lower moisture concentration (Bianchi Janetti, 2012; Petrick, 1969).
- *Vapour*: Moisture in vapour form can be transported as a result of three possible transport phenomena: vapour diffusion, evaporation or convective flow (Bianchi Janetti, 2012). Transporting moisture in vapour form is referred to as a drying technique (Bennamoun *et al*., 2013). Operating with a drying medium with a low partial pressure (low relative humidity) will prompt vapour diffusion (Nellis & Klein, 2012). Heat can be applied directly or indirectly to evaporate liquid from coal (De Korte & Mangena, 2004). Convective flow is driven by the moisture gradient caused from removal of vapour by means of a bulk fluid flow (Syahrul *et al*., 2002).

### *2.4.2. Removal of different types of moisture*

Figure 2.4.1 gives a summary of types of moisture associated with a coal particle at set conditions. There are a variety of methods available to reduce these different types of moisture content from the coal. These methods can be divided into two main categories according to the type of moisture it removes. While some techniques can only remove the free moisture, other techniques can remove the free moisture as well as the inherent moisture from the coal sample.

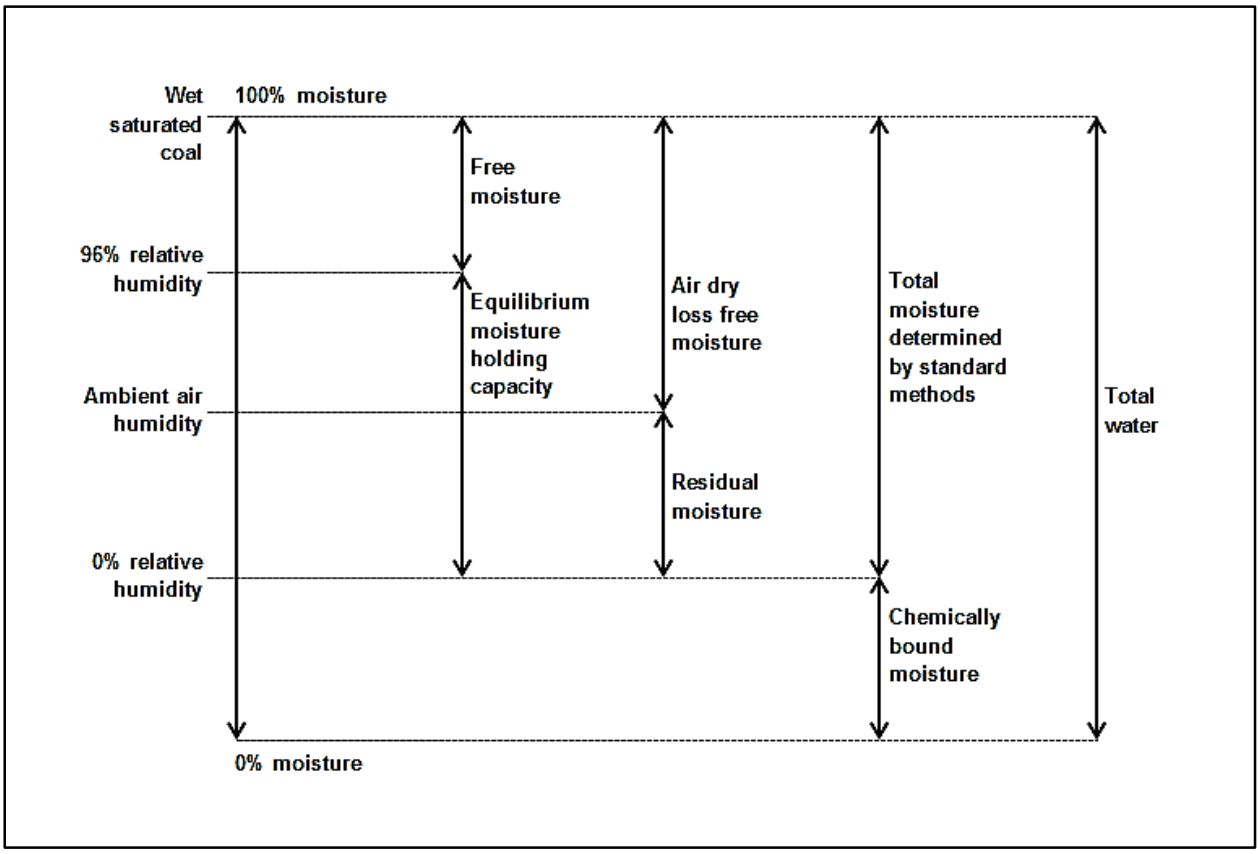


*Figure 2.4.1. Moisture associated with coal particles; taken from Buckley & Nicol (1995)*

- *Removal of free moisture*: The free moisture, indicated in Figure 2.4.1, includes the layers of moisture bound by hydrogen bonds filling the porous particle to form a saturated coal particle (Du Preez *et al*., 2012, Buckley & Nicol 1995). Free moisture also includes the excess water found in and around coal particles in a heap and water present when the coal is in a slurry state (Université de Liège, 2013). Free moisture is only bound with weak cohesion forces and can therefore easily be removed (The Southern African Coal Processing Society, 2015). Mechanical dewatering techniques are often used as an economical method to remove the majority of the free moisture content in liquid form. Vaporisation or chemical methods are also effective, however, it is not feasible to remove large amounts of moisture due to the higher cost of these techniques (De Korte & Mangena, 2004; Hand, 2000).
- *Removal of inherent moisture*: Figure 2.4.1 indicates that an equilibrium is reached when a coal sample is left in conditioned air with a temperature of 30˚C and 96% relative humidity (in accordance to ISO

1080). This is a pivotal point where a sample contains the maximum amount of inherent moisture and any additional moisture would be deemed as free moisture (Rong & Hitchins, 1995; Buckley & Nicol, 1995). Subjecting the coal sample to a relative humidity level lower than 96% will cause the particle to attain a new and lower moisture content. This is often referred to as the equilibrium moisture content or the limiting moisture content that a sample can have under specific temperature and relative humidity conditions. This is also the reason why the moisture content of a coal sample can vary according to the ambient air conditions or humidity level (Rong & Hitchins, 1995; Perry, 2007). The inherent moisture content can't be removed with mechanical dewatering techniques and requires a shift in the moisture equilibrium gradient to encourage evaporation or diffusion of moisture (Rong & Hitchins, 1995, Koretsky, 2004; Nellis & Klein, 2012).

### *2.4.3. Overview of dewatering or drying techniques*

- *Mechanical*: Mechanical dewatering techniques are often used to remove the excessive amount of free-flowing moisture by applying a pressure or concentration gradient across the wet coal sample. As a result, moisture in liquid form is easily shifted from the coal particles (Wakeman, 1984). Dewatering screens and centrifuges are commonly used to dewater coal particles larger than 0.25mm to required moisture levels. Vacuum or pressure filters are examples of mechanical dewatering technologies found in the industry to dry coal smaller than 0.25mm (Karthikeyan, *et al.*, 2009).
- *Vaporisation*: This process is described by the evaporation of moisture from the coal. High temperatures at or higher than the boiling point of water will cause the liquid to be vapourised, which will subsequently lead to increased vapour pressure of the moisture associated with the coal particles. When the vapour pressure is higher than the partial pressure of the surrounding drying medium, water will evaporate (De Korte & Mangena, 2004). The water in the form of vapour can then be removed by the drying medium (Syahrul *et al*., 2002). Heat is applied to induce evaporation either by means of convection or conduction (De Korte & Mangena, 2004). Examples of these thermal drying methods include rotary dryers, flash dryers, fluid bed dryers and dryers using super-heated steam or infrared radiation (Mohanty & Akbari, 2012; Wilson *et al.*, 1992). Moisture can also be removed by using a drying medium with a lowered partial pressure (relative humidity). The moisture is therefore transferred to the drying medium and is diffused into the surrounding air prompted by a moisture concentration gradient (Nellis & Klein, 2012).
- *Chemical*: Chemical drying techniques entail the addition of chemical media to assist dewatering. Methods using super adsorbents, gels or molecular sieves operate by shifting water from a wet coal sample to a drier medium (Mohanty & Akbari, 2012; Bratton *et al*., 2012; Hand, 2000). Flocculants and surfactants are also used to improve the settling of solids and altering the interface between the water and pore network to promote dewatering by removing liquid phase water at a faster rate (Nkolele, 2004; Asmatulu, 2001).

## 2.5. Coal fines and associated moisture

Mined coal is beneficiated after extraction to deliver a cleaner product containing less mineral matter (Dwari & Roa, 2007). Coal is generally classified and separated in different particle size ranges and processed separately to improve the efficiency of these beneficiation processes. Each mine may classify its coarse, intermediate, fine and ultra-fine particle size distributions differently (SANEDI, 2011). Table 2.5.1 gives a typical classification of these size ranges along with the resultant moisture content.

*Table 2.5.1. Particle size distribution; adapted from SANEDI (2011)*

| Classification | Particle size range (mm) | | Mass distribution | Moisture content (as received) |
|---|---|---|---|---|
| | Minimum | Maximum | | |
| Coarse | 12-15 | 100 – 250 | 61% | $5\%_{wt}$ |
| Intermediate | 1 | 12 | 28% | $9\%_{wt}$ |
| Fine | 0.1 – 0.5 | 1 | 7% | $13\%_{wt}$ |
| Ultra-fine | - | 0.1 – 0.15 | 4% | $27\%_{wt}$ |

Current mechanised mining and processing techniques are the main causes of the large production of fine and ultra-fine coal. Fine coal and ultra-fines can contain a moisture content of close to $30\%_{wt}$ depending on the particle size distribution and mineral matter content (Bourgeois & Barton, 1998; Hand, 2000). Table 2.5.1 indicates that around 11% of the mined coal contains a very large amount of water and the presence of these fines would indefinitely increase the overall moisture content of the mined coal, depending on the prior level of beneficiation of the fines (SANEDI, 2011). Even though the fines and ultra-fines are only a small cut of the total mined coal, it can contribute up to a third of the bulk moisture content (Mohanty &Akbari, 2012).

When fines are present in a coal product stream it would inevitably increase the total moisture and result in a lower calorific or burning value (Mangena *et al*., 2003). The moisture levels of these fines can't be reduced with mechanical dewatering methods, which are only adequate for lowering the moisture content in coarse coal (Reddick *et al.*, 2007). Consequently, the increased moisture contributes to higher processing and transport costs, while handling becomes more difficult as well (Firth & Swanson, 2002; Mangena *et al*., 2003). Fines and ultra-fines are usually separated from the coarser particle size distribution to avoid these operational difficulties and related costs. This finer fraction has calorific values similar to the run-of-mine coarser fraction, if it contains a low mineral matter content, and can therefore be a valuable resource if it could be dewatered cost-effectively (Reddick *et al.*, 2007).

The physical properties of the finer coal fraction enhance its ability to adsorb and retain high levels of moisture. Smaller particles have a greater surface area in bulk and the related surface tension ensures that more moisture adheres to the coal surface. These fine particles lump together in a filter cake and results in

small intra-particle radii. As a result, the increased capillary pressure ensures that the moisture is easily trapped in the filter cake (Toa *et al*., 2006). The finer coal size distribution has higher surface and capillary forces compared to the coarser fraction. As a result, fine coal and especially ultra-fine coal have the tendency to attract and retain much larger portions of water (Van der Merwe & Campbell, 2002).

## 2.6. Removing moisture from coal fines

Both thermal and mechanical drying techniques have an optimal particle size distribution and solid concentration, where moisture removal is more effective. Figure 2.6.1 shows these optimal regions for thermal drying and mechanical dewatering.

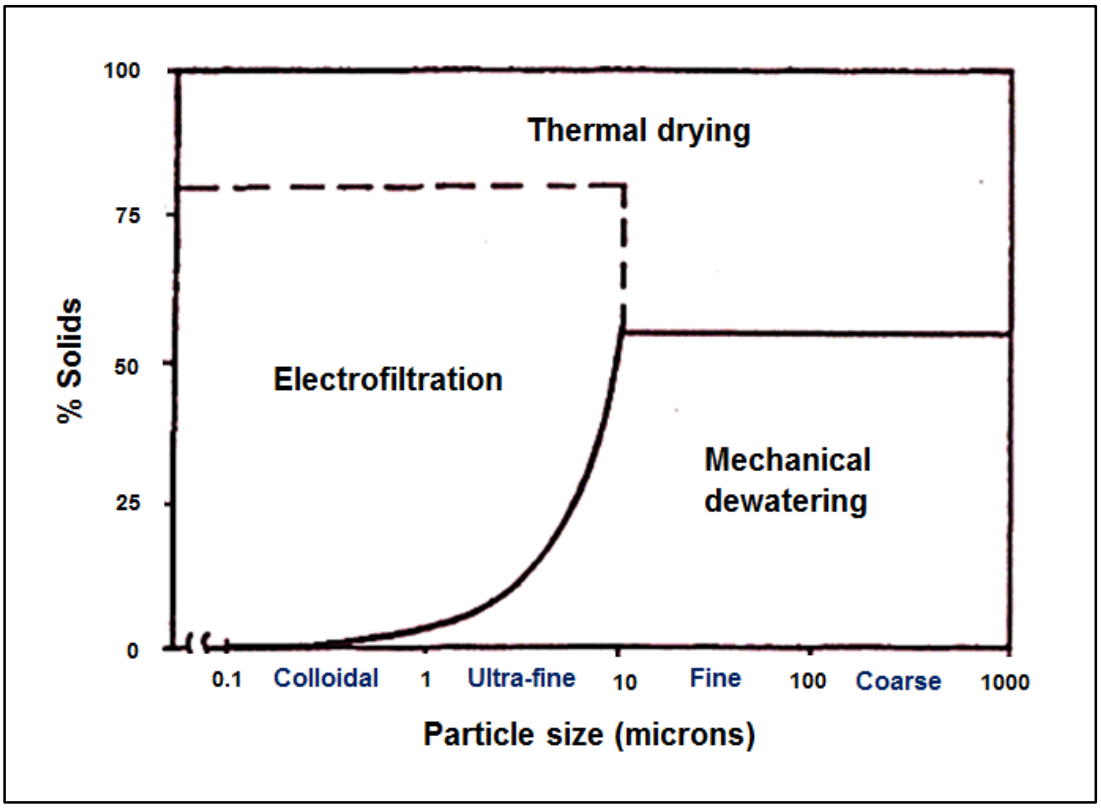


*Figure 2.6.1. Drying techniques for different particle size ranges; taken from Bourgeois et al. (2000)*

Mechanical dewatering is sufficient to lower the moisture content of coarse coal; however, the efficiency of mechanical dewatering methods reduces with the decrease in particle size (Campbell, 2006; Bourgeois *et al*., 2000). Mechanical dewatering can remove the moisture content of fine coal (+0.1 - 0.5mm) to about 15%$_{wt}$. When using mechanical dewatering methods for ultra-fine coal (-0.1mm), the moisture can only be reduced to about 25%$_{wt}$. Large volumes of water from the finer particle size distribution can therefore be reduced initially with mechanical methods, depending on the mineral matter, before resorting to thermal drying and advanced dewatering methods (Campbell, 2006; De Korte & Mangena, 2004; Hand, 2000).

Thermal methods are well known and very effective to deliver a coal product with low moisture levels (Reddick *et al*., 2007). According to Bourgeois *et al*. (2000) thermal drying is effective for the fine and ultra-fine coal fractions. However, thermal drying necessitates high energy cost and can be capital intensive. It is commonly accepted in the industry that the price of coal and environmental constraints do not justify the implementation of these thermal drying methods for neither run-of-mine nor clean coal (Reddick *et al*., 2007).

The scope of this study is to investigate alternative coal drying methods that can deliver a coal product with a low moisture content. The task is to obtain these results without relying on high temperatures to reduce the coal moisture content. High airflow drying and adsorption assisted drying were identified and investigated in this study. An overview of these technologies is given in Section 2.7 and Section 2.8, respectively.

## 2.7. High airflow drying

A fluidized bed operated with air is used in this study to investigate the efficiency of high airflow drying. Dense medium fluidized beds are generally used in industry to suspend a sample in the upflowing air and subsequently separate the particles according to its density to beneficiate and destone a sample (Luo & Chen, 2001). A typical representation of a fluidized bed can be seen in Figure 2.7.1.

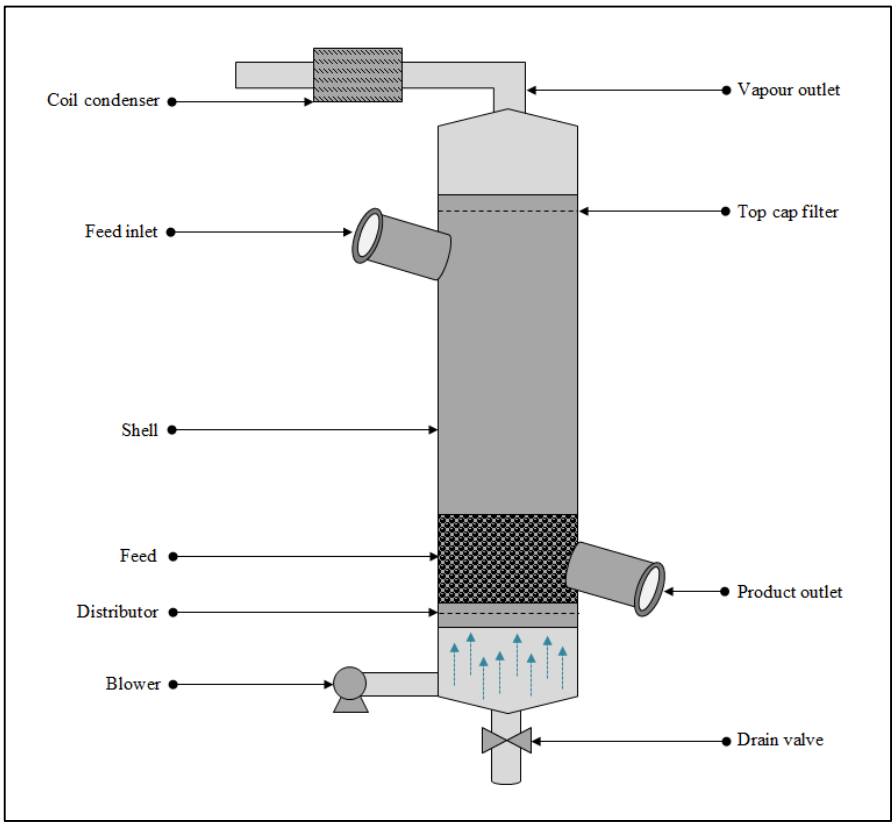


*Figure 2.7.1. Diagram of a typical fluidized bed*

High airflow drying in a fluidized bed uses the fluidizing air as the drying medium. The air or gas is blown in an upward direction and distributed evenly across the vessel. Introducing a constant airflow will cause the moisture to be carried away from the wet coal feed sample into the unsaturated capacity of the drying air. As the bulk coal sample gets drier, the top layers of the sample will separate from the bulk and get caught up in the air (Syahrul *et al*., 2002). At a bulk moisture content of between 5-7%$_{wt}$, the entire sample will be fluidized (Van Rensburg, 2014). The solid particles in the feed will get caught up and suspended in the upflowing air, breaking away from one another (Rhodes, 2008). As the coal particles is suspended in the fluidizing air, there is sufficient contact between the wet coal particles and the surrounding air to encourage further moisture transfer (Syahrul *et al*., 2002).

Moisture transport in the high airflow fluidized bed is initiated by the unsaturated nature of the drying air, which will prompt moisture to move from the wet solid to the drying air (Barbosa de Lima *et al*., 2016). The continuous airflow ensures that a constant flow of unsaturated air is in contact with the wet coal, leading to a continuous moisture transfer (Nellis & Klein, 2012). Figure 2.7.2 illustrates how drying air penetrates the wet bulk coal.

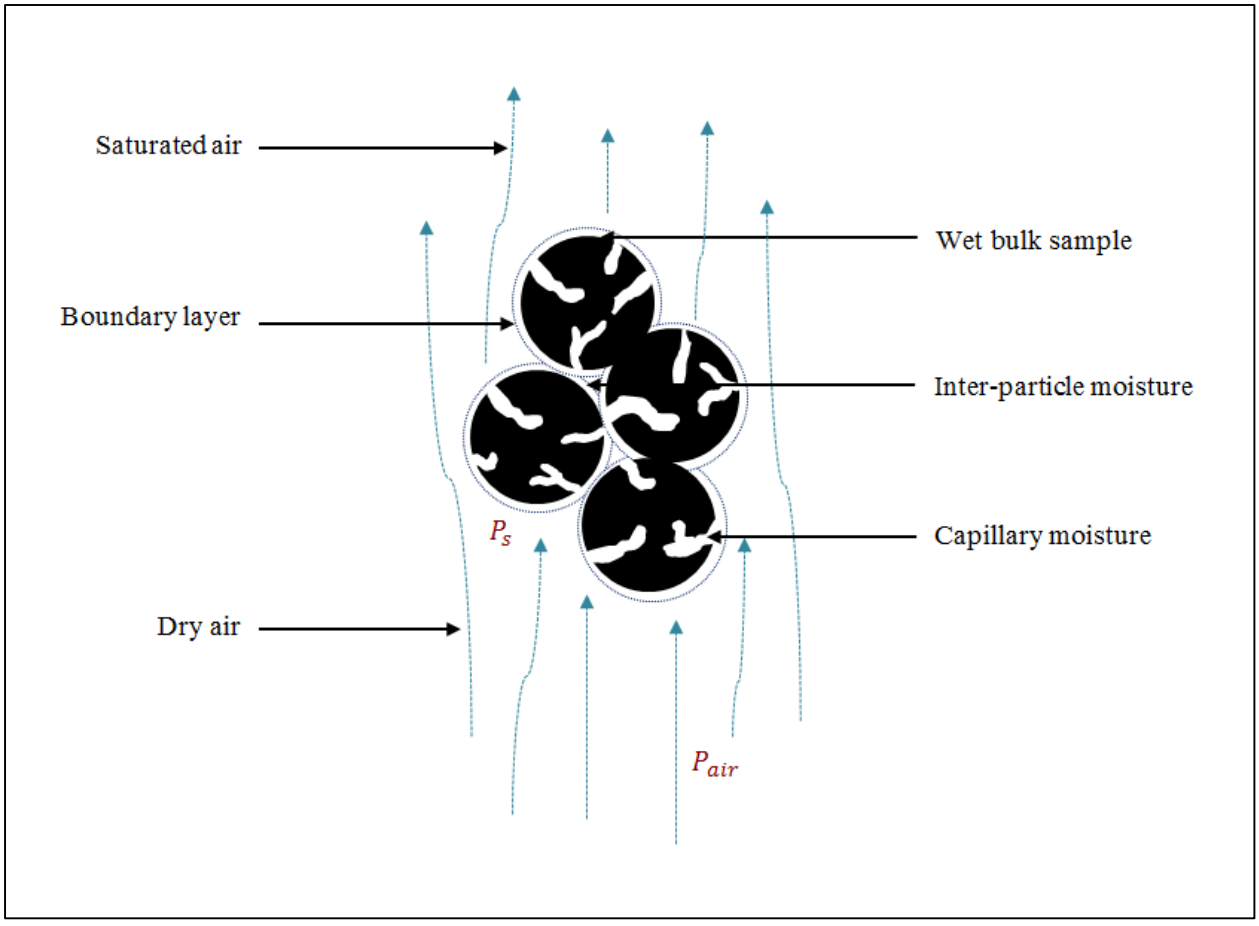


*Figure 2.7.2. Diagram of a high airflow through a wet coal sample; adapted from Barbosa de Lima et al., (2016)*

The moisture content in the drying air correlates to the partial pressure of water vapour in the air phase ($P_{air}$). The moisture associated with the wet coal sample occupies the interparticle voids and boundary layers surrounding the individual particles. The accumulated moisture contributes to the vapour pressure at the surface of the wet bulk sample ($P_s$). Moisture transport occurs when the partial pressure of the water vapour in the drying air is lower than the vapour pressure of the water vapour surrounding the wet bulk sample ($P_{air}<P_s$). Flowing air facilitates the removal of the boundary layer moisture from the wet surface. When this boundary layer of moisture is removed from the sample, the vapour pressure at the surface is lowered, which in return creates a moisture gradient between the exposed surface of the sample and the inner capillaries of the sample containing more moisture. Moisture will therefore be transferred from the capillary network and voids between the particles in the inner bed depth to the exposed surface of the sample, and, in due course, forming a new boundary layer of moisture that can also move towards the unsaturated drying medium (Barbosa de Lima *et al*., 2016).

Changes in the partial pressure or vapour pressure will disturb the moisture equilibrium between the wet bulk sample and the drying air. The following conditions will influence the moisture transport (Barbosa de Lima *et al*., 2016).

- *Partial pressure of drying air*: When the drying air has a low moisture content, it also means that the partial pressure of the air would be low. This forms a greater moisture concentration gradient between the air and high moisture content associated with the bulk coal sample, leading to moisture moving from the boundary layer of the coal sample to be captured in the drying air (Barbosa de Lima *et al*., 2016). Diffusion describes this mass transfer taking place as a result of the moisture concentration gradient formed (Nellis & Klein, 2012). Both the relative humidity and airflow rate of the drying medium influences the partial pressure of the air phase ($P_{air}$). Lowering the relative humidity of the drying air means that there will be less moisture present in the air surrounding the wet bulk sample. The larger moisture concentration gradient between the drying medium and the wet coal sample will encourage increase moisture transport at a faster rate. A higher airflow rate will ensure that the saturated air is continuously replaced with dry air at a fast rate. In return the frequent renewed low partial pressure of the air phase will continually create a large moisture concentration gradient to prompt moisture transport (Barbosa de Lima *et al*., 2016).
- *Vapour pressure at the surface of the wet bulk sample*: When increasing the temperature of the drying air, the temperature and pressure of the whole system will increase. Heated air will have a lowered relative humidity and increased capacity for moisture uptake, as described above. In addition, the high temperature can result in an energy exchange and transferal of heat to the wet sample. In such a case, the internal vapour pressure of the moisture associated with the bulk coal sample will also increase as moisture evaporates. The boundary layer moisture will then move to the drying capacity of the surrounding air phase, when the vapour pressure exceeds the partial pressure of the drying air (Barbosa de Lima *et al*., 2016).

The drying process with high airflow can be divided into three stages: initial period, constant rate period and falling rate period. These stages can be seen in the general drying curve, illustrated in Figure 2.7.3.

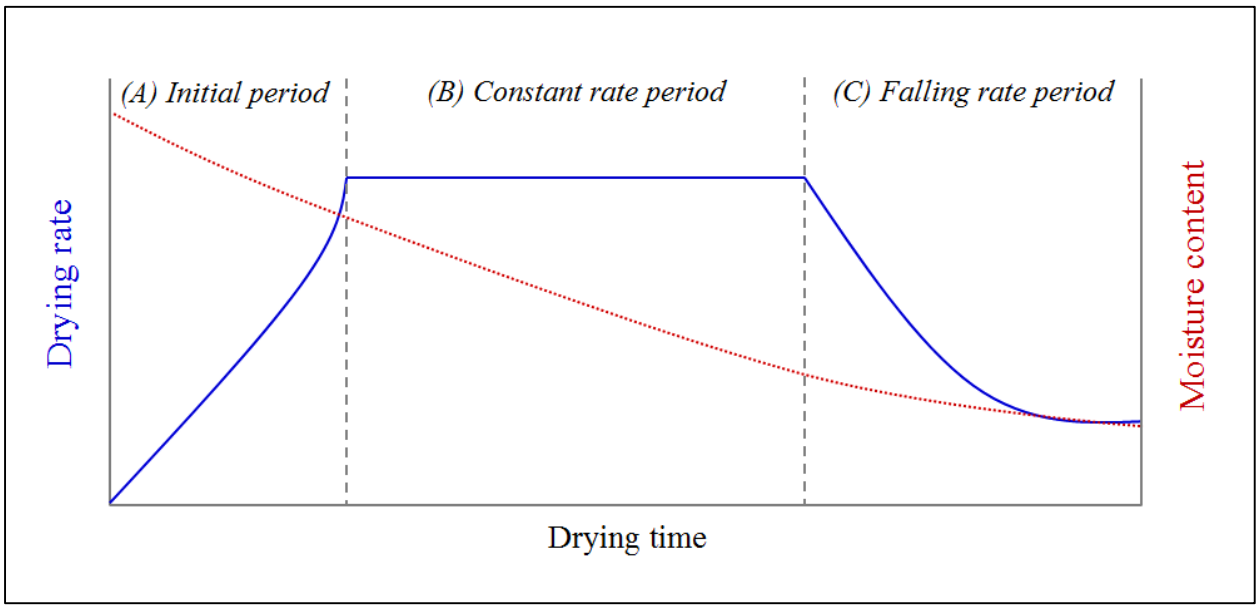


*Figure 2.7.3. General drying curve; adapted from De Korte & Mangena (2004)*

- *Initial period*: During the first stage of drying, the bulk coal sample is initially subjected to dry airflow, resulting in a large moisture concentration gradient. The large initial moisture content associated with the coal sample will also include ample free moisture that can easily be removed, contributing to a rapid initial moisture transport rate in the beginning of the drying process (De Korte & Mangena, 2004). Lowered partial pressure of the drying air will then ensure a faster drying rate in the initial period (Barbosa de Lima *et al*., 2016).
- *Constant rate period*: In the constant rate period the free moisture associated with the bulk coal sample is removed, but at a constant rate. The concentration gradient between the wet bulk coal sample and the drying air remains constant, while additional moisture is removed. During this stage, interparticulate moisture moves to the boundary layer where it can be removed and captured in the upflowing air. In other words, the boundary layer moisture removal at the surface as well as the internal moisture transfer is sufficient to keep the surface saturated to maintain a constant moisture transfer rate (Srikiatden & Roberts, 2006). The constant rate period will continue until all the free moisture or unbound moisture is removed (Barbosa de Lima *et al*., 2016).
- *Falling rate period*: The drying rate slows down when the drying air removed the free moisture and now has to remove the bounded moisture from the coal particles. The exposed surface of the coal sample is not saturated and consequently the interior moisture transport rate towards the surface is slower than the ability of the drying medium to remove the boundary layer (Srikiatden & Roberts, 2006). The capillary moisture thus requires time to move to the exposed surface or boundary layer to be carried away by the drying air, which slows down the drying rate (De Korte & Mangena, 2004).

The liquid bound to the particles are in state of low free energy and held as a result of the coal properties (Tsotsas *et al*., 2005; Srikiatden & Roberts, 2006). Drying takes place until the equilibrium moisture content is reached, which means that the partial pressure of the air phase and the vapour pressure at surface of the coal particles are equal (Barbosa de Lima *et al*., 2016). More moisture will only be forced from the capillary network when the vapour pressure of the drying medium is lowered. Therefore, changes in temperature, relative humidity and airflow rate of the drying air are able to form a new moisture gradient to disturb the phase equilibrium to promote further moisture transport during the falling rate period (Koretsky, 2004).

## 2.8. Adsorption assisted drying

This drying technique relies on the porous sorbent material to initiate moisture transfer from the wet coal sample to the surface and pore network of the adsorbent. Ceramic is often used as an adsorbent as this inorganic solid has a great affinity for water (Li *et al*., 2006; Lin *et al*., 2012). Ceramic has a hydrophilic and hygroscopic nature, making adsorption of liquid and water vapour possible (Almatus, 2017). During the production phase, the activated alumina is dehydrated to leave open active sites for water molecules to attach to the surface of the sorbent (Honeywell UOP, 2011). This sorbent material is manufactured to have interconnected cavities with a specific porosity and pore diameter to retain moisture (Honeywell UOP, 2011; Knaebel, 2006).

Porous ceramic spheres are combined with the wet coal fines in a rotary bed to investigate adsorption assisted drying in this study. A typical representation of a rotary bed can be seen in in Figure 2.8.1.

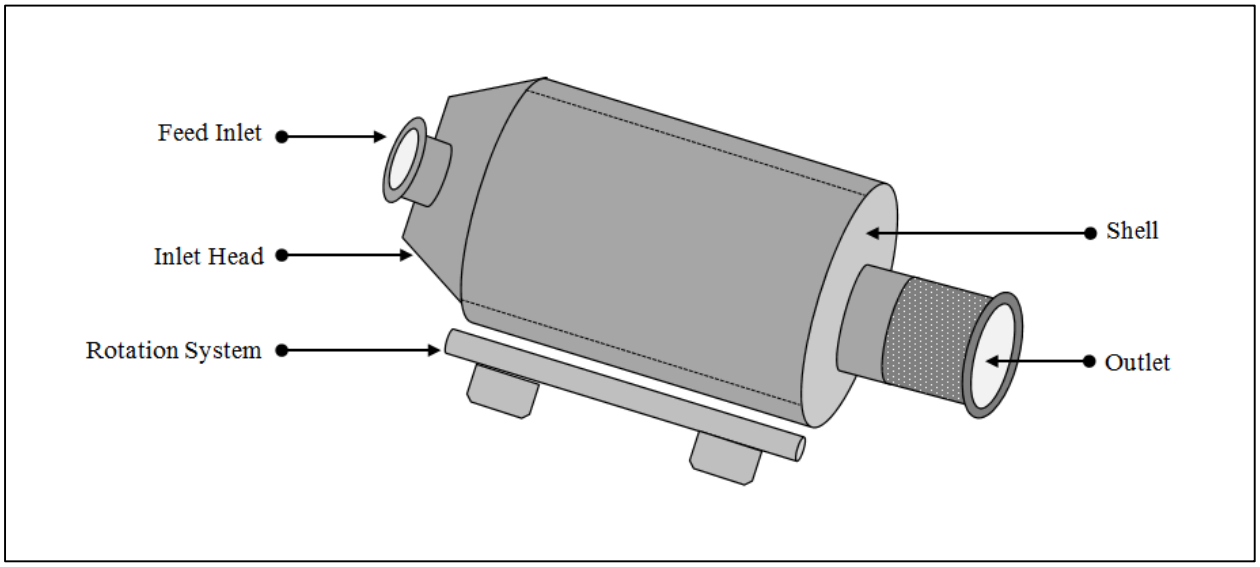


*Figure 2.8.1. Diagram of a rotary bed adsorber*

Figure 2.8.2 illustrates adsorption assisted drying, where moisture is removed from the wet coal particles (Mechanism A) to adhere to the sorbent material (Mechanism B).

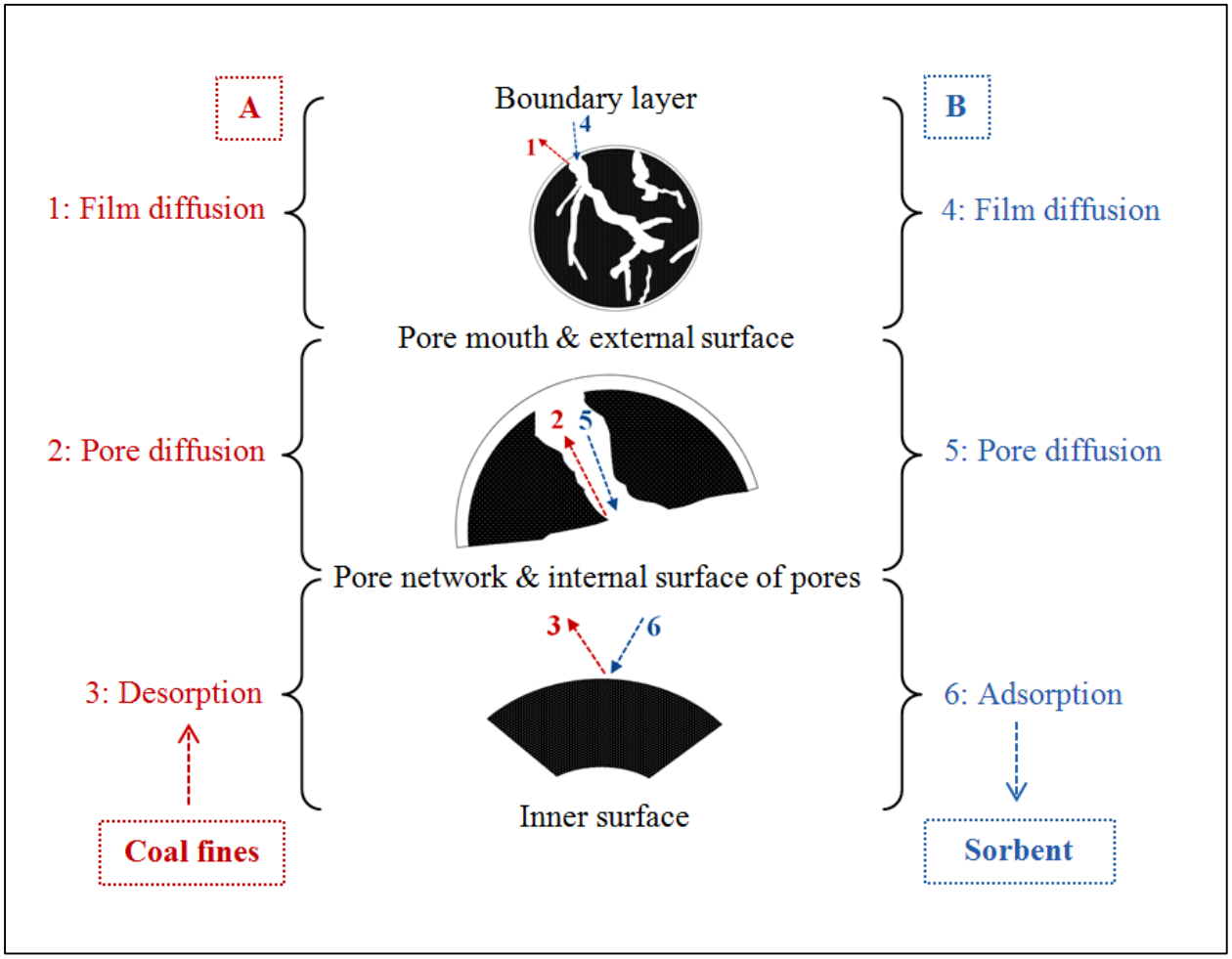


*Figure 2.8.2. Diagram of adsorption assisted drying; adapted from Dittmeyer & Emig (2008)*

The dewatering of coal by means of adsorbent assisted drying, occurs as a result of two simultaneous mechanisms, as indicated in Figure 2.8.2.

- *Mechanism A*: A large moisture concentration gradient is formed between the dry sorbent material and the wet bulk coal sample when brought into contact (Kudra & Mujumdar, 2009). Free moisture associated with the wet coal can easily move to be adsorbed by the sorbent material. Interparticulate and adhesion moisture forming part of the boundary layer moves to the sorbent material (Lin *et al*., 2012). As the boundary layer is displaced, additional moisture form the external surface areas of the coal particles moves to refill the boundary layer. This process is referred to as film diffusion as can be seen in Figure 2.8.2(1). The newly formed moisture concentration gradient encourages pore diffusion (2) and thereafter desorption from the inner sorbent surface (Klaewkla *et al*., 2011).

- *Mechanism B*: The moisture adsorbed from the wet coal bulk initially forms part of the boundary layer of the sorbent material. Film diffusion (4) causes the boundary layer moisture to move to the pore mouth opening and external surface areas of the sorbent material. Additional moisture transfer from the wet coal particles is encouraged when the boundary layer surrounding the sorbent material is removed. Pore diffusion (5) is referred to as the process where the moisture is transported into the pore network of the sorbent spheres. The final stage is the adsorption (6) of moisture unto the inner sorbent surface (Klaewkla *et al*., 2011). The binding or adsorption of water to the sorbent surface can be classified as three sequential stages, shown in Figure 2.8.3: chemisorption, physisorption and thereafter capillary condensation.

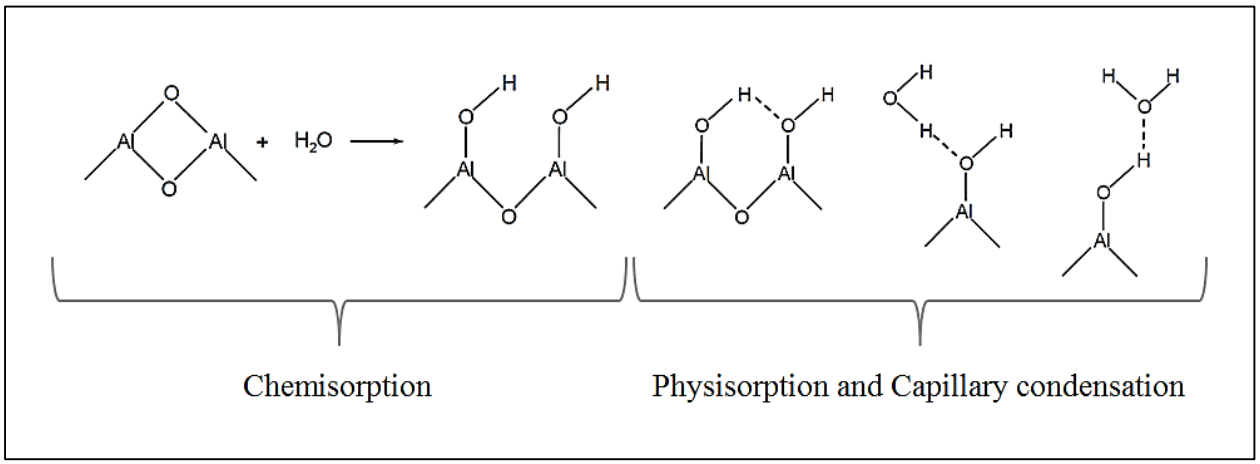


*Figure 2.8.3. Stages of moisture transport; adapted from Ducreux & Nedez (2011)*

The sorbent material has open sites on the outer surface available for moisture adsorption (Honeywell UOP, 2011). Figure 2.8.3 shows how water molecules dissociate, resulting in the H-atoms binding to the open O-atoms and the O-atoms binding to the Al-atoms. During chemisorption, the open oxide sites are filled to form the first layer of moisture (Ducreux & Nedez, 2011). Physisorption refers to the formation of additional layers of moisture that are bound to the first layer by means of cohesive Van der Waals forces (Almatus, 2017). Equilibrium is reached when the partial pressure of the surrounding moisture is equal to the partial pressure inside the sorbent particles. Increasing the partial pressure of the surrounding moisture will result in added layers of moisture, labelled capillary condensation (Ducreux & Nedez, 2011).

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# Chapter 3

## High airflow drying

This chapter is dedicated to introducing high airflow drying as a means to dewater fine coal. The papers presented in Chapter 3 describe the moisture related to fine coal and the moisture transfer when operating within a high airflow fluidized bed. This chapter firstly aims to determine the influence of a range of parameters on the dewatering rate and fine coal product moisture. Secondly, the study intends to determine the energy consumption of the fluidized bed and comparing its efficiency to drying technologies used in industry

## 3.1. Purpose and outline

Work completed at North-West University by Le Roux & Campbell (2003) established that a vacuum filter produced a drier filter cake when allowing for an increase in airflow through the cake, even at the expense of the applied pressure differential. In addition, it allowed for an increase in the rate of dewatering. The main focus of Chapter 3 is to examine and elaborate on the possibility to dry wet coal fines by means of high airflow. Extensive test work was completed in a high airflow fluidized bed and the results were presented in the form of two peer-reviewed journal articles and two papers published in conference proceedings.

- Paper 1 entitled "Fine coal dewatering using high airflow" compared coal drying in a fluidized bed using high airflow. The paper focused on establishing the benefit that high airflow has on the dewatering rate and final coal product moisture content. Driving forces aiding the dewatering capabilities of the fluidized bed were investigated. These parameters included temperature, relative humidity and airflow rate.
- Paper 2 entitled "Drying of fine coal using air in a fluidized bed" compared temperature, relative humidity and airflow rates to establish the best operating parameters within the set boundaries. The test work was completed on different coal samples, containing a variation in composition, quality and rank. In addition, the paper aimed to establish whether high airflow drying is feasible by comparing the energy requirement needed to dewater the coal versus the increase in calorific value of these dried coal fines. Lastly the energy requirements of the high airflow fluidized bed were compared to thermal drying technologies used in industry.
- Paper 3 entitled "Air drying of fine coal in a fluidized bed" defined the types of moisture related to fine coal and describes the dewatering process when operating with high airflow. The paper focussed on the determination of the dewatering efficiency of the high airflow fluidized bed on different fine coal size fractions. Thereafter the energy consumption for these operating conditions was compared to the energy consumption of other thermal drying technologies.
- Paper 4 entitled "Drying of fine coal using warm air in a fluidized bed" summarised all the experimental work completed on the high airflow fluidized bed. The results were compared by evaluating the dewatering rate, the moisture content of the fine coal product and the energy consumption during operation.

Additional information regarding the operating temperatures is given at the end of Chapter 3. A larger range of temperatures was investigated to establish the optimum temperature aiding improved dewatering capabilities of the high airflow fluidized bed. The challenges and possibilities to dewater finer coal particle size ranges were investigated.

## 3.2. Fine coal dewatering using high airflow (Paper 1)

This section describes the contributions made by the authors in completion of the paper titled "Fine coal dewatering using high airflow". General information is listed regarding the published paper along with information about the peer-reviewed journal.

### *3.2.1. Contribution by authors*

Miss M.J. van Rensburg was a postgraduate student completing a study of this work under the supervision of Prof. M. le Roux and Prof. Q.P. Campbell. The scope and rationale behind this study were formulated by Prof. M. le Roux and Prof. Q.P. Campbell. The experimental setups were designed by Miss van Rensburg and built by the technical support staff from the North-West University, in conjunction with Miss van Rensburg. Miss M.J. van Rensburg was responsible for completing experimental work, data recording and further calculations. The results and discussion of the experimental work presented in this paper came forth out of consultation between Miss M.J. van Rensburg, Prof. M. le Roux and Prof. Q.P. Campbell. The content of this paper was presented by Prof. M. le Roux at the XVII International Coal Preparation Congress (ICPC). The conference took place in Turkey, Istanbul on the 1$^{st}$ to the 6$^{th}$ of October 2013. Thereafter the work was revised and published in a peer-reviewed journal, written by Miss M.J. van Rensburg and edited by Prof. M. le Roux and Prof. Q.P. Campbell.

### *3.2.2. General information*

Information regarding the published paper is listed in Table 3.2.1.

*Table 3.2.1. Fine coal dewatering using high airflow (paper 1): General information*

| Category | Information |
|---|---|
| Paper name | Fine coal dewatering using high airflow |
| Authors | Le Roux, M., Campbell, Q.P. & Van Rensburg, M.J. |
| Journal | International Journal of Coal Preparation and Utilization, 34:220–227 |
| Year | 2014 |
| Copyright | ©Taylor & Francis Group, LLC |
| ISSN | 1939-2702 (Online) & 1939-2699 (Print) |
| DOI | 10.1080/19392699.2014.869939 |

# Fine coal dewatering using high airflow

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## *Abstract*

Fluidized bed drying is currently receiving much attention as a dewatering option after the beneficiation of fine coal. Apart from concerns about safety and combustion, the operating costs can be high if very high gas or air temperatures are used. The aim of this study was to investigate the removal of moisture from fine coal by using air at a lower temperature (25˚C-40˚C) within a controlled environment by lowering the relative humidity of air. It was firstly proven that fluidization has a major advantage over normal static beds when allowed to reach equilibrium. Hereafter, several parameters that influence the dewatering rate and final moisture content were tested, from which it was concluded that the relative humidity of air acts as the largest driving force for dewatering. It was, therefore, shown that this is a viable technology for the dewatering of fine coal.

*Keywords*: Dewatering, Drying, Fine coal, Fluidized bed, Warm air

## *Introduction*

Fine coal (defined in this article as between 1mm and 2 mm) is difficult to dewater and can contain a total moisture content of higher than 25%$_{wt}$ even after filtration (Le Roux & Campbell, 2003). This high-moisture content causes problems in handling as well as a decrease in the calorific value of the coal. An added disadvantage of a high moisture content is an increase in transportation and port costs. The difficulty in dewatering often leads to fines being discarded onto discard dams or being blended, as is, to the course beneficiated fraction. Such a blend will decrease the quality of the final product by increasing the final product moisture. Developing feasible fine coal beneficiation processes can result in potential revenue and, at the same time, reduce environmental problems (Reddick *et al*., 2007). Fluidization is proving to be one such option in beneficiating fine coal.

However, research conducted at North-West University found that elevated moisture content in the feed decreases the efficiency of the process (Terblanche, 2011). There are several methods to reduce the moisture content in fine coal, for example, pressure filtration, centrifuging, and thermal drying. Thermal drying remains the most effective water-reduction technique but the price of coal inhibits the use of thermal drying methods to dewater unbeneficiated coal (Reddick *et al*., 2007). Mechanical dewatering is generally incapable of delivering the required moisture levels, especially for coal fines. Previous work on vacuum filtration by Le Roux & Campbell (2003) yielded an increase in the dewatering capabilities of filter when the operational philosophy thereof was moved from a high-pressure differential that causes low airflow, to a low-pressure high-airflow regime.

### *Background*

Equilibrium moisture is defined as the moisture content of coal subjected to a specific temperature and humidity (these conditions are defined as 30°C and 96% relative humidity according to ISO 1080 [International Standards Organisation]). This moisture reports as intra-particulate moisture and as films on the surface of the particles and cannot be removed by mechanical methods. It needs to be evaporated from the particle. The amount of equilibrium moisture changes according to the changes in atmospheric conditions (Rong & Hitchins, 1995). Phase equilibrium between liquid and vapour is a state where the rate of evaporation from the liquid phase is the same as the rate of condensation of the vapour. Changes in the driving forces like temperature and partial pressure (defined as relative humidity) can disrupt the vapour-liquid equilibrium. Figure 3.2.1 illustrates how these driving forces lead to a change in the thermodynamic state of the pure substance.

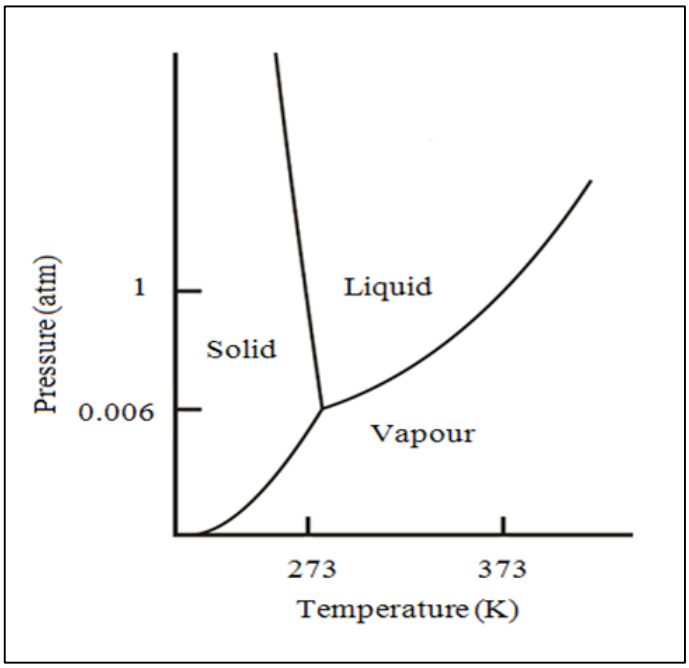


*Figure 3.2.1. Phase diagram of water*

Figure 3.2.1 shows that even slight increases in the temperature of the system, at constant pressure, may result in an equilibrium change between the liquid and the vapour, which will lead to the phase change of liquid to vapour. The phase change is driven by an increase in the vapour pressure of the water surrounding the coal particles to become higher than the partial pressure of the vapour fraction in the warm air (Koretsky, 2004). By replacing the newly formed vapour with drier (less moist) air, the system equilibrium is again disturbed causing some of the remaining liquid to again undergo a phase change to vapour. The system will move to a new equilibrium point where the liquid in the coal particle is in equilibrium with the vapour fraction of the dry air. This is defined as the irreducible equilibrium point of the specific water-air system. Solid particles in a fluidized bed behave like a fluid when suspended in the upward flowing medium. Therefore, drying in a fluidized bed is achieved by fluidizing the solids by means of the drying medium, in

this case, warm air. The water vapour is ultimately captured by the drying capacity of the up flowing warm air and transferred away from the wet solid particles (Syahrul *et al*., 2002). This sets in motion the process described in the paragraph above.

### *Material and Methods*

Bituminous coal from the Waterberg coal field in the northern Limpopo province of South Africa was used in the study. The results of the proximate analysis are given in Table 3.2.2.

*Table 3.2.2. Proximate analysis results (air-dried basis)*

| Test | Value |
|---|---|
| Moisture ($\%_{wt}$) | 1.8 |
| Ash ($\%_{wt}$) | 53.5 |
| Volatile matter ($\%_{wt}$) | 21.7 |
| Fixed carbon ($\%_{wt}$) | 23.1 |

Each sample consisted of 100 g of coal with a particle size range of +1mm-2mm. Before drying, some samples were conditioned in a climate chamber at a temperature of 25 °C and a relative humidity (RH) of 80% for two hours to reach its equilibrium moisture content at those conditions, while others were drenched in water and filtered to a total moisture content between 20–25$\%_{wt}$.

The experimental work focused on studying the changes in the equilibrium moisture content of the coal under air-varying relative humidity conditions, both for static nonfluidized bed and fluidized bed conditions. All the experiments were carried out with warm air ranging between 25 °C at 40 °C, which is slightly higher than the usual ambient temperature in South Africa. The first part of the experimental work was completed in a controlled climate chamber with the coal in a static nonfluidized state, while the second part was carried out using a fluidized bed at just over minimum fluidization velocity. Figure 3.2.2 is a schematic diagram of the experimental setup for the static bed tests.

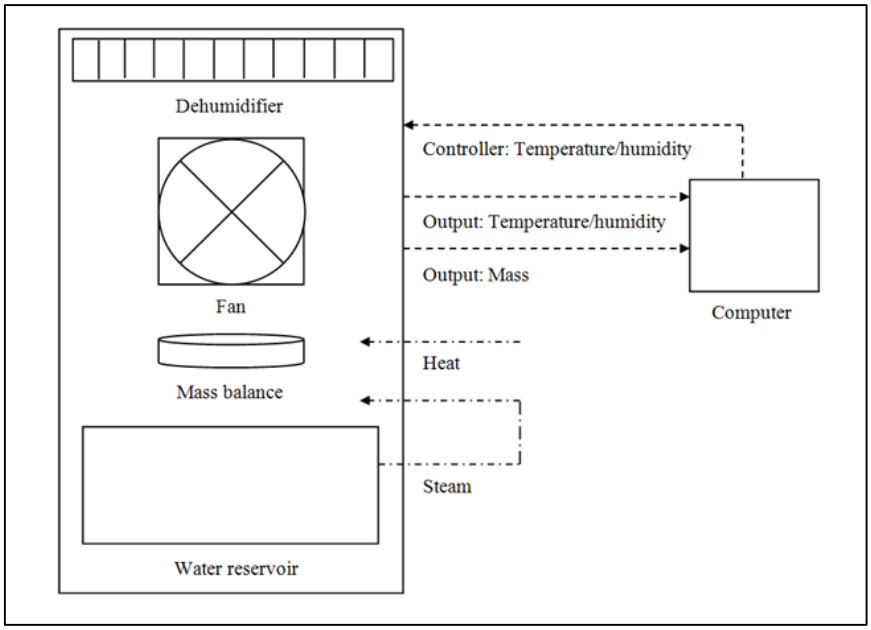


*Figure 3.2.2. Diagram of experimental setup (climate chamber).*

The prepared sample was placed in an open-top glass cylinder with a diameter of 8cm placed on a load cell. Changes in the mass of the coal were recorded on a computer in real time while the relative humidity and temperature of the air inside the climate chamber were controlled. For the second part of the project, a fluidized bed test cell was connected to the climate chamber for the blower to draw conditioned air at the correct relative humidity and temperature from the chamber. The air was returned to the chamber after fluidization to reduce the heating and/or cooling and drying loads required. The setup can be seen in Figure 3.2.3.

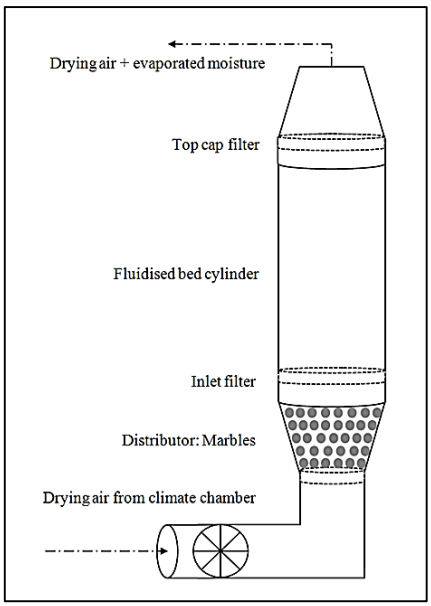


*Figure 3.2.3. Diagram of experimental setup (fluidized bed)*

A mesh was placed at the top and bottom of the fluidized bed cylinder to prevent fine particles from exiting. A packed bed of small glass marbles was used to distribute the up flowing air evenly across the cylinder. Humidity detectors were used to observe the moisture loss or gain in the airflow and values were correlated by weighing the samples before and at regular intervals during a test.

### *Results*

The bulk coal sample was conditioned at 25°C and 80% RH for about two hours to reach an equilibrium moisture content of 2.2%$_{wt}$. From here, subsamples were either added to a container and placed within the climate chamber or added to a fluidized bed attached to the climate chamber. The difference between the extents and rates of dewatering for a static and fluidized bed arrangement were compared. This was done by controlling the relative humidity at 30% for air temperatures of 25°C and 40°C as shown in Figure 3.2.4.

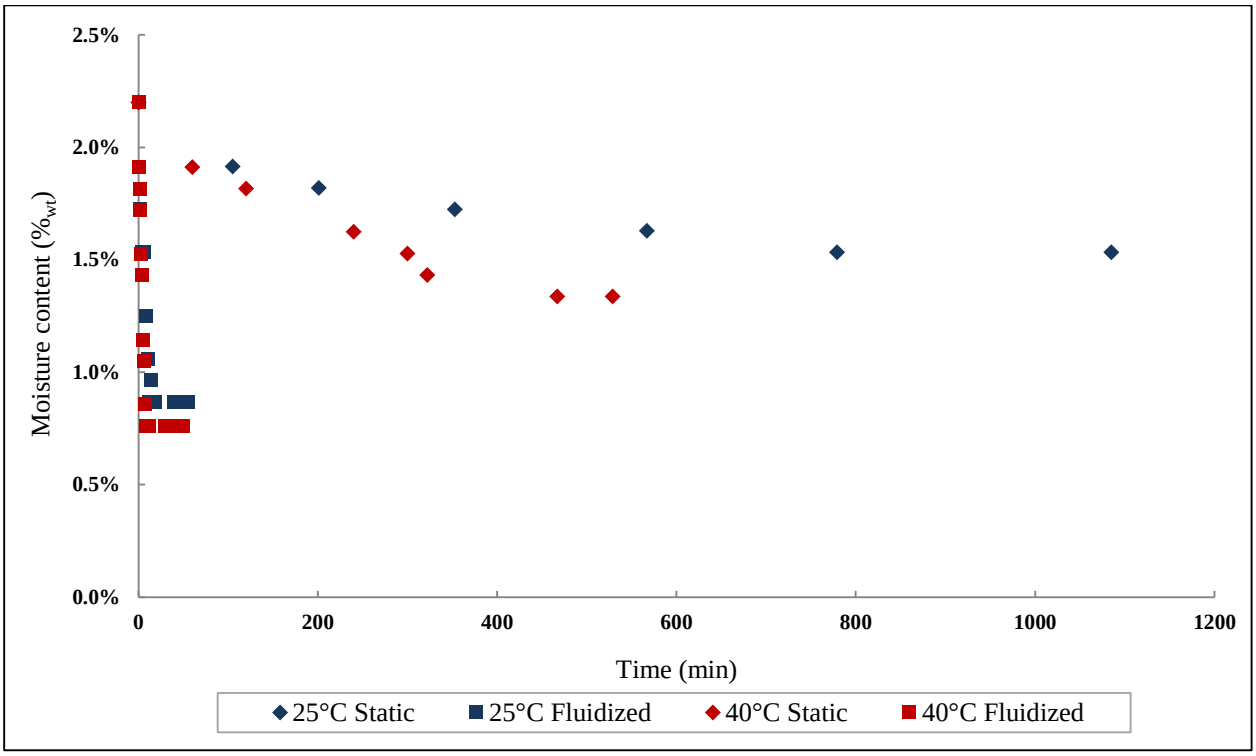


*Figure 3.2.4. Dewatering comparison of a static and fluidized bed at 30% relative humidity*

Successful drying of fine coal was possible for both arrangements, but there was an improvement in the extent and rate of dewatering for the fluidized bed arrangement. To study the influence of a step change in humidity at various ambient temperatures, the fluidized bed was operated at 25°C and 40°C, respectively, while suddenly changing the relative humidity from 70% to 30%. Figure 3.2.5 shows that a change in temperature has a smaller effect on the rate of dewatering than a change in humidity.

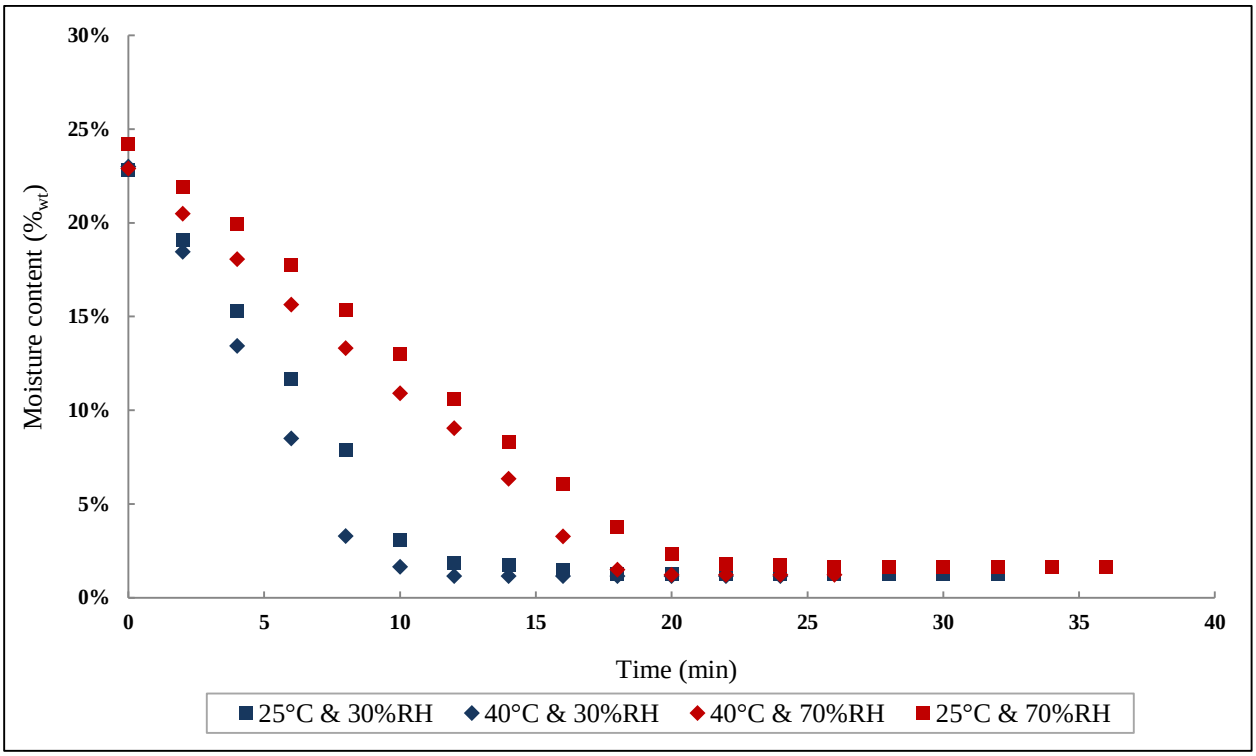


*Figure 3.2.5. Comparison between relative humidity and temperature influence on dewatering*

It is important to note that these changes only affected the dewatering rate and not the final moisture content of the coal. It can be concluded that the relative humidity of air is the main driving force in removing moisture in a fluidized bed. It can also be seen from the graph that changes in this driving force will affect the dewatering rate without significantly influencing its final moisture content. Buckley & Nicol (1995) described water associated with coal as being either interacting or no interacting with the coal surface, depending on the thermodynamic properties of the bulk water and the coal surface. The energy required to remove the interacting moisture layer is more than what can be supplied by the relative humidity driving force, and hence changes in the relative humidity will have little effect on the final moisture content. Removal of this water will require thermal drying at elevated temperatures. Required retention times to reach 8% total moisture (generally accepted in South Africa as an acceptable moisture content for thermal coal) varies between 6 and 14 minutes, depending on the relative humidity and temperature. For comparison purposes, the absolute value of the slopes of the linear part of the graph were calculated and are given in Table 3.2.3.

*Table 3.2.3. Initial drying rate constants*

| Relative humidity | Static bed k ($min^{-1}$) | Fluidized bed k ($min^{-1}$) |
|---|---|---|
| 30% | $8.07 \times 10^{-6}$ | $2.66 \times 10^{-2}$ |
| 50% | $7.10 \times 10^{-4}$ | $1.67 \times 10^{-2}$ |
| 70% | $2.70 \times 10^{-4}$ | $1.18 \times 10^{-2}$ |

Here, the data for 50% relative humidity, not shown in Figure 3.2.5, were included. It confirms what is seen in Figure 3.2.5, indicating a higher dependency towards changes in relative humidity than towards temperature changes. To test the sensitivity to other factors, it was decided to vary the initial feed moisture and fluidization air flow rate. Coal filter cakes with higher (about 26%) and lower (16%) total moisture were prepared as feed to the fluidization chamber. This was fluidized at an air temperature of 25 °C and a relative humidity of 50%. The data represent the same conditions but at varying starting moisture percentages.

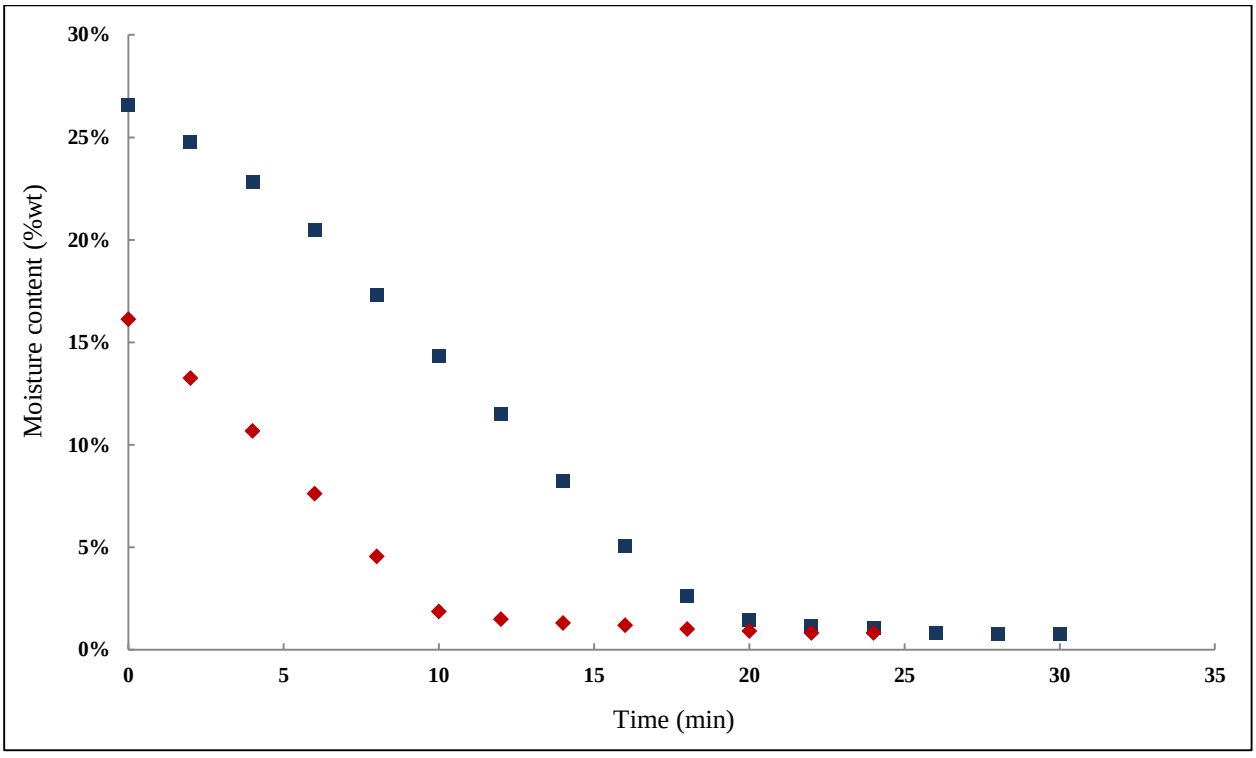


*Figure 3.2.6. Comparison of different feed moisture content on dewatering*

The results in Figure 3.2.6 show no difference in either the final moisture content or the dewatering rate of the fine coal, implying that a constant dewatering rate occurs independent of initial moisture level when the coal is subjected to air flow (Kelly & Spottiswood, 1997). Since there is a rapid transition from the critical dewatering point (the point where the rate of dewatering starts to decrease) to equilibrium moisture, the dewatering rates and final moisture content for both these cases are the same. Finally, the airflow rate

during fluidization was varied. Previously the fluidized velocity was operated at just above the minimum fluidization point. It was decided to increase the air velocity to the point where vigorous back-mixing occurred. This was done for both 25 °C and 40 °C at a relative humidity of 30%.

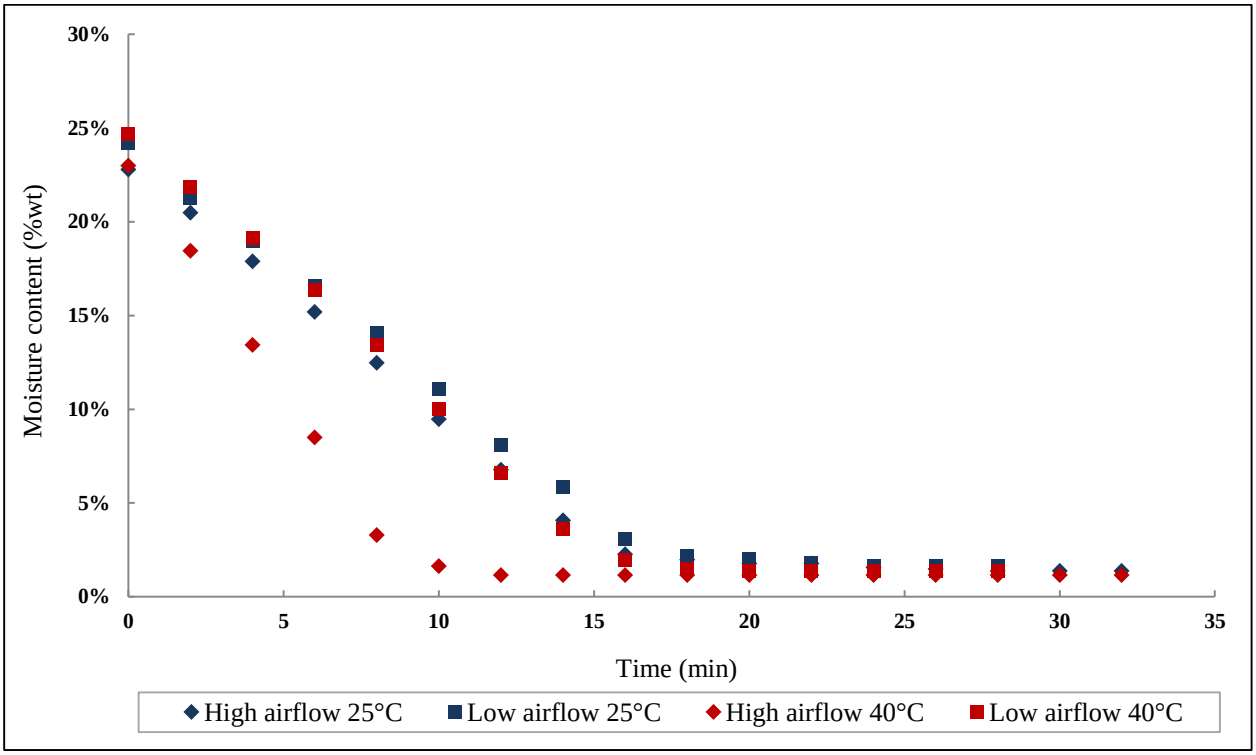


*Figure 3.2.7. Relationship between fluidization air flow rate and air temperature*

Figure 3.2.7 shows a strong temperature flow rate relationship. At higher temperatures, an increased flow rate resulted in an increased dewatering rate, since both back-mixing and a higher rate of temperature addition contributed to faster heat transfer into the micro pores of the coal particles.

### *Conclusion*

It was shown that fine coal dewatering is possible using a fluidized bed that is operated at low temperatures. Compared to a static non-fluidized bed, the rates of dewatering increased hundredfold while the final moisture content decreased by about half a percentage point. Relative humidity proved to be the main driving force for fine coal dewatering inside a fluidized bed. By lowering the relative humidity, the rate of dewatering increased without altering the final moisture content of the coal. It was ascribed to the different thermodynamic states of water associated with the coal surface. Because dewatering happened in the constant dewatering rate regime, the moisture content of the coal feed of the bed did not influence the rate of dewatering nor the final moisture content. Lastly, it was found that higher flow velocities, especially at increased temperature, improved the dewatering rate.

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- Coaltech
- South African Minerals to Metals Research Institute (SAMMRI).

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Reddick, J.F., Von Blottnitz, H. & Kothuis, B. 2007. A cleaner production assessment of the ultra-fine coal waste generated in South Africa. *The Journal of The South African Institute of Mining and Metallurgy*, 107:811-816.

Rong, R.X. & Hitchins, J. 1994. Preliminary study of correlations between fine coal characteristics and properties and their dewatering behaviour. *Minerals Engineering*, 8(3):293-309.

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Terblanche, A.N. 2011. Dry beneficiation of fine coal using a fluidized bed. Potchefstroom: NWU. (Project report - Honours).

## 3.3. Drying of fine coal using air in a fluidized bed (Paper 2)

This section describes the contributions made by the authors in completion of the paper titled "Drying of fine coal using air in a fluidized bed". General information is listed regarding the paper that was published in the conference proceedings of the XXVII International Mineral Processing Conference.

### *3.3.1. Contribution by authors*

The experimental setups and equipment used for the study are the property of the North-West University and are the same as described in Section 3.2. Miss M.J. van Rensburg was responsible for completing the experimental work and subsequent processing of the experimental data. The results and discussion of the experimental work and subsequent calculation were completed and written by Miss M.J. van Rensburg. The conclusions drawn from the results came from a discussion between Miss M.J. van Rensburg, Prof. M. le Roux and Prof. Q.P. Campbell. This paper was presented by Prof. M. le Roux at the XXVII International Mineral Processing Conference (IMPC) that took place in Santiago, Chile. The conference took place from 20-24 October 2014 and this paper was published in the conference proceedings thereafter.

### *3.3.2. General information*

Information regarding the paper published in the conference proceedings is listed in Table 3.3.1.

*Table 3.3.1. Drying of fine coal using air in a fluidized bed (paper 2): General information*

| Category | Information |
|---|---|
| Paper name | Drying of fine coal using air in a fluidized bed |
| Authors | Le Roux, M., Campbell, Q.P. & Van Rensburg, M.J. |
| Journal | Proceedings of the XXVII International Mineral Processing Congress |
| Year | 2014 |
| Copyright | © Gecamin, Chile All rights reserved gecamin@gecamin.com |
| Web address | http://www.impc2014.org/english/proceedings |

# Drying of fine coal using air in a fluidized bed

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## *Abstract*

Fluidized bed drying is currently receiving much attention as a dewatering option during the beneficiation of fine (defined here as between 1 mm and 2 mm particles) coal. Apart from concerns about safety and combustion, the operating costs can be high if very high gas or air temperatures are used. The aim of this study was to investigate the removal of moisture from fine coal by using air at a lower temperature (25 - 55°C) within a controlled environment by lowering of the relative humidity of the air. It was firstly proven that fluidization has a major advantage over non-fluidized beds, with regards to drying rate and final moisture content. Hereafter several parameters that influence the dewatering rate and final moisture content were tested, from which it was concluded that the relative humidity of air acts as the largest driving force for dewatering. Parameters tested included relative humidity, temperature and coal composition. Energy balances showed a positive nett energy increase in the dried coal during combustion when related to the energy input during drying. In comparison with thermal drying technologies, fluidized bed drying was proven to be less energy intensive. It was therefore shown that this is a viable technology for the dewatering of fine coal.

*Keywords*: Dewatering, Drying, Fine coal, Fluidization

## *Introduction*

Fine coal (defined in this paper as between 1 mm and 2 mm) is difficult to dewater and may contain a total moisture content of higher than 25%$_{wt}$ even after filtration (Le Roux & Campbell, 2003). This high moisture content causes problems in handling as well as a decrease in the calorific value of the coal. An added disadvantage of elevated moisture contents is an increase in transportation and port costs. The difficulty in dewatering often leads to fines being discarded onto discard dams, or being blended to the course beneficiated fraction. Such a blend will decrease the quality of the final product by increasing the final product moisture. Developing feasible fine coal recovery and beneficiation processes can result in potential revenue and, at the same time, reduce environmental problems (Reddick *et al*., 2007). Dry bed fluidization is proving to be one such an option in beneficiating fine coal. However research conducted at North-West University found that an elevated moisture content in the feed to a fluidized bed decreases the efficiency of the process (Terblanche, 2011). It causes large lumps to form due to agglomeration of the wet fine particles. These lumps behave as if un-liberated, decreasing its beneficiation ability. Moisture values between five and eight percent was recommended by Terblanche (2011) for optimum fine coal beneficiation in a

fluidized bed. The pre-drying of the coal feed to required moisture levels is therefore crucial in the dry beneficiation of the fines.

There are several methods to reduce the moisture content in fine coal, for example filtration (both pressure and vacuum), centrifuging and thermal drying. Thermal drying remains the most effective water reduction technique but the price of coal limits its use (Reddick *et al*., 2007). On the other hand, mechanical dewatering is generally unable to deliver the required moisture levels, especially for finer coal. Previous work on vacuum filtration by Le Roux & Campbell (2003) yielded an increase in the dewatering capabilities of the filter when the operational philosophy was changed from a high-pressure differential low airflow, to a low-pressure high airflow regime. The additional air flow that was induced, even at the expense of pressure differential, aided in the absorption of moisture from the coal fines to the air.

### *Background*

Equilibrium moisture is defined as the moisture content of coal subjected to a specific temperature and humidity (these conditions are defined as 30˚C and 96% relative humidity according to ISO (International Standards Organization) 1080). In general the term refers to the moisture holding capacity of coal at some specific temperature and humidity conditions. This moisture exists as intra-particulate moisture and as films on the surface of the particles and cannot be removed by mechanical methods. It needs to be evaporated from the particle. The amount of equilibrium moisture changes according to the changes in atmospheric conditions (Rong & Hitchins, 1995).

Phase equilibrium between liquid and vapor is a state where the rate of evaporation from the liquid phase is the same as the rate of condensation of the vapor. Changes in the driving forces like temperature and partial vapor pressure (defined as relative humidity) can disrupt the vapor-liquid equilibrium. Figure 3.3.1 illustrates how these driving forces lead to a change in the thermodynamic state of the pure substance.

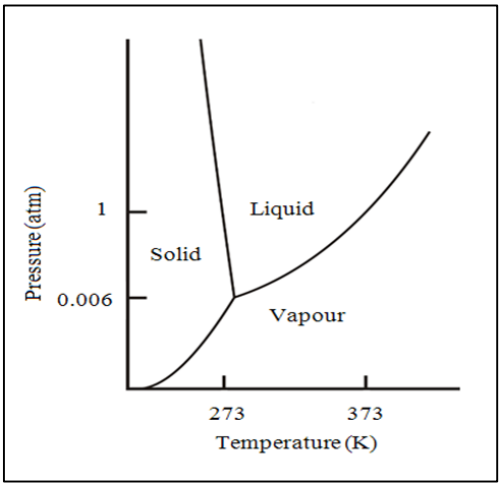


*Figure 3.3.1. Phase diagram of water*

Figure 3.3.1 shows that even slight increases in the temperature of the system, at constant pressure, may result in an equilibrium change between the liquid and the vapor, which will lead to the phase change of liquid to vapor. The phase change is driven by an increase in the vapor pressure of the water surrounding the coal particles to become higher than the partial pressure of the vapor fraction in the warm air (Koretsky, 2004). By substituting the newly formed vapor with drier (less moist) air, the system equilibrium is disturbed causing some of the remaining liquid to undergo a phase change to vapor. This will produce a new equilibrium point where the liquid in the coal particle is in equilibrium with the vapor fraction of the dry air. It is defined as the irreducible equilibrium point of the specific water/air system.

Solid particles in a fluidized bed behave like a fluid when suspended in the upward flowing medium. Therefore, drying in a fluidized bed is achieved by fluidizing the solids by means of the drying medium, in this case, warm dry air. The water vapor is ultimately captured by the drying capacity of the upwards flowing warm air and transferred away from the wet solid particles (Syahru *et al*., 2002). This sets in motion the process described in the paragraph above.

In a previous paper, Le Roux *et al*. (2014) discussed the validity in using warm, dry air as a drying medium for fine coal in a fluidized bed. This paper concluded that:

- Both the drying rate and the final equilibrium moisture content of the coal were significantly reduced when using a fluidized bed to dry the coal as compared to a non-fluidized (fixed) bed.
- The relative humidity of the air had a larger influence on the drying rate of the coal, for temperatures below 40°C, than the actual air temperature. The final equilibrium moisture content remained constant for any relative humidity and temperature environments below 40°C.
- The rate of dewatering and the final equilibrium moisture content were independent of the moisture content of the coal feed.
- Changes in the fluidization air flow rate did not influence the dewatering rate or final equilibrium moisture of the coal for air at 25°C. However, the rate of dewatering increased significantly when the air used for fluidization was slightly higher at 40°C. This trend still needs to be verified using different air temperatures.

### *Methodology*

The aim of this project was threefold: (a) to quantify the trends found by Le Roux *et al.* (2014) with regards to air temperature, humidity and air flow rate influences on the drying rate and final equilibrium moisture content of the coal; (b) To compare the behavior of different maceral types when dried in a fluidized bed and (c) to calculate the energy efficiency of such a drying system in relation to other technologies. This was done by feeding a wet fine coal in the form of filter cake product (approximately 25%$_{wt}$ moisture) to a fluidized bed. The air used to fluidize the material was received from a controlled climate chamber, and

kept in a closed loop circulation. The mass loss in the coal was determined by weighing the total fluidized bed at set time intervals. This done to determine the amount of moisture removed from the fine coal.

### *1. Apparatus used*

A CTS C-40/100 climate chamber (see Figure 3.2.2.a) was used to pre-condition the air required for both the static and fluidized bed tests. The climate chamber has capability of controlling the temperature and relative humidity of the air independently, thus enabling independent set points for these two variables.

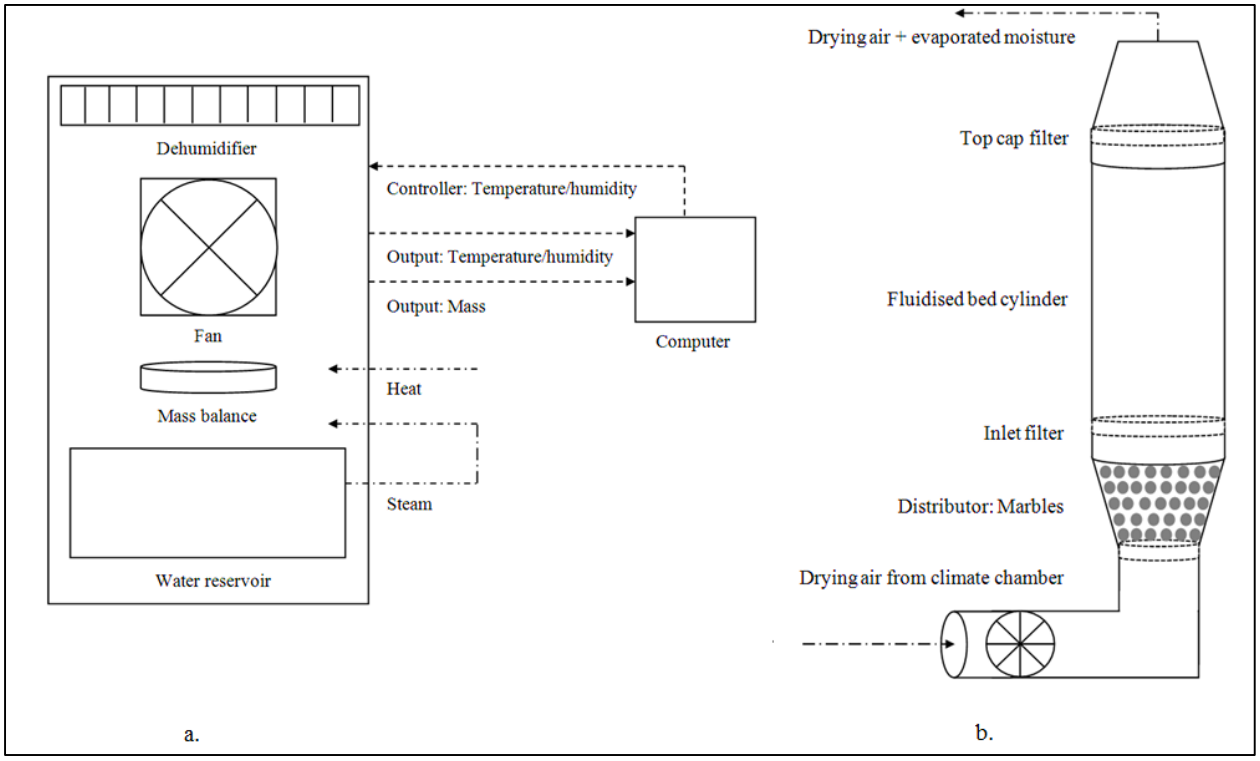


*Figure 3.3.2. A schematic diagram of (a) the CTS C-40/100 climate chamber and (b) the fluidized bed*

For the fluidized bed tests, a Perspex tube with a 100 mm inner diameter acted as a fluidized bed, and was attached to the outside of the climate chamber as shown in Figure 3.2.2.b,. Conditioned air was forced from the climate chamber, and used to fluidize the coal bed. The moist exit air was captured at the top of the bed, and recycled to the climate chamber to be reconditioned to the set points, therefore keeping the drying air in a closed loop. Drying rates and moisture contents were determined by removing the tube and measuring the mass loss of the coal bed at set intervals.

### *2. Coal analysis*

Bituminous coal from the Waterberg coal field in the Limpopo province of South Africa was used in the study. The sample was run-of-mine (ROM) coal that was visually sorted in a bright (vitrinite rich) and dull (inertinite rich) fraction. The results of the proximate analysis are given in Table 3.3.2, including the calorific values.

*Table 3.3.2. Proximate analysis results (air-dried base)*

| Analysis type | Vitrinite rich coal | Inertinite rich coal |
|---|---|---|
| Inherent moisture content ($\%_{wt}$) | 1.2 | 1.4 |
| Percentage ash ($\%_{wt}$) | 52.9 | 21.7 |
| Percentage volatile matter ($\%_{wt}$) | 20.5 | 21.2 |
| Fixed carbon ($\%_{wt}$) | 25.4 | 55.7 |
| Calorific value (MJ/kg) | 13.4 | 24.5 |

The proximate analysis in Table 1 shows that the vitrinite rich coal sample had a very high mineral content. This is common for Waterberg ROM coal due to the layered structure of the ore body. The result of this high mineral content is a low calorific value, as indicated in the table.

To validate the assumption that a visually bright coal sample was vitrinite rich while the dull sample was inertinite rich, a petrographic analysis was done to quantify the maceral composition. The results of this analysis are shown below in Table 3.3.3.

*Table 3.3.3. Maceral composition*

| Sample identification | Vitrinite rich coal | Inertinite rich coal |
|---|---|---|
| Vitrinite ($\%_{wt}$) | 40.1 | 9.2 |
| Liptinite (Exinite)($\%_{wt}$) | 4.6 | 3.5 |
| Reactive Semifusinite ($\%_{wt}$) | 14.8 | 17.7 |
| Inert Semifusinite ($\%_{wt}$) | 9.3 | 55 |
| Fusinite and Secritinite ($\%_{wt}$) | 1.7 | 1.1 |
| Micrinite ($\%_{wt}$) | 0.2 | 0.7 |
| Mineral matter ($\%_{wt}$) | 29.3 | 12.8 |

The results in Table 3.3.3 validate the assumption that the bright fraction was vitrinite rich and the dull fraction inertinite rich. However, this said, the dull coal does contain high values of reactive semifusinite and vitrinite which will contribute to a higher than expected calorific value as shown in Table 3.3.2.

The samples were then crushed, and the particle size analysis of the two different coal samples yielded similar $d_{50}$ values. The vitrinite rich sample had a $d_{50}$ of 1.50 mm while the $d_{50}$ of the inertinite rich sample was calculated as 1.55 mm. There was however a large difference between the coarse and fine particle fractions of the two coal samples, as can be seen in Figure 3.3.3. The vitrinite rich sample had more fine material than the inertinite rich coal sample. It is noted that this would possibly influence the dewatering characteristics of the two samples.

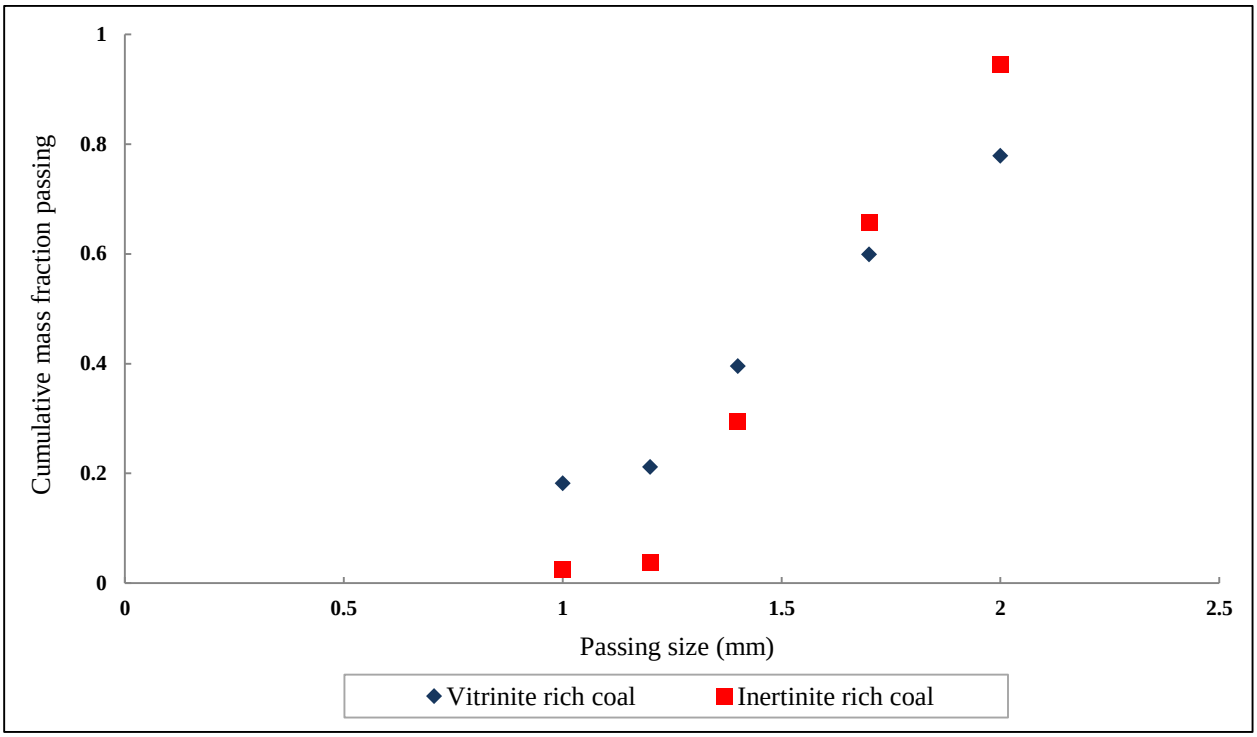


*Figure 3.3.3. Particle size distribution of the vitrinite and inertinite rich coal fractions*

### *Results and discussion*

It was possible to reproduce the previous trends published by Le Roux, Campbell & Van Rensburg (2014) as shown in Figure 3.3.4 and Figure 3.3.5. Figure 3.3.4 shows that the drying rate is affected by changes in both the temperature (solid markers) and relative humidity (hollow markers) of the air. A change in temperature, at constant humidity, had less influence on the drying rate than was the case for a change in relative humidity at constant temperature. Therefore, a combination of high temperature and low humidity will result in the highest drying rate of 2.86 percent per minute. The final equilibrium moisture content was shown to be independent (within experimental error) on changes in the relative humidity and temperature of the air. It can be concluded from this result that the moisture holding capacity of the fine coal particles, which is a function of the capillary pressure inside each individual particle, contributes largely to the final retention of moisture within each particle. Changes in air temperature and relative humidity do not increase the driving forces to such an extent that it is able to withdraw more moisture from each particle. This results in a final equilibrium moisture content that appears to be independent on these variables. Due to the construction of the test apparatus, the air flow rates could not be measured, but is described here from visual observation, as low (just above the minimum fluidization velocity) and high (well above the minimum fluidization velocity. Figure 3.3.5 shows that a change in the fluidization airflow rate from the minimum fluidization velocity to a higher velocity does have a positive effect on the drying rate of the coal, only at temperatures above 25°C. Similar drying rates and final equilibrium moisture contents were observed when coal was dried at 25°C using different fluidization rates. This differed from

the drying rates observed by changing the fluidization rate at 40°C and 55°C. A significant improvement in the drying rate was observed at elevated temperatures.

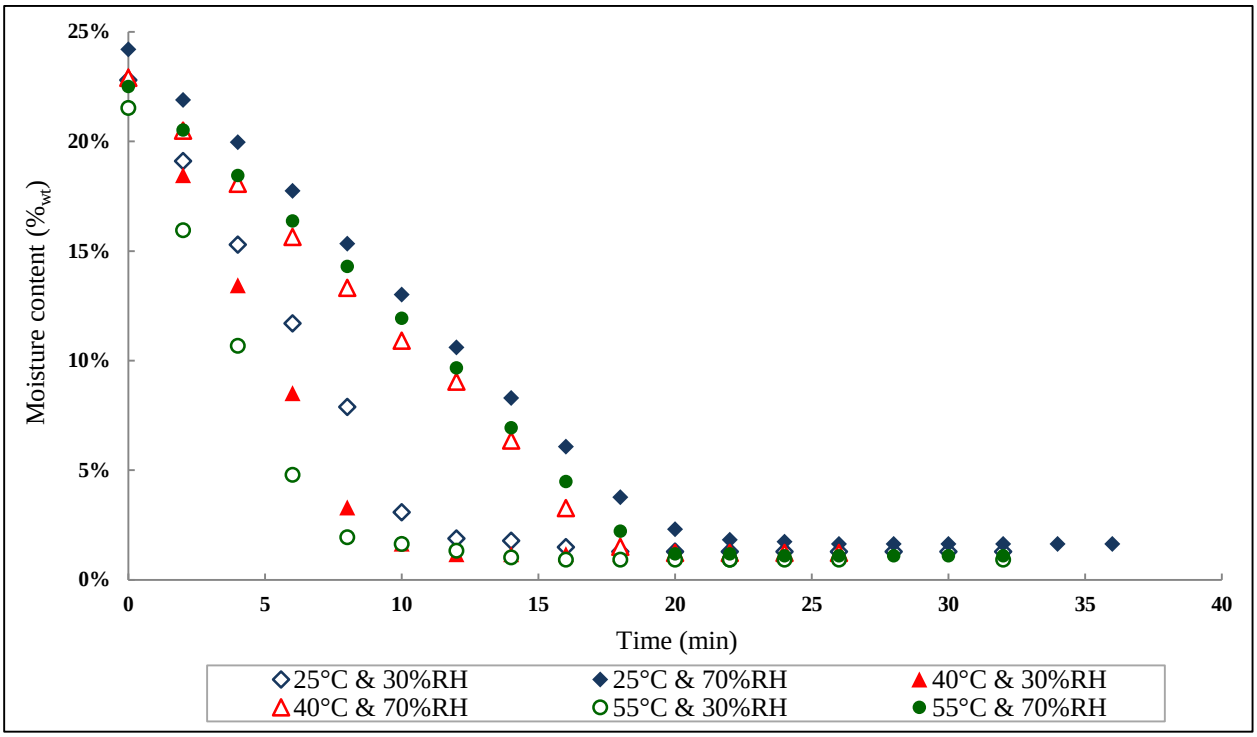


*Figure 3.3.4. Drying of filter cakes in a fluidized bed at different set points*

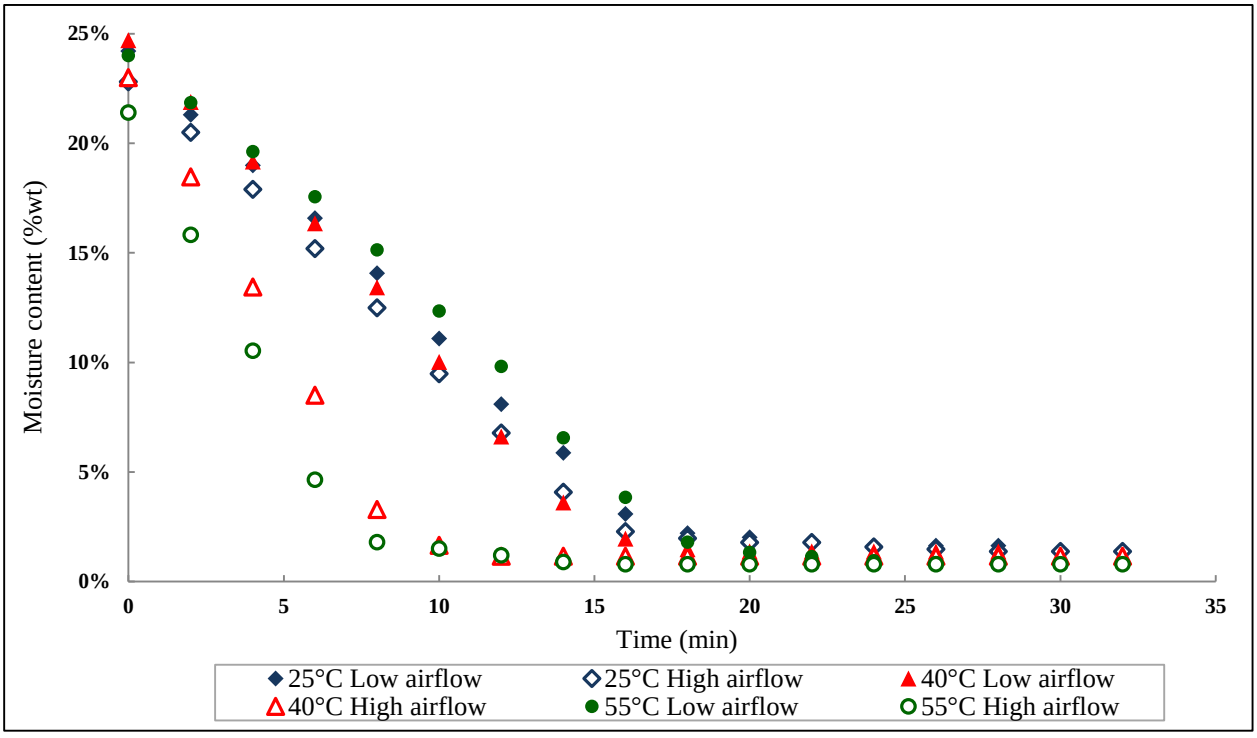


*Figure 3.3.5. Variation in fluidization air rate for the drying of filter cakes in a fluidized bed at 30% relative humidity*

### *1. The influence of varying maceral composition*

A comparison between the vitrinite rich and inertinite rich coal was make by drying the coal in a fluidized bed at 40°C, varying the relative humidity between 30% RH, 50% RH and 70% RH. The result of this comparison can be seen in Figure 3.3.6. It shows that both coals behave similarly and are largely dependent on the relative humidity of the air for drying. Both the drying rates and final equilibrium moisture content for the coals were similar within experimental error. However, there was a slight tendency for the vitrinite rich coal to have a higher drying rate at a high relative humidity (thus low driving force). This can be attributed to the differences in micro fracture and particle size of the two coals. The more brittle vitrinite rich coal had larger micro fracture and therefore smaller capillary forces within the fractures. This led to a higher dewatering rate. This coal also had slightly smaller PSD, as was shown in Figure 3.3.3, which contributed to a higher final equilibrium moisture.

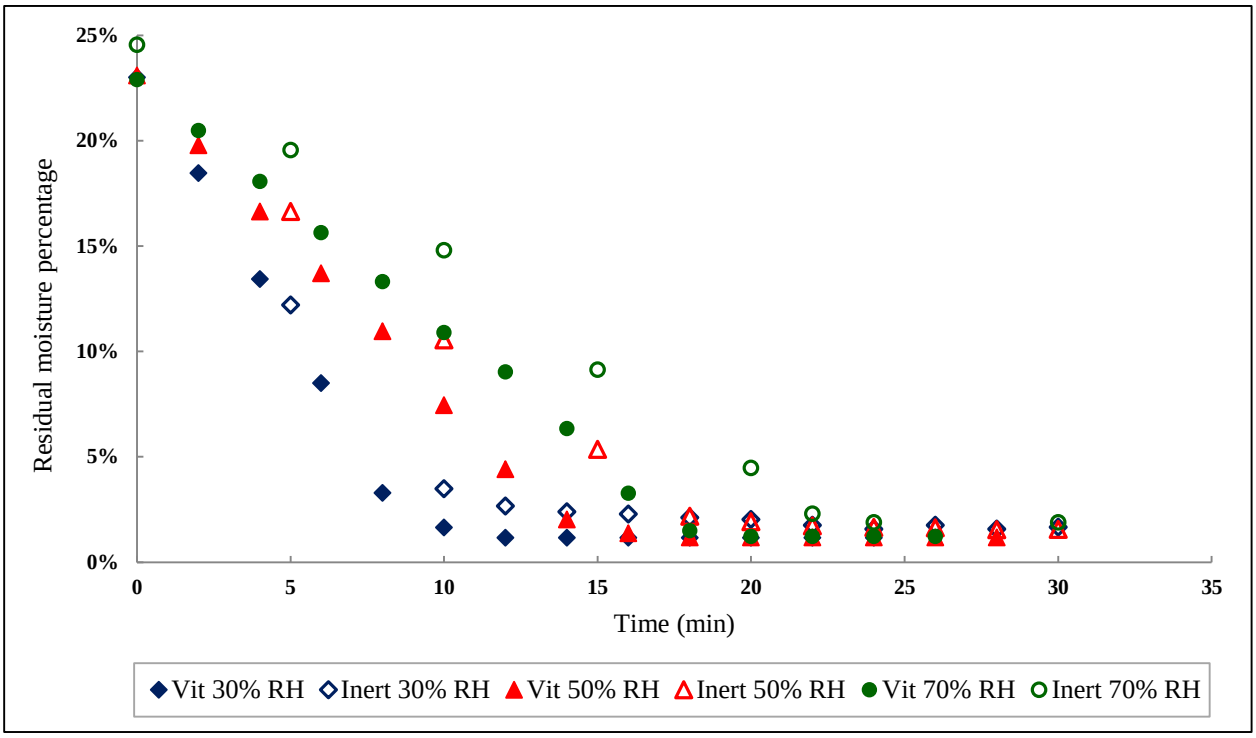


*Figure 3.3.6. Comparison between vitrinite (Vit) and inertinite (Inert) rich coal at 40°C*

### *2. Energy considerations*

The energy required to evaporate a certain mass of water using a fluidized bed was calculated for three cases: minimum final equilibrium moisture, 5% residual moisture and 10% residual moisture. All the temperature, relative humidity and airflow rate variations were taken into consideration. As a basis for the calculations, ambient conditions were assumed to be 25°C and 50% relative humidity. From here, the energy requirement was calculated as a function of the following variables:

- Change in enthalpy of the water
- Phase change of water for evaporation
- Conditioning of the air by the climate chamber
- Work done by the blower

The nett result is shown in Table 3.3.4, and shows a significant gain in energy for all scenarios which leads to the conclusion that this process is viable. It is possible to improve the overall energy efficiency to between 1.6MJ/kg and 3.8MJ/kg coal in the final product. This can be directly related to additional revenue since the coal can be sold at a higher value.

*Table 3.3.4. Energy gain by drying to different final moisture contents, per kilogram dry coal*

| | **Final equilibrium moisture** | **5% residual moisture content** | **10% residual moisture content** |
|---|---|---|---|
| Calorific value of the feed (MJ/kg) | 16.54 | 16.54 | 16.54 |
| Calorific value of the dry coal (MJ/kg) | 25.07 | 23.77 | 21.96 |
| Energy used for drying (MJ/kg) | 4.66 | 4.37 | 3.81 |
| Energy gain (MJ/kg) | 3.87 | 2.86 | 1.61 |

Wilson *et al*. (1992) compared the energy use of different thermal drying technologies as the energy used in kilojoules per kilogram water removed. A summary of their work is given in Table 3.3.5. Added to the table are similar calculations for using a fluidized bed dryer operating at moderate temperatures below 55°C. It shows that this method is less energy intensive as any of the listed thermal processes. This resulted in a positive energy gain whereas the thermal drying processes result in an energy loss, or is energy neutral. Note that this comparison was done for the worst-case scenario in the fluidized bed.

*Table 3.3.5. Energy comparison with thermal drying technologies*

| **Technology** | **Energy consumption per kilogram water removed (kJ/kg)** |
|---|---|
| Fluidized bed to equilibrium moisture | 2020 |
| Fluidized bed to 5% residual moisture | 2301 |
| Fluidized bed to 10% residual moisture | 2861 |
| Rotary dryer | 3700 |
| Rotary tube dryer | 3100 |
| Chamber dryer | 3150 |
| Pneumatic dryer | 3100 |

### *Conclusion*

It can be concluded that fine coal dewatering is possible using a low temperature fluidized bed. The main driving force in the removal of moisture from the coal is the relative humidity of the fluidizing air. Only when altering the air flow rate to above that of the minimum fluidization velocity does the temperature of the air become important. The rate of dewatering becomes directly proportional to the increase in air flow rate and air temperature. It was further shown that there is very little, if any, influence of the maceral composition on the rate of dewatering. The difference in behavior between the two coals was attributed to the difference in the PSD and micro fractures of the feed samples. This process was shown to be energy positive, resulting in an overall energy gain. It compared favorably with other thermal drying technologies.

### *Acknowledgements*

The authors would like to acknowledge the following institutions for their contribution towards this project:

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SAMMRI (South African Minerals to Metals Research Institute)

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## 3.4. Air drying of fine coal in a fluidized bed (Paper 3)

This section describes the contributions made by the authors in completion of the paper titled "Air drying of fine coal in a fluidized bed". In addition, information regarding the published paper is listed.

### *3.4.1. Contribution by authors*

The experimental work presented in this paper was completed by the combined efforts of two undergraduate students, Miss E.S. Peters and Miss C. Stiglingh, under the guidance of Miss M.J. van Rensburg. The results presented in this paper came forth out of discussions between Miss M.J. van Rensburg, Prof. M. le Roux, Prof. Q.P. Campbell, Miss E.S. Peters and Miss C. Stiglingh. This work was presented by Miss E.S. Peters at the 12th Annual Southern African Institute for Mining and Metallurgy Student Colloquium on 12 November 2014 in Randburg, South-Africa. Selected presentations were chosen to be published in the Journal of the Southern African Institute of Mining and Metallurgy.

### *3.4.2. General information*

Information regarding the paper published in the conference proceedings is listed in Table 3.4.1.

*Table 3.4.1. Air drying of fine coal in a fluidized bed (paper 3): General information*

| Category | Information |
|---|---|
| Paper name | Air drying of fine coal in a fluidized bed |
| Authors | Le Roux, M., Campbell, Q.P., Van Rensburg, M.J., Peters, E.S. & Stiglingh, C. |
| Journal | Journal of the Southern African Institute of Mining and Metallurgy, 115: 335-338 |
| Year | 2015 |
| Copyright | © The Southern African Institute of Mining and Metallurgy |
| ISSN | 2411-9717 (Online) & 2225-6253 (Print) |
| Web address | http://www.saimm.co.za |

# Air drying of fine coal in a fluidized bed

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## *Synopsis*

The demand for energy has continued to rise worldwide in line with population growth. The majority of South Africa's electricity is supplied by coal-fired power stations. The amount of fine coal (-2mm) generated at coal processing plants has increased, due mainly to mechanized mining methods. Fine coal retains more water, which lowers its heating value. Drying the coal is costly and it is difficult to achieve the required moisture content. Consequently, coal fines are often discarded. An estimated 8% of the total energy value of mined coal is lost1. Fluidized bed technology is often used to dry coal thermally, but this method is expensive and has an adverse environmental impact. The objective of this study was to investigate the removal of moisture from fine coal (<2mm) in a fluidized bed operated with dry fluidizing air at moderate temperatures as the drying agent. The effects of different air temperatures and relative humidity levels were investigated in a controlled environment. The study further investigated the influence of coal particle size on moisture removal. The drying rate was found to increase with increasing temperature. The relative humidity of the drying air had a more pronounced effect on the drying rate, even at temperatures as low as 25°C. It became more challenging to remove moisture as the particle size decreased. The gain in calorific value was greater than the energy required to dry the coal samples, showing that a fluidized bed using moderately warm dry air is an energy-efficient drying technology. The energy efficiency of the fluidized bed compared favourably with other thermal drying methods.

*Keywords*: Coal fines, Drying, Fluidized bed, Energy efficiency

## *Introduction*

The increased use of mechanized coal mining methods has resulted in greater amounts of coal fines being generated. Many operations report an estimated 6% of their ROM production to be in the -2mm size range. Fine and ultra-fine size ranges constitute about 11% of the nominal product and retain the bulk of the moisture (SANEDI, 2011). Given the problems associated with moisture in fine coal, it is important to investigate and improve available moisture removal techniques. Coal constitutes the primary source of energy in South Africa and is a major contributor to the economy, and therefore improving coal quality will in effect maximize the quantity of usable coal (De Korte & Mangena, 2004). With the use of effective dewatering methods, fine coal can be beneficiated and added to the coarse particle circuits without compromising the quality of the product and hence substantially increasing the overall plant yield (Condie & Veal, 1998). Condie & Veal (1998) suggest that by rule of thumb, for every ton of moisture removed the clean coal product stream is supplemented with about 4 ton of fine coal. This is a powerful incentive for

developing advanced dewatering techniques for fine coal particles. Additionally, excessive moisture adds to the mass-based transport costs of coal. For this reason, developing advanced efficient fine coal drying techniques is beneficial from an economical point of view (Campbell, 2006).

Rowan (2010) states that coal preparation plants generally discard coal fines with size fractions below 150µm into waste ponds. This poses a danger of spontaneous combustion, acid mine drainage, and dust release as the surface of the coal is exposed to ambient air and weathering conditions for long periods (De Korte & Mangena, 2004). Coal fines are more susceptible to water absorption than coarser coal and can contain up to 25%$_{wt}$ total moisture after filtration (Le Roux, 2003). Thermal drying methods are more efficient than mechanical dewatering techniques (De Korte & Mangena, 2004), but the price of coal limits the use of these methods (SANEDI, 2011). Studies conducted at North-West University showed that drying of fine coal (-2mm +1mm) in a fluidized bed is possible at low temperatures between 25°C and 40°C.

Work by Le Roux *et al*. (2012) on vacuum filtration showed that intentionally damaging a filter cake improved the airflow infiltration, leading to a lower pressure differential across the cake but increasing the dewatering efficiency. This work confirmed that high airflow conditions resulted in a lower final cake moisture content of 3–5%$_{wt}$. Further studies found that an increased airflow rate resulted in a more effective moisture transfer from the coal fines to the drying air (Le Roux *et al*., 2014).

The moisture content of fine coal particles is made up of surface, capillary, and chemically bound moisture (Rong, 1993) as depicted schematically in Figure 3.4.1.

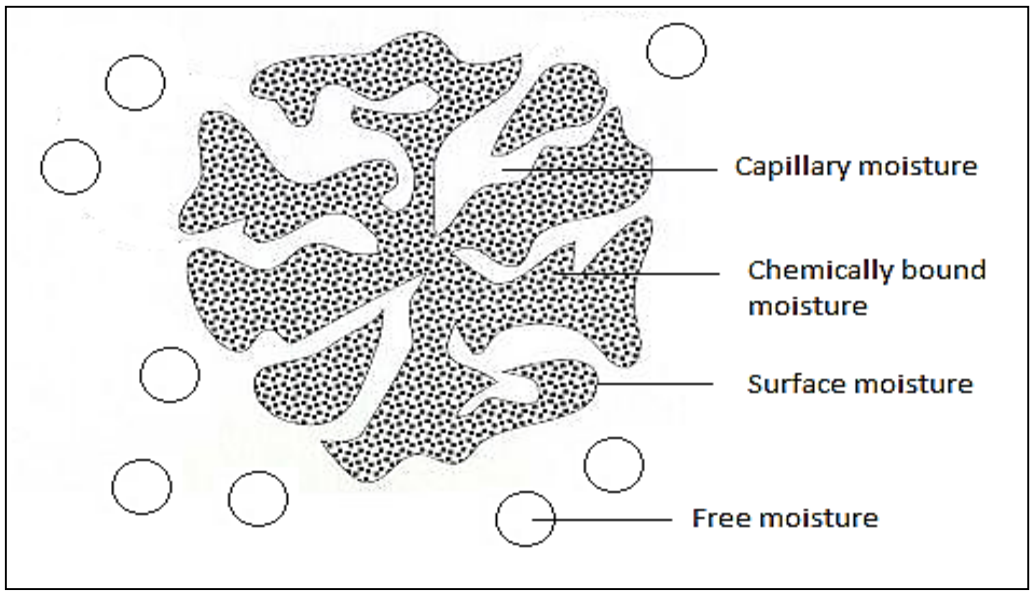


*Figure 3.4.1. Forms of moisture related to coal; adapted from Lemley et al. (1995)*

Free moisture is found on the exterior surface of coal particles (Condie & Veal, 1998), and can be removed by mechanical methods such as filters and centrifugal units. Capillary-bound moisture is absorbed and held tightly within micro-capillaries and micropores of individual coal particles (Rong, 1993). Removal of this moisture calls for thermal drying techniques for complete drainage (Condie & Veal, 1998). Chemically bound moisture is not included when measuring the total moisture content of the coal (Campbell, 2006), and can be removed only by pyrolysis. The equilibrium moisture content of coal is characterized as the moisture content at which the coal particles no longer gain or lose moisture, and it varies according to the temperature and relative humidity conditions of the atmosphere surrounding the particles. Mechanical methods are insufficient for the removal of this equilibrium moisture, which can be reduced only by means of evaporation (Le Roux *et al*., 2014). The relative humidity and temperature act as driving forces that change the phase equilibrium between vapour and liquid, with lower humidities and higher temperatures leading to moisture being absorbed from the particle by the drying medium (Koretsky, 2004).

## *Experimental method*

The aim of this project was to determine the effect of temperature, relative humidity, and particle size distribution on the efficiency of drying fine coal particles in a fluidized bed. The energy consumption during the drying process was calculated and compared to published data on thermal drying processes.

### *1. Sample preparation*

South African bituminous coal from the Waterberg coalfield was used for these experiments. The proximate analysis of this type of coal is given in Table 3.4.2.

*Table 3.4.2. Proximate analysis (air-dried basis)*

| Component identification | Percentage by weight |
|---|---|
| Fixed carbon | 39.98 |
| Moisture content | 2.58 |
| Ash content | 22.82 |
| Volatile matter | 34.62 |

The coal was crushed and sieved into three particle size ranges: fines (between 2mm and 1.18mm) and ultra-fines (between 1.18mm and 0.5mm). The samples were drenched in water for a day and the excess free moisture was removed by pressure filtration. The moisture content of each filtered sample was determined (SANS5925:2007) before the coal was fed to the fluidized bed for dewatering.

### *2. Apparatus*

A fluidized bed column (10cm inner diameter × 40cm length) was constructed from polycarbonate (Figure 3.4.2). The column was connected to a blower, which was used to draw conditioned air at a set temperature and relative humidity from a climate chamber (CTS climate test chamber Type: C-40/100). A packed bed of glass marbles in the bottom section of the fluidized bed acted as airflow distributor. Mesh covers (0.5mm aperture) were placed at the top and bottom sections of the fluidized bed to retain the bulk coal sample within the cylinder. The outlet air from the column was returned to the climate chamber, and was recirculated to the column after the temperature and relative humidity values attained the pre-set levels. For each test, 100g of fine coal sample with a total moisture content of approximately 25-35%$_{wt}$ (typical of a pressure filter product) was fed to the fluidized bed cylinder. The weight of the column was continually monitored during fluidization to determine the loss of moisture. A number of selected experiments were repeated in the fluidized bed to determine the repeatability of the results.

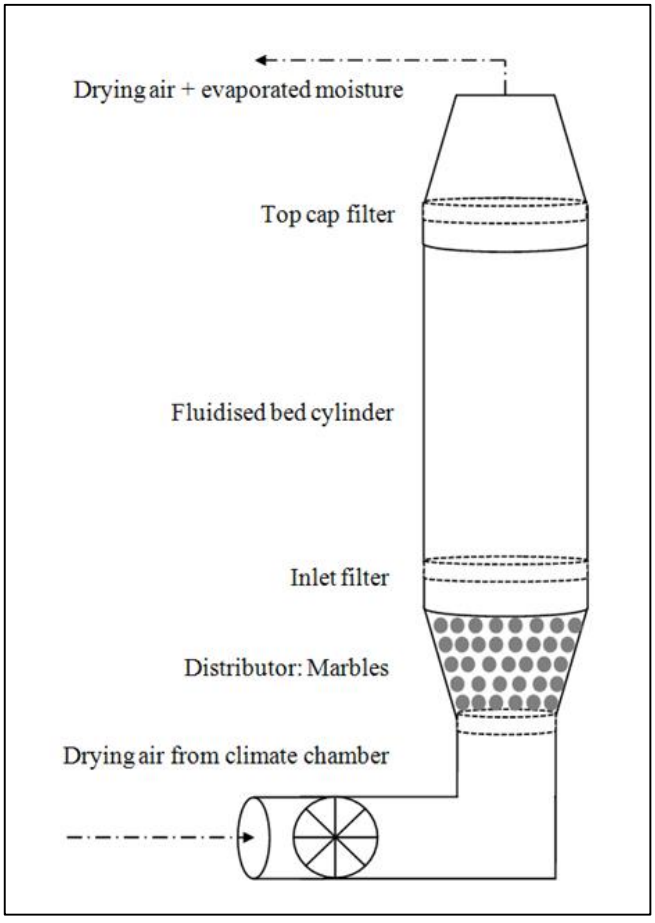


*Figure 3.4.2. Experimental setup of the fluidized bed; taken from Van Rensburg (2014)*

## *Results and discussion*

### *1. Influence of temperature*

To study the effect of air temperature, wet samples of 100g containing about 30%$_{wt}$ total moisture were placed in the fluidized bed cylinder, and drying air was introduced at a superficial velocity of 1.5-1.7m/s, which was slightly above the predetermined minimum fluidization velocity. Two sets of experiments were conducted at air temperatures of 25°C and 55°C respectively and a relative humidity (RH) of 30%. Figure 3.4.3 shows the moisture loss from the ultra-fine sample (-1.18mm+0.71mm) under these conditions.

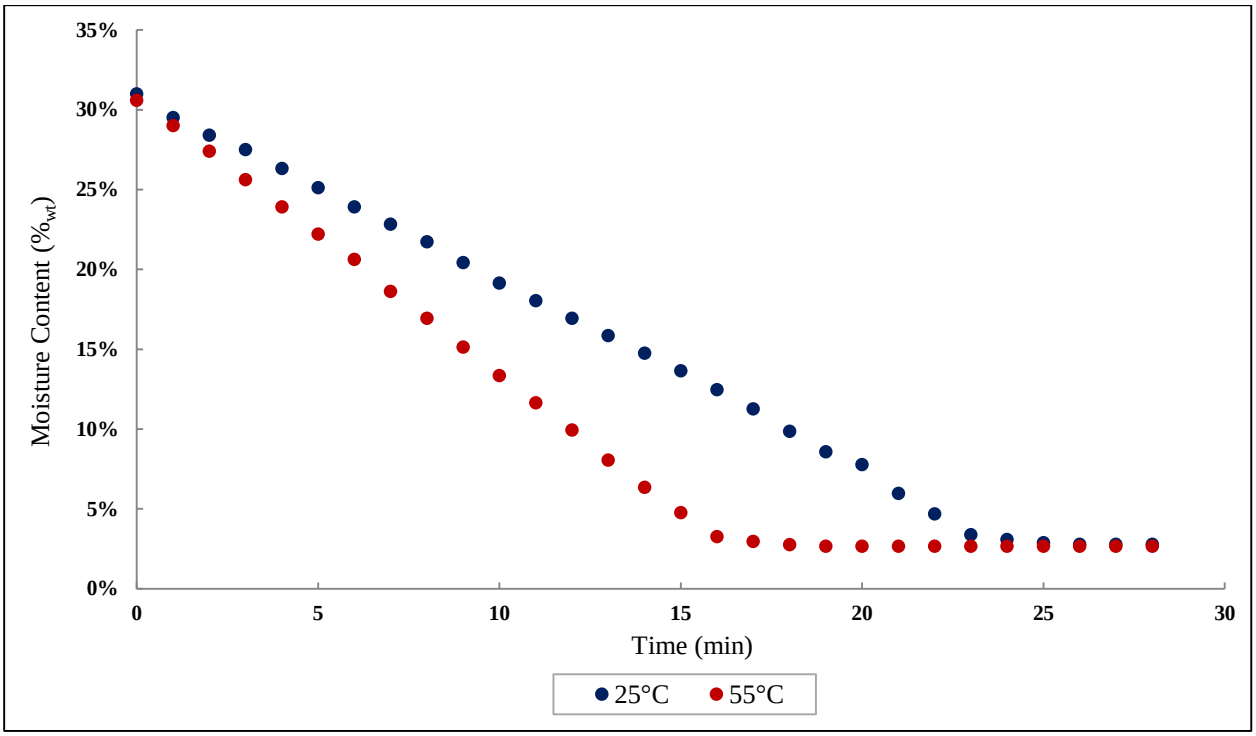


*Figure 3.4.3. Effect of temperature on the drying of -1.18mm+0.71mm coal at 30% RH*

The drying rate was quicker at 55°C than at 25°C. The drying time was reduced from 28 minutes to 21 minutes. This confirms the observation made by Rowan (2010) that elevated temperatures lead to higher dewatering rates. Higher temperatures disrupt the phase equilibrium and increase the amount of water transported from the coal sample into the surrounding air (Condie & Veal, 1998). Duplicate experimental runs proved the repeatability of the results, the maximum and minimum standard deviation being 3.40%$_{wt}$ and 0.12%$_{wt}$ respectively.

### *2. Influence of relative humidity*

For the next set of experiments, the fluidizing air was introduced at relative humidities of 30%, 50%, and 70% at a constant temperature of 55°C. The drying curves are shown in Figure 3.4.4.

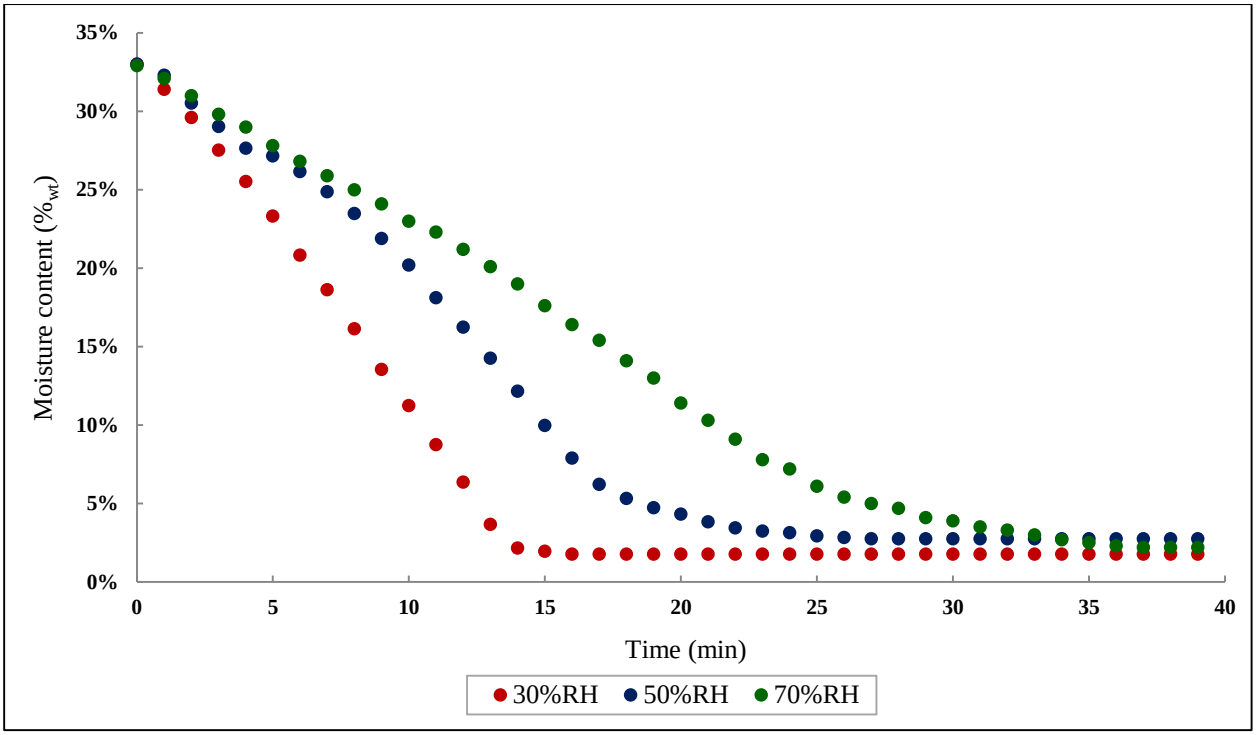


*Figure 3.4.4. Effect of relative humidity on the drying of the mixture -1.18mm+0.7 mm and +0.71mm-0. mm at 55°C*

A comparison of Figure 3.4.4 with Figure 3.4.3 shows that relative humidity has a greater effect on the drying rate than temperature. Lower relative humidities counteract the capillary forces retaining the moisture in the coal particle, leaving a dried product in about 14 minutes at 30% RH, compared to over 30 minutes for 70% RH at the same temperature. Higher relative humidities weaken the moisture transfer mechanism, and therefore the moisture is displaced from the capillary channels at a lower rate (Condie & Veal, 1998). Van Rensburg (2014) stated that the mechanism for the transfer of water molecules from the coal to the air is enhanced when the drying air contains low moisture levels. This leads to a high transfer rate of the water molecules from an area of high moisture content to an area of low moisture content.

### *3. Influence of particle size*

Three wet filter cake samples, all with an initial moisture content of 33%$_{wt}$ and different size ranges (-1.18mm+0.71mm, -0.71mm+0.50mm, and a 50/50 mixture of -1.18mm+0.71mm and -0.71mm+0.5mm), were dried in the fluidized bed using feed air at 55°C and 50% RH. Figure 3.4.5 shows the drying curves for these experiments.

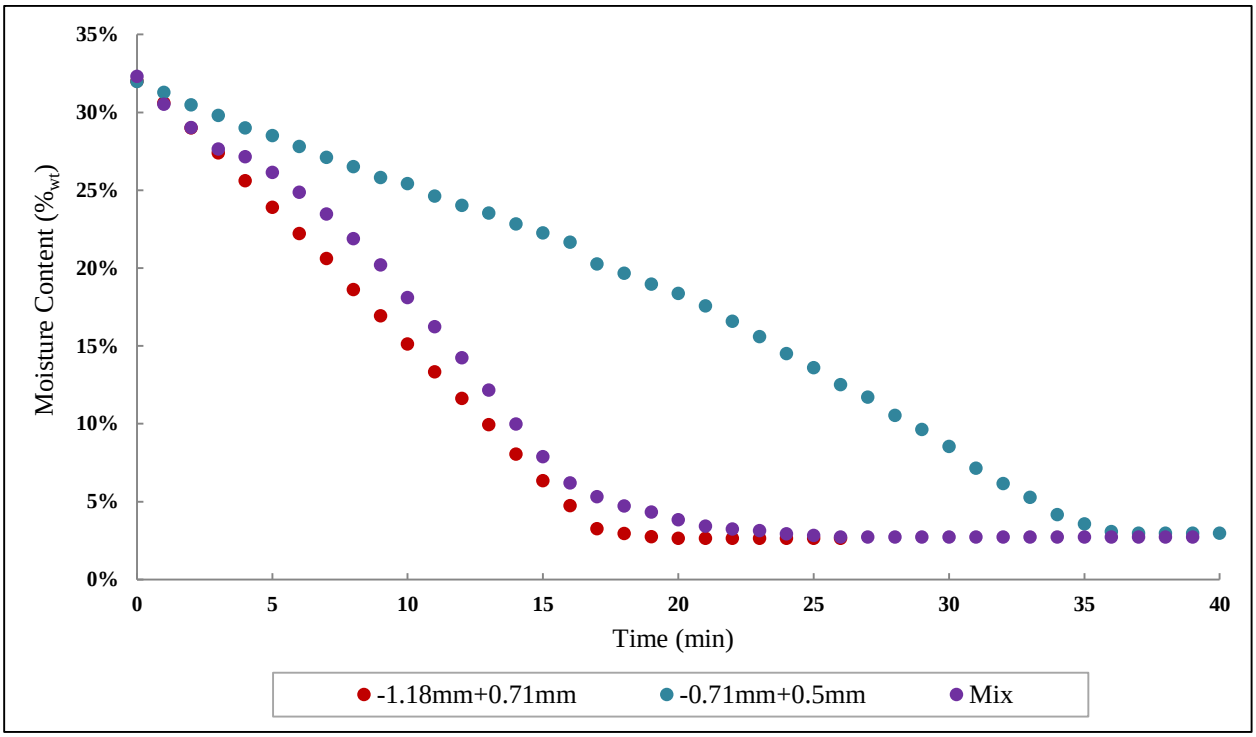


*Figure 3.4.5. Effect of particle size on the drying of coal at 55°C and 50% RH*

The coarse fraction (-1.18mm+0.71mm) and the 50% mixture showed similar drying responses, reaching a final moisture value in less than 20 minutes, while the finer fraction (-0.71mm+0.5mm) reached a similar final moisture value only after 37 minutes. This shows that it is increasingly difficult to remove moisture as the size of the coal particles decreases. Small particles have large surface areas and more micropores to absorb water, resulting in a higher degree of water retention (De Korte & Mangena, 2004).

### *4. Drying rates*

Figure 3.4.6 shows the different drying rates for fluidizing feed air conditioned at 25°C across the set relative humidity ranges.

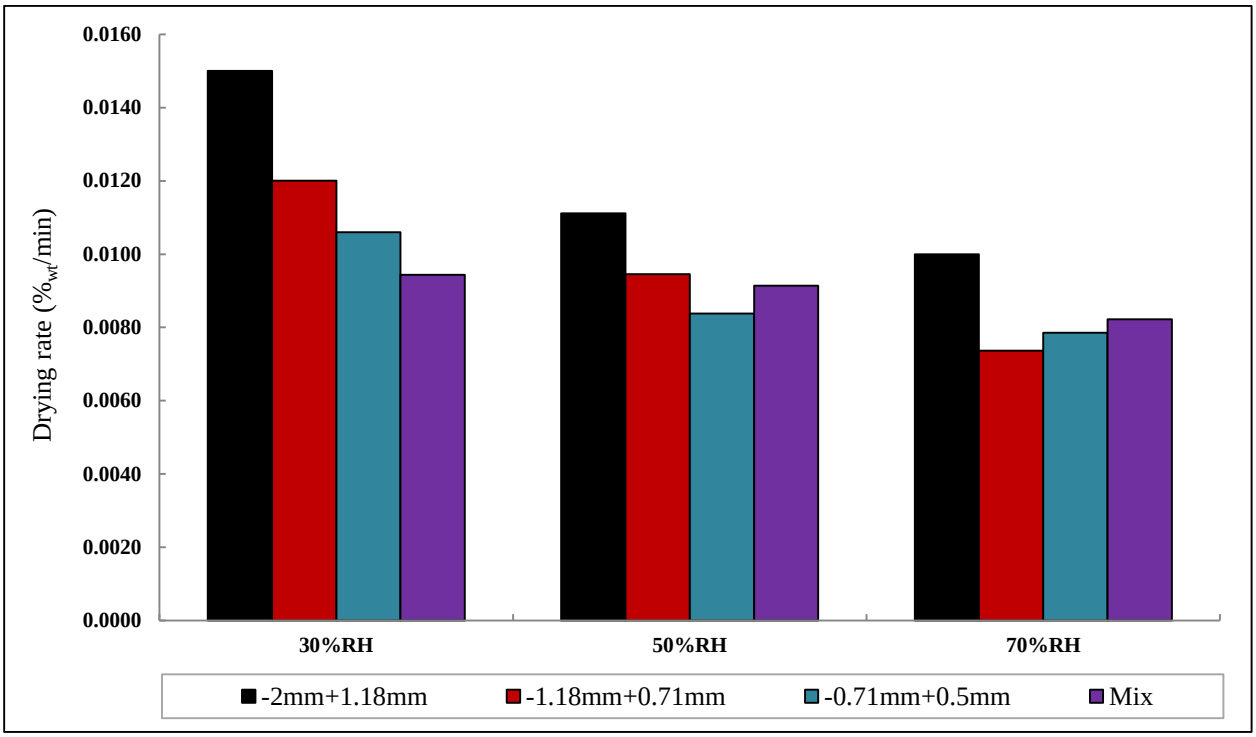


*Figure 3.4.6. Drying rates of different size fractions at 25°C*

A decrease in relative humidity clearly increases the drying rate for all particle size ranges. The drying rate increased from 0.010%$_{wt}$/min to 0.015%$_{wt}$/min for the -2mm+1.18mm particles at 25°C with 70% and 30% RH respectively. It is also apparent that the drying rate increased with an increase in particle size at less than 50% RH. It is noteworthy that at 25°C, particle size is not the rate-limiting factor at relative humidity conditions exceeding 50% RH. The -0.71mm+0.5mm fraction had the lowest drying rate at 25°C and 70% RH, while the fastest drying rate was for the -2 mm+1.18mm particle size range at 30% RH. It is clear that relative humidity has a more significant effect on the drying rate of the coal particles than temperature, hence dry air at moderately low temperatures is effective in drying fine coal.

### *5. Energy consumption*

The energy required during the drying process was calculated by considering the change in enthalpy of the water, the work done by the blower, as well as the energy required for the conditioning of the air. A temperature of 25°C and relative humidity of 50% were chosen as a basis for the calculations, since these were the average ambient conditions in the laboratory. The calorific value of the coal was upgraded by 8MJ/kg on average using air at these conditions as drying medium.

Figure 3.4.7 shows the calculated maximum and minimum of energy requirements to dry to three different moisture levels using the fluidized bed with those of other existing thermal drying technologies. It can be

seen that fluidization is more energy-efficient than other thermal processes, with the exception of the Fleissner process.

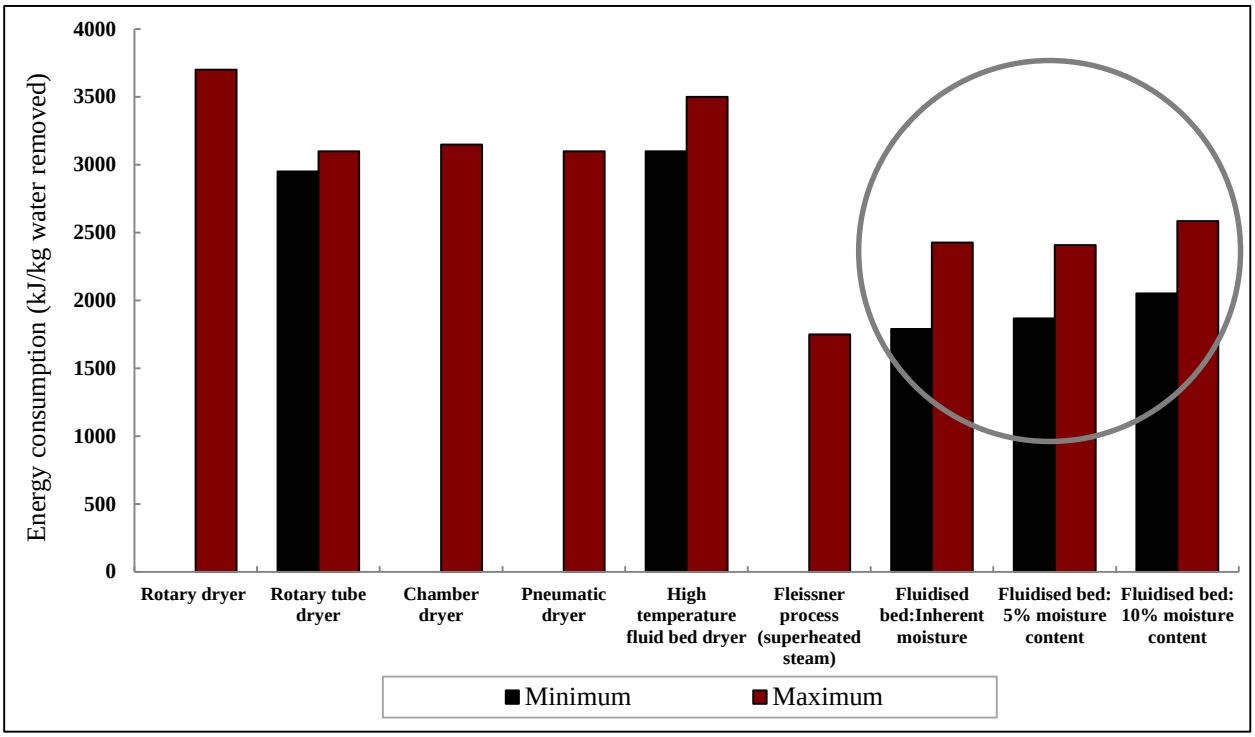


*Figure 3.4.7. Energy consumption of different thermal drying methods for coal in the -2mm+1.18mm particle size range*

### *Conclusion*

This work has shown that fine and ultra-fine coal particles can be dried at moderate temperatures and low relative humidities in a fluidized bed. The time required for fines is about half of that required to dry ultra-fines. The main driving force for removal of moisture from fine and ultra-fine coal is relative humidity. Energy calculations demonstrate that fluidization is more energy-efficient than other thermal drying processes. Using dry air at a moderate temperature in a fluidized bed to dry coal particles is thus a promising technique warranting further study and development, since it has a potential energy advantage as well the ability to increase the calorific value of the coal.

### *Acknowledgements*

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- NRF (National Research Foundation).

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## 3.5. Drying of fine coal using warm air in a fluidized bed (Paper 4)

This section describes the contributions made by the authors in completion of the paper titled "Drying of fine coal using warm air in a fluidized bed". General information is listed regarding the paper that was published in the conference proceedings of the Southern African Coal Processing Society's conference.

### *3.5.1. Contribution by authors*

Miss M.J van Rensburg and Miss E.S. Peters completed studies regarding high airflow systems under the supervision of Prof. M. le Roux and Prof. Q.P. Campbell. The same experimental setup and equipment from the North-West University was used to complete the experimental work for these studies. The experimental work and data processing were completed by Miss M.J van Rensburg and Miss E.S. Peters. The results and discussion of the experimental work presented in this paper came forth out of discussion between Miss M.J. van Rensburg, Prof. M. le Roux, Prof. Q.P. Campbell, and Miss E.S. Peters. This paper was written and presented by Miss M.J. van Rensburg at the Southern African Coal Processing society's conference held in Secunda, South Africa. The conference was held on the 25$^{th}$ to 27$^{th}$ of August 2015.

### *3.5.2. General information*

Information regarding the paper is listed in Table 3.5.1.

*Table 3.5.1. Drying of fine coal using warm air in a fluidized bed (paper 4): General information*

| Category | Information |
|---|---|
| Paper name | Drying of fine coal using warm air in a fluidized bed |
| Authors | Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & Peters, E.S. |
| Journal | Proceedings of the Southern African Coal Processing Society's conference |
| Year | 2015 |
| Web address | http://www.sacoalprep.co.za/ |

# Drying of fine coal using warm air in a fluidized bed

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## *Abstract*

Fluidized bed drying is currently receiving much attention as a dewatering option after the beneficiation of fine coal. The objective of this study was to investigate the removal of moisture from coal fines in a fluidized bed operating with air at moderate temperatures. The drying rate and energy consumption were determined for various operating parameters including relative humidity, temperature, airflow rate and particle size distribution. The overall energy consumption for the fluidized bed is lower than for all the dryer systems compared to and it compared favourably with other thermal drying technologies, proving to be a viable technology for the dewatering of fine coal.

*Keywords*: Dewatering, Drying, Fine coal, Fluidized bed, Warm air

## *Introduction*

According to Reddick *et al.* (2007) coal fines (defined in this report as smaller than 2mm) are produced as a result of mechanised mining methods. It was estimated by Mangena *et al.* (2003) that about 12% of South African mined coal is classified as fines. Fine coal is difficult to dewater and can contain a total moisture content of higher than 25%$_{wt}$ even after filtration (Le Roux, 2003). This high moisture content causes problems in handling as well as a decrease in the calorific value of the coal. An added disadvantage of high moisture content is an increase in transportation and port costs. The difficulty in dewatering often leads to fines being discarded into discard dams. This is an unacceptable waste management procedure as the discarded fines contribute to a number of environmental problems, such as dust release and acid mine drainage. These fines also have the potential of combusting spontaneously if the waste isn't properly managed. Often fine coal is cleaned, dewatered and blended with the course beneficiated fraction. However, the fines rarely reach a desirable quality and such a blend will reduce the quality of the final product by increasing the final product moisture (Reddick *et al.*, 2007).

The development of feasible fine coal beneficiation processes can result in potential revenue and, at the same time, reduce environmental problems (Reddick *et al*., 2007). Fluidisation is proving to be one such an option in beneficiating fine coal. Air dense medium fluidisation is a cheaper and effective alternative to beneficiate coal without using water, as wet beneficiating processes will only add water to the fines (Luo *et al.*, 2010). However, research conducted at North-West University found that elevated moisture content in the feed decreases the efficiency of the process. It was found that a moisture content of larger than 5-7%$_{wt}$ caused the coal particles to stick to the sides of the fluidized vessel or agglomerate to block sufficient airflow, both preventing the system to reach fluidisation state (Terblanche, 2011).

There are several methods for reducing the moisture content in fine coal, for example pressure filtration, centrifuging and thermal drying. Thermal drying remains the most effective water reduction technique but the price of coal inhibits the use of thermal drying methods to dewater unbeneficiated and clean coal (Reddick *et al*., 2007). Mechanical dewatering is generally incapable of delivering the required moisture levels, especially for coal fines. Previous work on vacuum filtration by Le Roux & Campbell (2003) yielded an increase in the dewatering capabilities of the filter when the operational philosophy thereof was moved from a high-pressure differential that causes low airflow, to a low-pressure high airflow regime. It was decided to focus on fluidized bed drying as it causes a low pressure system with high airflow.

### *Background*

This section of work describes the drying process during fluidisation. Since moderate temperatures are used for drying within this project, the temperatures never reach the boiling point of water. Therefore, the water does not reach a state where all the moisture gets evaporated and transported away from the wet sample. At these lower temperatures the moisture in the coal is mainly transferred to the drier air containing less moisture, as a result of the large concentration gradient between the wet coal and the dry air. The mass transfer during drying is called diffusion (Nellis & Klein, 2012).

A popular example to explain diffusion is by placing a glass of water in a room. The air in the room contains water vapour that is in the gaseous phase. Relative humidity is the moisture content relative to the saturation moisture content at the specified dry bulb temperature. The air near the open area of the glass of water is almost completely saturated with water vapour. The moment the water from the glass is transferred into the air, it transforms into a gaseous state called water vapour. The air further away from the glass contains less water vapour, thus a lower concentration. This phenomenon causes the water to be transferred from the air close to the water to the air further away. This process will continue until the water vapour in the whole room is equally distributed. If the relative humidity in the room is lower, there will be a larger mass concentration gradient and a higher vapour pressure deficit. On the other hand a higher relative humidity will decrease the mass concentration gradient (Nellis & Klein, 2012).

Phase equilibrium between liquid water and water vapour is a state where the rate of diffusion from the liquid phase is the same as the rate of condensation of the vapour. Changes in the driving forces like temperature and partial pressure can disrupt the vapour-liquid equilibrium. Figure 3.5.1. illustrates how these driving forces lead to a change in the thermodynamic state of the pure substance. Even slight changes in the temperature and/or relative humidity of the system, at constant pressure, may result in an equilibrium change between the liquid and the vapour, which will lead to the phase change of liquid to water vapour (Koretsky, 2004).

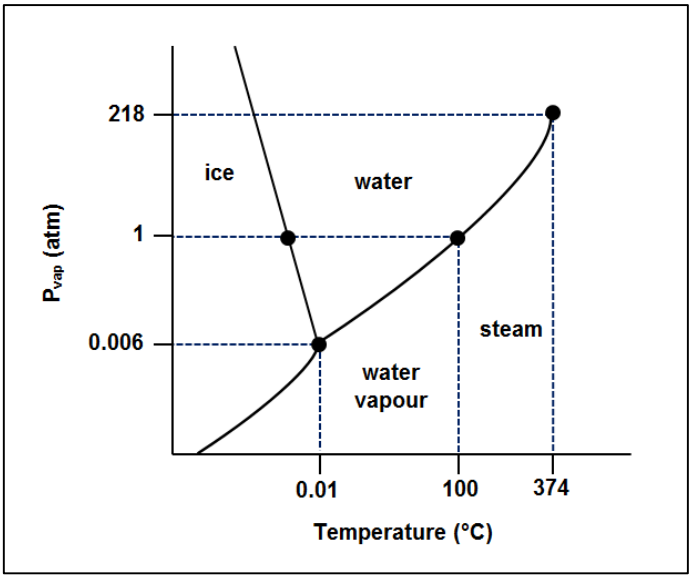


*Figure 3.5.1. Phase diagram of water; taken from the University of Texas (2013)*

By replacing the newly formed vapour with drier (less moist) air, the system equilibrium is again disturbed causing some of the remaining liquid to undergo a phase change to vapour. The system will move to a new equilibrium point where the liquid in the coal particle is in equilibrium with the vapour fraction of the dry air. This is defined as the irreducible equilibrium point of the specific water/air system.

Solid particles in a fluidized bed behave like a fluid when suspended in the upward flowing medium. Therefore, drying in a fluidized bed is achieved by fluidizing the solids by means of the drying medium, in this case, warm air. The water vapour is ultimately captured by the drying capacity of the upwards flowing warm air and continually transferred away from the wet solid particles (Syahrul *et al*., 2002). This sets in motion the process described in the paragraph above, constantly creating a larger concentration gradient.

## *Material and methods*

### *1. Sample preparation*

The vitrinite and inertinite rich coal samples were run off mine coal and used as is for the experimental work. The samples were visually sorted into a bright (vitrinite rich) and dull (inertinite rich) fractions. The samples were left in ambient air to dry, then crushed and sieved to a particle size ranges smaller than 2mm and thereafter mixed and split into 100g sub-samples. The sample either had an equilibrium moisture content or was a filter cake with a high moisture content. Before the experimental work, some samples were conditioned in the climate chamber at a temperature of 25°C and a relative humidity of 80% for two hours to reach its equilibrium moisture content at those conditions. Other samples were drenched in water and filtered to a total moisture content of about 25-35%$_{wt}$.

### *2. Apparatus used*

The fluidized bed test cell was attached to the side of the climate chamber and coupled with it in order for the blower to draw conditioned air from the chamber. The setup can be seen in the diagram in Figure 3.5.2.

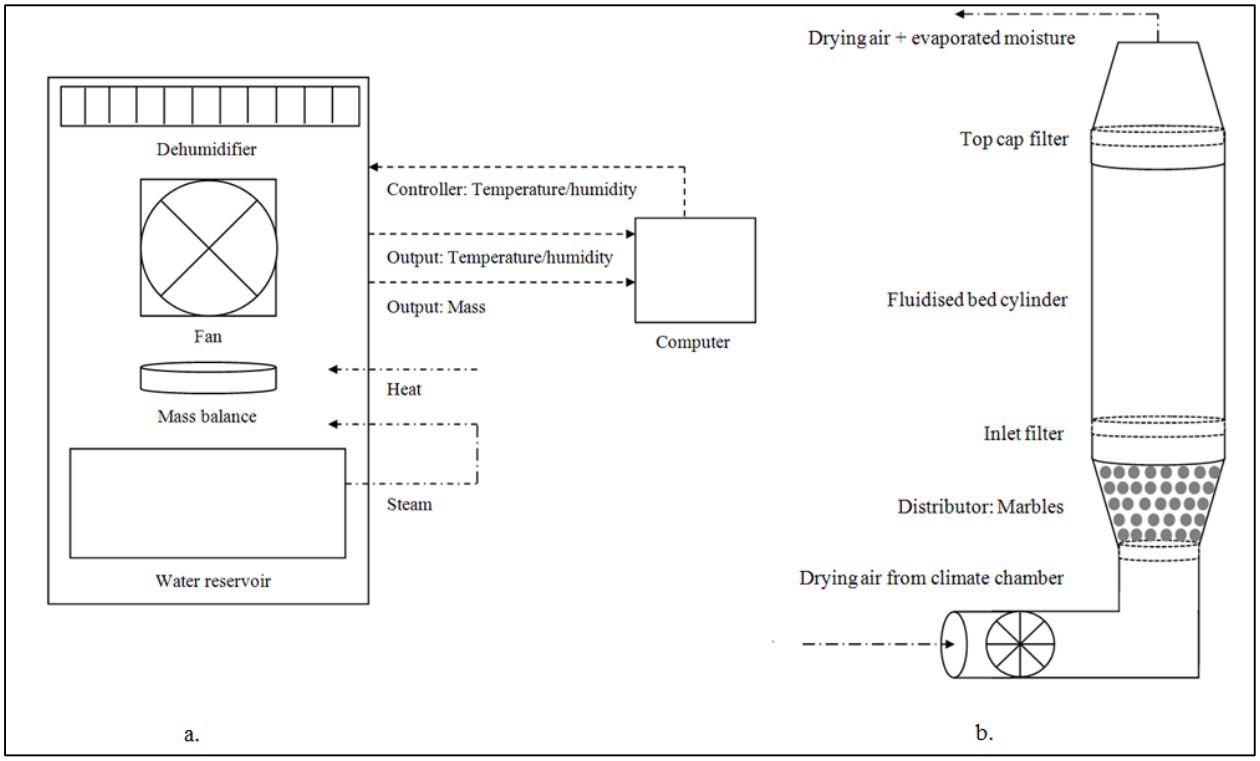


*Figure 3.5.2. A schematic diagram of (a) the climate chamber and (b) the fluidized bed*

A mesh cover was placed at the top and bottom of the fluidized bed cylinder to prevent fine particles from exiting. A fluidized vessel with a diameter of 10cm was used to correlate the results to the static bed test also did on a cylinder with the same diameter. A packed bed of small glass marbles was used to distribute the up flowing air evenly across the cylinder. Humidity detectors were used to observe the moisture loss or gain in the airflow and values were correlated by weighing the samples before, and at regular intervals during a test. The drying air and evaporated moisture was recycled back to the climate chamber to be conditioned again. The climate chamber was used to condition the fresh air before fluidisation as well as conditioning the recycled air throughout the experimental run.

### *Results and discussion*

The experimental work completed for this section of work focussed on determining the optimum operating parameters for fluidized bed drying operating with warm air as fluid. These operating parameters included the relative humidity, temperature, airflow rate and particle size distribution.

***1. Relative humidity***

Filter cakes with a particle size distribution of between 1mm and 2mm and a moisture content of about 25%$_{wt}$ were fed to the fluidized bed and dried with warm fluidizing air at 1.5-1.7m/s and 40°C. The drying air humidifies as it captures moisture from the wet coal particles and therefore, the air entering the fluidized bed was continually conditioned to maintain the process relative humidity. Figure 3.5.3. shows the drying curves at these process conditions.

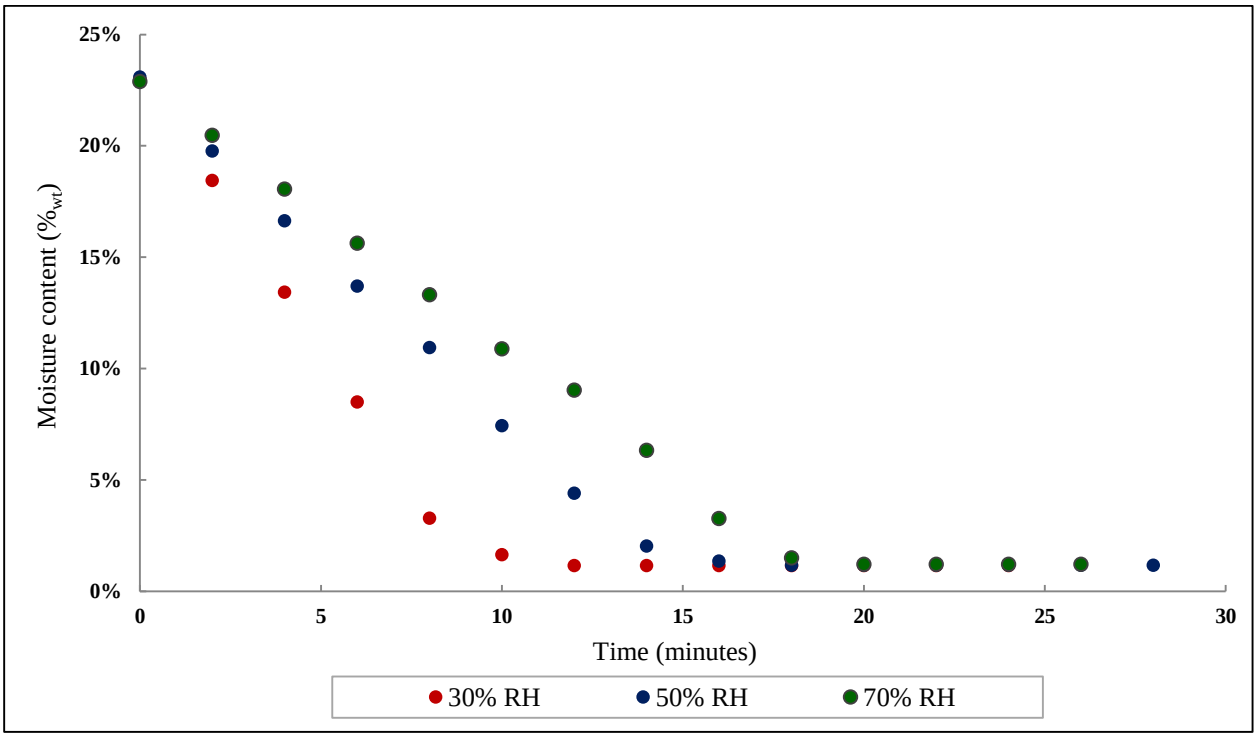


*Figure 3.5.3. Drying of filter cakes in a fluidized bed at 40°C and various relative humidity conditions*

Filter cakes dried at 30%, 50% and 70% relative humidity took about 10 minutes, 14 minutes and 18 minutes respectively to dry to its equilibrium moisture content. The drying performance just over minimum fluidisation velocity proved to be more efficient than static conditions without airflow as the drying time in a fluidized bed was 10 minutes to 18 minutes, while drying at static conditions took longer than 10 hours at best.

Introducing airflow to the system lead to a lower moisture content of the coal samples, but also proved to have the ability to increase the drying rate. It was determined that the airflow had the ability to remove more free moisture from the filter cake. In addition, more inherent moisture could also be removed by using up flowing air, resulting in a lower equilibrium moisture content. The moisture is ultimately captured by the drying capacity of the upward flowing warm air and transferred away from the wet solid particles (Syahrul *et al*., 2002).

The airflow in the fluidized bed replaces the newly formed vapour with drier (less moist) air. The moisture in the coal is mainly transferred to the drier air containing less moisture, as a result of the large concentration gradient between the wet coal and the dry air. Once the system equilibrium is disturbed again, some of the remaining liquid will undergo a phase change to vapour. This process causes a constant moisture concentration gradient that ultimately leads to faster drying rates.

### *2. Temperature*

This section of work focuses on determining the influence of the temperature as well as relative humidity on the drying rate. The filter cakes with a particle size distribution of between 1mm and 2mm and a moisture content of about 25%$_{wt}$ were fed to the fluidized bed operating with warm air at 25°C, 40°C and 55°C. The air entering the fluidized bed was conditioned to maintain a relative humidity of 30% and 50% with an airflow rate of 1.5-1.7m/s. Figure 3.5.4 shows the influence of temperature and humidity on the drying rate. Note that the hollow data points were added for readability and represent the data of 30% relative humidity.

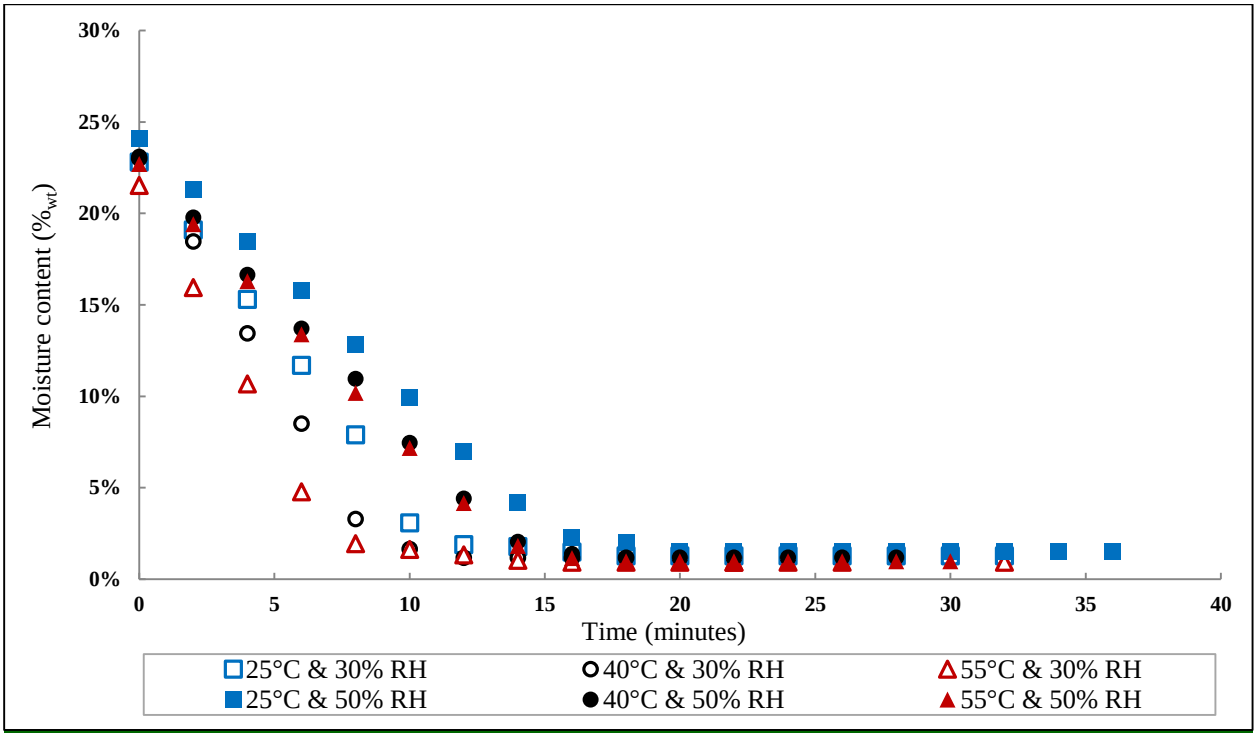


*Figure 3.5.4. Drying of filter cakes in a fluidized bed at 25°C, 40°C and 55°C and 30 and 50% RH*

The results yielded a better idea whether the temperature or relative humidity contributed the most to the drying rate. The lower relative humidity of 30% showed to increase the drying rate compared to the 50% relative humidity condition. This is expected as lower humidity conditions and thus lower partial pressures of the drying air increases its ability to absorb moisture from the wet coal sample at a faster rate.

It was clear that the drying rate for all three temperatures was alike at both relative humidity conditions however more so for the 50% relative humidity. The small changes in the drying rates indicated that an increase in temperature led to an increase in the drying rate across both humidity conditions. In addition it was also clear that the drying rates in the fluidized bed were much less sensitive to the temperature just as it was to relative humidity.

### *3. Airflow rate*

The next set of experiments was completed to demonstrate the extent to which the drying rate was improved by a variation in airflow conditions. Two airflow rates were introduced; one slightly above the minimum fluidisation level at about 0.8-1.1m/s and the other above fluidisation velocity causing vigorous mixing at 1.5-1.7m/s. Wet filter cakes of with a particle size distribution of between 1mm and 2mm each and a moisture content of about 25%$_{wt}$ were fed to the fluidized bed operating with warm air at temperatures of 25°C, 40°C and 55°C. The air entering the fluidized bed was conditioned to maintain a relative humidity of 30%. Figure 3.5.5 shows the drying curves at these conditions. Note that the hollow data points were added for readability and represent the high airflow conditions.

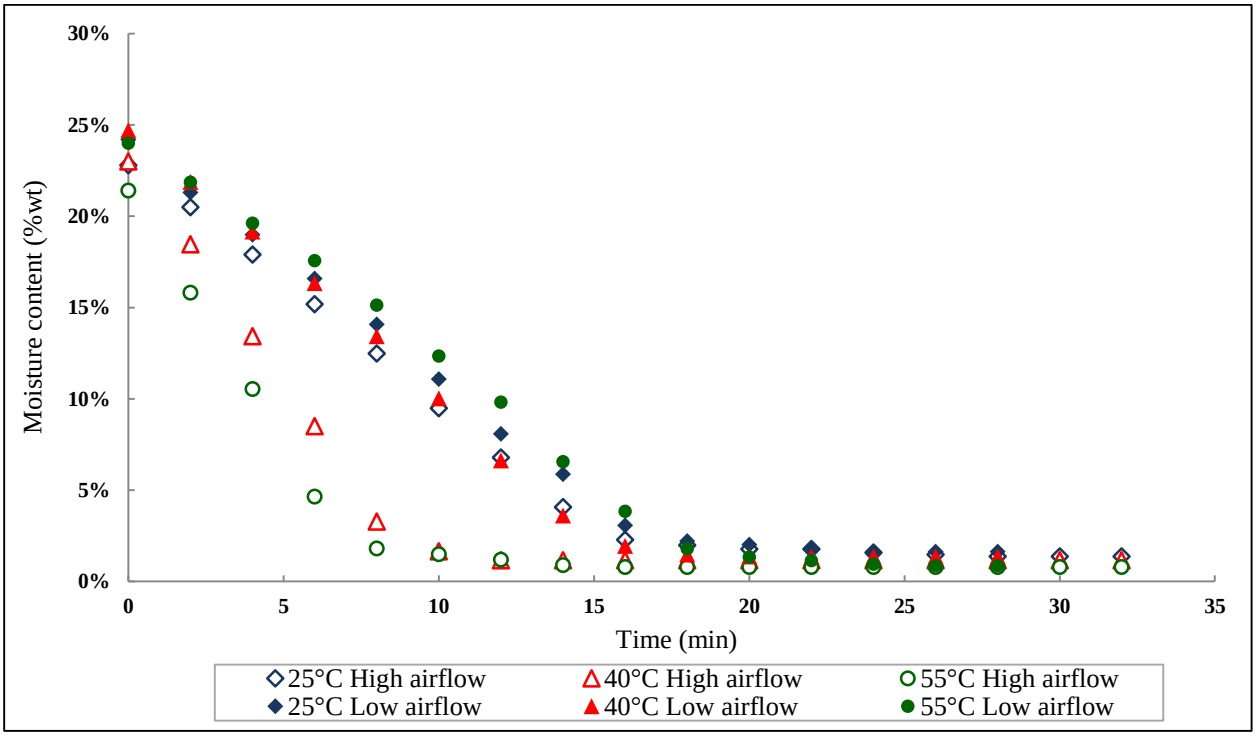


*Figure 3.5.5. Drying of filter cakes at low and high airflow in a fluidized bed at 25°C, 40°C and 55°C and 30% RH*

The results from Figure 3.5.5 indicated that the drying rate of the filter cakes placed in the fluidized bed was improved significantly when using high airflow rates. However, this only seemed to be true for the higher temperatures of 40°C and 55°C. The difference in the drying rate between the low and high airflow

conditions at 25°C, proved to be so small that it falls within experimental error. The high airflow rate at 25°C proved to have a similar drying rate than the samples dried at low airflow conditions.

An increase in the air velocity will bring forth a larger drag force on the particles and more of the particles will break loose from the wet sample to be fluidized (Syahrul *et al*., 2002). An increase in the airflow rate caused vigorous mixing that most likely caused more interaction between the drying air and the wet solid particles. As a result, more moisture was captured and transferred away by the up flowing drying air, leading to a faster drying rate. Furthermore, the higher airflow was also able to replace the newly formed vapour with drier air at a much faster rate. Therefore, the higher airflow caused the system to reach a concentration gradient more rapidly resulting in a faster drying rate.

### *4. Particle size distribution*

Three wet filter cake samples, all with an initial moisture content of 33%$_{wt}$ and different size ranges (-1.18mm +0.71mm, -0.71 mm +0.50mm, and a 50/50 mixture of -1.18mm+0.71mm and -0.71mm+0.5mm), were dried in the fluidized bed using feed air at 55°C and 50% RH. Figure 3.5.6 shows the drying curves for these experiments.

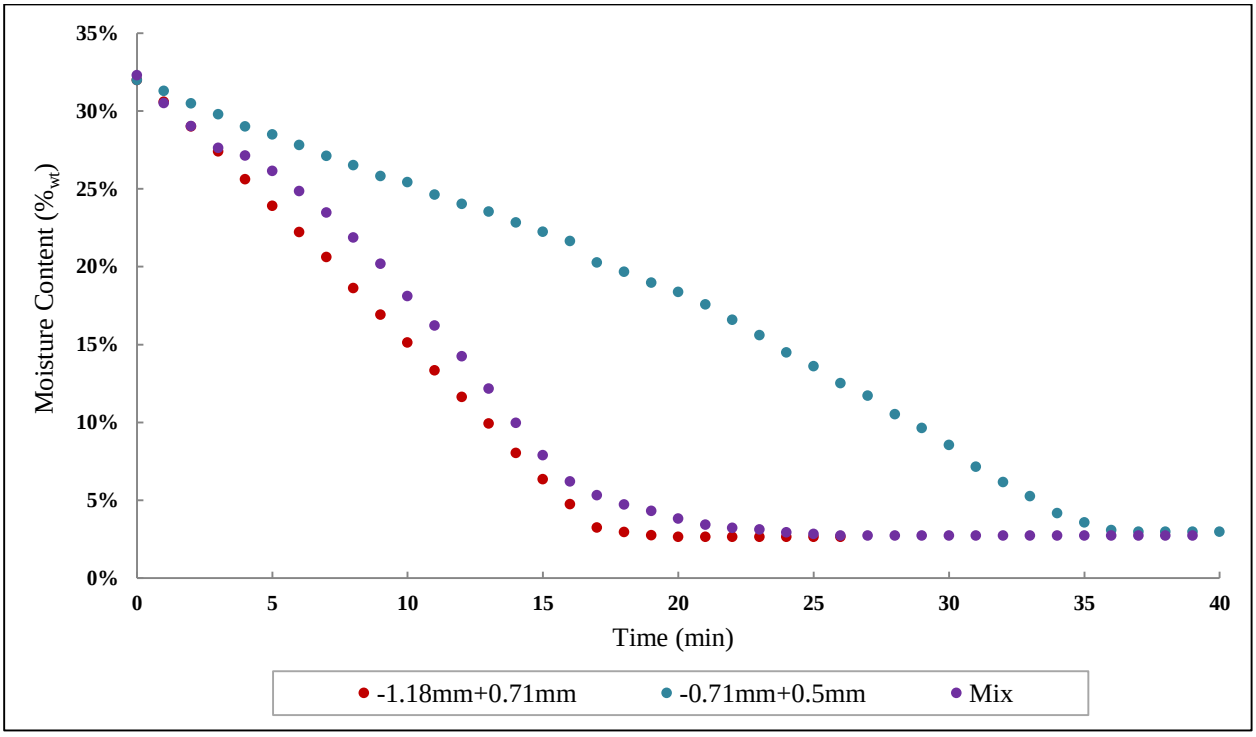


*Figure 3.5.6. Particle size variations at 55°C*

The coarse fraction (-1.18mm+0.71mm) and the 50% mixture showed similar drying responses, reaching a final moisture value in less than 20 minutes, while the finer fraction (-0.71mm+0.5 mm) reached a similar

final moisture value only after 37 minutes. This shows that it is increasingly difficult to remove moisture as the size of the coal particles decreases. Small particles have large surface areas and more micro pores to absorb water, resulting in a higher degree of water retention (De Korte & Mangena, 2004).

### *Energy considerations*

The energy required to evaporate a certain mass of water using a fluidized bed was calculated for three cases: minimum final equilibrium moisture, 5% residual moisture and 10% residual moisture. All the temperature, relative humidity and airflow rate variations were taken into consideration. As a basis for the calculations, ambient conditions were assumed to be 25°C and 50% relative humidity. From here, the energy requirement was calculated as a function of the following variables:

- Change in enthalpy of the water
- Phase change of water for evaporation
- Conditioning of the air by the climate chamber
- Work done by the blower

The nett result is shown in Table 3.5.2, and shows a significant gain in energy for all scenarios which leads to the conclusion that this process is viable. It is possible to improve the overall energy efficiency to between 1.6MJ/kg and 3.8MJ/kg coal in the final product. This can be directly related to additional revenue since the coal can be sold at a higher value.

*Table 3.5.2. Energy calculations: Upgrading of coal*

| Moisture content | Sample Identification | Vitrinite rich coal | Inertinite rich coal |
|---|---|---|---|
| $10\%_{wt}$ | Energy consumed for drying (MJ/kg) | 2.99 - 3.48 | 2.50 - 3.81 |
| | Improvement of calorific value (MJ/kg) | 5.42 | 5.42 |
| | Energy gain (MJ/kg) | 2.43 - 1.94 | 2.92 - 1.61 |
| $5\%_{wt}$ | Energy consumed for drying (MJ/kg) | 3.64 - 4.45 | 3.15 - 4.37 |
| | Improvement of calorific value (MJ/kg) | 7.22 | 7.23 |
| | Energy gain (MJ/kg) | 3.58 - 2.77 | 4.08 - 2.86 |
| Inherent | Energy consumed for drying (MJ/kg) | 4.02 - 4.78 | 2.99 - 4.66 |
| | Improvement of calorific value (MJ/kg) | 8.59 | 8.53 |
| | Energy gain (MJ/kg) | 4.57 - 3.81 | 5.54 - 3.87 |

Wilson *et al.* (1992) did a study on low rank coal and listed a number of dryer types and the energy they consumed per unit moisture removed. The energy consumption for the fluidized bed is lower than for all the dryer systems showed in Figure 3.5.7, this includes the mechanical dewatering and thermal drying systems.

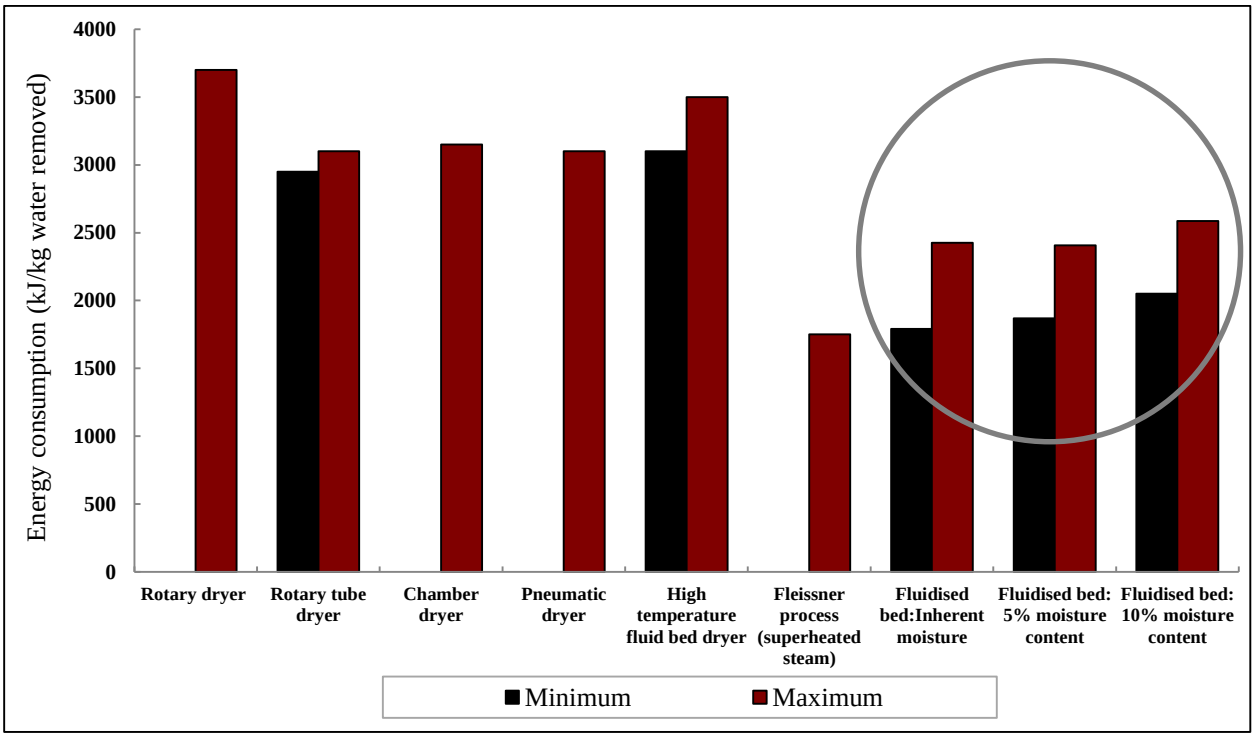


*Figure 3.5.7. Comparison between the fluidized bed and the other drying systems*

Almost all the dryers consumed more energy than 2256.9 $kJ/kg$, the basic indication of energy needed for a thermal drying operation. This is just a preliminary correlation; however the fluidized bed used in this study proved to be much more energy efficient.

### *Conclusions*

It was determined by this study that drying of fine coal is possible using air at temperatures below 60°C. In addition it was proven that the airflow and relative humidity of the drying air at these temperatures contributed to faster drying rates. The drying rates for the coal samples dried in the fluidized bed were all linear, up until it reached a point within the range between 1-2%$_{wt}$ from the final equilibrium moisture content of the bulk coal sample. It was also concluded that drying was more efficient using airflow causing a low pressure than high pressure low airflow systems. It was determined that filter cakes can be dried in the fluidized bed to a point where effective fluidisation can follow. All the drying processes at all the airflow rates, temperature and relative humidity conditions were energy efficient. This process was shown to be energy positive, resulting in an overall energy gain. The overall energy consumption for the fluidized bed is lower than for all the dryer systems compared to and it compared favourably with other thermal drying technologies. It was therefore shown that this is a viable technology for the dewatering of fine coal.

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## 3.6. Additional information

This section focuses firstly on elaborating on the operating conditions required for the high airflow drying. Secondly, the effect of feed size distribution in the fluidized bed is clarified.

### *3.6.1. Operating conditions*

The results discussed in paper 1 to paper 4 indicated that it was possible to dewater fine coal of +0.5mm-2mm by means of high airflow at low relative humidity conditions. In addition, the process was able to deliver the target moisture at low average temperatures of 25°C, 40°C and 55°C. The target moisture could typically be reached within 7.5-12 minutes, depending on the drying air conditions. Further studies were completed to determine the influence of lower and higher temperatures on the drying rate. The experimental work was completed in the same high airflow fluidized bed under relative humidity conditions of 30%, 50% and 70%. The results of the investigation are shown in Figure 3.6.1.

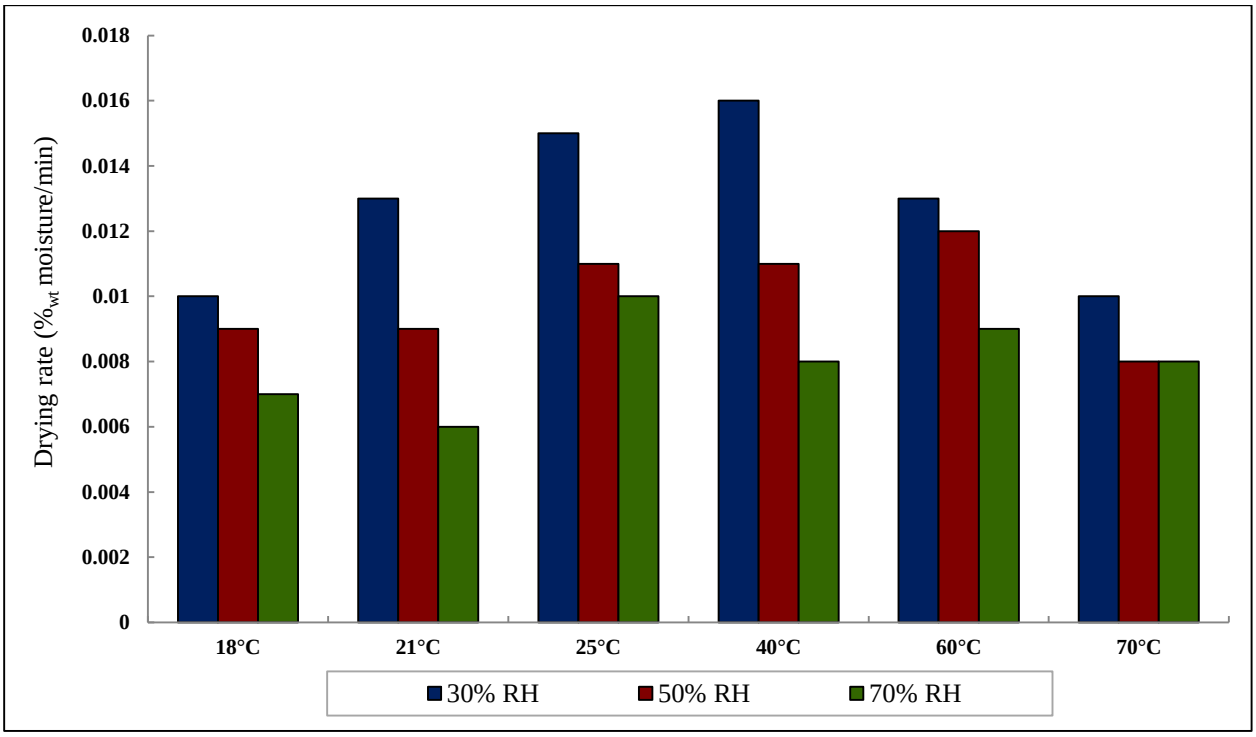


*Figure 3.6.1. Drying rates of coal under airflow temperatures between 18°C and 70°C*

During drying, moisture is transferred from the wet coal to the unsaturated capacity of the dry fluidizing air (Barbosa de Lima *et al*., 2016). The continuous airflow ensures that a constant flow of unsaturated air is in contact with the wet coal to create a moisture gradient. Furthermore, a moisture gradient is created within the bulk coal sample and pore network of the particles that ensures that moisture diffuses through the bulk sample to the exposed surface, to be captured by the passing air when in contact. The transferred moisture in the air is then transported away from the coal, leaving a new moisture content equilibrium

which will again create a moisture gradient with the passing air. Creating a constant moisture gradient prompts dewatering, leading to a drier coal product. This will continue until the dewatering force and moisture holding force is equal to each other, which is a function of the air temperature and humidity levels and coal moisture holding capacity.

An increase in the drying air temperature will subsequently lead to an increased moisture holding capacity of air. A larger concentration gradient will form as a result of the lowered moisture content of the drying air. Therefore, elevated temperatures will increase the moisture transfer rate and, ultimately, promoting moisture to leave the coal particles and form a new equilibrium between the coal moisture and air phase (Barbosa de Lima *et al*., 2016). Increased temperatures will also lead to higher levels of evaporation and result in the increase of vapour pressure in and around the coal sample which will promote further moisture transfer (Koretsky, 2004; Barbosa de Lima *et al*., 2016). An increase in the drying rate can be seen in Figure 3.6.1 resultant from temperature increases. When operating at low temperatures as shown in Figure 3.6.1, the diffusion mainly depends on the moisture gradient as the drying air conditions do not encourage additional transfer of moisture.

As a rule, warmer air can absorb more moisture compared to cold air (Sun & Wang, 2016). However, for this specific setup, the temperature benefit could only be seen up until 40°C across all three relative humidity conditions. It was found that vapour formed and condensed unto the cylinder wall of the fluidized bed at temperatures higher than 40°C. When the temperature increases inside the vessel, the temperature of the vessel wall remains colder than the inside throughout the duration of the experimental run. When the vapour comes in contact with the colder surface at a temperature below the saturation temperature of the vapour in the drying air, the vapour condenses to liquid unto the surface. At this dew point, the drying air is saturated with moisture which enables condensation to occur. The moisture is released in liquid droplet form unto the cold surface of the cylinder (Sun & Wang, 2016). This scenario influenced the high airflow drying efficiency in two ways. Firstly, the moisture in the surrounding drying air led to an increase in the partial pressure of the drying air resulting in a decrease in the moisture concentration gradient. According to Barbosa de Lima *et al*. (2016), drying takes place when the partial pressure of the drying air is lower than the vapour pressure of the moisture surrounding the coal particles. When the surrounding air is saturated, it reduces the dewatering capacity of the drying medium. Secondly, the existence of condensate droplets on the sides of the vessel, adds to the operating time because unsaturated or partially saturated air now has to remove the condensate as well. The drops of condensate flowing down the cylinder adds to the moisture in the coal sample that has to be removed, subsequently increasing the drying time required to lower the coal sample moisture content.

The results from Figure 3.6.1 indicate that irrespective of temperature fluctuations, moisture transfer was still taking place. Therefore, the moisture concentration gradient created between the wet coal fines and the drier fluidizing air is the main contributor to the drying rate. The factors positively influencing the moisture gradient include: airflow rate, relative humidity and elevated temperatures up to 40°C. Forcing

more air through the wet filter cake will enhance moisture movement and result in drier product (Barbosa de Lima *et al*., 2016). Replacing the air in the drying system with more unsaturated air at a faster rate will create a continuous and larger moisture concentration gradient. A reduction in the relative humidity means that the drying air contains less vapour, decreasing its saturation with a lower partial pressure, which encourages moisture transfer (Nellis & Klein, 2012). It was therefore established that average atmospheric and slightly elevated temperatures were sufficient for the dewatering capabilities of the high airflow fluidized bed. Moreover, high airflow and lower relative humidity conditions were the main driving forces promoting faster dewatering rates.

### *3.6.2. Feed size distribution*

Paper 1 to paper 4 showed that it was possible to dry fine coal in a fluidized bed operating with high airflow. However, the efficiency of the drying process depends on the size distribution of the feed. Wet filter cake samples with a particle size distribution of -1.18mm+0.71mm and -0.71mm+0.50mm were placed in the fluidized bed. Both samples had an initial moisture content of 33%$_{wt}$ prior to the experimental run. Figure 3.6.2 shows the drying curves for these experiments.

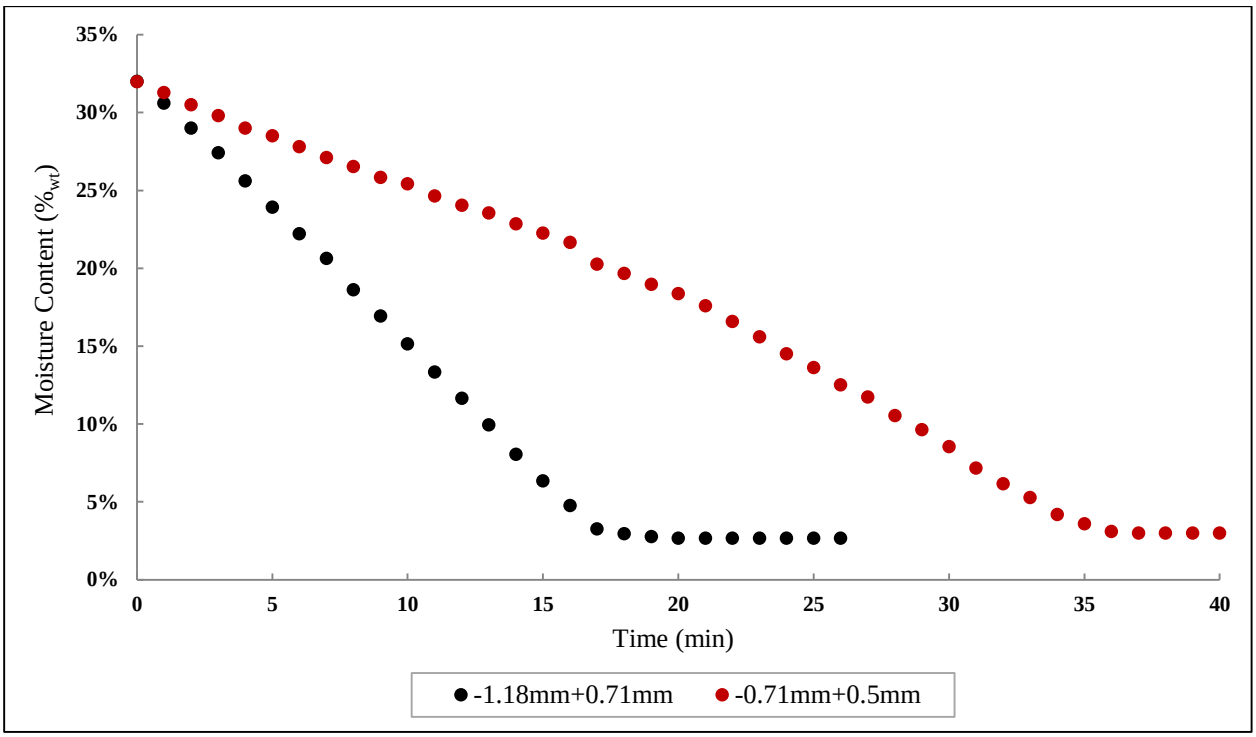


*Figure 3.6.2. Effect of particle size on the drying rate at 55°C and 50% RH*

Table 3.6.1 shows the drying times of coal samples with particle size distributions of -1.18mm+0.71mm and -0.71mm+0.50mm. These experiments were completed at temperatures of 25°C and 55°C and relative humidity conditions of 30%, 50% and 70%.

*Table 3.6.1. Effect of particle size on the drying rate at 25°C and 55°C at various relative humidity conditions*

| Particle sizes | Temperature | Drying time (min) | | |
|---|---|---|---|---|
| | | 30% RH | 50% RH | 70% RH |
| -1.18mm+0.71mm | 25°C | 28 | 36 | 39 |
| | 55°C | 22 | 20 | 25 |
| -0.71mm+0.50mm | 25°C | 39 | 47 | 51 |
| | 55°C | 37 | 59 | 78 |

Figure 3.6.2 shows that the coarser fraction of -1.18mm+0.71mm could reach the final equilibrium moisture content in less than 20 minutes, while the finer fraction required 37 minutes in total. Table 3.6.1 shows that this trend could also be seen across various relative humidity conditions at 25°C and 55°C. The smaller particles required significantly more drying time compared to the larger particles. Even though the high airflow could ensure that the bulk coal sample reached final equilibrium moisture values close to the inherent moisture content level, it took longer to reach this point due to the intrinsic properties of the finer fraction. Adjustments to the drying air are required in order to improve the removal rate of free and bound moisture from the coal sample. This can typically be achieved by lowering the partial pressure of the drying air ensuring an improved moisture uptake capacity and rate.

Smaller particles have a larger total surface area that results in increased surface tension, which in turn increases the likelihood to hold onto more moisture at external surface of the particles as well as to the internal surface of the capillary network (De Korte & Mangena, 2004). The surface tension consequently holds unto the moisture which requires additional drying time.

Capillary pressure exerted by inter and intra particulate voids ensures the moisture is held within the pore network. Moisture is consequently more challenging to remove from smaller pores as the capillary pressure increases the holding capacity of the coal. During drying the airflow invade and drain the capillary network of the porous coal to reduce the equilibrium moisture to below that of the inherent moisture levels. The capillary network is breached according to the pore size, where the larger pores are reached and drained first (Aminzadeh & Or, 2016). Therefore, the presence of smaller particles will indefinitely lead to increased drying time. The smaller pore radii between the finer particles in a heap lead to an increased moisture holding capacity within the bulk sample (Toa *et al*., 2006). This additional free moisture held in the feed sample adds to the percentage moisture retained and adds to the drying time required when drying a sample containing a high percentage of fines.

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# Chapter 4

## Adsorption assisted drying

The focus of Chapter 4 is to introduce adsorption drying where sorbent material is combined with coal fines to initiate moisture transfer. This chapter aims to give a description of the adsorption process and the subsequent regeneration and re-use of the sorbent material. The aim is to investigate a range of parameters to make suggestions regarding the main driving forces required for efficient adsorption assisted dewatering. The possibility and requirements for dewatering ultra-fine coal are also discussed.

## 4.1. Purpose and outline

Studies completed by Bland & McDaniel (2014), Bratton *et al*. (2012) and Kudra & Mujumdar (2009) points to the possibility of using sorbent material as a non-thermal alternative method to reduce the moisture content of coal. The main focus of Chapter 4 is to verify whether it is possible to dewater fine coal by means of adsorption assisted drying. Alumina- and silica-rich ceramic spheres were used as sorbent material to remove the water associated with coal fines. Results from the finding are presented in the form of 2 papers published in conference proceedings and one paper submitted to a peer-reviewed journal.

- Paper 5 entitled "Drying of coal fines assisted by ceramic sorbents" gives an introduction and description of contact adsorption drying implemented to dewater fine coal. The aim of this paper is to define how operating conditions such as temperature, particle size variations and sorbent to coal ratios would influence the adsorption efficiency. In addition, the possibility to regenerate and re-use the sorbent material was investigated.
- Paper 6 entitled "Adsorbent assisted drying of fine coal" examines the adsorption process by investigating additional experimental parameters; different sorbent material and a larger coal particle size distribution. The influence of mixing the feed by means of cascading bed motion to induce improved contact between the sorbent material and coal fines was investigated. The results are summarised by comparing the dewatering rate and final moisture content of the coal achieved under the investigated experimental parameters.
- Paper 7 entitled "Contact sorption: A method to reduce the moisture content of coal fines" aims to address the adsorption process and describe the conditions promoting moisture transfer from the wet coal fines to the dry sorbent material. The paper summarises all experimental conditions and parameters investigated and gives a conclusion about the main driving forces promoting the dewatering rate. Results of test work regarding sorbent regeneration and re-use are discussed as well. Thereafter the energy consumption was compared to the energy consumption of other drying technologies.

Additional experimental work was completed to determine the influence that elevated surrounding temperatures have on the coal-ceramic system and the dewatering rate and final moisture content of the coal fines. The possibility to dewater ultra-fine coal of -0.212mm was investigated and suggestions are made regarding the best process conditions to achieve the desired target moisture of these ultra-fines.

## 4.2. Drying of coal fines assisted by ceramic sorbents (Paper 5)

This section describes the contributions made by the authors in completion of the paper titled "Drying of coal fines assisted by ceramic sorbents". General information is listed regarding the paper that was published in the conference proceedings of the XVIII International Coal Preparation Congress.

### *4.2.1. Contribution by authors*

The field of study and reasoning behind this study was determined by Prof. M. le Roux and Prof. Q.P. Campbell. The experimental setup for adsorption drying was the responsibility of Miss. M.J. van Rensburg, Prof. M. le Roux and Prof. Q.P. Campbell. The experimental parameters and procedures were determined by Miss. M.J. van Rensburg. The experimental work was completed by undergraduate students under the supervision of Miss. M.J. van Rensburg, Prof. M. le Roux and Prof. Q.P. Campbell. The results showed in this paper came out of discussions between the authors and undergraduate students. The paper was written and presented by Miss. M.J. van Rensburg at the XVIII International Coal Preparation Congress (ICPC). The conference took place in Saint-Petersburg, Russia from the 28$^{th}$ of June to the 1$^{st}$ of July 2016. This paper was published in the conference proceedings.

### *4.2.2. General information*

Information regarding the published paper is listed in Table 4.2.1.

*Table 4.2.1. Drying of coal fines assisted by ceramic sorbents (paper 5): General information*

| Category | Information |
|---|---|
| Paper name | Drying of coal fines assisted by ceramic sorbents |
| Authors | Van Rensburg, M.J., Le Roux, M. & Campbell, Q.P. |
| Journal | Proceedings of the XVIII International Coal Preparation Congress, 741-746 |
| Year | 2016 |
| Copyright | © Springer International Publishing Switzerland |
| ISBN | 978-3-319-40943-6 (Online) & 978-3-319-40942-9 (Print) |
| DOI | 10.1007/978-3-319-40943-6_114 |

# Drying of coal fines assisted by ceramic sorbents

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## *Abstract*

It is proposed to introduce contact sorption drying as a method to reduce the moisture content in coal fines. The aim of this study was to investigate the possibility of drying fine and ultra-fine coal using porous ceramic as the moisture sorbent. The main focus of this report is to define how the air temperature, particle size variations and mixing ratio would influence the contact between coal and ceramic for effective moisture adsorption. Drying of coal fines assisted by ceramic sorbents proved to be a viable concept as the ceramic was able to not only reduce the moisture content of fine coal, but of ultra-fine coal as well. The larger surface area of smaller ceramics allowed for efficient contact and consequently higher dewatering rates. The addition of more ceramic resulted in better contact with the wet coal and reduced the operating time quite significantly. Improved contact between the coal and ceramic therefore proved to be the main driving force during adsorption drying.

*Keywords*: Alumina, Ceramic, Coal, Drying, Fines, Moisture, Sorbent, Sorption

## *Introduction*

Mangena *et al*. (2003) estimated that about 12% of South Africa's mined coal can be classified as fine and ultra-fine coal. Due to its large surface area, the coal fine fraction retains the majority of the moisture in mined coal and can contain a moisture content of higher than 25% by weight (Le Roux, 2003). Compared to coarse coal, the fine and especially the ultra-fine fraction are far more difficult to dewater to an acceptable moisture content. As a result of the difficulty in dewatering, the fines are often dumped into discard dams or slurry ponds. Consequently, these disposal methods lead to a series of environmental problems such as acid mine drainage, dust release, spontaneous combustion and it also occupies large areas of land. Aside from the environmental problems, the wasted coal fines have heating values comparable to the coarse coal fraction when dried (Reddick *et al*., 2007). It would then be sensible to investigate and implement cost effective and efficient drying methods to salvage the wasted fines and process the mined fine fraction. It is important to use coal wisely as it is the primary energy resource in South Africa (Fourie *et al*., 1980).

In fine coal processing the mechanical dewatering techniques are ineffective as these methods cannot reduce the moisture content to a desirable level. Dewatering of coal fines often relies strongly on thermal methods as coal fines are known to retain water (Le Roux & Campbell, 2003). There are several conventional thermal drying methods, however not all of these systems are ideal in terms of energy consumption and safety during operation (Kudra & Mujumdar, 2009).

It is proposed to introduce contact sorption drying as a method to reduce the moisture content in coal fines by creating a mass concentration gradient between the wet coal and dry sorbent. The aim of this study was to investigate the possibility to dry fine and ultra-fine coal using porous ceramic as moisture sorbent. The investigation focuses on defining how the temperature, particle size variations and mixing ratio will influence the contact between the coal and ceramic and consequently the moisture transfer. The efficiency of the contact drying technique would lay in the possibility of separating the coal and ceramic and furthermore regenerate the ceramic for re-use.

### *Background*

Ceramic is an inorganic solid that is relatively cheap as many manufactures produce it from waste material (Lin *et al*., 2012). Ceramic is used as an adsorbent due to its permeability and extensive pore size distribution. It is specifically favoured due to its retention ability and the permeate flux it causes (Li *et al*., 2006). According to Lin *et al*. (2012) ceramic is unique as it is porous, yet has great mechanical and thermal stability making it suitable for industrial purposes.

Contact sorption drying takes place in three main stages as indicated in Figure 4.2.1. During the first stage the wet coal comes in contact with the dry ceramic and a small amount of moisture transfer takes place. This phase relies mainly on effective contact between the material and sorbent. The moisture is adsorbed unto the surface of the sorbent through diffusion and then penetrates through the pores of the sorbent. This set in motion the macro scale diffusion due to the large moisture concentration gradient between the wet coal and dry ceramic. The majority of the contact sorption drying takes place during the second stage and reaches a clear equilibrium where no major moisture transfer takes place. At the completion of the drying process, minor penetration and diffusion will take place between the sorbent and material leading to a very slow drying rate. Moisture transfer between sorbent-sorbent particles and material-material particles will result in minor fluctuations in the final equilibrium moisture content (Kudra & Mujumdar, 2009).

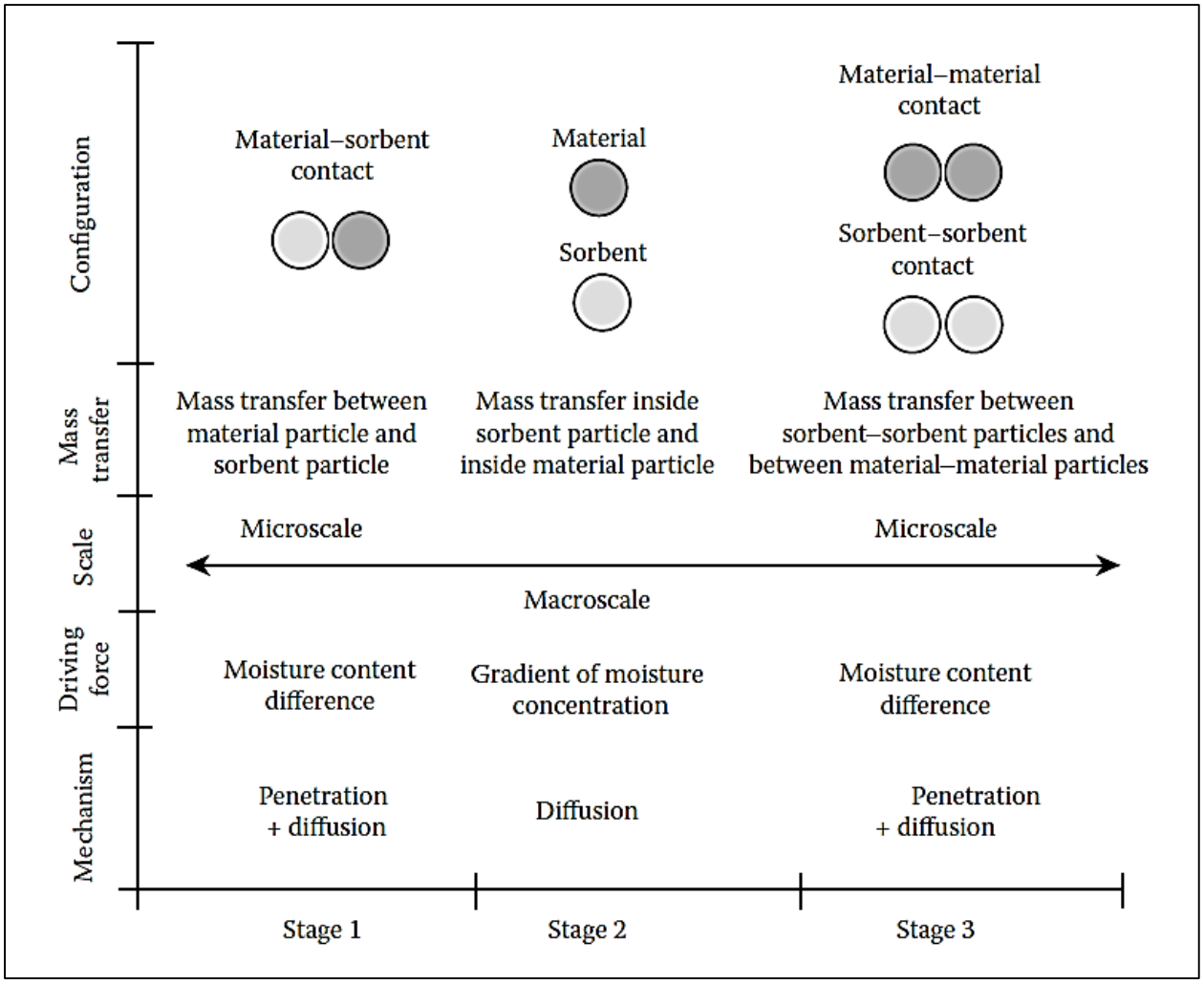


*Figure 4.2.1. Drying mechanism for contact sorption drying; taken from Kudra & Mujumdar (2009)*

### *Experimental*

This report aims to define how the temperature, size variations and ratio will influence the contact between coal and ceramic for effective adsorption. The efficiency of contact sorption drying was tested on fine coal as well as ultra-fine coal.

### *1. Equipment*

The experimental work was based on laboratory scale units to test the proof of concept and Figure 4.2.2 gives a layout for this contact sorption drying process. Firstly, the drying process took place within the rotating adsorber, after which the loaded ceramic and dry coal were separated by screening. Finally, the saturated ceramic was dried within a packed bed to be re-used in the contact sorption drying. The adsorber was designed to rotate the enclosed cylinder with a diameter of 8cm at about three revolutions per minute to ensure sufficient contact between the coal and ceramic. The cylinder was specifically placed horizontally

to prevent the coal and ceramic from separating due the large difference their particle size and density. Laboratory sieves were used to separate the saturated ceramic and dried coal before the ceramic was placed in a packed bed to be dried. Wet ceramic was easily separated from the dry coal and the packed bed dryer regenerated the ceramic to a point where it could be re-used. Note that only results from the rotary adsorber are discussed in this report.

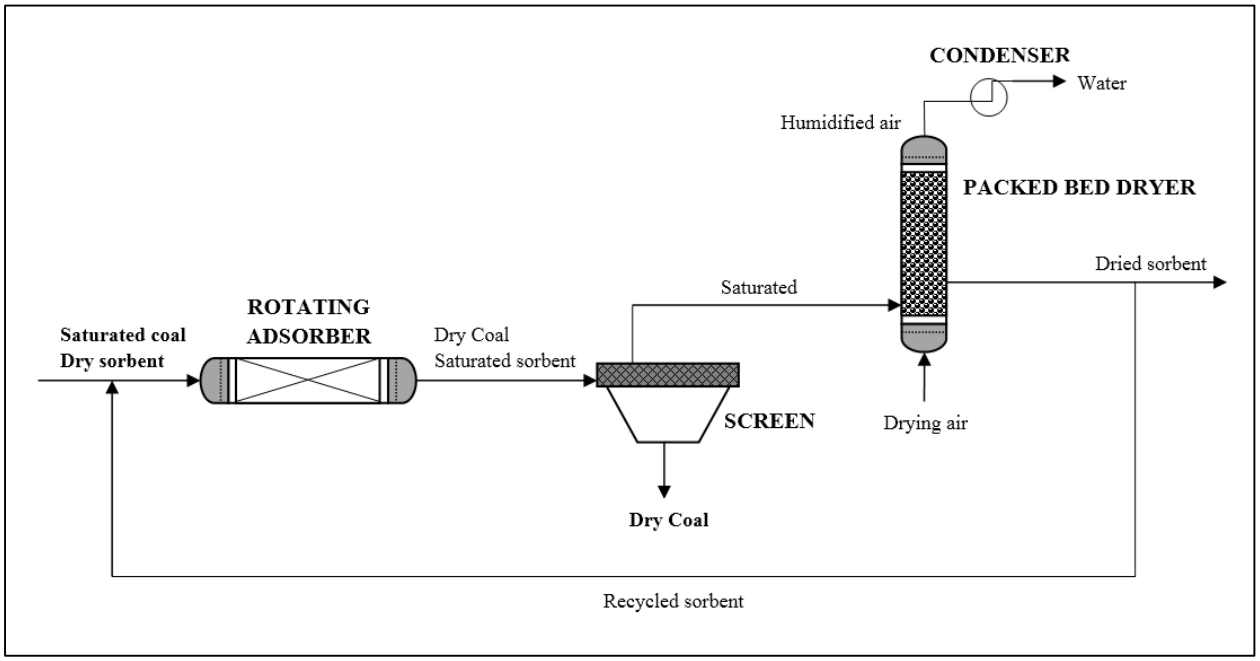


*Figure 4.2.2. Diagram of contact sorption drying and regeneration process*

### *2. Material*

Coal from the Highveld coal field in South Africa was used in this study. The samples were initially left to dry in ambient air and thereafter crushed to a fine coal fraction of +1mm-2mm and an ultra-fine coal fraction of smaller than 0.5mm. A sample splitter was used to produce uniform samples of 100g each to obtain more repeatable experimental data. Afterwards the samples were drenched in water and filtered to a total moisture content of about 14-16%$_{wt}$ for the fine coal fraction and 18-25%$_{wt}$ for the ultra-fine coal fraction. Porous ceramic containing about 82-85%$_{wt}$ of Alumina oxide was used as an adsorbent to transfer water away from the coal. The test work was completed using ceramic spheres of between +6mm-10.5mm and +12mm-20mm.

### *Results and discussion*

Fine coal was dried within the rotary adsorber and the moisture content of both the ceramic and coal was determined at various intervals. The experiment was conducted at 25°C and the material used included fine coal and ceramic with a particle size distribution of +1mm-2mm and +6mm-10.5mm respectively. Figure

4.2.3 shows that the moisture loss from the coal correlates with the moisture uptake in the ceramic spheres. The majority of the moisture transfer took place within the first 5 minutes indicating that the moisture within the bulk coal sample could rapidly be reduced from about 19%$_{wt}$ to 9%$_{wt}$. After the major moisture transfer, the drying rate slowed down significantly as the coal reached a level close to its final inherent moisture content. It was observed that towards the completion of the experiment that the coal adsorbed a small amount water again, but it was adsorbed by the ceramic again soon after. This phenomenon occurred continually after the coal and ceramic reached equilibrium. Kudra & Mujumdar (2009) states that these moisture fluctuations are referred to as stage 3 during the drying process.

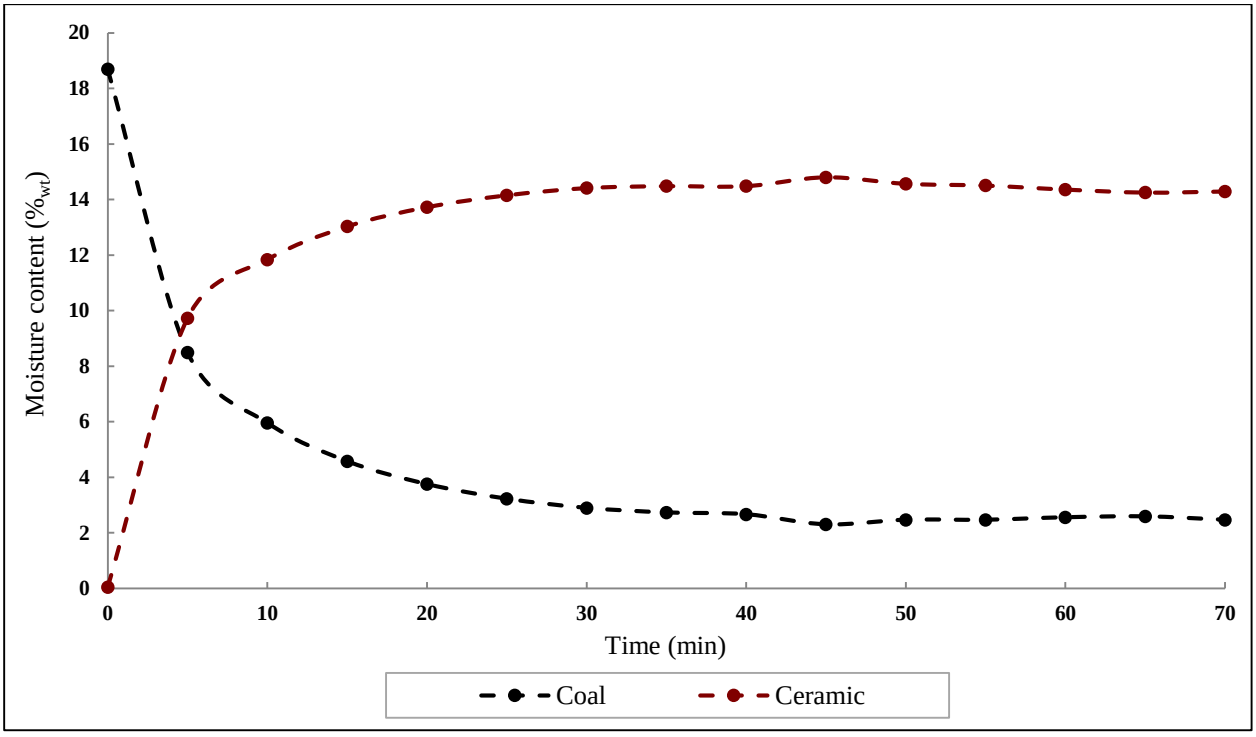


*Figure 4.2.3. Moisture transfer during contact drying*

During this stage variations in the moisture content are due to the moisture transfer between sorbent-sorbent, material-material as well as sorbent-material particles. Initially the contact sorption drying took place in an enclosed container at static conditions, but it was found that there was a lot of vigorous fluctuation in the data. A rotary adsorber was introduced to ensure maximum contact between the coal and ceramic and Figure 4 shows the improvement in the data thereafter.

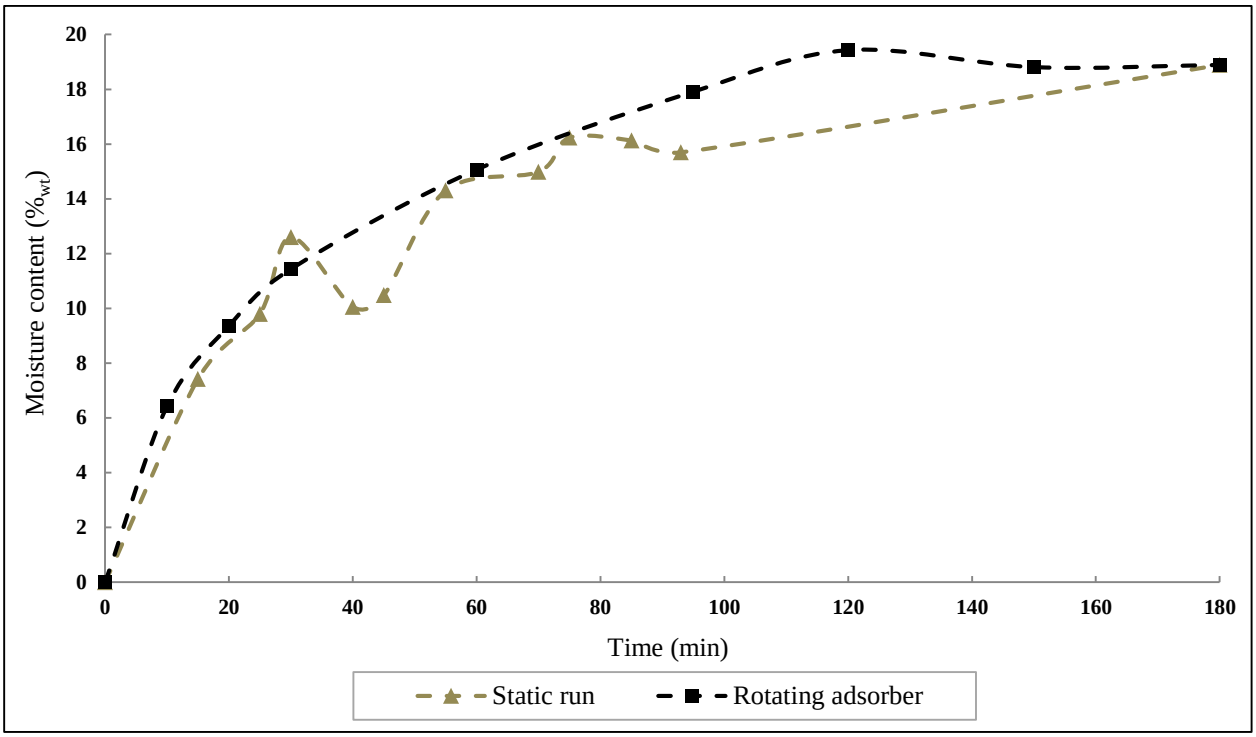


*Figure 4.2.4. Static versus rotating adsorber*

Ceramic spheres between size ranges of +6mm-10.5mm and +12mm-20mm were used to determine the difference in adsorption rate of moisture from ultra-fine coal samples at 25°C. The results obtained from these two experimental runs are given in Figure 4.2.5.

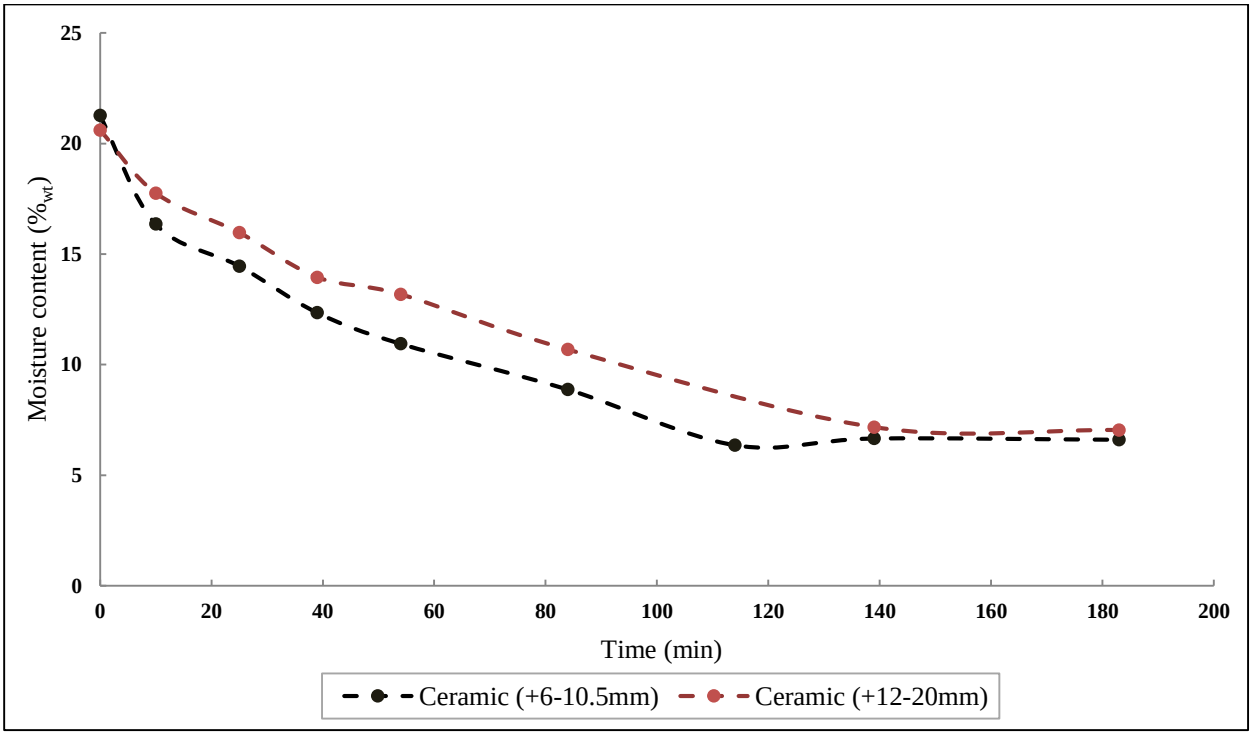


*Figure 4.2.5. Variation in ceramic size*

It was found that the smaller ceramic spheres had the ability to adsorb more moisture from the coal at a much faster rate, when compared to the larger ceramic particles. Asmatulu & Yoon (2012) stated that finer particles attract and retain water mainly because they have a larger surface area compared to large particles. The larger surface area creates surface and capillary forces aiding in the adsorption process. It was therefore found that increasing the surface area by working with smaller ceramic, improved the contact during adsorption. However, it is important to keep the size ratio between the ceramic spheres and the fine coal particles large enough to aid in the separation thereof. Figure 4.2.6 shows the difference in the sorption rate when fine and ultra-fine coal were dried.

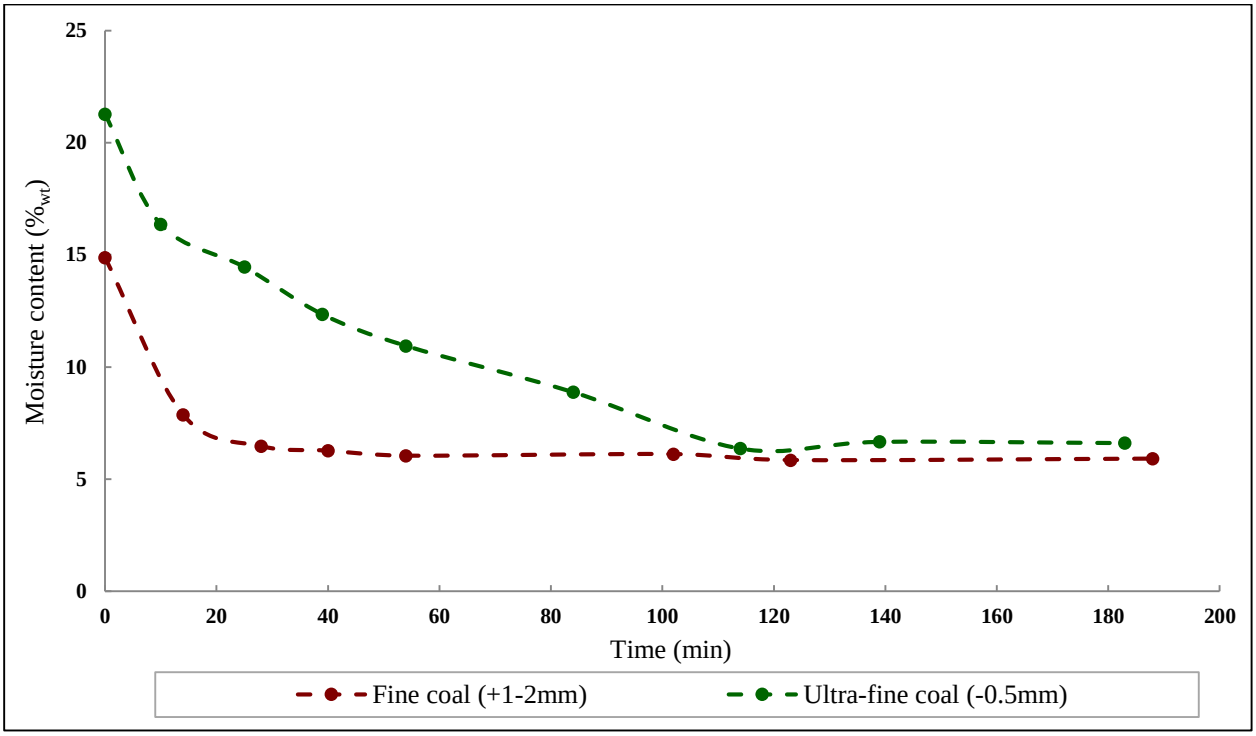


*Figure 4.2.6. Drying rate of fine and ultra-fine coal*

Ceramic with a size range of +6mm-10.5mm was used for adsorption at a temperature of 25°C. The ultra-fine coal fraction had a higher moisture content and took much longer to dry compared to the fine coal particles. The fine coal showed a total of 8%$_{wt}$ moisture reduction in 14 minutes, while the ultra-fine particles took 87 minutes to reduce about 8%$_{wt}$. The larger surface area of the ultra-fine coal creates more surface and capillary forces that prevent the moisture from leaving the finer coal particles (Asmatulu & Yoon, 2012). Even though the ultra-fine particles took very long to dry, it must be noted that contact sorption drying was able to reduce the moisture content of the ultra-fine coal to its inherent moisture content. Moreover these results were achieved with just a rotary adsorber at atmospheric conditions without the need of expensive operating conditions. Bratton *et al*. (2012) also found that adsorbents were able to transfer water away from wet particles, irrespective of particle size.

Fine coal samples of 100g each were placed within the rotary adsorber at temperatures of 25°C, 40°C and 55°C. Ceramic in a ratio of 1:1 were added to the one experiment, while the other experiment operated with more ceramic in a 1:3 ratio. The coal to ceramic ratio of 1:3 resulted in a faster dewatering rate compared to the feed ratio of 1:1. Increasing the amount of ceramic lead to more efficient contact between the coal and ceramic as more surface area of the ceramic was available for moisture transfer. Introducing elevated temperatures to the system didn't show a significant improvement in the drying rate. Figure 4.2.7 however illustrates that temperature had an effect on the final moisture content and a temperature of 55°C could reduce the moisture content by an additional 1%$_{wt}$.

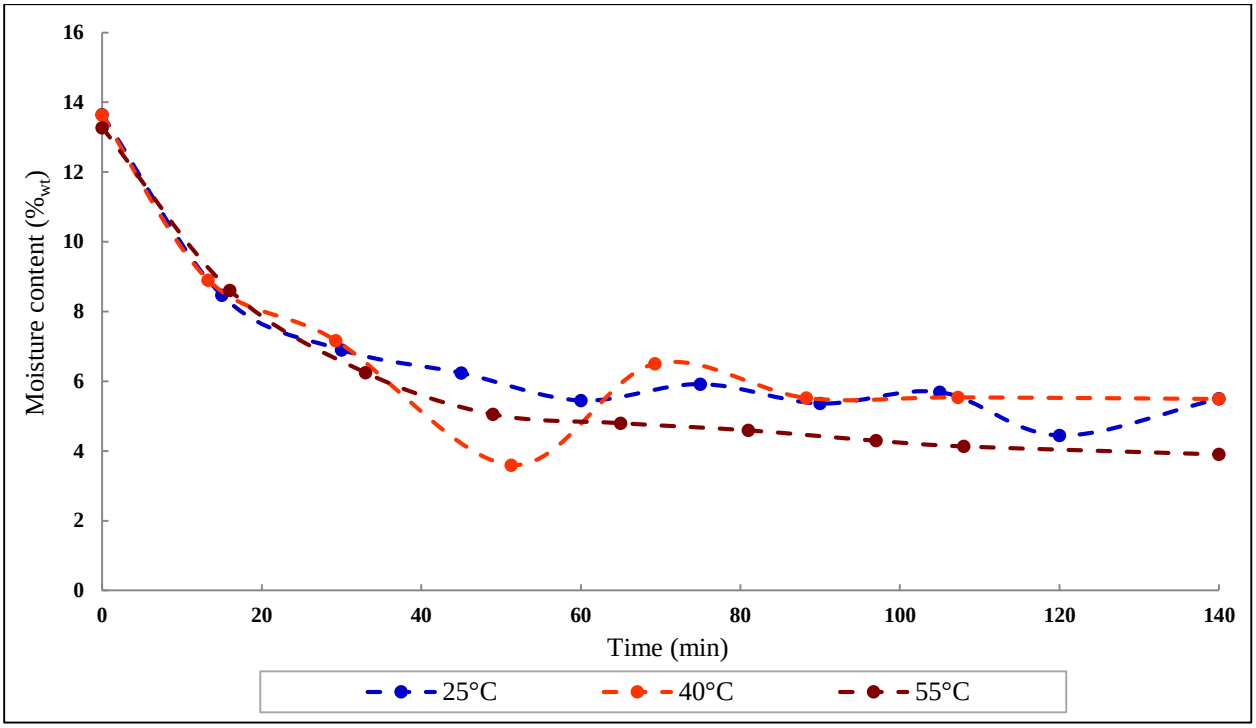


*Figure 4.2.7. Ceramic to coal ratio of 1:1*

It can be seen in Figure 4.2.7 that the temperature had a larger effect on the coal moisture content towards the completion of the experiment. As a 1:1 ratio was already packed and had already reached optimum contact, the temperature could improve the transfer rate. This however had no noticeable effect in the first few minutes of drying. Figure 4.2.8 shows that changes in temperature didn't have an effect when optimal contact ratio between coal and ceramic were in place.

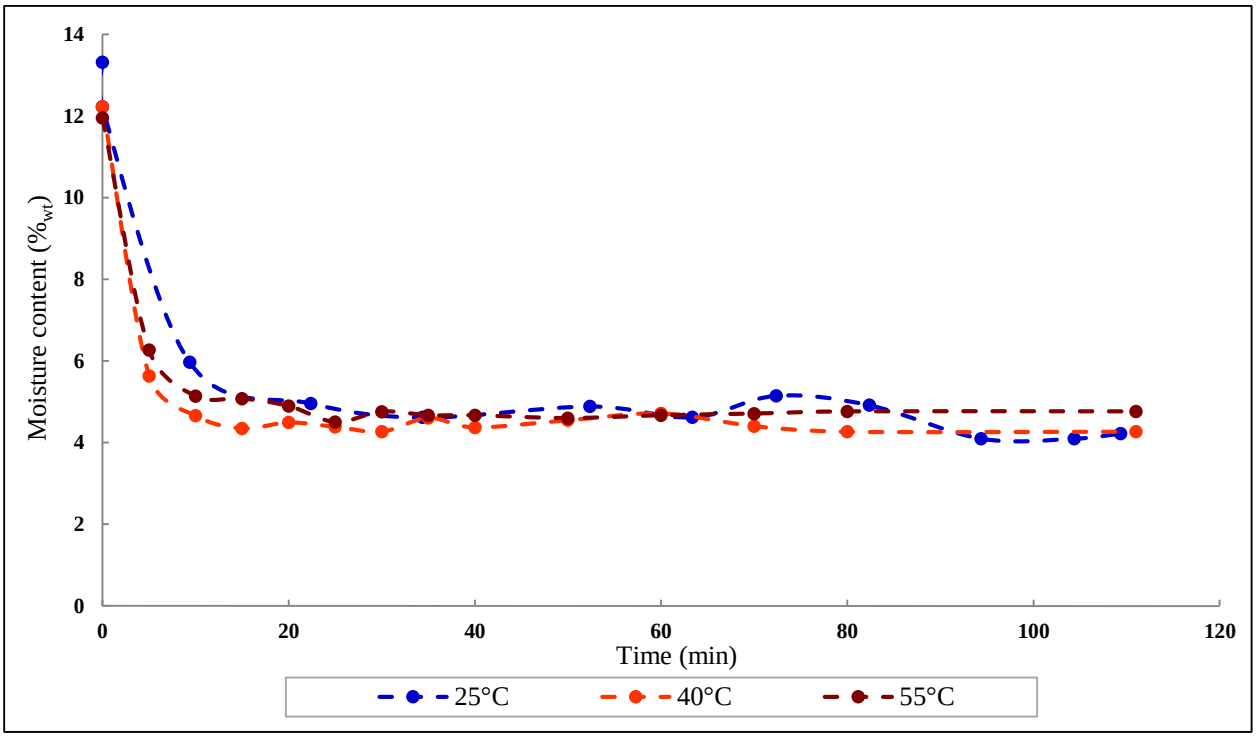


*Figure 4.2.8. Ceramic to coal ratio of 1:3*

### *Conclusion*

Ceramic was able to not only reduce the moisture content of fine coal, but of ultra-fine coal as well. The ceramic could reduce the moisture content irrespective of the size of coal dried. Working within a rotary adsorber ensured maximum contact between the coal and ceramic leading to more consistent results. Smaller ceramic had a larger surface area that allowed more efficient contact and consequently faster dewatering rates. The addition of more ceramic resulted in better contact with the wet coal and reduced the operating time quite significantly. In conclusion the results showed that improved contact between the coal and ceramic is the main driving force during adsorption drying.

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## 4.3. Adsorbent assisted drying of fine coal (Paper 6)

This section describes the contributions made by the authors in completion of the paper titled "Adsorbent assisted drying of fine coal". General information is listed regarding the paper that was published in the conference proceedings of the Southern African Coal Processing society's' conference.

### *4.3.1. Contribution by authors*

Prof. M. le Roux and Prof. Q.P. determined the direction and scope for this study. Miss. M.J. van Rensburg, Prof. M. le Roux and Prof. Q.P. planned the experimental design that was built at the North-West University. Miss, E.S. Peters completed experimental work on the apparatus under the supervision of Miss. M.J. van Rensburg. The interpretation and the discussion of these results were a combined effort between all four authors. The content of this paper was presented by Miss. E.S. Peters at the Southern African Coal Processing society's' conference held in Secunda, South Africa. The conference was held on the 22$^{nd}$ to 24$^{th}$ of August 2017.

### *4.3.2. General information*

Information regarding the published paper is listed in Table 4.3.1.

*Table 4.3.1. Adsorbent assisted drying of fine coal (paper 6): General information*

| Category | Information |
|---|---|
| Paper name | Adsorbent assisted drying of fine coal |
| Authors | Peters, E.S., Le Roux, M., Campbell, Q.P. & Van Rensburg, M.J. |
| Journal | Proceedings of the Southern African Coal Processing Society's conference |
| Year | 2017 |
| Web address | http://www.sacoalprep.co.za/ |

# Adsorbent assisted drying of fine coal

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*School of Chemical and Mineral Engineering, North-West University, Potchefstroom, South Africa.*

## *Abstract*

It is commonly found that fine coal (-0.5mm) and ultra-fine coal (-0.1mm), dewatered by mechanised methods, is still blended with coarse coal since it contains approximately 15-20%$_{wt}$ surface moisture (De Korte & Mangena, 2004). This high moisture levels poses a problem for utility companies as moisture retention lowers the effective heating value of the coal. Mohanty & Akbari (2012) remarked that by reducing the surface moisture levels of the fine coal product by 50%, the overall turnover of a typical colliery can potentially be improved by ±6%. Searches for innovative, cost efficient, and eco-friendly drying techniques have intensified (Bratton *et al.*, 2012). One such advanced dewatering process that was developed employs drying media to adsorb remaining surface moisture from the coal fines.

This investigation was primarily focussed on successfully, and feasibly employing adsorbent material to lower the surface moisture content of coal fines. It was found that the surface moisture levels of the fine coal was effectively reduced from ±0.30g(moisture)/g(coal and moisture) to well-below 0.08 g(moisture)/g(coal and moisture) within 10 minutes. The cascading-bed drying technique consumed considerably less time than the fixed-bed drying technique.

The best performing adsorbent to coal mass ratio was found to be 2:1, while the -2mm+1mm fine coal delivered the lowest product moisture levels and the -1mm+0.5mm produced the highest overall initial desorption rates during the cascading-bed drying technique. In addition, it was found that alumina and silica-based adsorbent yielded similar drying performances, whereas the 3mm adsorbents proved to have increased desorption rates over the 5mm adsorbents.

*Keywords*: Adsorbents, Fine coal; Moisture content

## *Introduction*

Coal fines are generated by the increase in mechanization on coal mines and plants, and have the ability to retain large amounts of moisture due to its inherently large surface areas (Reddick *et al*., 2007). The bulk of the moisture is retained by fine (+0.1mm-1mm) and ultra-fine (-0.15mm) coal fractions, which constitutes about 11% of the nominal product (SANEDI, 2011). This poses a problem for utility companies as moisture retention lowers the effective heating value of the coal. Coal fines are often dewatered, and combined with the coarse coal stream; however, as the coal fines rarely meet the desirable moisture levels, the quality of the final coal product stream suffers (Reddick, 2006).

In the past, whenever mechanical dewatering techniques failed to deliver contract specifications, the solution has leaned towards thermal drying, which is the most effective and expensive drying technique (Bratton *et al*., 2012). In recent years, research has stretched beyond the field of conventional drying towards cost-effective and environmentally friendly drying techniques. A study conducted by Bland & McDaniel (2014) showed that the moisture content of coal fines was trimmed down to single digit values by implementing porous drying media. Therefore, this study is focussed on investigating the ability of employing adsorbent material as an agent for drying coal fines.

### *Background*

The World Coal Association (2014) reported that coal meets about 30% of the global energy demand. Although coal is a non-renewable fuel, it is still considered an important energy source worldwide (Eraydin, 2009). South Africa's economy relies largely on coal as a basis of foreign proceeds, and forms a vital national energy source (Reddick, 2006). This reliance, along with the abundant coal reserves still accessible in South Africa, safeguards coal mining for many years to come. Even though this prospect seems promising on an energy basis, mining industries have a large impact on the environment.

Coal fines are generated by the increase in mechanization on coal mines, and have the ability to retain large amounts of moisture due to its inherently large surface areas (Reddick *et al.*, 2007). The bulk of the moisture is retained by fine (+0.1mm-1mm) and ultra-fine (+0.1mm-0.15mm) coal fractions, which constitutes about 11% of the nominal product (SANEDI, 2011). This poses a problem for utility companies as moisture retention lowers the effective heating value of the coal. Coal fines are often dewatered, and combined with the coarse coal stream; however, as the coal fines rarely meet the desirable moisture levels, the quality of the final coal product stream suffers (Reddick, 2006).

Commonly, fine coal dewatered by the best-mechanized methods is still directed to the coarse coal circuit containing approximately 18%$_{wt}$ moisture (Mohanty & Akbari, 2012). Mohanty & Akbari (2012) remark that the overall turnover of a typically colliery can potentially be increased by 6% if the current final moisture levels of the fine coal is cut by half. This is discouraging for the coal preparation industry, which caters for a market sector calling for lower final moisture levels, as in the case of coal-based power stations. In the past, whenever mechanical dewatering techniques failed to deliver contract specifications, the solution has leaned towards thermal drying which is the most effective (and expensive) drying technique (Bratton *et al*., 2012). When implemented properly, this technique is able to achieve coal moisture levels equal to inherent moisture, increasing the calorific value of the coal (Bratton *et al*., 2012). However, the coal industry has grown weary of these techniques because of installation, operation and maintenance cost implications, as well as pollutant emissions (Bratton *et al*., 2012). From an economic standpoint, Rong (1993) reasoned that moisture inclusion in coal adds to the weight of coal, and therefore the mass-based transportation costs increase. Consequently, the majority of the fine and ultra-fine coal generated is still disposed of (SANEDI, 2011).

Even though the practice of dumping coal fines into settlement ponds, and coal impoundments is validated to be economical, it is not environmentally friendly (Campbell, 2006). The worldwide abundance of these sites is proof of the longstanding dilemma (Bland and McDaniel, 2014). As coal is a sulphur bearing sedimentary rock, disposal waste management is undesired as it may cause acid rain, and/or acid rock drainage. In response, government enforced legislations have become more stringent, public apprehensions have increased, and rehabilitation ventures, incurred by mining companies, have become progressively more expensive (Reddick, 2006). All of this point out the need for improved productivity, efficient consumption/utilization of resources, and the reduction of waste production (Reddick, 2006).

In recent years, searches for innovative, cost efficient, and eco-friendly drying techniques have intensified (Bratton *et al*., 2012). One such advanced dewatering process employs drying media to adsorb remaining surface moisture from the coal fines after mechanical dewatering. In a similar study conducted by Bland and McDaniel (2014), it was found that the moisture content of coal fines was trimmed down to single digit values by implementing porous drying media. Yang (2015) conducted a similar study in which it was found that the mechanically dewatered coal product moisture was reduced from $19\%_{wt}$ to $9\%_{wt}$ by contacting with activated alumina adsorbents for ±5 minutes. This moisture reduction in the fine coal circuit will spur a beneficial increase in the fine coal mass, which can be redirected to augment the clean coarse coal circuit (Bratton *et al*., 2012). The dewatered clean fine coal adds to the plant's yield without compromising the calorific value of the final product. Mohanty & Akbari (2012) expect the increase in production revenue to outweigh the installation costs, and elevate the overall profitability of the coal preparation plant within time.

### *Experimental*

The run-of-mine (ROM) coal used for this study is sub-bituminous coal originating in the Highveld coalfield located in Mpumalanga, South Africa. During coal preparation, the coal was crushed and screened into three particle size ranges namely +1mm-2mm, +0.5mm-1mm and +0.25mm-0.5mm. Prior to experiments, the coal fines were drenched in water for 24 hours where after it was filtered to create a fine coal filter cake that acted as feed to the drying vessels. These 5.5cm long polypropylene vessels has an inner diameter of 5.5cm and was operated in two ways: The vessels were left upright and stationary to form a fixed bed, or rotated at 3rpm on rollers to form a cascading mixed bed. All the tests were conducted inside a climate controlled room which is set at 25°C and 40% relative humidity (RH).

The drying performance of two adsorbent types, an alumina-based adsorbent (F-200 activated alumina) and a silica-based adsorbent (Silsorb N10) were evaluated. The adsorbents were left exposed to the surrounding air in the climate-controlled room for 24 hours in order to reach a similar equilibrium starting point when added to the coal fines. Samples of the coal and adsorbents were collected during the experiment at set time intervals, and the surface moisture for each sample was analysed in a vacuum oven, respectively. General desorption and adsorption curves were constructed from the surface moisture results, and

essentially illustrated the surface moisture exchange between wet coal and dry porous adsorbents. Figure 4.3.1 shows a diagram of the fixed-bed and cascading bed experimental procedures.

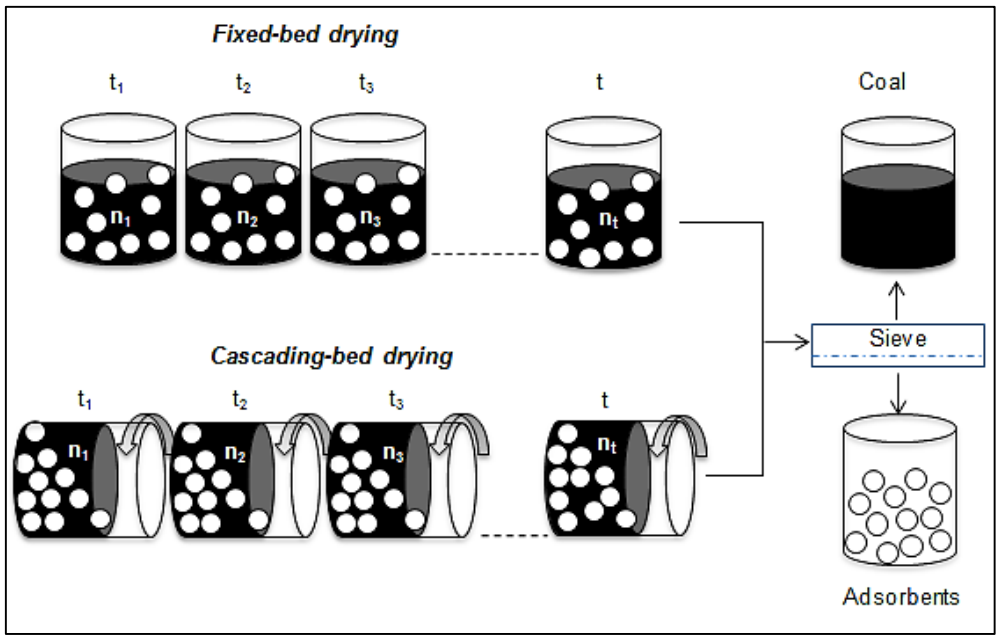


*Figure 4.3.1. Drying techniques used during adsorbent assisted drying*

### *Results and discussion*

Due to the large amount of results obtained from this study, an example of a desorption curve will be shown in Figure 4.3.2. This will be discussed in detail; where after a summary of results for all variables will be given.

Figure 4.3.2 shows the desorption and adsorption curves for a 1:1 mass ratio of +1mm-2mm coal and 3mm (a) alumina-based and (b) silica-based adsorbents. The moisture desorption (drying) curves of the coal samples, having a feed moisture of 18%±2.20%, is represented on the graph by the red line when using alumina and grey line for the silica. A typical thermal coal product target line of 8% moisture (Bland & McDaniel, 2014) is indicated by the horizontal black dashed line.

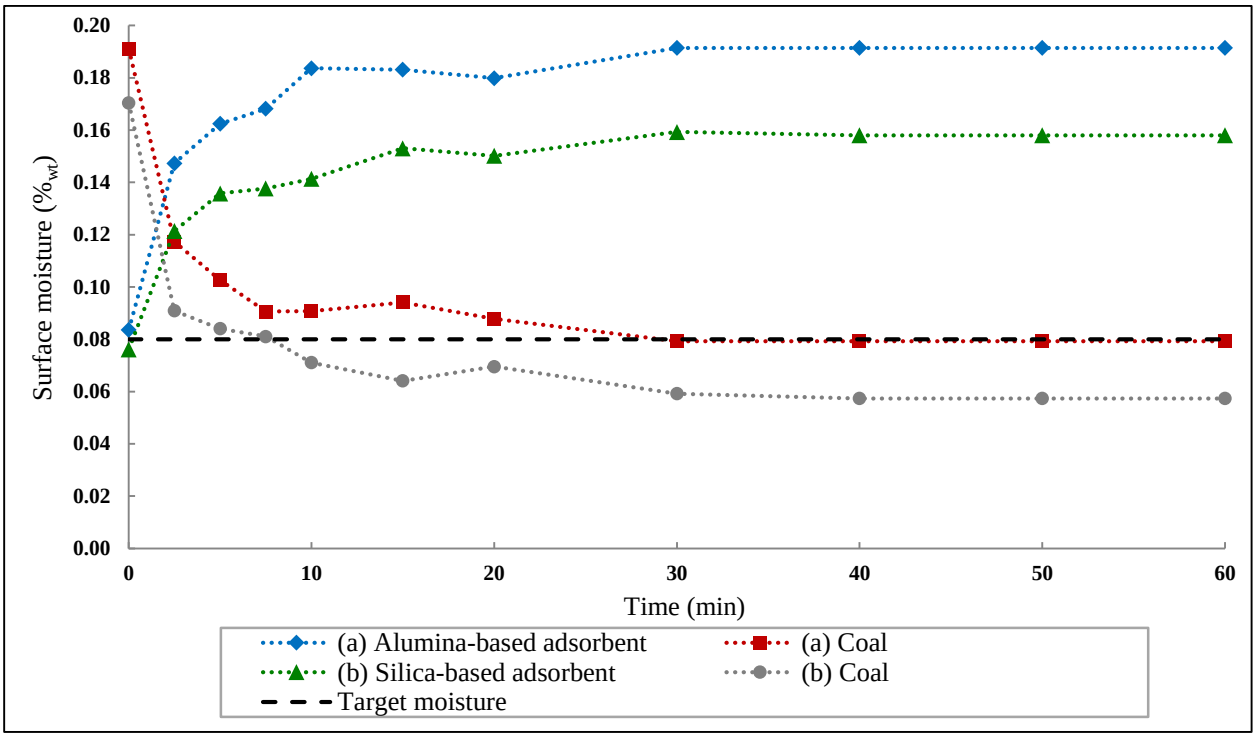


*Figure 4.3.2. Adsorption-desorption curves of -2mm+1mm coal and 3mm adsorbents*

In Figure 4.3.2, after 10 minutes of drying, the respective adsorbent types were able to reduce the surface moisture content of the coal fines by more than 50% for both cases. It is further clear to note that coal target moistures were achieved, or very close to it, before 10min operation time has lapsed. The process was left to continue for 60 minutes to ensure that equilibrium between the moisture in the coal, the adsorbents, and the surrounding air was reached. Since very little deviation in coal and/or adsorbent moisture content was observed after 30min, it can be concluded that equilibrium conditions were reached for both instances.

A water balance showed indifferences between the mass moisture displacement from the coal and that adsorbed by the adsorbents. . This imbalance in moisture was ascribed to moisture vapour collecting in the surrounding air inside the enclosed vessels. The process therefore also alters the relative humidity equilibrium of the surrounding air which in turn influences the total moisture mass transferred from the coal particles to the adsorbent. The resulting conclusion is that moisture transfer occurs in both liquid and vapour form, as indicated by Figure 4.3.3.

When dry adsorbents are introduced into the system, direct transfer of liquid moisture contained within the inter-particulate voids of the fine coal filter cake occurs immediately. Parallel to this, water vapour is drawn from the atmosphere to the adsorbent particles which alter the relative humidity equilibrium between the coal particles and its surroundings, creating a moisture concentration gradient. To correct the gradient, available coal surface moisture will evaporate until equilibrium is reached again. This cycle of liquid and

vapour transfer will continue until the system reaches a new equilibrium point where forces acting on the free moisture in the system are equal between the coal, adsorbent and atmosphere.

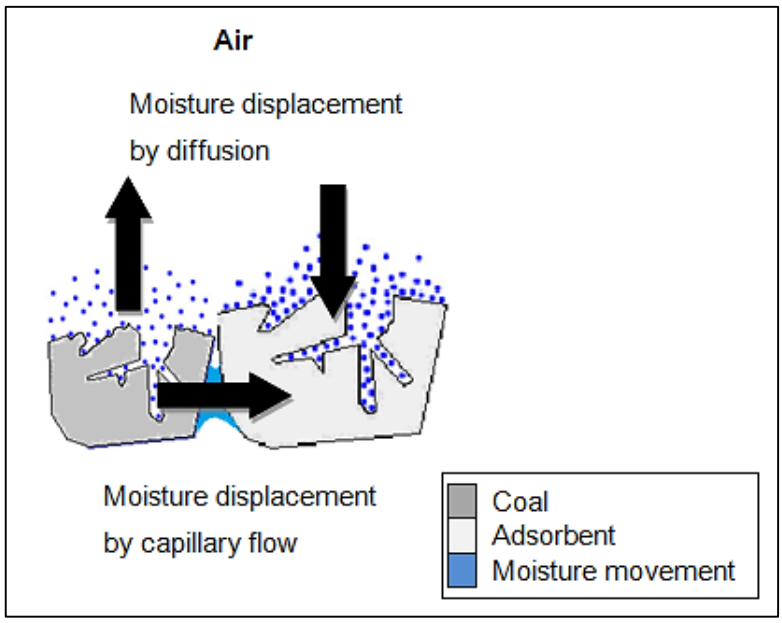


*Figure 4.3.3. Drying mechanism; adapted from ALDACS (2013)*

Liquid surface moisture held on the external surface and larger interconnecting pores between coal particles is transferred to the adsorbents by capillary flow through the interphase between the coal and the adsorbents. As the amount of liquid moisture on the coal's surface decreases, moisture displacement by capillary flow becomes negligibly small (Kudra & Mujumdar, 2009). When surface moisture is removed, moisture located in the capillaries of the coal particles migrates to the surface of the coal at a sufficient rate to compensate for the deficit. The moisture proceeds to diffuse through the interstitial air between the particles along the concentration gradient. The point of equilibrium depends largely on the relative humidity conditions of the air surrounding the particles (Le Roux *et al*., 2014). The starting moisture in the surrounding air contributes to the initial 40%RH, and adds to the amount of moisture adsorbed by the adsorbents. The moisture difference is retained in the air surrounding the coal and adsorbent particles as inherent moisture equilibrium is reached by the system.

### *1. Influence of motion*

The rate at which surface moisture is transferred between particles is greatly dependent on the amount of surface area available for contact. According to Bratton *et al*. (2012), surface contact between the adsorbent material and coal fines is enhanced when placed in a mixed system. This was achieved by feeding the coal and adsorbents to a slow rotating cylindrical vessel that ensured particle movement similar to cascading beds inside a mill. In this way, inter-particle contact is stimulated without affecting the structural integrity

of the coal or adsorbent particles. The fixed-bed results were compared to the cascading-bed results and are shown below in Figure 4.3.4 where +0.5mm-1mm coal was mixed with 3mm alumina-based sorbents in a 1:1 mass ratio and fed to both systems.

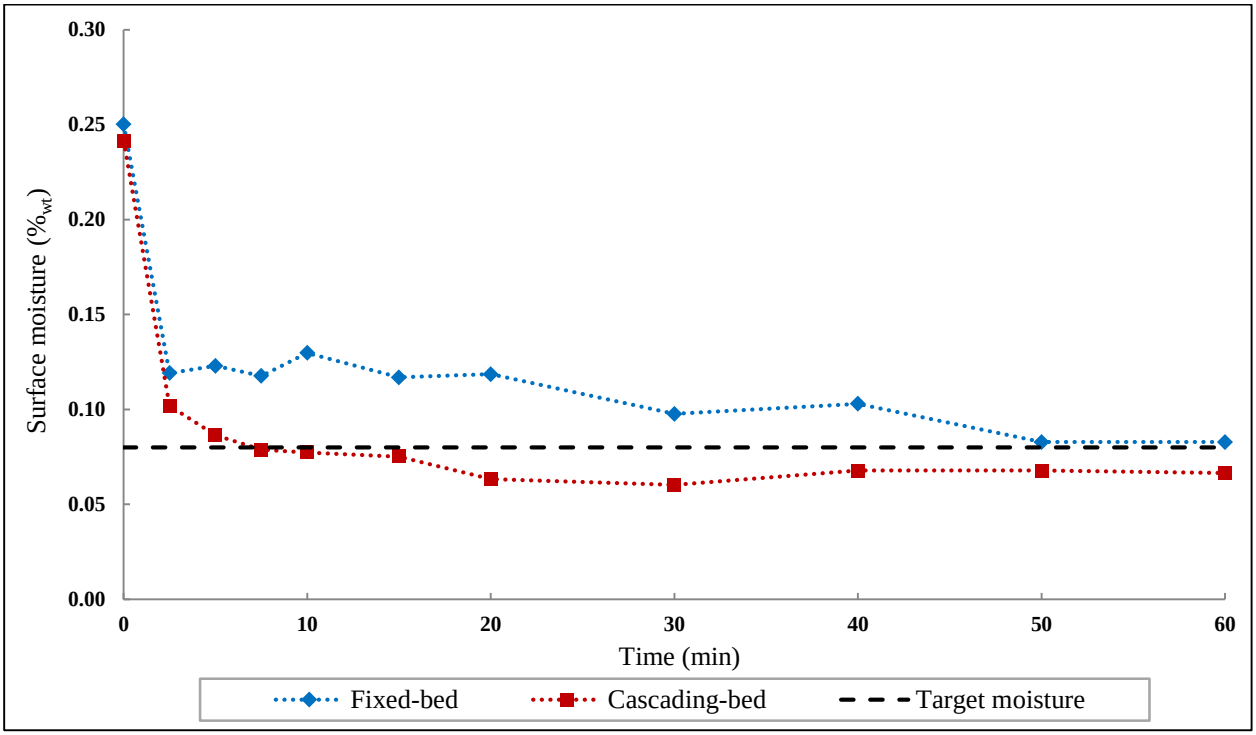


*Figure 4.3.4. Desorption curves of -1mm+0.5mm coal and 3mm alumina-based adsorbent*

The desorption curves in Figure 4.3.4 shows a similar initial desorption rate for the first 2.5 minutes. Thereafter it is clear to distinguish between the superior drying rates of the cascading bed as appose to that of the fixed bed; all due to an increase in contact surface area between the coal particles and the sorbents. At the end of 60 minutes drying time, the equilibrium surface moisture of the coal particles is very similar for both systems. Therefore, it can be concluded that particle mixing results in an increased drying rate but has little to no influence on the final equilibrium surface moisture content of the coal.

### *2. Summary of results*

Both sorbent types performed similar with respect to the drying of fine coal. Additional testing showed that the silica-based adsorbent had a more layered structure than the alumina-based adsorbent, culminating in an almost impenetrable core (which was used as seed to grow the ceramic beads). This layered structure caused weakness in the outer layers of the beads, resulting in size degradation through chipping and abrasion when introduced to the cascading bed. For this reason, the alumina-based adsorbent is preferred, and a summary of its drying performance is given in Table 4.3.2.

*Table 4.3.2. Alumina-sorbent drying performance*

| **3mm Alumina sorbent particles** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sorbent:Coal | 3:1 | | 2:1 | | 1:1 | | 0.5:1 | |
| Particle sizes (mm) | Initial dewatering rate (%/min) | Time to reach target moisture (min) | Initial dewatering rate (%/min) | Time to reach target moisture (min) | Initial dewatering rate (%/min) | Time to reach target moisture (min) | Initial dewatering rate (%/min) | Time to reach target moisture (min) |
| -1 | 0.027 | 2 | 0.03 | 1.9 | 0.023 | 2.3 | 0.02 | 15.7 |
| -0.5 | 0.063 | 3.6 | 0.068 | 3.5 | 0.056 | 7.1 | 0.031 | - |
| -0.25 | 0.073 | 4.6 | 0.068 | 5.8 | 0.052 | 44.6 | 0.034 | - |
| **5mm Alumina sorbent particles** | | | | | | | | |
| Sorbent:Coal | 3:1 | | 2:1 | | 1:1 | | 0.5:1 | |
| Particle sizes (mm) | Initial dewatering rate (%/min) | Time to reach target moisture (min) | Initial dewatering rate (%/min) | Time to reach target moisture (min) | Initial dewatering rate (%/min) | Time to reach target moisture (min) | Initial dewatering rate (%/min) | Time to reach target moisture (min) |
| -1 | 0.025 | 2.7 | 0.034 | 2.3 | 0.024 | 8.2 | 0.021 | 34.5 |
| -0.5 | 0.059 | 8.7 | 0.054 | 6 | 0.047 | 11.8 | 0.027 | - |
| -0.25 | 0.055 | 10.8 | 0.059 | 8.9 | 0.048 | 26.9 | 0.037 | - |

Table 4.3.2 shows the drying performance for the alumina-based sorbents. For each of the ceramic bead sizes (3mm and 5mm) the table gives the initial drying rate of the coal, as well as the time it took the coal to reach the target surface moisture of 8%. This is done for different coal particle sizes and sorbent to coal mass ratios. It is evident from the table that the 3mm sorbent size outperformed the 5mm sized ones. This is to be expected due to an increase in surface area, and hence increased possible contact points, for smaller sized particles compared to the same amount of larger ones. The same reasoning apply when looking at the feed coal particle sizes, but unfortunately this time to the detriment of the system. Larger particle sizes are easier to dewater than the finer ones, leading to faster dewatering rates and shorter time needed to reach 8% surface moisture.

Increased contact area can again be forwarded as the reason why larger sorbent to coal mass ratios performed better overall. However, both sorbent sizes showed very little difference between the 3:1 and 2:1 sorbent to coal mass ratios. Economic considerations in terms of vessel size and sorbent amounts would prefer the use of a 2:1 mass ratio. This may even be reduced to a 1:1 ratio for larger coal feed sizes. When the feed ratio drops below 1:1, the sorbent struggled to dry the coal at sufficient rates to validate the use of this process. It is even worse when using fine coal feed sizes. From the table it can be seen that a sorbent to coal mass feed ratio of 0.5:1 is unable to dry -1mm coal particles to the target surface moisture of 8%.

### *Conclusions*

From this study it can be concluded that adsorbent assisted drying of fine coal is possible and yield final coal surface moistures close to the measured inherent moisture of the coal. For a set target surface moisture of 8% (typical of a thermal coal product), the best performing tests were able to achieve that level within 10min of operation, depending on the feed coal moisture. The conditions of these tests were as follow:

- 3mm alumina-based ceramic adsorbent
- 2:1 sorbent to coal mass feed ratio
- Cascading bed
- All the tested coal particle sizes

### *Acknowledgements*

- SACPS
- DST – SARChI

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Any opinion, finding or conclusion or recommendation expressed in this material is that of the author(s) and the NRF does not accept any liability in this regard.

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## 4.4. Contact sorption: A method to reduce the moisture content of coal fines (Paper 7)

This section describes the contributions made by the authors in completion of the paper titled "Contact sorption: A method to reduce the moisture content of coal fines". The paper was submitted to the International Journal of Coal Preparation and Utilization.

### *4.4.1. Contribution by authors*

The experimental setup for adsorption drying was the responsibility of Miss M.J. van Rensburg, Prof. M. le Roux and Prof. Q.P. Campbell. The experimental parameters and direction of study were developed by all the authors. The experimental data was collected by Miss E.S. Peters and undergraduate students under the supervision of Miss M.J. van Rensburg, Prof. M. le Roux and Prof. Q.P. Campbell. The results presented in this paper came out of discussions between the authors and undergraduate students. This paper was written by Miss M.J. van Rensburg and edited by Prof. M. le Roux and Prof. Q.P. Campbell.

### *4.4.2. General information*

Information regarding the published paper is listed in Table 4.4.1.

*Table 4.4.1. Contact sorption: A method to reduce the moisture content of coal fines (paper 7): General information*

| Category | Information |
|---|---|
| Paper name | Contact sorption: A method to reduce the moisture content of coal fines |
| Authors | Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & Peters, E.S. |
| Journal | International Journal of Coal Preparation and Utilization, 1-15 |
| Year | 2018 |
| Copyright | ©Taylor & Francis Group, LLC |
| ISSN | 1939-2702 (Online) & 1939-2699 (Print) |
| DOI | 10.1080/19392699.2018.1541895 |

# Contact sorption: A method to reduce the moisture content of coal fines

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## *Abstract*

This paper introduces contact sorption with ceramic sorbents as a method to reduce the moisture content of coal fines produced by coal processing plants. The proposed method was tested on laboratory scale where ceramic spheres with diameters of 3mm and 5mm were combined with wet coal fines of size fractions between 0.25mm and 2mm and. The coal had an initial moisture content of 0.25g(Water)/g(Coal and water), and was dewatered using contact sorption to an average moisture content of 0.13g(Water)/g(Coal and water) after 2.5 minutes and 0.05g(Water)/g(Coal and water) after 10 minutes, respectively. This paper focuses on identifying the solid phase conditions essential to improving the contact sorption drying technology, proving that contact between the coal and sorbent material is the main driving force behind this technology. Increasing the sorbent to coal mass ratio and using smaller sorbents with a larger surface area resulted in improved contact and consequently improved moisture mass transfer. The final coal moisture content that could be achieved was independent of coal particle size. Current studies show a reliance on thermal drying technologies to dry the saturated sorbent material, whereas this paper proves that drying with high airflow at low temperatures is sufficient to regenerate the sorbent material. The loaded sorbent material could easily be separated from the dried coal product by dry screening, and could be dried and regenerated afterwards in an air-blown packed bed within 10 minutes. The re-use of sorbent material showed no decrease in its dewatering efficiency, and it was shown to be possible to re-use the sorbents for a large number of cycles. Contact sorption can prove to be a cost-effective and efficient drying method to dewater coal fines in the industry.

*Keywords*: Coal beneficiation, Fine coal dewatering, Contact sorption drying

## *Introduction*

A significant portion of the mined coal in South Africa is often discarded in an effort to deliver a product meeting the requirements of the various industries (Department of Energy, 2017). According to the Department of Mineral Resources (2014), the South African coal industry discarded around 2000Mt of coal over the past 20 years. About 50Mt of discarded coal fine slurry is added every year because it is challenging to dry the coal fines (defined here as +0.15mm-1mm) and ultra-fines (-0.15mm) since it retains a large fraction of water. Apart from occupying large areas of land, the discarded coal also creates a series of environmental problems such as acid mine drainage, dust release and spontaneous combustion (Reddick *et al*., 2007). Conventional dewatering and drying methods may prove to be inefficient, costly or even dangerous (Parekh, 2009; Kudra & Mujumdar, 2009). Studies by

Campbell *et al*. (2004) showed that current mechanical dewatering methods like centrifuges, filters and dewatering screens are not able to dry coal fines to a satisfactory moisture level. It is therefore important to investigate and propose cost-effective and practical solutions to recover the discarded fines, since coal is a non-renewable resource that will continue to play a pivotal role in the South African and world economy for years to come (Statistics South Africa, 2015). This paper proposes contact sorption by using porous ceramics as a method to reduce the moisture content of coal fines. The aim of this paper is to address the process of dewatering coal fines and the regeneration of the used sorbent.

### *Background*

Coal fines contain a substantial amount of moisture due to its large surface area as a result of its porous nature. This moisture can be classified according to where it is located, as illustrated in Figure 4.4.1. Inter-particulate water is contained in the crevices between two or more particles, while adhesion water forms a film or boundary layer around a particle or agglomerate. Interparticle water and adhesion water are collectively referred to as surface moisture. This moisture forms a layer of water on the surface of a particle, which includes the surfaces of the pore network walls. On the other hand, capillary forces in the pore network attract and entrain moisture (Asmatulu & Yoon, 2012). This is known as capillary water. Interior sorption water is contained within the particle, i.e. chemically bounded within the structure of the coal during formation (Karthikeyan *et al.*, 2009).

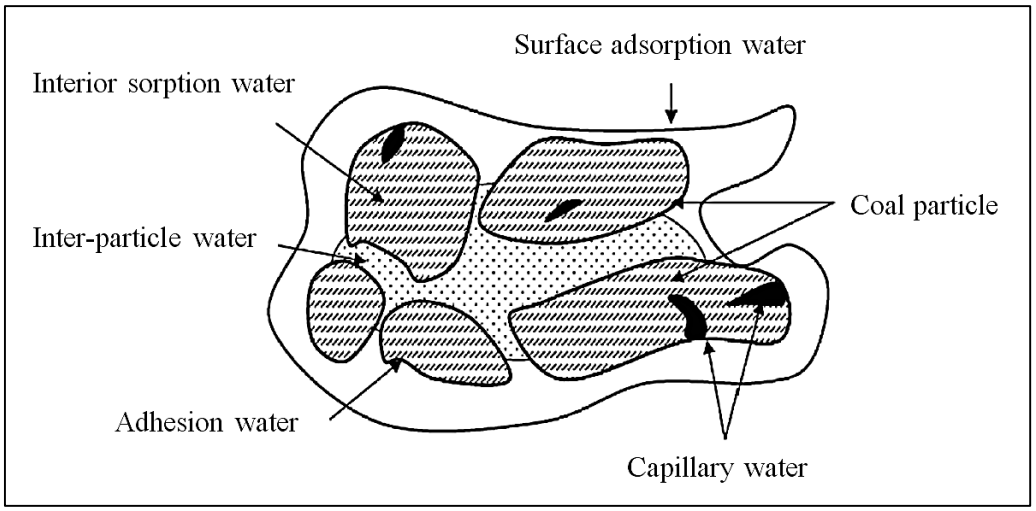


*Figure 4.4.1. Classification of moisture; adapted from Karthikeyan et al., (2009)*

The proposed drying technique involves the use of porous ceramic spheres to initiate desorption and moisture transfer from coal fines, where water is desorbed from the coal fines and adsorbed onto the surface of the ceramic sorbent. Ceramic is favoured as an adsorbent since it is hydrophilic and has an extensive pore network and moisture retention ability (Li *et al*., 2006; Lin *et al*., 2012). Ceramic is a manufactured inorganic solid that contains varying quantities of alumina and silica and is often produced to a specific

porosity value (Knaebel, 2004). During the manufacturing process, the sorbent's water of hydration is removed to activate the sorbent surface for adsorption. Such dehydration produces a porous solid with a strong affinity for water (Honeywell UOP, 2011). The mechanical and thermal stability of porous ceramic material also makes it useful for industrial purposes (Lin *et al*., 2012).

### *1. Contact sorption drying*

Contact sorption drying refers to the transfer and accumulation of moisture at the interphase between two phases such as liquid and vapour on the sorbent surface (Parashar, 2015). This paper will focus on sorption, where water in both the liquid and vapour phases is the adsorbate that gathers on the surface of the porous ceramic adsorbent. This adsorbate comes from the free moisture as well as the desorbed surface and capillary moisture associated with the porous coal particles. The proposed drying method is driven by two mechanisms occurring simultaneously: desorption of moisture from coal and adsorption of moisture onto the ceramic sorbent surface. The word 'sorption' is a collective term used to denote both desorption and adsorption when both processes happen at the same time (Dąbrowski, 2001). The diagram in Figure 4.4.2 illustrates the two mechanisms and the sequential stages during contact sorption drying.

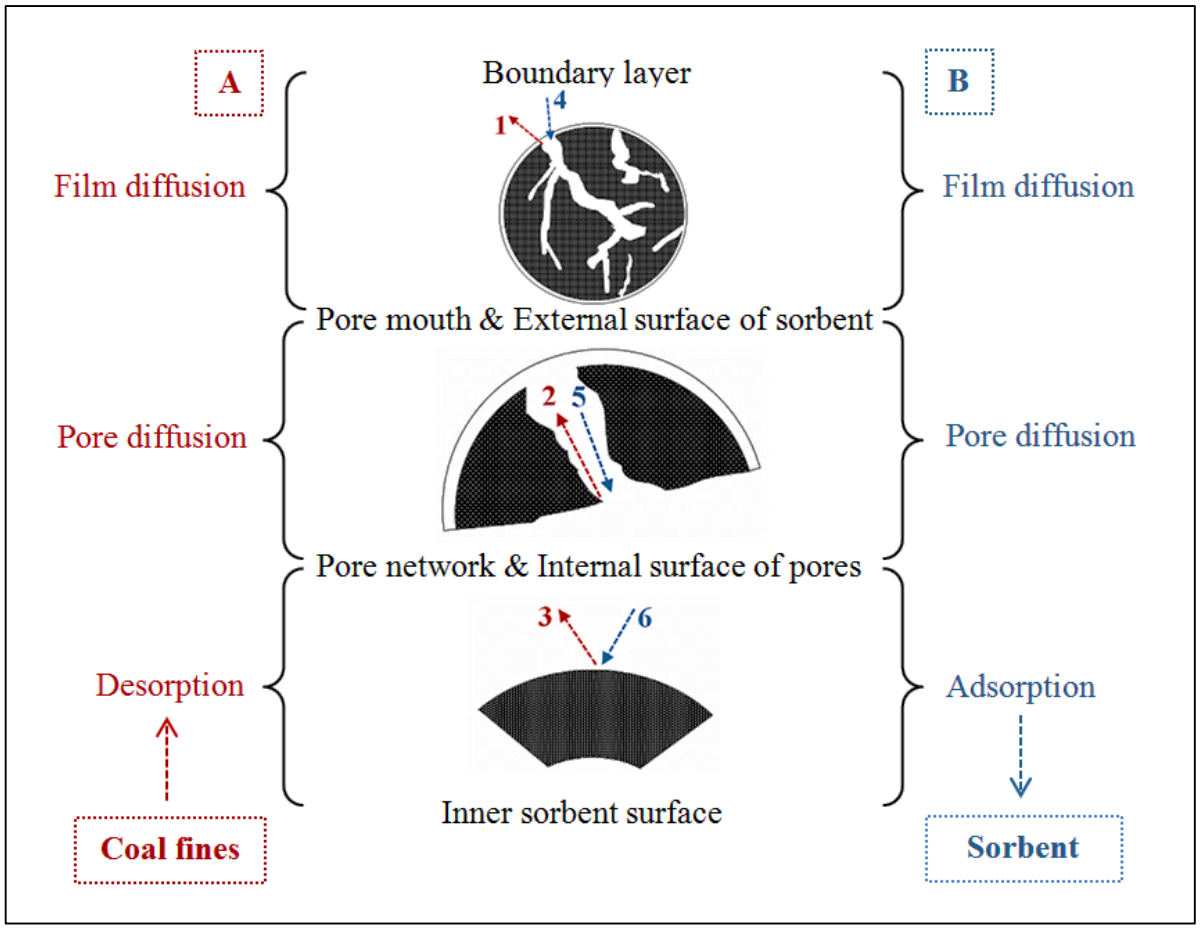


*Figure 4.4.2. Diagram of the contact sorption drying process; adapted from Dittmeyer & Emig (2008)*

Mechanism A: Mass transfer or diffusion of moisture is initiated when the wet coal fines are brought into contact with the dry sorbent material (Kudra & Mujumdar, 2009). Free moisture that is not attached to the coal particles is readily attracted to the sorbent material. The ceramic material's greater affinity for water, compared to that of the coal fines, causes displacement of inter-particulate and adhesion moisture from the boundary layer to the sorbent material (Lin *et al*., 2012). Thereafter, film diffusion (1) occurs and moisture from the pore mouth and external surface area move to fill the boundary layer. Subsequently, pore diffusion (2) and desorption (3) take place to transfer the moisture from the pore network and the internal coal surface (Klaewkla *et al*., 2011).

Mechanism B: Desorbed moisture, as described in Mechanism A, is transferred to the sorbent. Free moisture as well as desorbed surface and capillary moisture forms part of the boundary layer surrounding the sorbent material. Film diffusion (4) causes moisture to move to the external surface of the sorbent and pore-mouth. From here moisture moves into the pore network of the sorbent, known as pore diffusion (5), and ultimately adheres (6) to the active sites on the surface of the sorbent (Klaewkla *et al*., 2011). Water accumulates at the surface of an adsorbent as a result of the surface tension at these active sites. Van Der Waals forces bind a monolayer of moisture to the surface of the sorbent and create opportunity for multilayer adsorption. Since the Van Der Waals forces are weak, the moisture is relatively free to move on the surface of the sorbent and can therefore subsequently be easily removed (Bhaskar, 2014).

Factors affecting contact sorption drying can be divided into two main categories: the fluid phase conditions, referring to the operating conditions of the water adsorbate, and solid phase conditions related to the properties of both the sorbent and the coal fines.

Fluid phase conditions: Since physical adsorption is an exothermic process, it operates optimally at a lower temperature. According to Le Chatelier's principle, the adsorption abilities of a system increase with a decrease in temperature (Parashar, 2015; Bhaskar, 2014). An increase in pressure will promote adsorption to the saturation point, but would not promote additional flow into the pore network of the sorbent because of the incompressibility of water (Parashar, 2015). Superficial velocity and a larger fluid concentration difference across the sorbent material would cause a flow of moisture to the sorbent, enhancing the mass transfer (Klaewkla *et al*., 2011).

Solid phase conditions: Because sorption is a surface phenomenon the process benefits from a larger surface area (Parashar, 2015). Smaller particles have larger surface areas available for sorption (Asmatulu & Yoon, 2012). Sorbents are manufactured to have a specified degree of porosity and a large internal surface area to increase their adsorption abilities (Honeywell UOP, 2011). In a coal-sorbent mixture, the larger the sorbent to coal ratio in the system, the better the contact between the sorbent and wet coal, which benefits moisture transfer (Kudra & Mujumdar, 2009).

### *2. Regeneration*

Physical adsorption is a reversible process and the sorbent can be dried and regenerated to be re-used (Bhaskar, 2014). To dry the loaded sorbent, it is proposed to use ambient air as the drying medium. Subjecting the loaded sorbent in a packed bed with a continuous supply of air at a low relative humidity would result in a continuous concentration difference and improved moisture transfer from the sorbent to the drying air. The continuous flow of drying air transfers moisture away from the boundary layer (Nellis & Klein, 2012). This sets the film and pore diffusion into motion and results in desorption of moisture from the inner pore network. Consequently, the inherent moisture moves towards the external surface and boundary layer to be carried away in the dry air, ultimately resulting in a dried, regenerated sorbent (Klaewkla *et al*., 2011). This can easily be achieved as the moisture is held by weak Van Der Waals forces, and is relatively free to move.

## *Experimental*

### *1. Material*

Medium-rank C bituminous coal from the Highveld coal field in South Africa was used in this study. The proximate analysis and the sulphur content of the coal are given in Table 4.4.2.

*Table 4.4.2. Proximate analysis (air dry basis) and sulphur content*

| Test type | Composition ($\%_{wt}$) | Test method standard |
|---|---|---|
| Inherent moisture | 3.6 | ACT-TPM-010 rich on ISO11722: 1999 |
| Ash yield | 14.9 | ACT-TPM-011 rich on ISO 1171: 2010 |
| Volatile matter | 29.6 | ACT-TPM-012 rich on ISO 562: 2010 |
| Fixed carbon | 51.9 | (By difference) |
| Total sulphur | 0.97 | ACT-TPM-013 rich on ISO 19579: 2006 |

As-received coal samples were left to dry under ambient conditions and later crushed and sieved to produce samples of +1mm-2mm, +0.5mm-1mm and +0.25mm-0.5mm. The samples were then submerged in water and dewatered in a filter press to a total moisture content ranging from 15-30$\%_{wt}$ depending on the size fraction. Two types of ceramic sorbent spheres were used in the study: a predominantly alumina-containing one, and the other one rich in silica, as shown in Table 4.4.3.

*Table 4.4.3. Compositions of ceramic sorbents*

| Mineral content | Composition (%wt) | |
|---|---|---|
| | Alumina-rich sorbent | Silica-rich sorbent |
| Aluminium oxide ($Al_2O_3$) | 92.7 | 3 |
| Silicon oxide ($SiO_2$) | 0.02 | 97 |
| Iron (iii) oxide ($Fe_2O_3$) | 0.02 | _ |
| Sodium oxide ($Na_2O$) | 0.3 | _ |

Scanning Electron Microscopy (SEM) was used to examine the external surface and internal pore network to see where the fissures in the structure are located. The sorbent was placed in a water solution containing a colour pigment, gentian violet, and thereafter Light Electron Microscopy (LEM) was used to observe the sorption into the pore network. The micrographs for both the alumina and silica-rich sorbents are shown in Figure 4.4.3 and the physical properties are compared in Table 4.4.4.

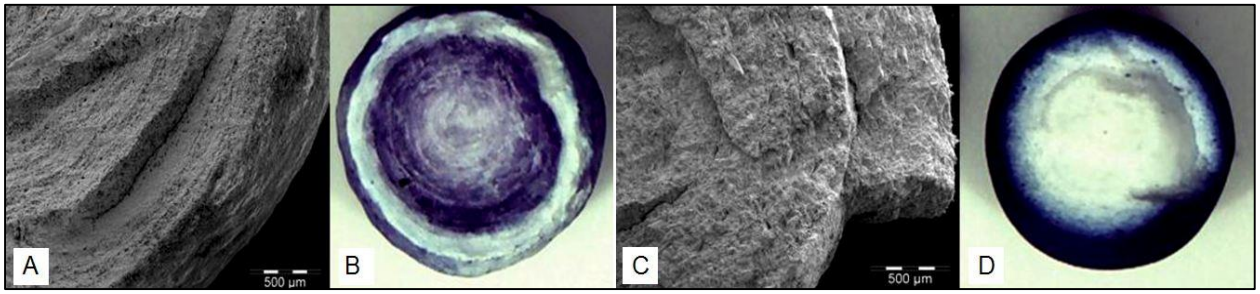


*Figure 4.4.3. (A) Alumina-rich sorbent: SEM scan; (B) Alumina-rich sorbent: LEM scan; (C) Silica-rich sorbent: SEM scan; (D) Silica-rich sorbent: LEM scan*

*Table 4.4.4. Physical properties of ceramic sorbents, 3mm and 5mm (as received)*

| Physical properties | Alumina-rich sorbent | Silica-rich sorbent |
|---|---|---|
| Surface area ($m^2/g$) | 350 | 750 |
| Pore volume ($cm^3/g$) | 0.5 | 0.4 |
| Bulk density ($kg/m^3$) | 769 | 800 |
| Moisture ($\%_{wt}$) | 1.8 | 1.69 |

The LEM scans for both sorbents showed their porous nature enabling them to adsorb and retain water. The colouring in Figure 3(B) shows that the water in the alumina-rich sorbent is able to penetrate the surface and move toward the core of the particle. Figure 4.4.3(D) shows that the silica was manufactured from some seed material and formed a shell-like structure. It is evident from Figure 4.4.3(D) that the water could not enter the seed material and accumulated mainly in the porous outer shell. The shell-like structure of the silica-rich sorbents caused a large surface area of 750$m^2/g$, while the alumina-rich sorbents had a surface

area of 350m$^2$/g. The pore volume due to crevices and layers in alumina-rich sorbent is 0.5cm$^3$/g, as opposed to a pore volume of 0.4cm$^3$/g for the silica-rich sorbent.

### *2. Equipment and process conditions*

The experimental work was done on a laboratory scale unit shown in Figure 4.4.4.

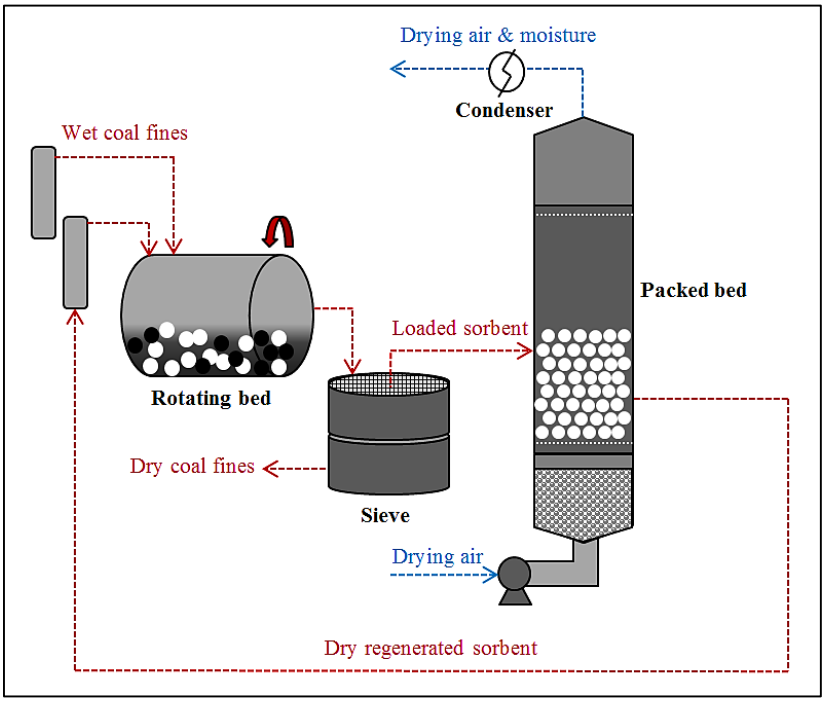


*Figure 4.4.4. Diagram of the laboratory setup for contact sorption drying and regeneration*

The wet filter cake and dry sorbent, with known moisture contents, were mixed together in a vessel of diameter 5.5cm and length 5cm, rotating at 3 revolutions per minute. The continuous rotating motion caused good contact between the sorbents and the fine coal to promote contact sorption drying. The ambient conditions at which the vessels were loaded were 22°C and 40% relative humidity. The experiments were done at the following conditions:

- *Motion*: Stationary and rotating bed
- *Sorbent type*: Alumina-rich and silica-rich sorbent
- *Sorbent to coal mass ratio*: 0.5:1, 0.75:1, 1:1, 2:1 and 3:1
- *Sorbent particle size*: 3mm and 5mm
- *Coal size fraction*: +1mm-2mm, +0.5mm-1mm and +0.25mm-0.5mm

The rotating bed setup consisted of 10 cylinders each containing an identical coal and sorbent mixture at the same conditions. At a certain time interval, one of the cylinders was removed and the loaded sorbent

and coal fines were separated with a laboratory sieve. The moisture content of each of the coal and sorbent samples was determined using the standard method (SANS 5925:2007). The moisture-loaded sorbents were then placed in a cylinder with an inner diameter of 8 cm, and subjected to an upward stream of conditioned air with a velocity of 1.5-1.7m/s at 22°C and 40% relative humidity to dewater the sorbents and carry the moisture away.

## *Results and discussion*

### *1. Contact sorption drying*

The base case experiment was the dewatering of +0.5mm-1mm coal fines in the rotating vessels with 5mm alumina-rich sorbent in a 1:1 mass ratio. The results were repeatable since the relative standard error across various experiments ranged between 0.6% and 2.8% for all samples. Figure 4.4.5 shows the results of the moisture transfer between the coal fines and the sorbent during a typical run for a rotating bed with +0.5mm-1mm coal fines in a 1:1 ratio with 5mm alumina-rich sorbent.

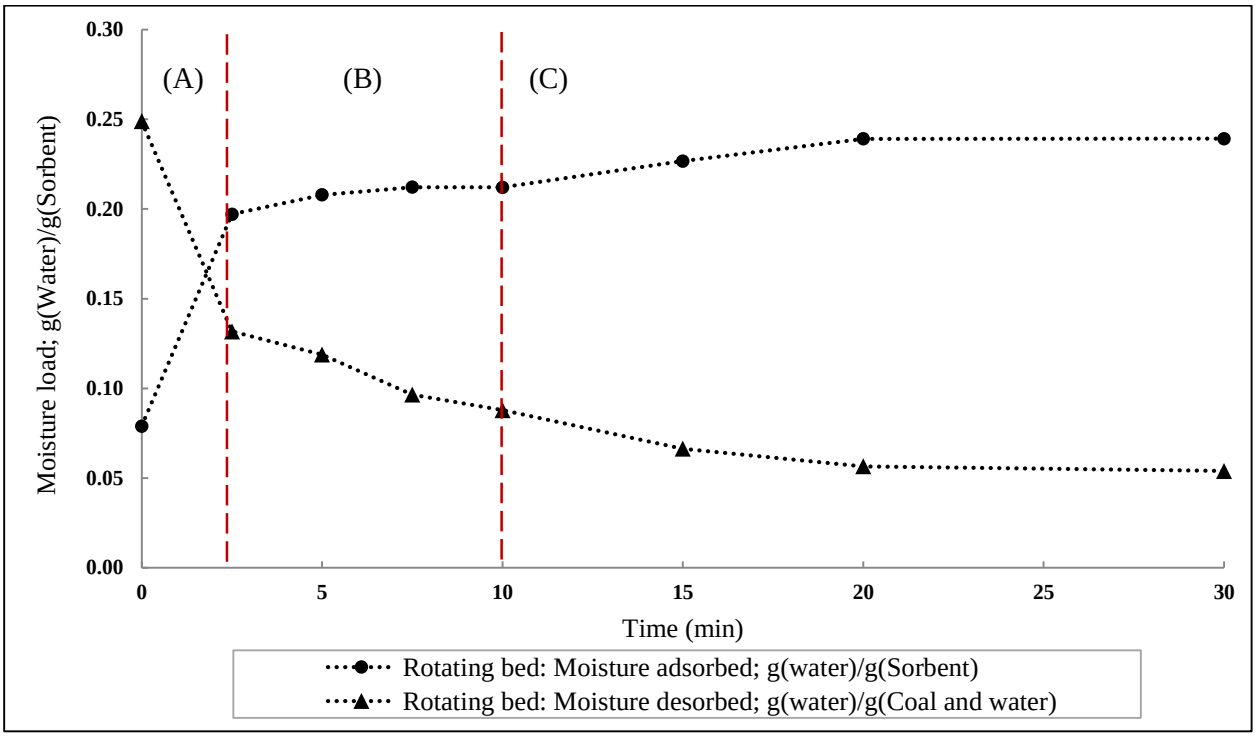


*Figure 4.4.5. General moisture transfer; +0.5mm-1mm coal fines in a 1:1 ratio with 5mm alumina-rich sorbent*

The moisture transfer is driven by two simultaneous mechanisms: desorption of moisture from coal fines and adsorption of moisture onto the sorbent surface. Free moisture and inter-particulate moisture are initially transferred during the first stage of dewatering as indicated by stage A in Figure 4.4.5. According to Klaewka *et al*. (2011), this stage usually happens very fast. This is due to the abundance of open pores available for adsorption and a greater concentration gradient. After 2.5 minutes the rate of drying decreases,

as indicated by stage B. In this stage the sorbent pores are saturated to a point where the concentration gradient between the coal and sorbent is less. An equilibrium is reached in stage C. This typical run proved that it was possible to dewater coal fines with an initial moisture content of 0.25g(water)/g(coal and water) to 0.13g(water)/g(coal and water) after 2.5 minutes, and to 0.05g(water)/g(coal and water) after 10 minutes.

*1.1. Motion*

The next set of experiments was done to determine whether the relative motion of sorbent and coal has an effect on the sorption efficiency. Coal fines of +0.5mm-1mm in a 1:1 mass ratio with 5mm alumina-rich sorbent were combined and left as a stationary mass in the same cylindrical vessels as before. The experiment was then repeated under the same conditions while the vessels were rotated at 3rpm. A typical result is shown in Figure 4.4.6.

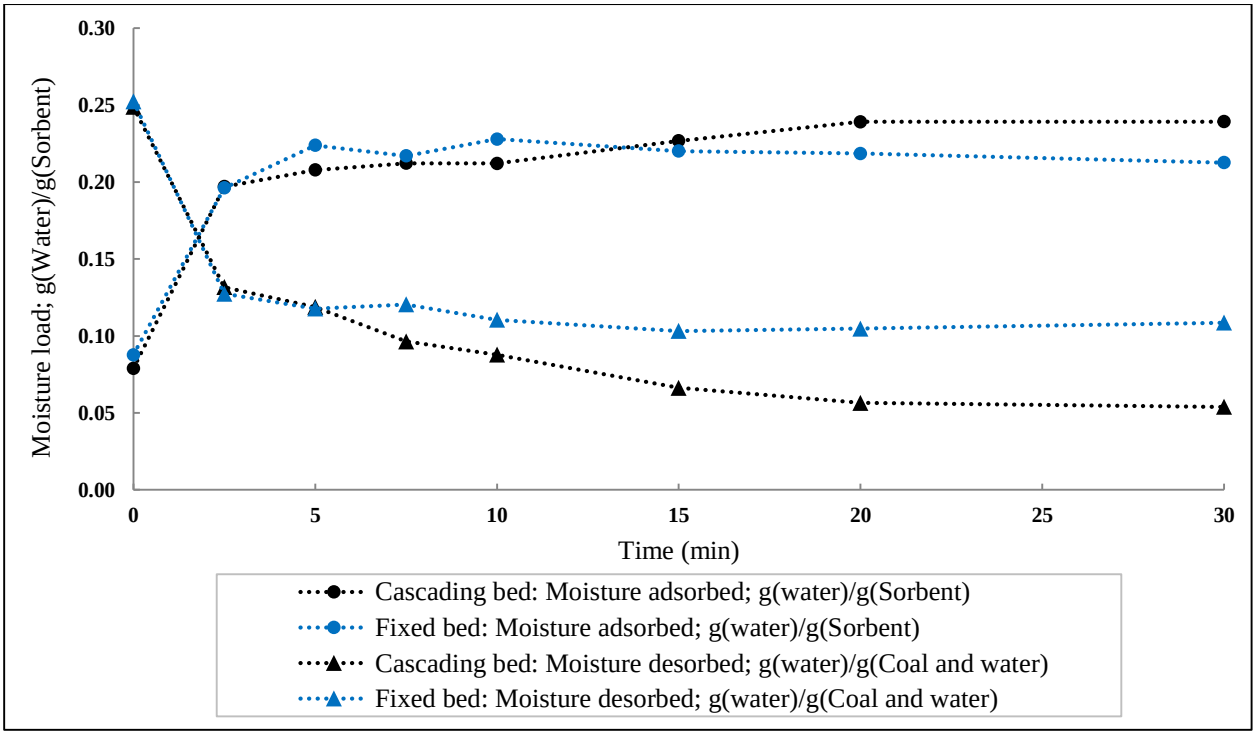


*Figure 4.4.6. Influence of motion; +0.5mm-1mm coal fines in a 1:1 ratio with 5mm alumina-rich sorbent*

It was found that the initial moisture transfer rate was similar for both cases, supporting the proposition that the rate is driven by free liquid phase transfer from the coal particles to the sorbents. This mechanism can occur wherever there is physical contact between the coal and the sorbents. Thereafter, the moisture transfer rate in the stationary test settled at a final moisture content of 0.11g(water)/g(coal and water), whereas the coal in the rotating bed had a final surface moisture content of 0.05g(water)/g(coal and water). This difference in the moisture transfer rate during this phase is due to vapour phase moisture transfer from coal

to the sorbents. When the solids are in motion, a higher fraction of surface area is exposed to the surroundings, resulting in a higher rate of moisture evaporation from the coal surface. When the water vapour comes into contact with the sorbent surface, it diffuses through the boundary layer to condense in its pore network.

*1.2. Sorbent type*

To study the effect of different sorbent types, a rotating experiment was conducted. Alumina-rich or silica-rich sorbents were added to +0.5mm-1mm wet coal in a 1:1 mass ratio. The resultant dewatering profiles are shown in Figure 4.4.7.

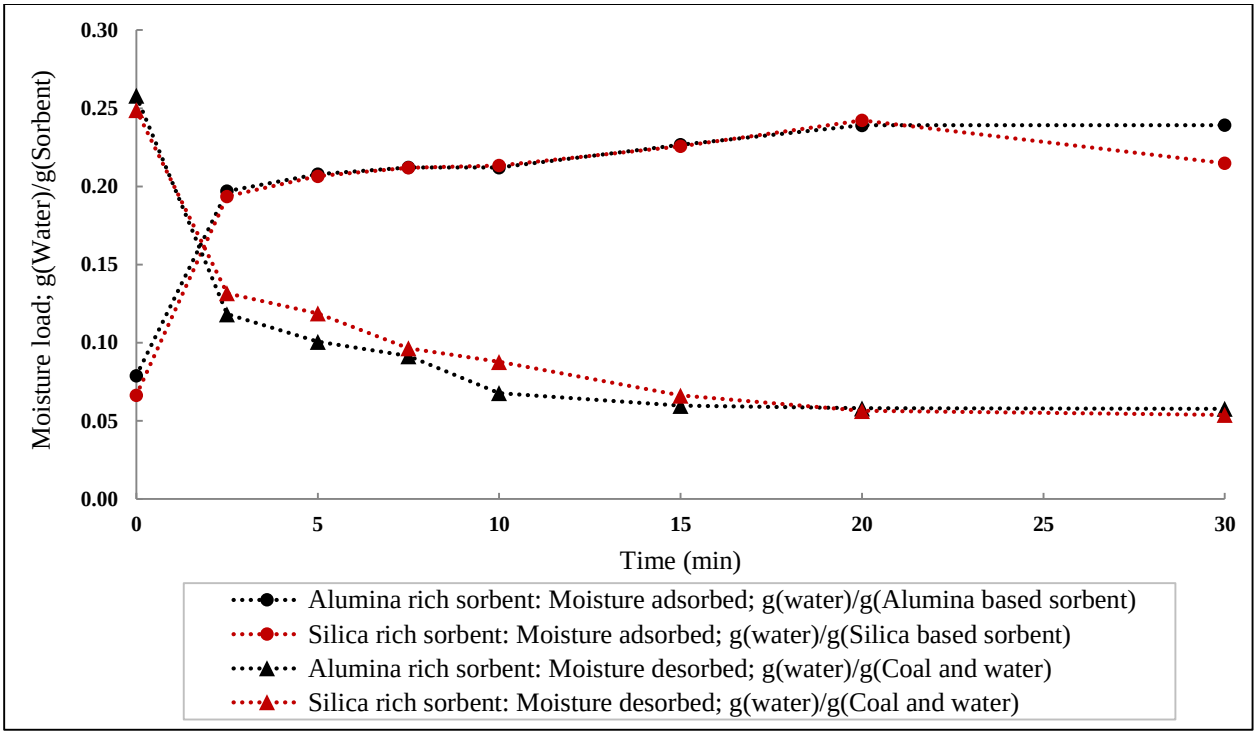


*Figure 4.4.7. Sorbent type; +0.5mm-1mm coal fines in a 1:1 ratio with 5mm sorbent*

Both the alumina-rich and silica-rich sorbent material had an initial moisture content between 6% $_{wt}$ and 7%$_{wt}$ before the tests, while the wet coal fines had a moisture content around 25%$_{wt}$. A similar behaviour in terms of the initial moisture transfer rate and final moisture was observed for the different sorbents. There was however, a slight difference in the way the system behaved from 2.5 minutes onwards as the moisture transfer was slower for the silica-rich sorbent during this phase. It was ascribed to the layered structure of the silica sorbent which caused lower pore volume and hence lower adsorption rate. This low adsorption rate causes a slower change in the system, which in turn influences the rate of moisture desorption from the coal particles.

*1.3. Sorbent to coal mass ratio*

To determine whether the mass ratio of dry coal to sorbent affects the dewatering profiles of the system, the rotating vessels were loaded with +0.5mm-1mm fine coal filter cake. Alumina-rich sorbent was added in 3:1, 2:1, 1:1, 0.75:1 and 0.5:1 sorbent to coal mass ratios. The resultant dewatering curves under rotating conditions are shown in Figure 4.4.8.

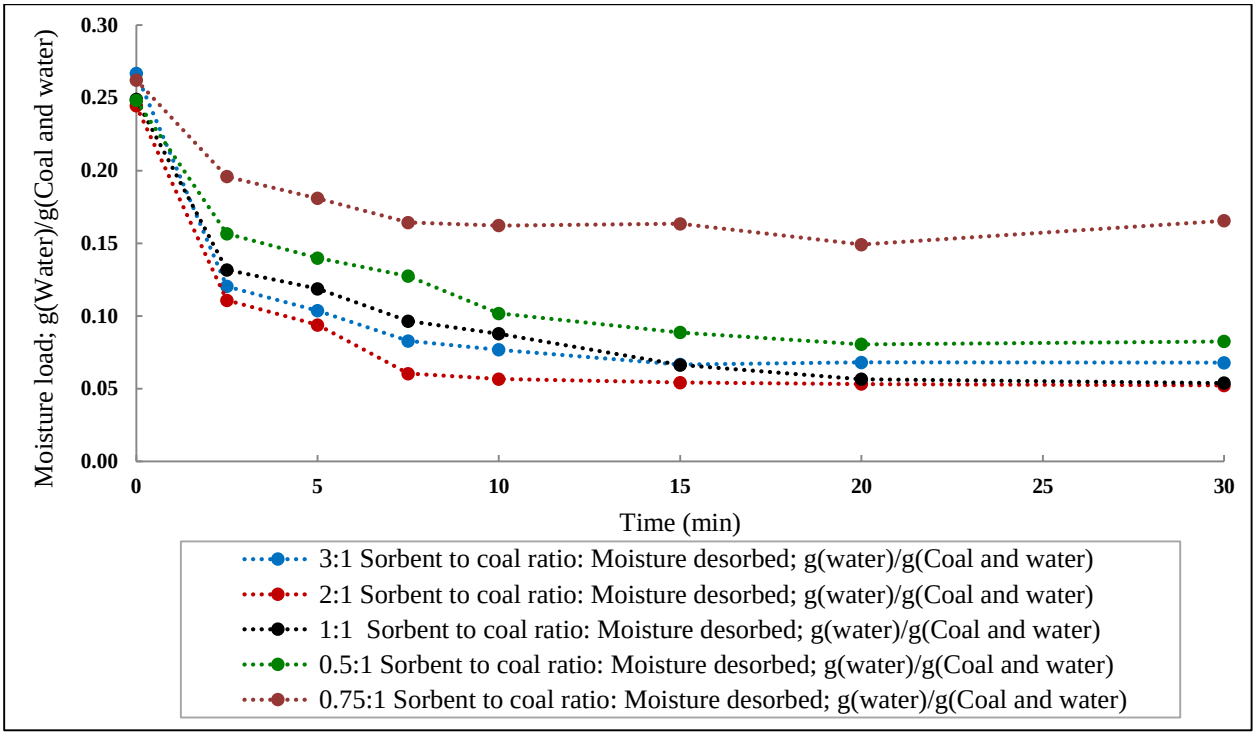


*Figure 4.4.8. Sorbent to coal ratio; +0.5mm-1mm coal fines with 5mm sorbent*

Figure 4.4.8 shows an enhanced dewatering capability with an increase in sorbent mass with only minor improvement beyond a 1:1 ratio. The increase in available sorbent surface area resulted in faster moisture transfer from the coal to sorbent surface, especially during the vapour transfer phase. It seems entirely possible to achieve a typical thermal coal contract target surface moisture of between $8\%_{wt}$ and $9\%_{wt}$ in less than 10 minutes at a ratio of 1:1. If capital and regeneration costs are taken into account, the 1:1 sorbent to coal ratio shows most promise for larger scale application.

At the lower sorbent to coal ratios, less contact between the sorbent and coal slowed the diffusion of moisture. It resulted in the early saturation of sorbent particles, making them incapable of creating a driving force from the coal particles to the sorbents. This is in line with the findings of Kudra & Mujumdar (2009) who showed that increased sorbent to coal ratios caused more efficient contact as more surface area of the solid phases was available for moisture transfer. Bratton *et al*. (2012) also concluded that the drying performance could be regulated by adjusting the sorbent to coal ratio.

*1.4. Sorbent particle size*

A series of experiments were done to determine the influence of different sorbent particle sizes on the sorption rate and final moisture content of coal fines. The results are displayed in Figure 4.4.9. Alumina-rich sorbent of 3mm and 5mm was used in a 1:1 mass ratio with +0.5mm-1mm coal fines.

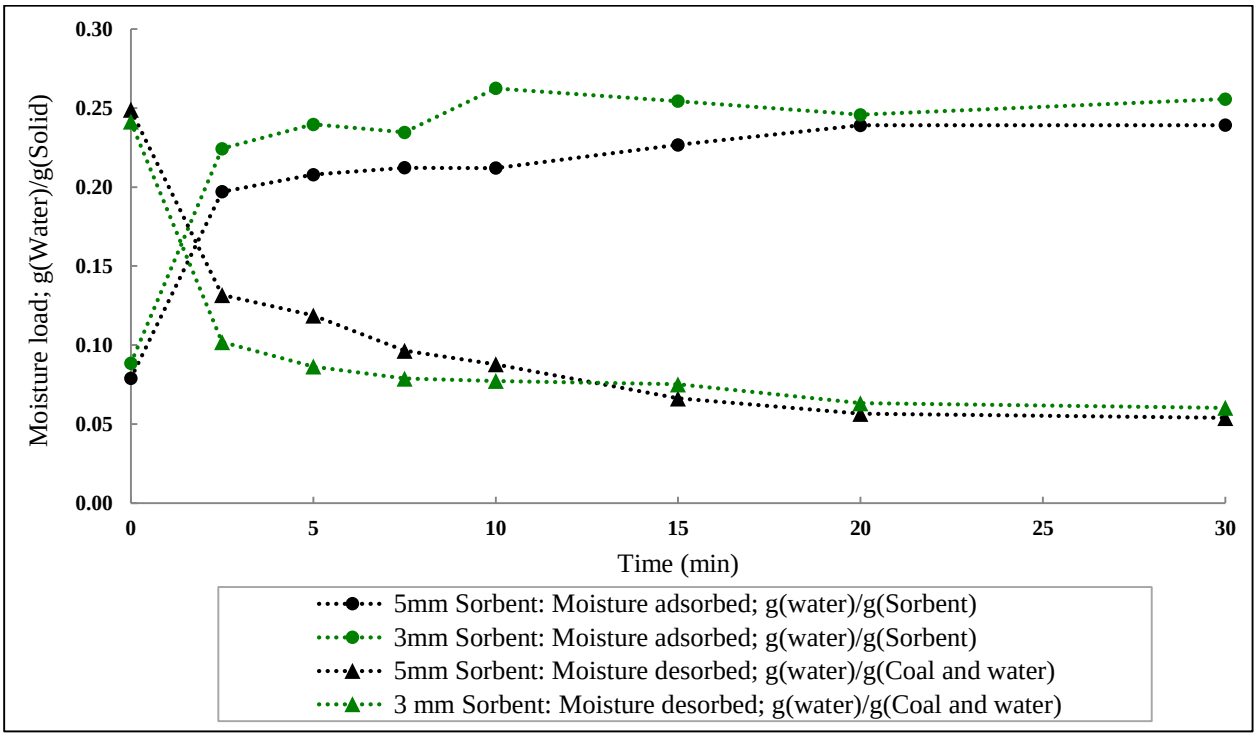


*Figure 4.4.9. Sorbent size of 3mm and 5mm; +0.5mm-1mm coal fines in a 1:1 ratio with sorbent*

It is evident from Figure 4.4.9 that the sorbent diameter had an effect on the adsorption rate of moisture onto the sorbent, probably as a result of the change in sorbent surface area. It was found that the 3mm diameter alumina-rich spheres had a faster liquid and vapour transfer rate than the 5mm diameter spheres. This is confirmed by the finding of Asmatulu & Yoon (2012) who stated that finer sorbent particles attract and retain moisture mainly because of the larger surface area exposure compared to coarser sorbent particles. The sorbent size did not influence the final surface moisture content of the coal, however. This is confirmed by Bratton *et al*. (2012).

*1.5. Coal size fraction*

The effect of coal particle size (+1mm-2mm, +0.5mm-1mm and +0.25mm-0.5mm) was tested and results are shown in Figure 4.4.10. The experiment was performed with 5mm alumina-rich sorbents at a sorbent to coal mass ratio of 2:1.

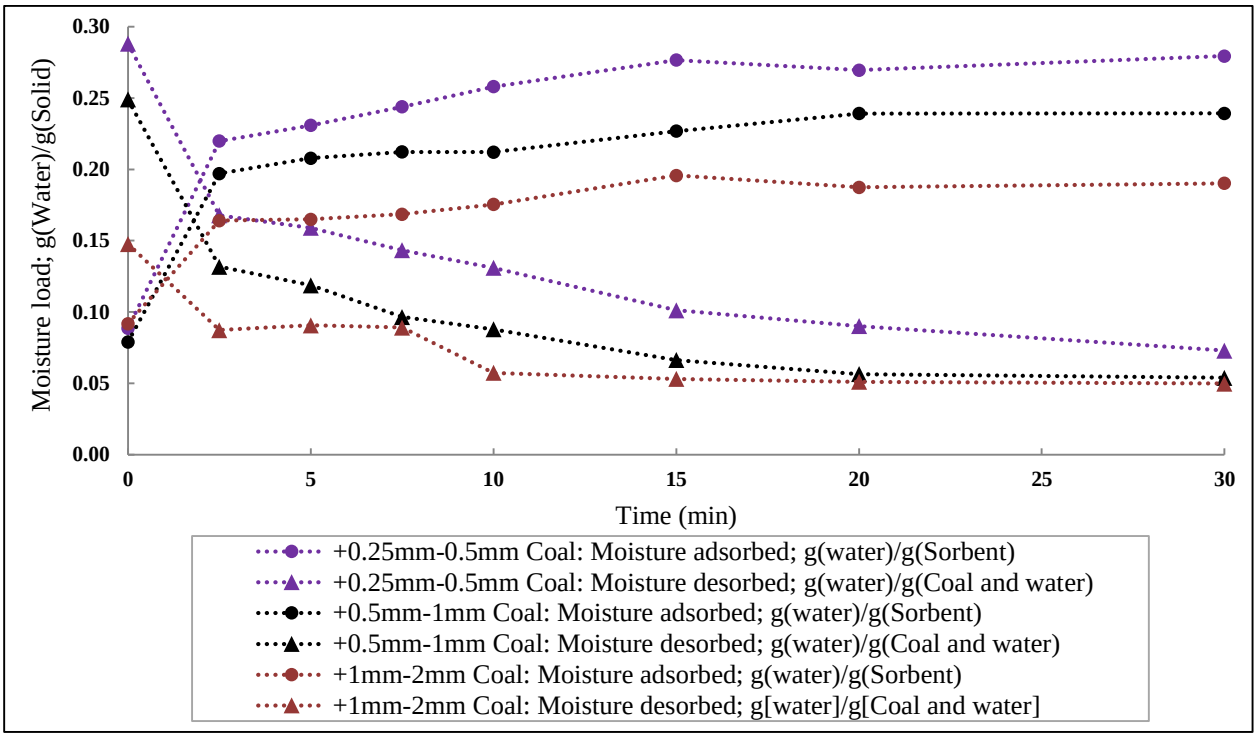


*Figure 4.4.10. Different coal size fractions in a 1:1 ratio with 5mm sorbent*

The results show that the different coal size fractions contained different initial moisture content values, as expected. The larger surface area of the smaller coal sizes creates more surface- and capillary forces, increasing each particle's moisture holding capacity (Asmatulu & Yoon, 2012). The excess free moisture and inter-particulate moisture of the smaller sizes created a larger moisture concentration gradient resulting in faster sorption rates. The initial adsorption rates for the +1mm-2mm, +0.5mm-1mm and +0.25mm-0.5mm size fractions were 1.48g(water)/g(sorbent)/min, 1.50g(water)/g(sorbent)/min and 0.79g(water)/g(sorbent)/min, respectively. Consequently it took 2.5 minutes to dewater the +1mm-2mm fraction to below 0.10g(water)/g(coal and water), whereas the +0.5mm-1mm fraction took 7.5 minutes. The finest fraction (+0.25mm-0.5mm) reached 0.10g(water)/g(coal and water) only after 15 minutes. Even though the finer particles took longer to dry, it must be noted that contact sorption could successfully reduce the moisture content to a similar value irrespective of particle size. It can be deduced that the strong moisture holding capacity of the finer fractions was overcome by the sorbent's affinity for water resulting in mass transfer still taking place (Lin *et al*., 2012).

### *1.6. Re-using sorbents*

Sorbent material was re-used in sequential contact sorption runs to determine how many cycles could be completed before the sorbent reached some maximum moisture holding capacity. These experiments also tested if there were any changes in the moisture transfer rates due to different initial moisture contents of the sorbent.

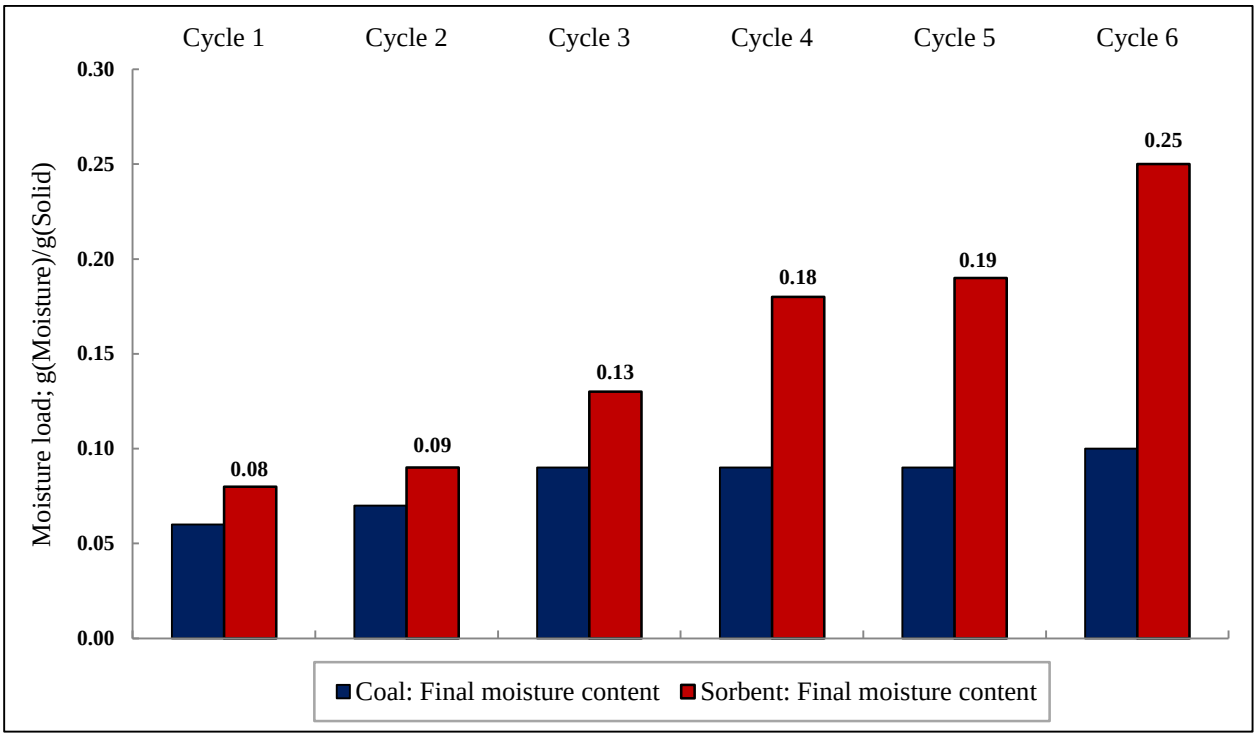


*Figure 4.4.11. Re-use of sorbent, +1mm-2mm coal fines in a 3:1 ratio with 5mm alumina-rich sorbent*

It was found that the repeated use of the sorbents yielded very similar coal equilibrium moisture contents, while the loading on the sorbents increased after each cycle. There was no evidence that sorbent loading reached saturation even after five additional cycles. It is therefore possible to re-use the same sorbent for several cycles before regeneration becomes a necessity, therefore ensuring a lower operating cost. Figure 4.4.11 shows that even a sorbent with a 20%$_{wt}$ surface moisture level can be successfully used to dewater coal.

***2. Sorbent regeneration***

To run this process in an eco-friendly and cost-effective way, sorbent regeneration is necessary (Kulkarne & Kaware, 2014). This ensures active sorbent operation in consecutive cycles with uniform performance (Knaebel, 2004). After separating the dried coal fines from the saturated sorbent by means of sieving, the loaded sorbents were regenerated in a simple packed bed configuration using conditioned air at a flow rate of 1.5-1.7m/s at 22°C and 40% relative humidity. Under these conditions the ceramic moisture content was decreased from approximately 25%$_{wt}$ to below 10% $_{wt}$ in 10 minutes. The moisture could be successfully desorbed from the sorbent since it was bound to the surface by means of weak Van Der Waals forces. A test was done to compare the sorption efficiency of unused versus regenerated sorbents, as shown in Figure 4.4.12.

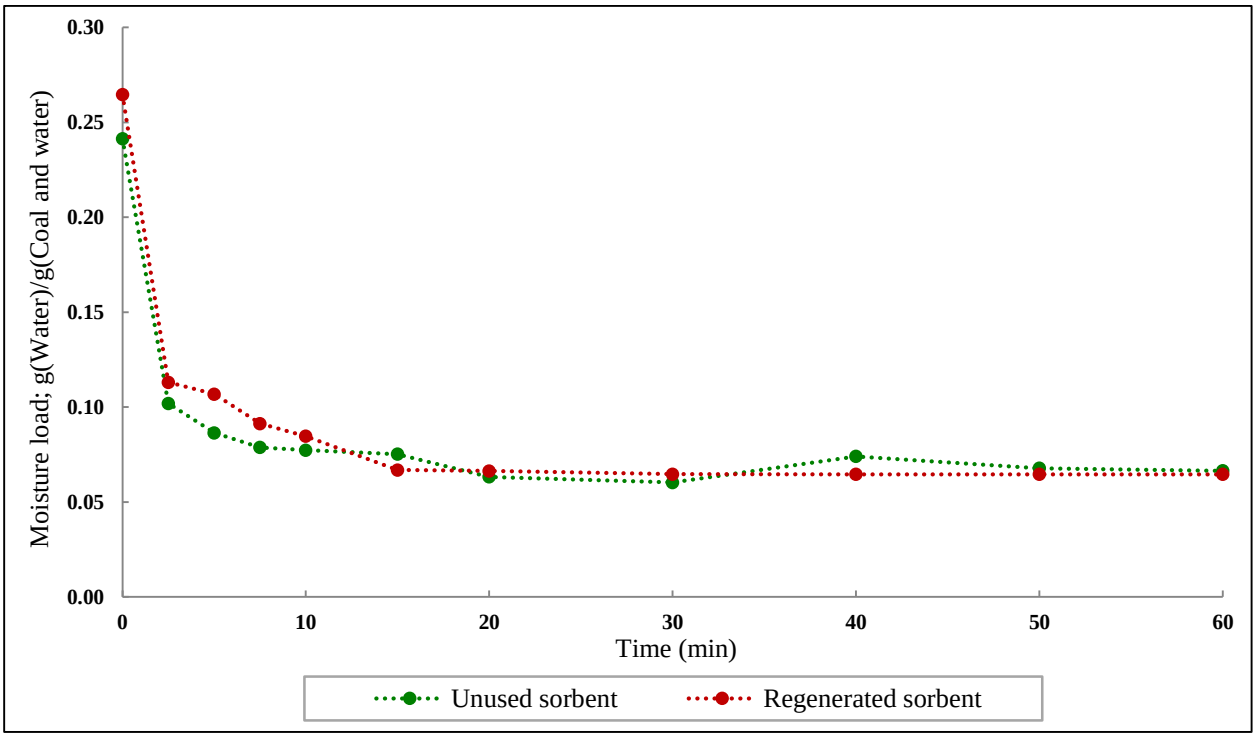


*Figure 4.4.12. Unused and used sorbent; +0.5mm-1mm coal fines in a 1:1 ratio*

There is a remarkable similarity between the performance of unused and regenerated sorbents during all three moisture transfer phases. It supports the success of a packed bed of sorbents using ambient air at low relative humidity to drive off the adsorbed moisture. By recycling the sorbents in a closed loop in a larger process, significant reduction in capital and operational expenditures can be achieved. Bratton *et al*. (2012) reported similar findings, observing no substantial difference in the effectiveness of sorbents in coal drying after regeneration.

### *Conclusion*

The proposed contact sorption process is driven by the mass transfer of moisture caused by a concentration gradient. Two mechanisms occur simultaneously: desorption of moisture from the coal and adsorption of moisture onto the sorbent. These results were achieved with just a rotating bed at atmospheric conditions without the need of expensive processing. It was found that the contact between the coal fines and sorbent was the main driving force for sorption drying at ambient temperatures. The contact can be improved by increasing the sorbent to coal ratio or by using smaller sorbents with a larger surface area. The moisture content could be reduced successfully within a reasonable time of less than 10 minutes, irrespective of the size of coal. Regeneration of the sorbents was possible and it could be re-used without any decrease in drying efficiency. It was shown that contact sorption with the associated ambient temperature air drying of used sorbents, could be a cost-effective and efficient method to dewater coal fines in the industry.

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## 4.5. Additional information

Additional experiments were completed to firstly determine the influence of elevated temperatures on the dewatering rate of coal. Secondly, a series of tests were completed to determine the possibility to dewater ultra-fines of -0.212mm coal as well.

### *4.5.1. Operating conditions*

The results from the papers in this chapter indicated that the adsorption process was successful at average atmospheric conditions of 22˚C and 40% relative humidity as set in the climate-controlled laboratory at the North-West University. Additional experiments were conducted to determine whether an increase in air temperature surrounding the wet coal/sorption mixture, would increase the rate and total amount of moisture transported from the fine coal to the sorbent material. The experimental work was completed at 25˚C, 40˚C and 55˚C to investigate the influence in air temperature as indicated in Figure 4.5.1. The results in Figure 4.5.1 show the adsorption rate of moisture onto +6mm-10.5mm ceramic spheres when dewatering coal with a particle size distribution of -2mm+0.5mm in relative humidity conditions of 40%.

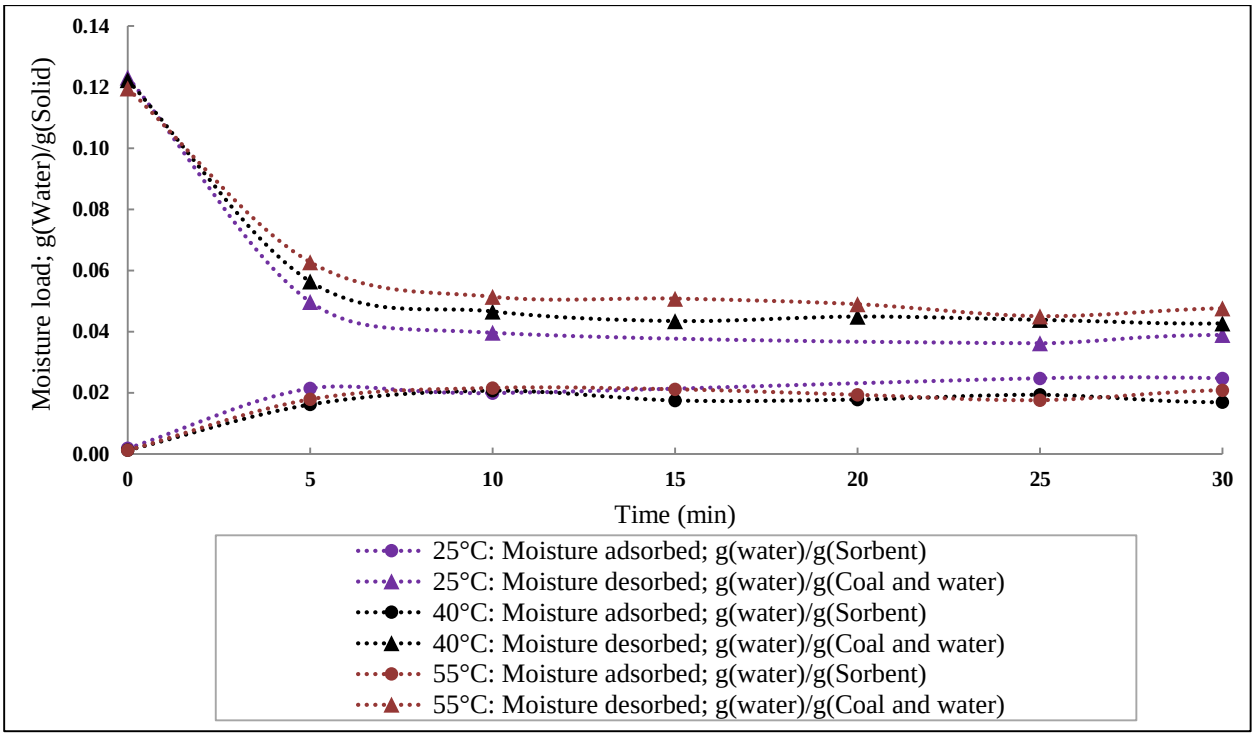


*Figure 4.5.1. Adsorption rates at temperatures between 25°C, 40°C, & 55°C*

The results from Figure 4.5.1 showed that elevated temperatures did not have a significant influence on the dewatering rate or final equilibrium moisture content of the coal. The experiments completed at 25°C indicated that slightly more moisture could be desorbed compared to the experiments conducted at 40°C and 55°C. The elevated temperatures caused a slight evaporation of moisture in the system, which resulted

in less overall moisture in the liquid form that could to be desorbed from the coal. Similar results were found when observing the influence of elevated temperatures when operating at different sorbent to coal ratios.

The adsorption process can be described thermodynamically in terms of Gibbs energy in Equation 4.5.1.

$$\Delta G = \Delta H - T\Delta S \qquad \textit{Equation 4.5.1}$$

Where, $\Delta G$ is the Gibbs free energy, $\Delta H$ the heat of enthalpy, $T$ the temperature and $\Delta S$ the entropy. Physical adsorption is an exothermic process, which means that the process occurs spontaneously just by bringing the dry sorbent material and wet coal in contact. This results in a decrease in the free energy of the system, and a decrease in the Gibbs free energy ($\Delta G < 0$). The movement of adhesive moisture is restricted which results in a decrease in the entropy ($\Delta S$). Therefore, the heat of enthalpy ($\Delta H$) is negative, indicating that the process is exothermic (Parashar, 2015). This means that lower temperatures are sufficient for adsorption to occur. Le Chatelier's principle states that adsorption capabilities would decrease with an increase in the temperature (Parashar, 2015; Bhaskar, 2014). In addition, the elevated temperatures caused slight evaporation of moisture in the system, which led to less liquid moisture to be adsorbed. This explains why the small temperature elevations shown in Figure 4.5.1 did not significantly affect the dewatering capabilities of the sorbent material or the final coal product moisture content.

Adsorption therefore does not rely on the fluid phase conditions like temperature, but rather on the contact between the coal fines and sorbent material. Adsorption is rather promoted by the properties of the sorbent material. These alumina- and silica-rich ceramic sphere or beads are therefore produced to have a high degree of porosity which results in a large internal and external surface area. For that reason, adsorption is improved, with the increase in available surface area for the moisture to adhere to the sorbent (Honeywell UOP, 2011; Kudra & Mujumdar, 2009). Increasing the surface area increases the number of open sites with a low moisture concentration at the surface. This surface phenomenon will increase the moisture concentration gradient between the dry sorbent and the surrounding moisture from the coal fines, which will be advantageous for adsorption (Parashar, 2015).

### *4.5.2. Feed size distribution*

The results from papers 5 to 7 show that it is possible to dewater coal size fractions of +1mm-2mm, +0.5mm-1mm and +0.25mm-0.5mm. Drying of fines smaller than 0.212mm proved to be more challenging compared to these courser fractions as these wet ultra-fines tend to form agglomerates prior and during the experimental run. These agglomerates affected the adsorption efficiency as can be seen in the resultant dewatering curves shown in Figure 4.5.2. Alumina-rich sorbent spheres with a diameter of 3mm were added in a 1:1 mass ratio with coal in the rotary bed.

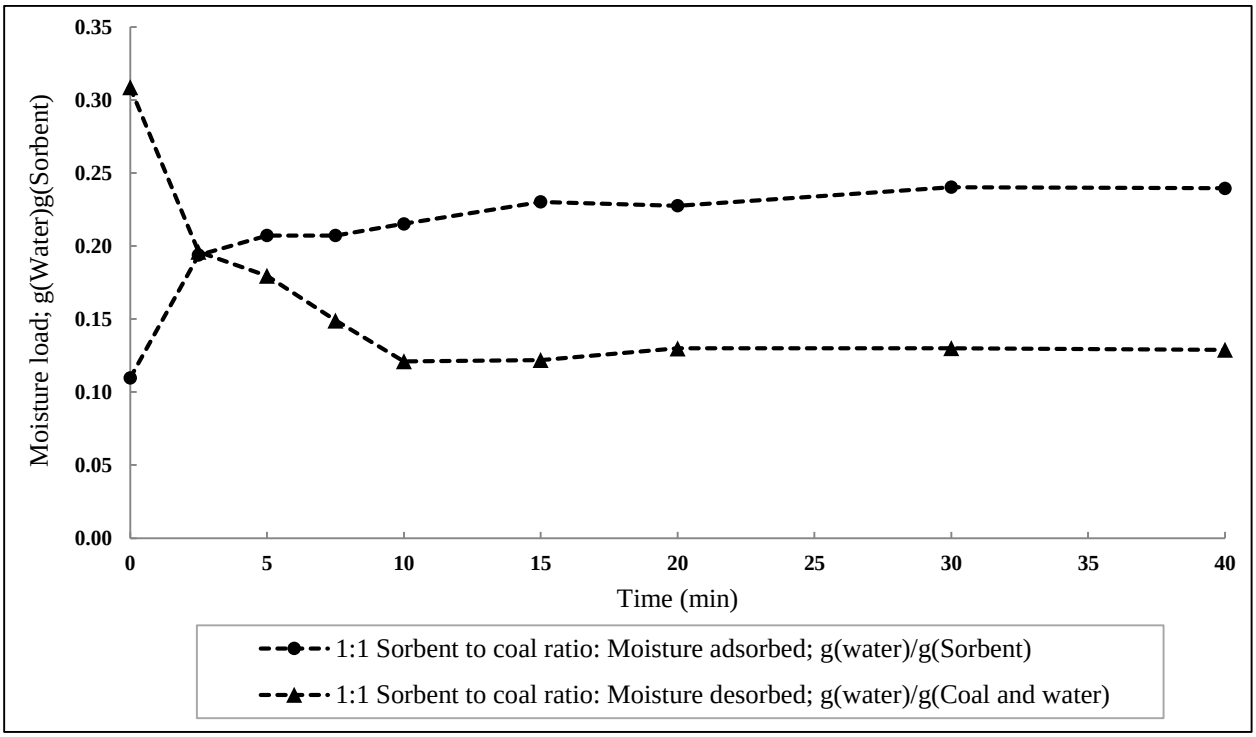


*Figure 4.5.2. Broken filter cake; -0.212mm coal fines with 3mm alumina-rich sorbent*

The coal ultra-fines could be dewatered from a moisture content of about 30%$_{wt}$ to about 12%$_{wt}$ within 10 minutes. When drying larger particle size distributions (+1mm-2mm, +0.5mm-1mm and +0.25mm-0.5mm), a ratio of 1:1 can achieve a typical thermal coal contract target surface moisture of 8-9% in less than 10 minutes. During the 40 minutes of the experimental run shown in Figure 4.5.2, the ultra-fines could not be dewatered to a moisture content as low as the coarser fraction. The sorbent material wasn't able to break the agglomerates during rotation and tumbling in the rotating bed as illustrated in Figure 4.5.3.

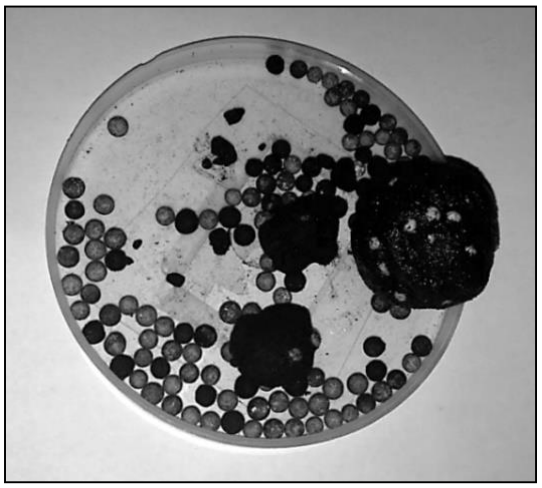

*Figure 4.5.3. Agglomerates found in test sample; -0.212 mm coal fines with 3mm alumina-rich sorbent*

When fines agglomerate to form larger clumps, the tightly bounded outer crust becomes challenging to penetrate (Pietsch, 2002). This indefinitely affects the desorption of moisture from the coal and hence reduce the efficiency of the process. The inner sections of the agglomerate will remain wet as only the agglomeration of coal and sorbent spheres affected the final moisture content in the different ultra-fine samples and therefore the moisture content varied quite significantly according to the size of agglomerates formed with some tests reporting a final moisture content as high as 20%$_{wt}$. The ultra-fines formed agglomerates that caused the moisture content to be more or less the same for the majority of the experimental run. Only the outer surface of the agglomerate is exposed to the sorbent material for moisture transport. The formation of agglomerates therefore reduces the total surface area available for contact sorption (Pietsch, 2002). Consequently, the agglomerates decrease the drying rate in the system and this result in a higher overall coal product moisture content.

It was observed in the laboratory that the experiments relied heavily on how the filter cake was inserted into the cascading bed. It is suggested to break the filter cake sample before inserting in the cylinder. It is also suggested to put a couple of steel balls into the rotating bed, together with the wet ultra-fines and sorbent material as shown in Figure 4.5.4.

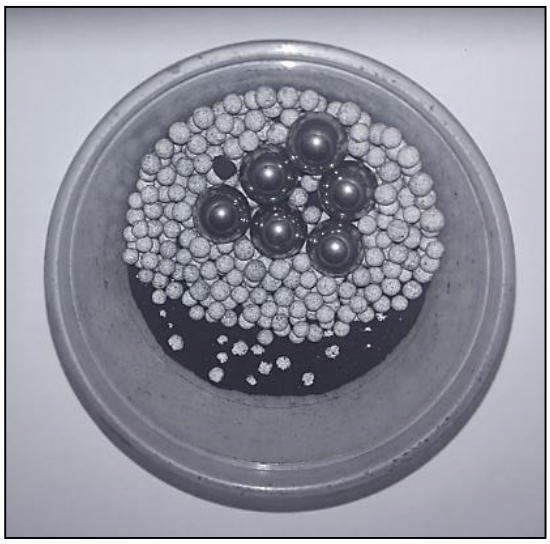

*Figure 4.5.4. Sample containing ultra-fines ( -0.212 mm), 3mm alumina-rich sorbent and steel balls*

The steel balls were able to break the agglomerates down without breaking the sorbent material when rotated with the sample at 3 revolutions per minute. It should be noted that higher revolution per minute or larger scale operations might affect the breakage of the sorbent material when operating with steel balls in the mixture. Figure 4.5.4 shows a photograph of a test sample, where the ultra-fines typically did not form large agglomerates and the moisture content of the ultra-fines could be reduced even further. Without the presence of agglomerates, the ultra-fine coal could reach moisture content levels comparable to the larger fractions. Leaving the broken ultra-fines in the cylinder with the sorbent material for a few hours, could eventually dry the coal sample to as low as 6%$_{wt}$.

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# Chapter 5

## Evaluation between high airflow drying and adsorption assisted drying

The focus of Chapter 5 is to compare the key advantages and limitations of high airflow drying versus adsorption assisted drying. These two drying techniques are evaluated by focussing on the best operating parameters, drying efficiency, energy consumption and operational difficulties. In conclusion a decision is made regarding the most feasible and practical drying method.

## 5.1. Operating conditions

A list of experimental operating conditions tested on the laboratory scale apparatus is given in Section 5.1. The best tested operating conditions for both the high airflow fluidized bed and the adsorption rotating bed are summarised and compared. This summary contains the key results from the investigated operating conditions, which are fully discussed in Chapter 3 and Chapter 4 of this thesis.

### *5.1.1. High airflow drying*

The following variables were tested during operation of the high airflow fluidized bed.

| | |
|---|---|
| *Relative humidity* | 30, 50 and 70% RH |
| *Airflow rate* | Non-fluidizing conditions, minimum fluidization velocity as per load (0.8-1.1m/s) and above minimum fluidization velocity (1.5-1.7m/s) |
| *Temperature* | 18°C, 21°C, 25°C, 40°C, 55°C, 60°C and 70°C |
| *Maceral composition* | Waterberg Inertinite rich coal and Waterberg Vitrinite rich coal |
| *Feed coal moisture content* | Equilibrium moisture content of 2.5%$_{wt}$ and filter cake moisture content ranging between 15-30%$_{wt}$, depending on feed particle size |
| *Coal size ranges* | +1mm-2mm, +0.71mm-1.18mm,0.5mm-0.71mm and a 50/50 mass mixture containing +0.71mm-1.18mm and +0.5mm-0.71mm. |

It was established that the drying efficiency of the high airflow fluidized bed relied mainly on the ability of air to displace the moisture associated with the coal fines at an acceptable rate. This was achieved by increasing the airflow rate of the drying air and by lowering the moisture content (relative humidity) thereof. The larger moisture gradient created between the wet coal fines and the drier fluidizing air enabled quicker removal of moisture from coal to the air. Drying within the fluidized bed was, therefore, most efficient when operated with air at 30% relative humidity with an airflow rate above the minimum fluidization velocity.

An increase in the drying air temperature will subsequently lead to a lowered relative humidity. A larger concentration gradient will form as a result of the lower moisture content of the drying air. Therefore, elevated temperatures will increase the moisture transfer rate (Barbosa de Lima *et al*., 2016). For this specific laboratory setup, the temperature benefit could, however, only be ascertained up to an air temperature of 40°C. At higher temperatures, accompanied with higher relative humidity conditions, the surrounding drying air quickly became saturated with moisture. This moisture in the surrounding drying air led to an increase in the partial pressure of the drying air and a subsequent decrease in the moisture concentration gradient between the air and the coal fines. The dewatering rate will decrease or even come

to a halt when the partial pressure of the water vapour in the drying air exceeds the vapour pressure of the moisture surrounding the wet bulk sample (Barbosa de Lima *et al*., 2016). However, for this specific setup, the temperature benefit could only be ascertained up to 40°C across all three relative humidity conditions. It was found that vapour formed and condensed unto the cylinder wall of the fluidized bed at temperatures higher than 40°C.

Results reported in Chapter 3 indicate that it was possible to reduce the moisture of coal starting from about 30%$_{wt}$ moisture to a level where fluidization of agglomerates was possible. As time elapsed, even more water was displaced and the agglomerated particles loosened up to form a uniformed fluidized bed with singular particles. During the fluidizing state, the coal moisture content was on average between 5-7%$_{wt}$. From this stage, further reduction of moisture could take place as the air percolated through the lifted coal bed. It was found that the high airflow could, therefore, reduce the unbounded moisture surrounding the coal particles and thereafter remove the moisture to a level below the inherent moisture content of the coal. This process was shown to be independent of maceral composition or feed moisture (feed moisture did influence the total drying time, but not drying rate or final equilibrium moisture content), but showed to be largely dependent on the particle size of the feed coal.

Equilibrium moisture values nearing the predetermined inherent moisture content of all coal size fractions were reachable, however, the finer fraction required a much longer drying time. The coal size distributions of -2mm+1mm, -1.18mm+0.71mm and -0.71mm+0.5mm reached its respective final equilibrium moisture content in 7 minutes, 20 minutes and 37 minutes. As expected, the smaller sized coal particles have a larger available surface area which in turn increases both the monolayer and multi-layer moisture holding capacity of each individual particle and consequently increases the difficulty in removing moisture from the bulk sample. It is this property of fine coal which contributes to the increase in drying time needed to reach the final equilibrium moisture level.

### *5.1.2. Adsorption drying*

The following variables were tested when drying coal by means of adsorption assisted drying.

| | |
|---|---|
| *Temperature* | 22°C, 25°C, 40°C and 55°C |
| *Sorbent type* | Alumina-rich ceramic (84.02%$_{wt}$ and 92.70%$_{wt}$ Aluminium oxide) and Silica-rich ceramic (97.0%$_{wt}$ and 64%$_{wt}$ Silica oxide) |
| *Sorbent diameter* | Alumina-rich ceramic (3mm, 5mm, +6mm-10.5mm, +12mm-20mm) and Silica-rich ceramic (6mm, 13mm) |
| *Sorbent to coal ratio* | 0.5:1, 0.75:1, 1:1, 2:1 and 3:1 by weight |
| *Coal size range* | +1mm-2mm, +0.5mm-2mm, +0.5mm-1mm, +0.25mm-0.5mm and -0.212mm |

| | |
|---|---|
| *Bulk coal moisture content* | Filter cake moisture content ranging between 15-30%$_{wt}$ depending on feed particle size |
| *Sorbent state* | Unused and regenerated (dried in atmosphere and dried with airflow) |
| *Motion* | Stationary bed and rotating bed (3-4 revolution/min) |

The results from the investigation and research, discussed in Chapter 4 showed that adsorption assisted drying is able to reduce the surface moisture content of fine coal to a final equilibrium value between 4-6%$_{wt}$ but struggled to reduce the moisture content to levels below the inherent moisture value. It was established that, due to the exothermic nature of the adsorption process, temperature elevations did not affect the initial dewatering rate (Parashar, 2015).

Adsorption, therefore, relies on the contact between the coal fines and sorbent material. Both the sorbent types, containing various quantities of Aluminium and Silica oxide, had similar sorption capabilities. However, the use of smaller sorbent sizes resulted in a faster dewatering rate compared to the larger sorbents particles. This was shown by this difference in the time it took to dewater the coal to 8%$_{wt}$. The 3mm sorbents took 5min to obtain the target moisture of 8%$_{wt}$, whereas the 5mm sorbent took 10 minutes, whilst the +6-10.5mm sorbents took 16 minutes. Smaller sorbent material has a larger exposed surface area, improving contact between the sorbent outer surface and the free moisture surrounding the coal fines, which in turn improves the transfer rate of moisture between the coal and sorbent.

The experimental work showed that the best results were achieved when feeding the rotating vessel a sorbent to coal mass ratio of 1:1 or 2:1, both allowing for maximum surface contact. The addition of ceramics at a mass ratio higher than 3:1 did not show a significant improvement in the dewatering rate. This hold true for both fresh (new) sorbents and sorbents that were regenerated in a packed bed using high airflow at ambient conditions.

A decrease in drying rate was observed when drying finer coal. Even though these particles took longer to dry, it must be noted that comparable final moisture contents were reached, irrespective of the coal particle size. None of the +1mm-2mm, +0.5mm-2mm, +0.5mm-1mm and 0.25mm-0.5mm coal particles showed any form of agglomeration during the drying process, but the ultra-fine -0.212mm particles did agglomerate to form pseudo larger and more compacted particles, leading to a higher final equilibrium product moisture. The inner voids of the agglomerate will largely remain filled with water due to very high intra-capillary forces which counters the movement of moisture to the outer surface of the pseudo particle and hence inhibits moisture transfer to the sorbents. In addition, the presence of agglomerates reduces the total surface area available for contact sorption (Pietsch, 2002). By adding a couple of steel balls to the feed material, it was possible to break open these agglomerated coal particles which released the moisture from the intra-particulate voids. It proved that final equilibrium moisture levels below the set target of 8%$_{wt}$ were achievable.

### *5.1.3. Comparison: Operating conditions*

Both drying techniques proved to be effective in drying coal fines without the need of introducing costly high temperatures to assist in the process. High airflow drying relied on a fast airflow rate at low relative humidity to dewater the wet coal fines, while the adsorption assisted drying relied on improved contact between the sorbent material and wet coal fines. It was established that adsorption assisted drying could only reduce the moisture content to deliver a coal product moisture of 4-6%$_w$. High airflow could reduce some of the moisture to below the inherent moisture content of the coal sample, resulting in a final moisture content around 1%$_{wt}$. It should be noted that drying beyond this point would be a waste of energy as the moisture would revert to its inherent moisture content in normal atmospheric conditions. Both the high airflow fluidized bed and the adsorption assisted drying in the rotating bed showed evidence of being able to reach lower moisture levels.

## 5.2. Drying efficiency

This section describes the drying efficiency in terms of the initial drying rate and final equilibrium moisture content reached by the wet coal samples. In Section 5.2.3 the drying efficiency of both the high airflow drying and adsorption drying is compared.ve

### *5.2.1. High airflow drying*

Table 5.2.1 gives a list of test results found when drying a typical PSD of +1mm-2mm fines with an initial moisture content of about 15%$_{wt}$ in a fluidized bed using an airflow rate of 1.5-1.7m/s and containing a relative humidity of 30%.

*Table 5.2.1. Drying efficiency for high airflow drying*

| Test result | High airflow at 25°C | High airflow at 40°C |
|---|---|---|
| Drying rate in 2.5 min | 1.90%wt/min | 2.96%wt/min |
| Moisture reduction in 10 min | 10.21%wt | 9.65%wt |
| Time required to reach 8%wt target moisture | 2min | 2min |
| Final moisture content | 1.88%wt within 6min | 1.94%wt within 4min |

The results depicted in Table 5.2.1 indicate a higher dewatering rate for airflow at 40 °C compared to 25 °C. Air at 25 °C and 40 °C could dewater the coal to reach the target moisture content of 8%$_{wt}$ within 2 minutes. The coal sample had an inherent moisture content of 2.58%$_{wt}$ and operating with high airflow could reduce the moisture content of the filter cake to a value below its inherent moisture content. Increasing the temperature resulted in a lowered relative humidity of the drying air, which in return increased its capacity for moisture uptake. This increase ensures that more moisture is removed at a faster rate (Barbosa de Lima

*et al*., 2016). For this reason, the drying air with a temperature of 40°C had a faster initial drying rate and could reach the target and final moisture content at a faster rate compared to a drying air temperature of 25°C.

### *5.2.2. Adsorption drying*

A list of drying efficiency test results found from adsorption drying, can be seen Table 5.2.2. Wet coal filter cake samples with an initial moisture content of 15%$_{wt}$ and a particle size distribution of +1mm-2mm were dried with 3mm alumina-rich sorbent material. The ambient conditions at which the vessels were loaded were 22°C and 40% relative humidity. The results are given for samples dried in a 1:1 and a 2:1 sorbent to coal ratio.

*Table 5.2.2 Drying efficiency for adsorption drying*

| Test result | Adsorption in a 1:1 ratio | Adsorption in 2:1 ratio |
|---|---|---|
| Drying rate in 2.5 min | 2.3%wt/min | 3%wt/min |
| Moisture reduction in 10 min | 7.48%wt | 7.55%wt |
| Time required to reach 8%wt target moisture | 2min | 2min |
| Final moisture content | 6.3%wt within 5min | 6.1%wt within 5min |

The results from Table 5.2.2 show that 1:1 and 2:1 sorbent to coal ratios could reach the target moisture of 8%$_{wt}$ within 2 minutes. The experimental results of all the conditions listed in Section 5.1.2 showed that the majority of the moisture was removed within the first 2.5 minutes and thereafter the drying rate slowed down. The sorbent material was only able to reduce the free moisture from fine or ultra-fine coal and delivered a coal product moisture of about 6%$_{wt}$.

The sorbent to coal ratio of 2:1 had a faster initial drying rate compared to the 1:1 feed ratio. Adding more sorbent material enhanced increased contact between the sorbent and coal particles, leading to more moisture being transferred at a faster rate (Honeywell UOP, 2011; Kudra & Mujumdar, 2009). Consequently, the 2:1 feed ratio could reach the target moisture in half the time whilst achieving a lower final equilibrium moisture content compared to the 1:1 feed ratio. However, a higher sorbent to coal ratio will drastically increase the equipment cost and cost related to downstream regeneration processes.

### *5.2.3. Comparison: Drying efficiency*

High airflow drying as well as adsorption assisted drying took about 2 minutes to reach a target moisture of 8%$_{wt}$. However, the high airflow fluidized bed delivered a final coal product with a moisture content lower than the inherent moisture of the coal sample, whereas adsorption could not reach these low moisture

levels. It should be noted that 8%$_{wt}$ moisture content was chosen as guideline to typical thermal coal needs in South Africa. In addition, at this moisture level, dust control is readily attainable and eliminates expensive dust control systems. Drying the coal beyond this point will result in unnecessary drying time wastage and an escalation in operational costs. In conclusion, both methods were efficient when focussing exclusively on the drying rate and time required for reaching the 8%$_{wt}$ target moisture.

## 5.3. Energy efficiency

The net energy result of the process was determined by calculating the difference in energy used by the setup for drying the coal and the gain in calorific value of the coal during combustion. A target moisture of 8%$_{wt}$ was again used as the reference for the coal product. This section focuses on determining whether the high airflow drying and/or adsorption assisted drying processes can efficiently dewater fine coal particles resulting in a net energy gain. These calculations were applied to the laboratory setups used and it should be noted that the calculated results are initial estimates only. The energy consumption for the high airflow fluidized bed and adsorption drying are discussed in Section 5.3.1 and Section 5.3.2, respectively.

### *5.3.1. High airflow drying*

The laboratory setup used for high airflow drying of coal mainly included a climate chamber which supplied the conditioned air at set temperature and relative humidity levels, a fluidized bed as shown in Figure 5.3.1 and a small-scale blower. The balance was made up of piping for air circulation.


*Figure 5.3.1 Photograph of the climate chamber and fluidized bed*

The climate chamber (CTS C-40/100 with a 100-litre chamber) produced conditioned air at a prescribed temperature and relative humidity. The energy required by the climate chamber to condition the air includes the energy spent on enthalpy and phase changes of water, calculated from ambient conditions of 25 °C and

50% relative humidity ($W_i$). The power requirement of the 2000Watt climate chamber was taken into account ($W_c$) to determine the total energy consumption of the climate chamber, as calculated from Equation 5.3.1. The climate chamber was used to continually condition the feed air at the start and during the drying process, which is reflected in the total time term, *t*.

$$Q_{Climate\ chamber} = (W_c + W_i)\ t \qquad \textit{Equation 5.3.1}$$

A blower was attached to the climate chamber which was used to draw conditioned air from the climate chamber and supply the required airflow to the fluidized bed to enable stable operation just above the minimum fluidization velocity point. The blower used 700Watt ($W_b$) for the high airflow rate. The energy consumption of the blower was calculated from Equation 5.3.2.

$$Q_{Blower} = W_b \cdot t \qquad \textit{Equation 5.3.2}$$

The total energy consumption was the addition of the two above mentioned energy inputs, calculated from Equation 5.3.3 for the time required to reduce the moisture content of the coal product to 8%$_{wt}$.

$$Q_{High\ airflow\ drying} = Q_{Climate\ chamber} + Q_{Blower} \qquad \textit{Equation 5.3.3}$$

The results shown in Table 5.3.1 are applicable to the drying of moist coal fines in a size range of +1mm-2mm supplying conditioned fluidizing air at a velocity of 1.7m/s, having a 30% relative humidity and temperatures of 25°C or 40°C. Table 5.3.1 shows the energy requirements at the conditions named in this paragraph.

*Table 5.3.1 Energy consumption for high airflow drying*

| Energy consumption | kJ/kg coal load | kJ/kg water removed |
|---|---|---|
| Fluidizing air at 25˚C | 3240 | 46.29 |
| Fluidizing air at 40°C | 3240 | 46.29 |

Table 5.3.1 showed that both the fluidizing air at a temperature of 25°C and 40°C consumed the same energy to deliver a coal product moisture to 8%$_{wt}$. All of this was done for the feed air having a relative humidity of 30%.

The energy gain for the high airflow fluidized bed was determined by calculating the difference between the energy consumption of the process and the improvement of the calorific value of the dried coal sample, as shown in Equation 5.3.4.

$$Q_{Energy\ gain} = Q_{CV\ upgrade} - Q_{High\ airflow\ drying} \qquad \textit{Equation 5.3.4}$$

where $Q_{CV\ upgrade}$ was calculated from Equation 5.3.5. The calorific value upgrade was determined by calculating the difference in the calorific value between the wet filter cake and dried coal sample.

$$Q_{CV\ upgrade} = Q_{CV\ of\ dried\ sample} - Q_{CV\ of\ filter\ cake}$$ *Equation 5.3.5*

The energy gain results for the high airflow fluidized bed can be found in Table 5.3.2. The results are shown for drying coal fines in a size range of +1mm-2mm with drying air at a speed of 1.7m/s and 30% relative humidity to a moisture content of 8%$_{wt}$.

*Table 5.3.2. Energy gain for upgrading coal with high airflow drying*

| Type | Energy (MJ/kg feed) | |
|---|---|---|
| | **Fluidizing air at 25°C** | **Fluidizing air at 40°C** |
| Calorific value of feed ($Q_{CV\ of\ filter\ cake}$) | 16.54 | 16,54 |
| Calorific value of dry coal at 8% moisture ($Q_{CV\ of\ dried\ sample}$) | 22.64 | 22.64 |
| Calorific value upgrade ($Q_{CV\ upgrade}$) | 6.10 | 6.10 |
| Energy consumption ($Q_{High\ airflow\ drying}$) | 3.24 | 3.24 |
| Energy gain ($Q_{Energy\ gain}$) | 2.86 | 2.86 |

It is noted from Table 5.3.2 that a resultant energy gain was achieved for both air temperature considerations. This gain in energy was significantly more at the higher temperature setting than for the lower air temperatures, which is attributed to the reduction in drying time.

### *5.3.2. Adsorption drying*

The laboratory setup used for adsorption drying can be seen in Figure 5.3.2. It consisted out of a rotating bed (a) for adsorption drying, laboratory sieves (b) to separate the sorbent material from the fine coal, and packed bed setup (c) to dry the used sorbent for reuse.

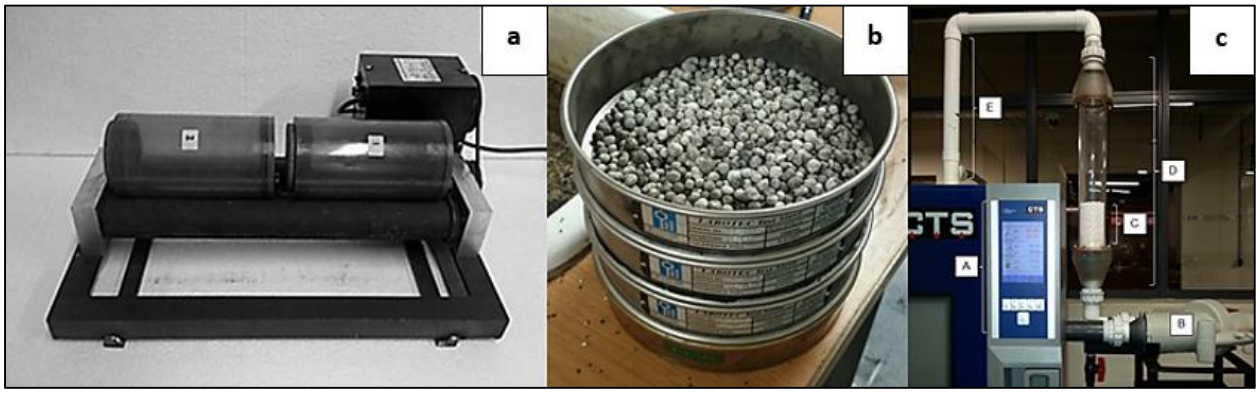


*Figure 5.3.2 Photographs of the rotating bed (a), sieves (b) and packed bed (c)*

Cylinders containing sorbent material and wet coal fines were placed on rollers that rotated at 3-4 revolutions per minute. The power draft of the motor used to rotate the bed ($W_r$) shown in Figure 5.3.2(a) was 40 Watt. It was used to calculate the energy consumption of the rotary bed using Equation 5.3.5.

$$Q_{Rotating\ bed} = W_r \cdot t \qquad \textit{Equation 5.3.5}$$

The saturated sorbent material was separated from the dried coal, illustrated here in Figure 5.3.2(b), and thereafter placed in a packed bed for drying (Figure 5.3.2(c)). The climate chamber (CTS C-40/100 with a 100-litre chamber) shown in Figure 5.3.2(c) was used to produce conditioned drying air resembling atmospheric conditions (25°C and 40-80% relative humidity). Controlling the air conditions aided in producing repeatability for the tests. The energy required to alter the temperature and relative humidity is indicated by ($W_i$). The climate chamber had a power requirement of 2000 Watt ($W_c$) and the energy consumption of the climate chamber was calculated from Equation 5.3.6.

$$Q_{Climate\ chamber} = (W_c + W_i)\ t \qquad \textit{Equation 5.3.6}$$

The packed bed used drying air at a temperature of 25°C and 40-80% relative humidity, fed at a velocity of lower than 1.5m/s. The blower's power usage was 350 Watt ($W_b$) and the energy consumption for the 10 minutes regeneration time ($t$) was calculated by Equation 5.3.7.

$$Q_{Blower} = W_b \cdot t \qquad \textit{Equation 5.3.6}$$

The total energy consumption for adsorption drying was calculated by Equation 5.3.7 for the time required to reduce the moisture content of the coal product to 8%$_{wt}$.

$$Q_{Adsorption\ drying} = Q_{Rotating\ bed} + Q_{Climate\ chamber} + Q_{Blower} \qquad \textit{Equation 5.3.7}$$

The results are shown for drying coal fines in a size range of +1mm-2mm with sorbent material in a 1:1 ratio. Table 5.3.3 gives the range of energy consumption by the total process for extreme air conditions used in the packed bed dryer.

*Table 5.3.3. Energy consumption for adsorption drying*

| Energy consumption | kJ/kg coal load | kJ/kg water removed |
|---|---|---|
| Packed bed air at 40% RH | 1098 | 15.69 |
| Packed bed air at 80% RH | 1098 | 15.69 |

The energy consumption of adsorption included the energy requirements of the rotating bed and the regeneration process of the sorbent material. The energy gain was calculated from Equation 5.3.8 where the calorific value upgrade ($Q_{CV\ upgrade}$) was calculated from Equation 5.3.9.

$$Q_{Energy\ gain} = Q_{CV\ upgrade} - Q_{Adsorption\ drying} \quad \textit{Equation 5.3.8}$$

$$Q_{CV\ upgrade} = Q_{CV\ of\ dried\ sample} - Q_{CV\ of\ filter\ cake} \quad \textit{Equation 5.3.9}$$

The results were completed for drying coal fines in a size range of +1mm-2mm in a vessel having a sorbent material to coal mass feed ratio of 1:1. The results indicate a calorific value upgrade by drying the coal fines to a moisture content of 8%$_{wt}$. The energy gain results can be seen in Table 5.3.4.

*Table 5.3.4 Energy gain for upgrading coal with adsorption drying*

| Type | Energy (MJ/kg feed) | |
|---|---|---|
| | **Air at 40% RH** | **Air at 80% RH** |
| Calorific value of feed ($Q_{CV\ of\ filter\ cake}$) | 16.54 | 16,54 |
| Calorific value of dry coal at 8% moisture ($Q_{CV\ of\ dried\ sample}$) | 22.64 | 22.64 |
| Calorific value upgrade ($Q_{CV\ upgrade}$) | 6.10 | 6.10 |
| Energy consumption ($Q_{High\ airflow\ drying}$) | 1.10 | 1.10 |
| Energy gain ($Q_{Energy\ gain}$) | 5.0 | 5.0 |

Both relative humidity conditions delivered similar results when drying to a target moisture of 8%$_{wt}$ within 10 minutes as presented in Table 5.3.4. Drying the wet filter cake by means of adsorption proved to be energy efficient, as it showed a significant energy gain when upgrading the calorific value of the coal samples. The low energy consumption can be ascribed to the adsorption and regeneration processes both operating at ambient conditions. The regeneration process in the packed bed was accomplished at lower airflow velocities at ambient conditions. Therefore, even when taking the regeneration process of the sorbent material into account, the process still proved to be energy efficient.

### *5.3.3. Comparison: Energy efficiency*

Comparing the results described in Section 5.3.1 and Section 5.3.2, it was clear that adsorbent drying was more energy efficient than high airflow drying, specifically for drying wet coal fines of +1mm-2mm to the target moisture of 8%$_{wt}$. The maximum energy gain using the high airflow fluidized bed was 2.86MJ/kg per coal feed, whereas the adsorption drying resulted in an energy gain of 5.0MJ/kg coal feed. It is evident that adsorption drying had a significantly higher energy gain compared to the energy gain resulting from high airflow drying. This can mainly be ascribed to the lower energy consumption of the moisture adsorption and desorption processes onto the ceramics. Therefore, adsorption drying proved to be viable and in return will result in extra revenue as less money will be required for energy to upgrade the coal to a saleable product.

## 5.4. Operational difficulties

This section is focussed on observing possible operation difficulties found on the laboratory scale apparatus and the consequences thereof are discussed in detail. Section 5.4 lays out key problem areas to improve on when developing a larger scale unit.

### *5.4.1. High airflow drying*

*Agglomerates*: It was found during experimental runs that channelling of the airflow correlated with fluctuations within the distribution of the coal feed. This resulted in particles sticking to side of the fluidized bed cylinder. A photograph of the agglomerates adhering to the side of the fluidized bed vessel can be seen in Figure 5.4.1.

*Figure 5.4.1 Agglomerates adhering to the side of the fluidized bed*

Airflow could not sufficiently penetrate these agglomerates adhering to the side of the vessel and consequently could not reduce their moisture content. The inner sections of the agglomerate remained wet since only the outer layers of the agglomerate came in contact with the drying air. Partial penetration of air is caused by the tight bonds between the wet fine coal particles, preventing air from fully penetrating it (Pietsch, 2002). Therefore, the final product moisture depended on this operational difficulty and the coal product moisture was found to vary depending on the amount on agglomerates accumulating on the side of the fluidized bed vessel. Airflow distribution needs to be optimised to prevent channelling of air and to produce a consistent airflow.

- *Condensate*: Operating at temperatures above 40°C along with a high relative humidity caused the formation of vapour that in return formed condensate in this specific fluidized bed setup. This vapour reached its saturation limit and at these temperatures, the air can no longer hold the vapour

(WeatherStreet.com, 2013). When the temperature increases inside the vessel, the temperature of the vessel wall remains colder than the inside during the duration of the experimental run. When the vapour comes in contact with the colder surface at a temperature below the saturation temperature of the vapour in the drying air, the vapour condenses to liquid unto the surface. At this dew point, the drying air is saturated with moisture which enables condensation. The moisture is released in liquid droplet form unto the cold surface of the cylinder as can be seen in Figure 5.4.2(a) (Sun & Wang, 2016).


*Figure 5.4.2(a) Condensate and (b) fine coal adhering to the side of the fluidized bed*

This phenomenon influenced the high airflow drying efficiency in two ways. Firstly, the moisture in the surrounding drying air led to an increase in the partial pressure thereof resulting in a decrease in the moisture concentration gradient. According to Barbosa de Lima *et al*. (2016), drying takes place when the partial pressure of the drying air is lower than the vapour pressure of the moisture surrounding the coal particles. When the surrounding air is saturated, it reduces the dewatering capacity of the drying medium. Secondly, the existence of condensate droplets on the sides of the vessel, adds to the operating time because unsaturated or partially saturated air now has to remove the condensate as well. The drops of condensate flowing down the cylinder, as seen in Figure 5.4.2(a), add to the moisture in the coal sample that has to be removed, subsequently increasing the drying time required to lower the coal sample moisture content.

The formation of water droplets on the inner walls of the fluidized vessel has the added effect of having fine coal particles adhering to the droplet surface, as can be seen in Figure 5.4.2(b). The accumulation of fine coal particles on the droplets tends to form agglomerates that will behave similarly with regards to

moisture retention than the ones described in the preceding paragraphs. Therefore, operation of the fluidized bed using moist air can have a double negative effect on the efficiency of the moisture removal from fine coal.

- *Attrition*: The movement of particles in the fluidizing air caused attrition and consequently the formation of ultra-fine particles. An experiment was conducted to dry a filter cake sample with a particle size distribution of -0.71mm+0.5mm, having a $d_{50}$ of 795µm, with drying air at 25°C and 30% relative humidity. The particle size range of the sample was determined prior and after the drying process and the results can be seen in Figure 5.4.3.

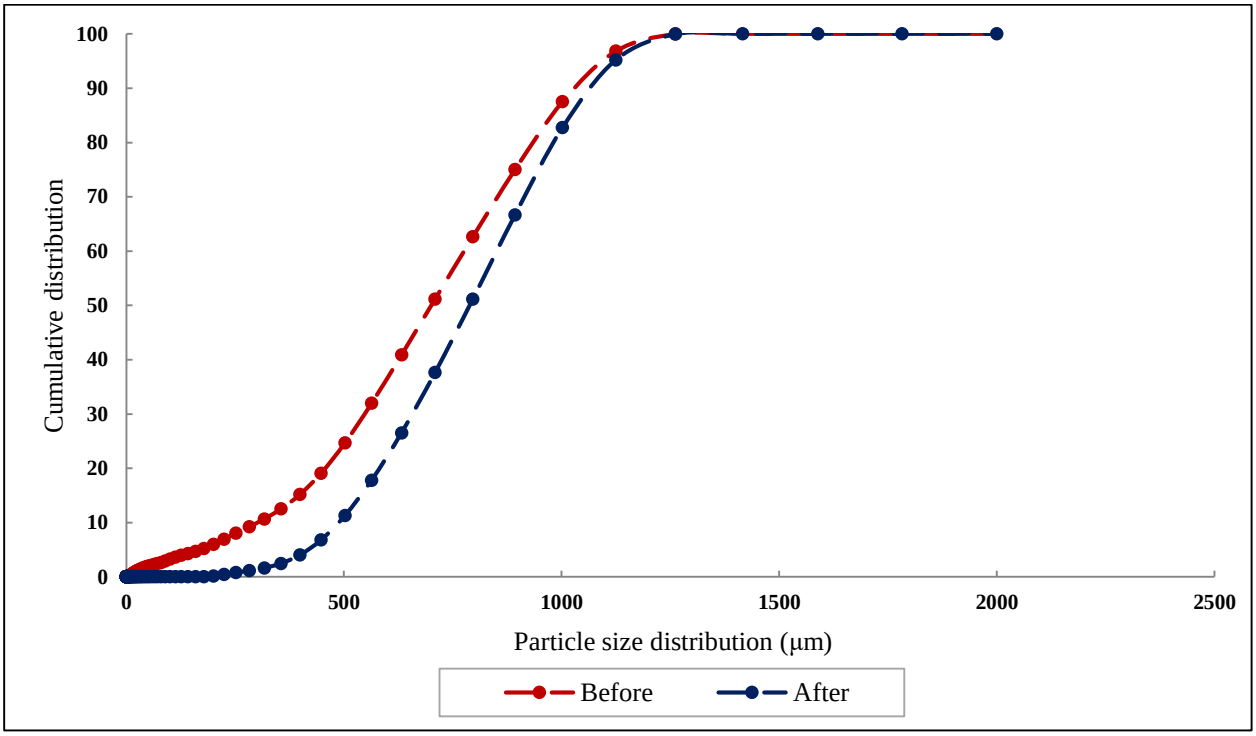


*Figure 5.4.3 Cumulative undersize distribution of coal (-0.71mm+0.5mm)*

Figure 5.4.3 shows evidence that the particles collided and attrition occurred when operating inside the fluidized bed. The product particle size range showed an increase in finer material, now yielding a $d_{50}$ of 709 µm. Formation of fines and ultimately dust is not uncommon and it is suggested to have outlet filters installed on the fluidized bed to prevent dust release.

### *5.4.2. Adsorption drying*

The need to add adsorption material to this process entails an additional capital and operational expense. If these materials are not used to the utmost efficiency with regards to durability and ease of regeneration, the

constant replacement costs involved would not justify the use of this process to dry fine coal. With this in mind, it is important to study the influence of these two parameters on the recycling of the ceramics.

- *Durability of sorbent material*: The condition of the sorbent material was investigated before and after the adsorption process as well as after the regeneration in the packed bed. Figure 5.4.4 shows Light Electron Microscopy (LEM) graphs of (a) unused, (b) used and (c) air-dried alumina-rich sorbent beads. The highly magnified micrographs made it possible to study the outer surface of these sorbent beads.

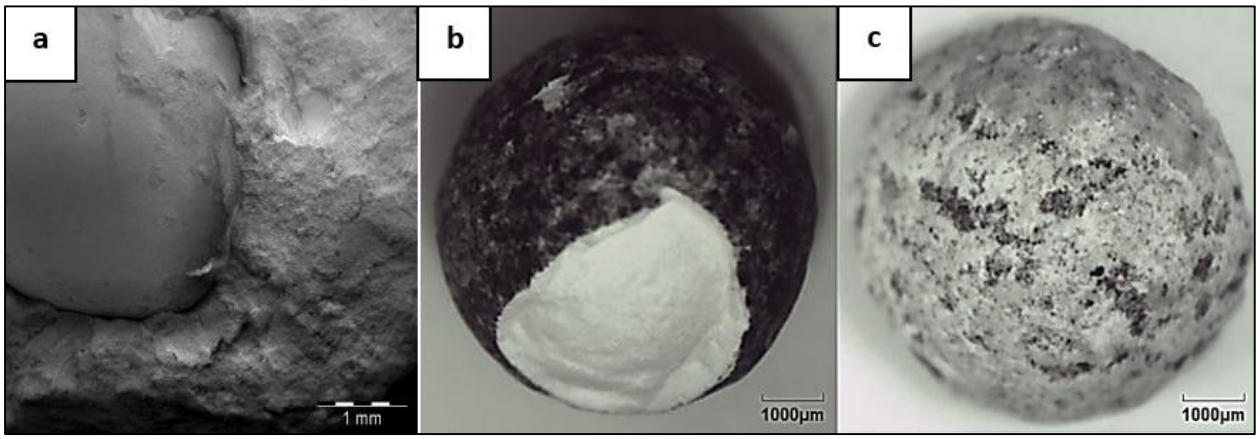


*Figure 5.4.4(a) Unused, (b) Used and (c) regenerated alumina-rich sorbent bead*

Figure 5.4.4(a) shows that the unused sorbent material with the appearance of cervices on the sorbent surface. Please note that a part of the ceramic bead in Figure 5.4.4(b) was broken open to reveal the inner parts and did not break off during an experimental run. Figure 5.4.4(b) shows that the coal dust accumulated on the surface of the sorbent particle after it has been used. It was confirmed from the photo that limited traces of coal dust penetrated the internal pore network of the bead forming an outer shell around it. Figure 5.4.4(c) shows the external surface after regenerating the alumina-rich sorbent material. Some dust could be seen in the crevices of the external surface; however, the majority of the fines were removed by the regeneration step. This was true for all coal particle size distributions including the sizes smaller than 212µm. The micrograph shown in Figure 5.4.4(c) indicates that there is no visible damage to the alumina-rich sorbent bead. Figure 5.4.5 shows the corresponding LEM micrographs of (a) used and (b) air-dried silica-rich sorbent spheres.

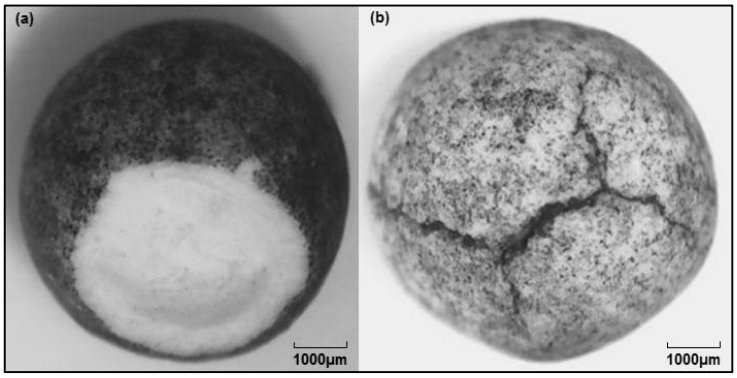

*Figure 5.4.5(a) Used and (b) regenerated silica-rich sorbent bead*

Figure 5.4.5 shows that the coal dust accumulated on the silica-rich sorbent bead could be removed with the regeneration process. A crack in the sorbent bead is visible in Figure 5.4.5(b) pointing to the brittle nature of the silica-rich sorbent. The sorbent material was produced from seed material to form layers with gaps between these layers for adsorption.

During the experimental runs, it was observed that the silica-rich sorbent beads chipped in the adsorption and regeneration process. Breakage experiments were completed by drying coal fines with sorbent material fed in a 1:1 ratio in a steel mill operated at 12 revolutions per minute. Figure 5.4.6 shows the extent of breakage of the alumina- and silica-rich sorbent material over a period of 120 minutes.

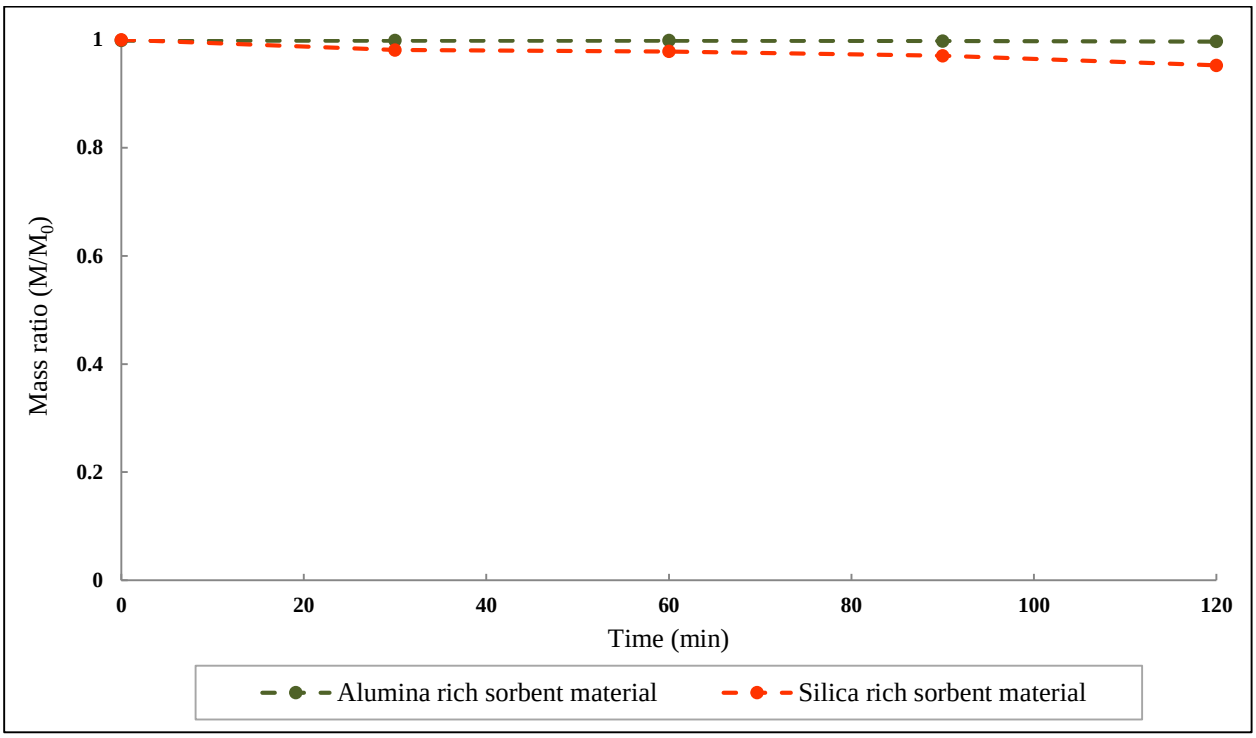


*Figure 5.4.6 Breakage experiments; alumina- and silica-rich sorbent material*

The results from the experiments, as shown in Figure 5.4.6, indicated that the activated alumina-rich sorbent material did not show any signs of breakage or attrition during the extended experimental run, whereas the silica-rich sorbent did show small signs of outer surface deteriorations. Extensive usage of the silica-rich sorbents will ultimately lead to a high level of abrasion and chipping, causing contamination of the coal product and more frequent replacement of the sorbents. It is therefore advised to operate this process using alumina-rich sorbent material to reduce the risk of possible breakage.

- *Reuse of sorbent material*: The second property of a useable sorbent relates to its ability to be regenerated and reused, expecting constant and repeatable performance. Experimental test runs were completed by using regenerated sorbent material to dry the wet coal samples. Figure 5.4.7 shows the sorbent moisture that was reached when operating with unused sorbent material as well as used and air-dried sorbent material. Used material refers to sorbent cleaned and left in ambient conditions to dry, where air-dried refers to sorbent material regenerated with airflow in a packed bed.

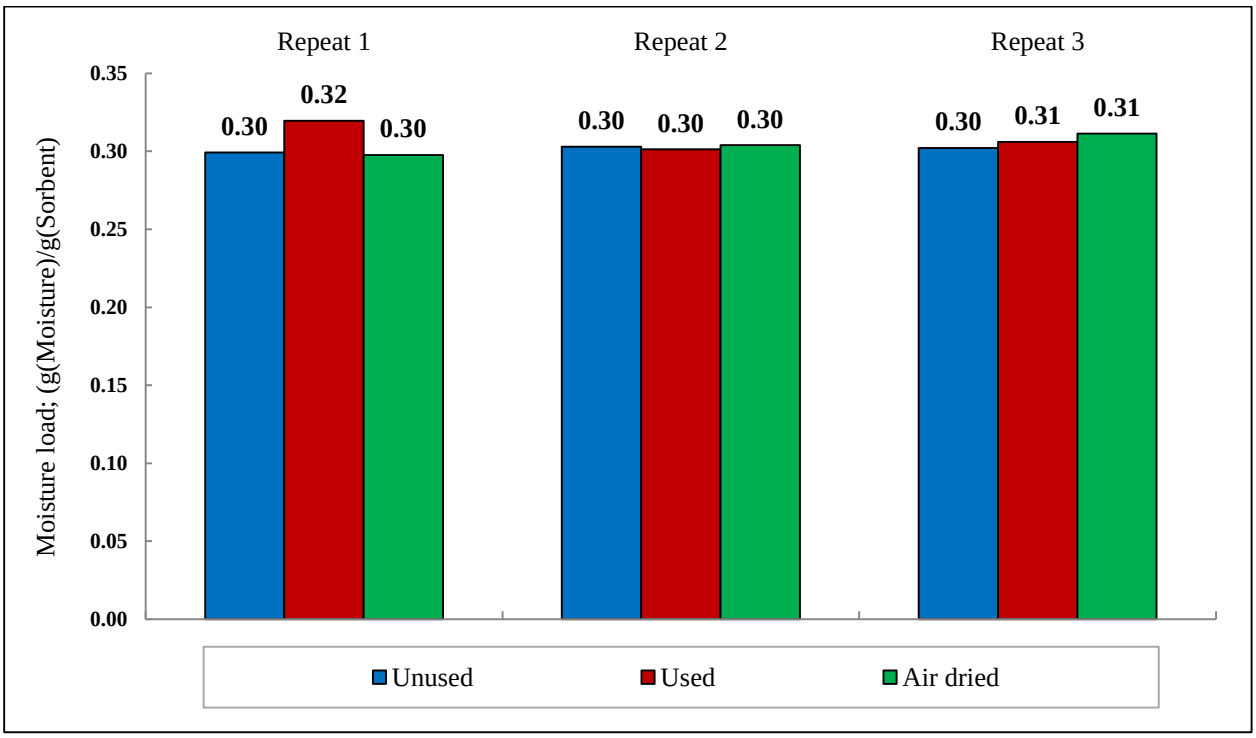


*Figure 5.4.7 Coal moisture; operated with unused, used and air-dried alumina-rich adsorbents*

Figure 5.4.7 shows that the regenerated sorbent material could adsorb similar amounts of moisture compared to the unused sorbent. Repeating the adsorption and regeneration experiments showed that it is possible to re-use the sorbent material. Moreover, the regenerated sorbent material showed similar adsorption capabilities when compared to the unused sorbents, as can be seen in Figure 5.4.8. An average standard deviation of 0.49%$_{wt}$ on the drying rate was found between the regeneration experiments. Figure 5.4.8 shows the drying efficiency of both the unused and regenerated sorbent.

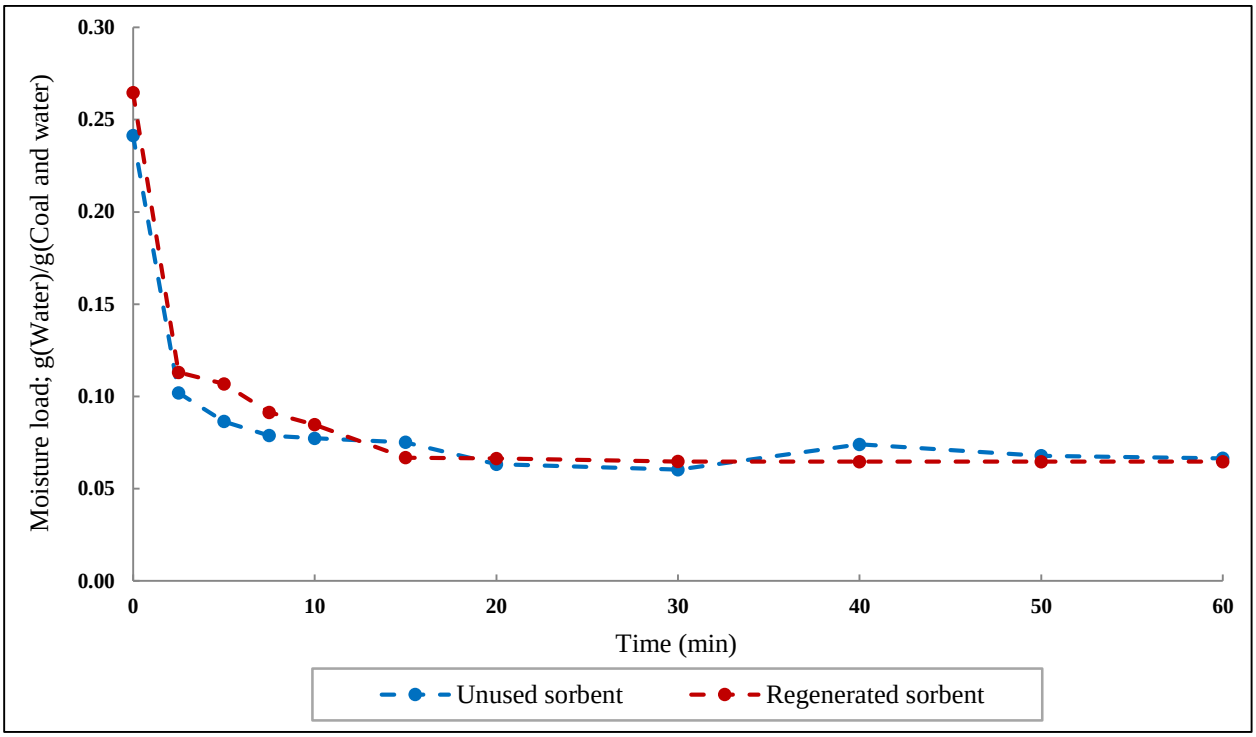


*Figure 5.4.8 Unused and regenerated sorbent; +0.5mm-1mm coal fines in a 1:1 ratio*

The desorption curves in Figure 5.4.8 show that the unused and regenerated sorbent material yielded similar initial drying rates and final coal product moistures. Therefore, it was concluded that the regenerated sorbent could be reused to deliver a dried coal product with repeatable drying rates resulting in a consistent drying efficiency. Reusing the sorbent material in the industry will justify the required capital investment.

### *5.4.3. Comparison: Operational difficulties*

It was found that the high airflow fluidized bed depended on evenly distributed airflow to prevent channelling of drying air or the formation of agglomerates on the cylinder surface. On the contrary, sorbent material in a rotating bed ensured that agglomerates were broken into smaller pieces, with the exception of the ultra-fine particles. High airflow resulted in attrition of the coal particles, while this was not the case with adsorption drying. It is, however, advisable not to operate with sorbent material with a shell-like structure to ensure the durability of the sorbent material. It should also be noted that he sorbent material didn't move in the up flowing air in the packed bed and therefore no attrition took place during the regeneration process. It was, therefore, established that adsorption assisted drying was generally easier to operate.

## 5.5. Conclusion

Adsorption drying proved to be an effective non-thermal method to reduce the moisture content of fine and ultra-fine coal. The loaded sorbent material could easily be restored to a reusable state by subjecting it to ambient airflow in a packed bed or even by leaving it in ambient conditions to dry. Adsorption drying was easy to operate and the sorbent material could successfully be regenerated and reused with repeatable efficient drying cycles. Even when taking energy consumption of adsorption drying and regeneration in the packed bed into account, the overall process was still more energy efficient than it was for high airflow drying. As a result, adsorption drying had a higher energy gain which will have a direct result on the revenue as a smaller amount related to operating costs will be required to upgrade the wet coal fines to a saleable coal product.

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# Chapter 6

## Moisture transport during adsorption assisted drying

Adsorption drying was chosen as the most suitable and efficient method to dry fine and ultra-fine coal. Results from Chapter 4 and Chapter 5 indicated that adsorption assisted drying is a feasible dewatering method. This chapter aims to clarify the moisture transport mechanism involved and establish the main operating conditions that influence this drying mechanism. Operating conditions inhibiting or promoting moisture transport are investigated and explained in further detail.

## 6.1. Purpose and outline

As shown in Chapter 4 and Chapter 5 contact sorption with the associated ambient temperature air drying could be a cost-effective and efficient method to dewater coal fines. The main focus of Chapter 6 is to establish the possibility to describe the moisture transport during adsorption assisted drying Understanding the nature of moisture transport and the factors influencing the movement of moisture during drying will be the key factor in improving this advanced drying technology. The findings are presented in one paper submitted to a peer-reviewed journal and additional information is given in Section 6.3.

- Paper 8 entitled "Moisture transport during contact sorption drying of coal fines" aims to investigate the drying mechanism during adsorption assisted drying. The phase of moisture, liquid or vapour, during drying is established, while the factors restricting or promoting the movement of moisture are examined.

Additional information is given to elaborate on moisture transport when operating with elevated temperatures while drying ultra-fine coal samples. Investigating the effect of these parameters on moisture transport unlocks the possibility to make suggestions to improve operability and to find design limits of the drying technology.

## 6.2. Moisture transport during contact sorption drying of coal fines (Paper 8)

This section describes the contributions made by the authors in the completion of the paper titled "Moisture transport during contact sorption drying of coal fines". The paper was submitted to the International Journal of Coal Preparation and Utilization.

### *6.2.1. Contribution by authors*

Apparatus and equipment from the North-West University was used to complete experimental work presented in this paper. The scope of the experimental work was determined by Miss M.J. van Rensburg under the guidance of Prof. M. le Roux and Prof. Q.P. Campbell. The experimental set-up and work were completed by Miss M.J. van Rensburg. Miss M.J. van Rensburg was responsible for interpreting the results and establishing possible drying mechanisms to describe the specified results. Further interpretation of the experimental results and description of the drying mechanism came from the discussion between Miss M.J. van Rensburg, Prof. M. le Roux and Prof. Q.P. Campbell. This paper was written by Miss M.J. van Rensburg and edited by Prof. M. le Roux and Prof. Q.P. Campbell.

### *6.2.2. General information*

Information regarding the published paper is listed in Table 6.21.

*Table 6.2.1. Moisture transport during contact sorption drying of coal fines (paper 8): General information*

| Category | Information |
|---|---|
| Paper name | Moisture transport during contact sorption drying of coal fines |
| Authors | Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & Peters, E.S. |
| Journal | International Journal of Coal Preparation and Utilization, 1-16 |
| Year | 2018 |
| Copyright | ©Taylor & Francis Group, LLC |
| ISSN | 1939-2702 (Online) & 1939-2699 (Print) |
| DOI | 10.1080/19392699.2018.1541895 |

# Moisture transport during contact sorption drying of coal fines

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## *Abstract*

Studies have shown that contact sorption drying is a feasible technique to dewater fine (+0.15mm-0.5mm) and ultra-fine (-0.15mm) coal. The aim of this paper is to further investigate the drying mechanism involved. It could be shown that moisture transfer occurred primarily in the liquid phase, requiring direct contact between the coal and sorbent particles to facilitate movement of the water. Moisture transfer was enhanced by operating with a higher sorbent to coal mass ratio. When drying smaller coal particle size ranges, the resistance to liquid transport decreased, leading to better desorption results. These improvements were mainly as a result of a greater contact area between the sorbent and coal particles.

*Keywords*: Activated alumina; Fine coal; Dewatering; Contact sorption drying; Moisture transport

## *Introduction*

Coal fines and ultra-fines are inevitably generated due to mechanised mining and processing methods (De Korte & Mangena, 2004). Coal fines, defined here as +0.15mm-0.5mm, can adsorb and retain up to 25%$_{wt}$ of its weight in water (Bourgeois & Barton, 2007). The ultra-fines, those particles smaller than 0.15mm, can retain a total moisture content of more than 30%$_{wt}$ even after filtration. Consequently, it has become a common practice in the mining industry to blend as much as possible of these wet fine products with coarser, drier coal or otherwise dispose of it to prevent difficulties during handling and transportation, or avoid moisture penalties (Hand, 2000). To date, the South African coal mining industry has produced and disposed of approximately 1 billion tonnes of wet fine coal. It is estimated that about 60 Mt of coal is added annually to the discarded fraction (SRK Consulting, 2016). These fines may have calorific values comparable to coarser run-of-mine coal, making discarded fines a potentially valuable resource to be recovered (Reddick *et al*., 2007).

Mechanical dewatering methods are only able to partially remove the surface moisture associated with coal, and are therefore insufficient when processing the finer fractions (Wakeman, 1984). Thermal drying yields a drier final product, but its operation can be difficult, unsafe and can involve great capital and operating costs (De Korte & Mangena, 2004; Hand, 2000). It was shown that contact sorption drying could reduce the moisture content of the fine coal fractions by removing much of the surface moisture (Van Rensburg *et al*., 2018). The aim of this paper is to identify the mechanism of moisture transport during contact sorption drying of fine coal. The focus is to firstly determine whether moisture transfer between the coal and a sorbent material occurs in liquid or vapour form, or possibly both. Secondly, the paper will focus on the factors influencing and inhibiting moisture transport between the particles. A clear understanding of the

process nature and influences during moisture transport will be the key factor in improving this advanced drying technology.

## *Background*

### *1. Moisture related to coal*

Moisture content is one of the aspects upon which a coal product is graded. Penalties apply for supplying a thermal coal product with higher moisture content than contractually agreed to. It affects boiler performances negatively, which in turn lowers the efficiency of the coal fired power station. Therefore, the dewatering of coal fines forms an integral part of coal processing (Hand, 2000).

Moisture associated with coal can be divided into three categories according to its location and the manner in which it is bound to the coal particle.

#### *1.1. Chemically bound moisture*

This portion of water is found in the crystalline structure of a coal particle. It can only be removed from the coal structure with pyrolysis and for that reason cannot be removed with thermal drying or mechanical dewatering methods. Chemically bound moisture is not accounted for in the measurement of the total moisture content, whereas inherent and free moisture are included (Buckley & Nicol, 1995; Campbell, 2006).

#### *1.2. Inherent moisture*

This type of moisture is externally bound to the coal surface area as well as internally bound to the surface area of the pore network. Adhesion forces cause moisture to adhere to the insides of the cracks and capillaries in a coal particle, forming a thin moisture film on the internal and external surface of each individual coal particle (The Southern African Coal Processing Society, 2015). The adhesion moisture cannot be removed with the use of mechanical dewatering techniques (Campbell, 2006). Techniques making use of a dry medium, air or gas, at elevated to high temperatures are able to reduce the adhesion moisure (Campbell, 2006; Tsotsas *et al*., 2016).

#### *1.3. Free moisture*

Additional moisture is bound to the inherent moisture of the coal particle by means of cohesion forces. Cohesion forces such as surface tension and capillary pressure are responsible for retaining this type of water. This means that water is able to bind to the moisture film to form multiple moisture layers on each particle (The Southern African Coal Processing Society, 2015).

Fine and ultra-fine coal tend to contain more moisture compared to larger coal particles. These smaller particles have a larger total surface area, increasing its surface tension and in return its ability to attract and

retain water. When lumped together, the smaller intra-particulate pore radii associated with small particles increase the capillary forces inside, for example, a filter cake, which in turn increases the moisture holding capacity (Toa *et al*., 2006).

### *2. Moisture affinity of sorbent material*

Activated alumina is an inorganic solid that is manufactured from predominantly aluminium oxide, in combination with trace elements of silicon-, iron (iii)- and sodium oxides (BASF, 2009). The sorbent is manufactured to have interconnected cavities containing water of hydration in its molecular structure. During the final manufacturing phase, the water of hydration is removed thermally from the molecular structure to create open sites, leading to its great affinity for water (Honeywell UOP, 2011). Activated alumina is hydrophilic in nature, causing a small contact angle between the water and solid surface, resulting in the adsorption of water in liquid form. The sorbent material is also hygroscopic in nature, creating an additional affinity for water vapour from the atmosphere (Almatis, 2017). These sorbents are produced with a tailor-made enhanced pore distribution and surface area to increase its sorption and retention capacity. An increased available surface area leads to an increased number of active sites where water can adhere to the sorbent surface. The sorbent beads used in this study were designed to have an average pore volume of $0.5 cm^3/g$, creating sufficient space for accumulation of water (BASF, 2009). Activated alumina is largely chemically inert to many liquids and gasses, causing it to maintain its solid structure during moisture adsorption and therefore enabling regeneration or dehydration (Ducreux & Nedez, 2011).

### *3. Moisture transport*

Adsorption refers to the process where vapour or liquid molecules are transported to a solid surface, accumulating at the boundary where these two phases are in contact (Dąbrowski, 2001). Moisture transport into the capillary network is the result of three sequential stages; chemisorption, physisorption and capillary condensation. These stages are illustrated in Figure 6.2.1 (Ducreux & Nedez, 2011).

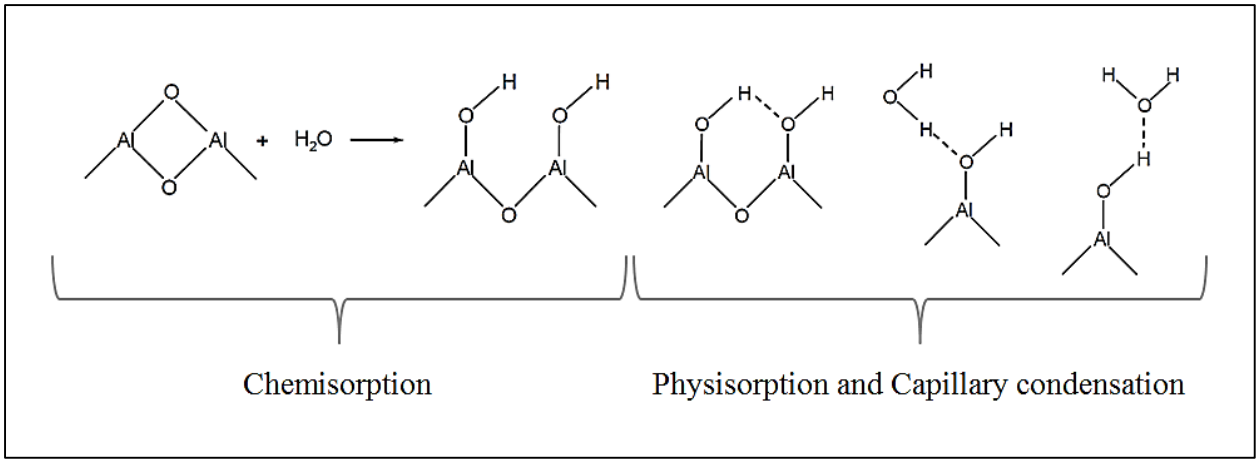


*Figure 6.2.1. Stages of moisture transport; adapted from Ducreux & Nedez (2011)*

3.1. *Chemisorption*

The first stage is defined as the addition of water molecules to the sorbent bead's outer surface as well as the surface area within the pore network. The open sites of the sorbent bead promote moisture adsorption (Honeywell UOP, 2011). Water molecules dissociate and bind to these open oxide sites. Figure 6.2.1 illustrated how H-atoms bind to the O-atoms, while the O-atoms bind to Al-atoms to form a layer of moisture. The first layer adheres to the open sites on the sorbent surface (Ducreux & Nedez, 2011). The polar nature of water makes it possible for it to bind onto to the oxygen-containing functional groups on the surface. Consequently, these open oxide sites promote water adsorption and in return makes it possible for multilayers to accumulate (Strydom *et al*., 2015).

3.2. *Physisorption*

The second stage occurs after the first layer of moisture is formed on the sorbent surface. During physisorption, the additional water is bound to the first layer or moisture film by hydrogen bonds, and the water molecules are held together by cohesive van der Waals forces to form multilayers of water (Ducreux & Nedez, 2011). Van der Waals forces are weak forces, making this water layer easy to move around or to be removed (Bhaskar, 2014). Equilibrium is reached when the porous sorbent is filled with the available liquid or vapour (Ducreux & Nedez, 2011).

3.3. *Capillary condensation*

Changes in the surrounding conditions will affect the equilibrium between the coal fines, sorbent material and associated moisture. The accumulation of additional multilayers of moisture after physisorption is labelled as capillary condensation (Ducreux & Nedez, 2011).

## *Experimental*

### *1. Materials used*

The study was done on a sub-bituminous coal product from the Highveld coal field, South Africa. A proximate analysis was done (Table 6.2.2) and it proved to be a low ash product with an inherent moisture content close to 4%$_{wt}$. The coal was air dried and sieved into the three particle size ranges (Table 6.2.3), sealed and stored in a conditioned room at 22°C and 40% relative humidity. Each sample was opened and placed in these conditions for at least 24 hours to reach equilibrium before being used.

*Table 6.2.2. Proximate analysis (air dry basis)*

| Sample identification | Composition (%$_{wt}$) | Test method standard |
|---|---|---|
| Inherent moisture | 3.6 | ACT-TPM-010 based on ISO11722: 1999 |
| Ash yield | 14.9 | ACT-TPM-011 based on ISO 1171: 2010 |
| Volatile matter | 29.6 | ACT-TPM-012 based on ISO 562: 2010 |
| Fixed carbon | 51.9 | (by difference) |

Industry standard and labelled F-200 activated alumina was used as the sorbent material. The material contained 93%$_{wt}$ aluminium oxide and the balance consisted of silicon-, iron (iii) - and sodium oxide. The sorbent material is uniformly shaped into 3 mm and 5 mm diameter spherical beads containing a total open pore volume of $0.5cm^3/g$. Table 2 lists the physical properties of the sorbent material.

*Table 6.2.3. Physical properties of 3mm and 5mm F-200 activated alumina*

| Physical properties | 3mm | 5mm |
|---|---|---|
| Surface area ($m^2/g$) | 350 | 340 |
| Pore volume ($cm^3/g$) | 0.5 | 0.5 |
| Bulk density ($kg/m^3$) | 769 | 769 |
| Moisture (%$_{wt}$) | 1.8 | 1.8 |
| Crush strength (kg) | 14 | 25 |
| Abrasion loss (%$_{wt}$) | 0.1 | 0.1 |

F-200 activated alumina was specifically chosen as a sorbent due to its high resistance to breakage, very low abrasion index and high total surface area, making it suitable for industrial adsorption applications (BASF, 2009; Lin *et al*., 2013). The as-received moisture content of the beads (in their packages) was 1.8%$_{wt}$; however, both the 3mm and 5mm sorbent contained approximately 8-10%$_{wt}$ moisture after conditioning in the climate controlled room prior to use.

### *2. Equipment and procedure*

Two sets of laboratory scale experiments were completed: contact sorption drying experiments, and focussed experiments to validate the mechanism of moisture transfer.

2.1. *Contact sorption drying*

For each run, the fine coal samples with particle size ranges as shown in Table 6.2.4, were drenched in water, filtered (using a laboratory pressure filter) and loaded into a set of 10 identical 5.5 cm diameter by 5 cm long cylindrical vessels, together with the conditioned sorbents. These vessels were placed on rollers and were rotated at 3 revolutions per minute to ensure a slight cascading movement of particles inside the vessel. This aided in effective mixing between the coal and sorbent particles. By having a series of vessels, it was possible to stop individual containers at different time intervals to analyse its contents. This was done by emptying the contents onto a laboratory sieve to separate the coal from the loaded sorbent. It was therefore possible to determine the levels of moisture in both the coal and the sorbent material after different contact times. A schematic of this setup can be seen in Figure 6.2.2.

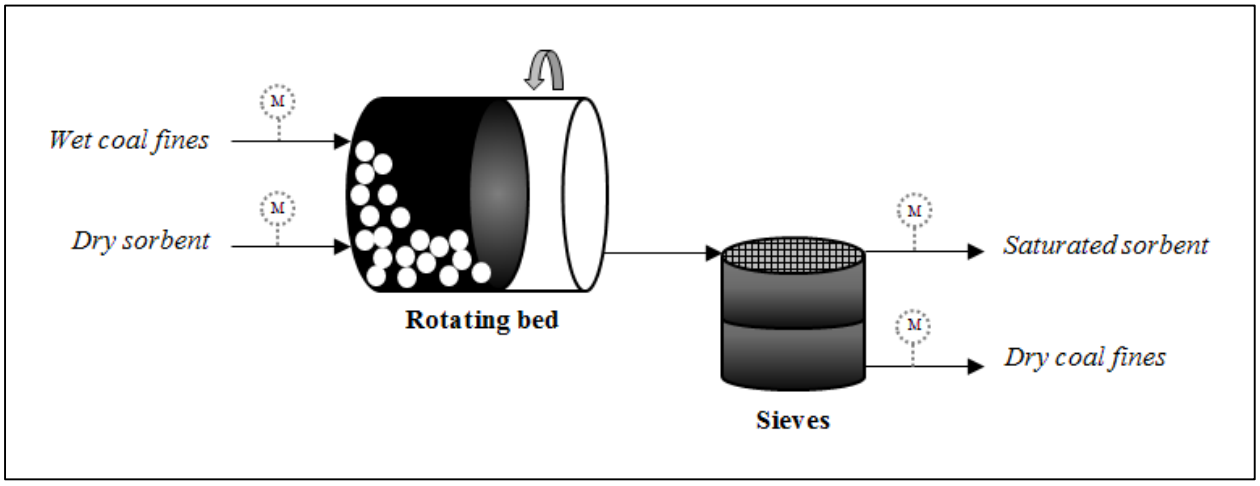


*Figure 6.2.2. Diagram of the laboratory setup; rotating bed, sieves and moisture analysers*

The initial and final moisture contents of the sorbent material and fine coal were determined according to the ISO standard method (SANS 5925:2007), as indicated by 'M' in Figure 6.2.2. Different experimental runs were performed for the conditions listed in Table 6.2.4.

*Table 6.2.4. Contact sorption drying; variables tested*

| Variable | Conditions |
|---|---|
| Adsorbent to coal mass ratio | 0.5:1 |
| | 0.75:1 |
| | 01:01 |
| | 02:01 |
| | 03:01 |
| Adsorbent diameter | 3mm |
| | 5mm |
| Coal particle size ranges | +0.25mm-0.5mm |
| | +0.5mm-1mm |
| | +1mm-2mm |

*2.2. Transfer mechanism determination experiments*

A set of 8 experiments were completed to determine whether the transfer of moisture between the coal and the sorbent occurred primarily in the vapour or liquid phase. Figure 6.2.3 is a schematic representation of the experimental setups to determine the transfer mechanism.

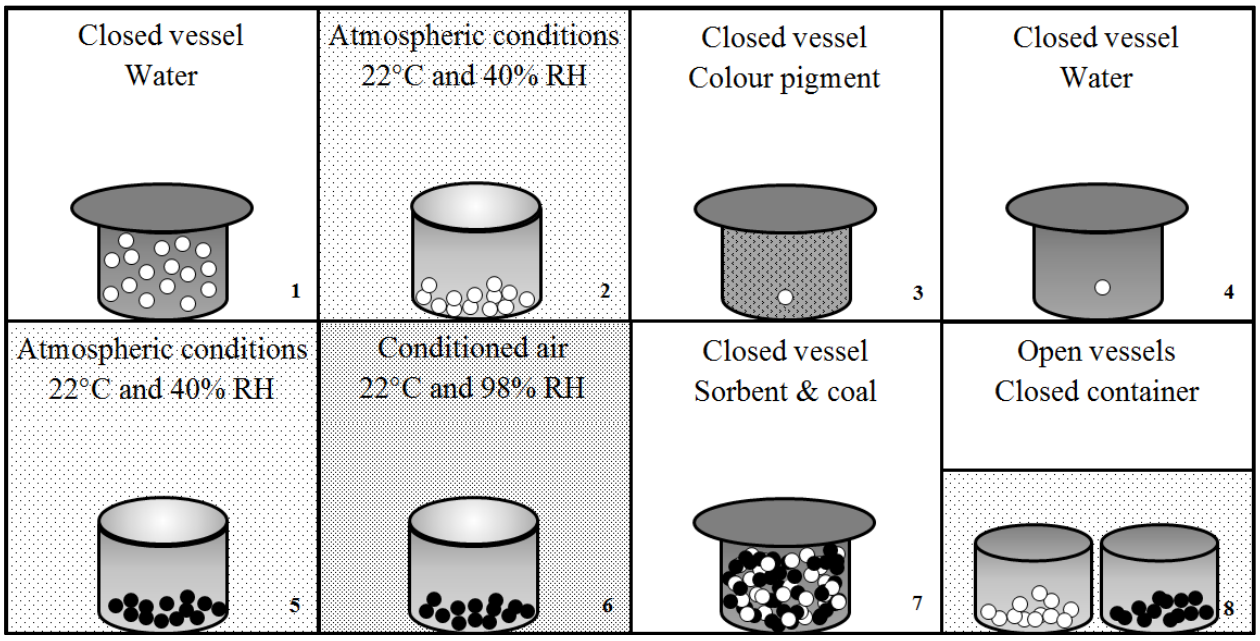


*Figure 6.2.3. Experimental setups: transfer mechanism determination experiments*

The following experimental procedures were followed for each of the setups indicated in Figure 6.2.3:

(1) A vessel was completely filled with water to which a known mass of conditioned sorbents was added. The vessel was sealed, and the sorbents were allowed to adsorb the liquid for a period of 40 minutes to reach the maximum adsorption capacity.

(2) An empty vessel was filled with a known mass of dry sorbent material, with an initial moisture content of 8-10%$_{wt}$, and was left exposed to controlled atmospheric conditions of 22°C and 40% relative humidity. This made it possible to determine the rate of vapour adsorption onto the sorbent under said conditions. In addition, this was used to determine the moisture load capacity of the sorbent material in equilibrium with the atmosphere.

(3) A single sorbent bead was placed in water containing gentian violet as a pigment. The colouring was used to examine the diffusion path of the water into the sorbent pore network of the activated alumina.

(4) This setup was similar to setup 1, with the exception of using only one sorbent bead instead of many. This allowed for the elimination of sorbent-sorbent surface interaction and isolated the adsorption capabilities of a single bead exposed to liquid water.

(5) In setup 5, a wet coal filter cake (similar to those fed in the first set of sorption tests) was added to an open vessel to be exposed to controlled atmospheric conditions, similar to setup 2. Since the moisture level in the filter cake would naturally approach its inherent moisture level, this setup was used to determine the water vapour desorption rate and amount from the coal to the atmosphere at said conditions.

(6) The previous setup was repeated, but this time inside a climate chamber that provided a constant environment of conditioned air at 22°C and 98% relative humidity. These conditions simulated saturated air to determine how it would influence desorption of water vapour from a wet coal filter.

(7) In the seventh setup, mixtures of wet coal filter cake and conditioned sorbents were added to a vessel and filled to capacity. This was done in order to eliminate as much as possible of the air that surrounded the particles and hence limit any possible water vapour transfer. This setup made it possible to study predominantly liquid water transfer from the coal fines to the sorbent.

(8) In the last setup, two open vessels, one filled with conditioned sorbent beads and the other with wet filter cake, were sealed off inside a third container starting at 22°C and 40% relative humidity. Direct contact between the coal and sorbents prevented liquid-liquid transfer, and only vapour transfer from the coal fines to the surroundings and from the surroundings to the sorbents could be determined.

The sorbent and coal samples in each of the experimental setups were weighed before and after different time intervals to determine the moisture loss/gain. This was confirmed by doing moisture analyses based on a standard method (SANS 5925:2007).

### *Results and discussion*

The results and discussions will be presented in three different categories. Firstly, there will be a discussion on the general contact sorption drying results obtained, where after the findings from the focussed tests to determine the transfer mechanism will be discussed. The final aim will be to put forward a suggested mechanism by which moisture transfer occurs.

#### *1. Contact sorption drying*

Figure 6.2.4 shows a typical desorption/adsorption response for a coal-sorbent system. In this example, 3 mm diameter spherical activated alumina beads were added to the series of rotating vessels in a one-to-one mass ratio with +0.25mm-0.5mm wet coal filter cake. The atmospheric conditions inside the vessels at the start were at 22°C and 40% relative humidity. Samples were taken at set time intervals, as discussed above, and the moisture content of both the coal and sorbents were analysed and recalculated to give the exact moisture content in grams. Repeated tests gave a maximum experimental error of 2.7%.

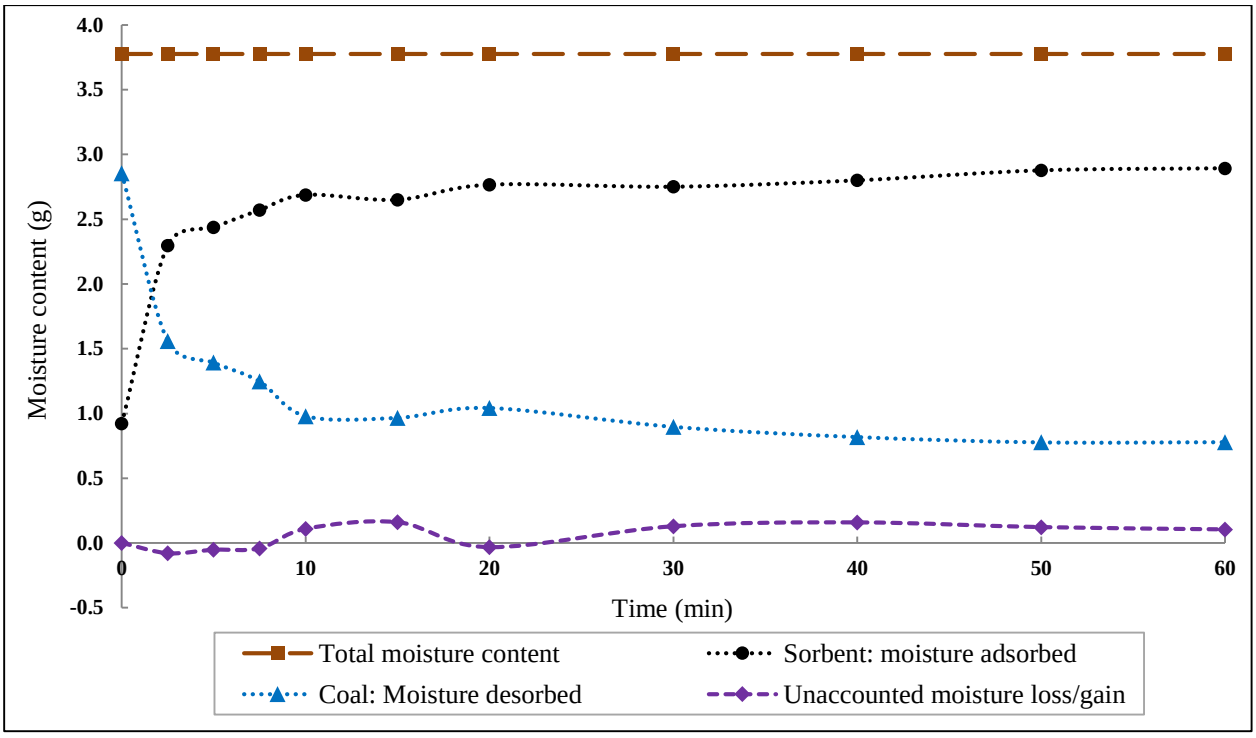


*Figure 6.2.4. Contact sorption drying; 3mm sorbent, +0.25mm-0.5mm coal fine, 1:1mass ratio*

The total moisture content in Figure 6.2.4 refers to the initial enclosed moisture content present in the vessel, which consisted of the sum of the masses of the moisture in the sorbent material, moisture in the wet coal fines and moisture vapour in the atmosphere. It was assumed that the total moisture content stayed constant throughout the experimental run as the moisture transfer took place within an enclosed cylinder.

The unaccounted moisture loss or gain indicated in Figure 6.2.4 represents the deviation from the total moisture content.

When a mixture of wet coal fines and conditioned sorbents are fed to the vessels, transport of moisture from the coal onto the sorbent surface occurs. The activated alumina beads' high affinity for moisture creates a driving force leading to water transport from the coal particles to the sorbent (Bratton *et al*., 2012). In this example, the moisture content of the 10 g coal samples was reduced from 2.85g to 1.56g in 2.5 minutes and reached a value of 0.98g within 10 minutes. The difference in moisture between the desorbed and adsorbed amounts accounts for changes in the relative humidity of the surrounding air, which contributed $1.52 \times 10^{-4}$ g moisture deviation at the onset of the test. These minute fluctuations in value, as shown in Figure 4, gives rise to the theory that direct liquid transport from coal to the sorbents dominates vapour transport.

***2. Transfer mechanism determination experiments***

To evaluate this theory, a set of 8 experiments, as explained above, was designed to determine whether moisture transfer occurred in liquid or vapour form or a combination thereof.

*2.1. Sorbent: Adsorption of liquid or vapour*

Setup 1 made it possible to determine the liquid moisture adsorption ability of the sorbent material. The presence of air and subsequently the possibility for vapour transfer were excluded. Setup 2 excluded the influence of liquid moisture adsorption and focussed on investigating moisture adsorption onto the alumina from the surrounding vapour. The aim was to measure the rate and total amount of moisture that can possibly be adsorbed in liquid or vapour phase. During the contact sorption drying experiments, the coal required a maximum of 40 minutes to dry. It was therefore decided to determine the amount of liquid or vapour moisture that can be adsorbed within the same time frame. Figure 6.2.5 shows the changes in the moisture content of the sorbent samples over this time period of 40 minutes.

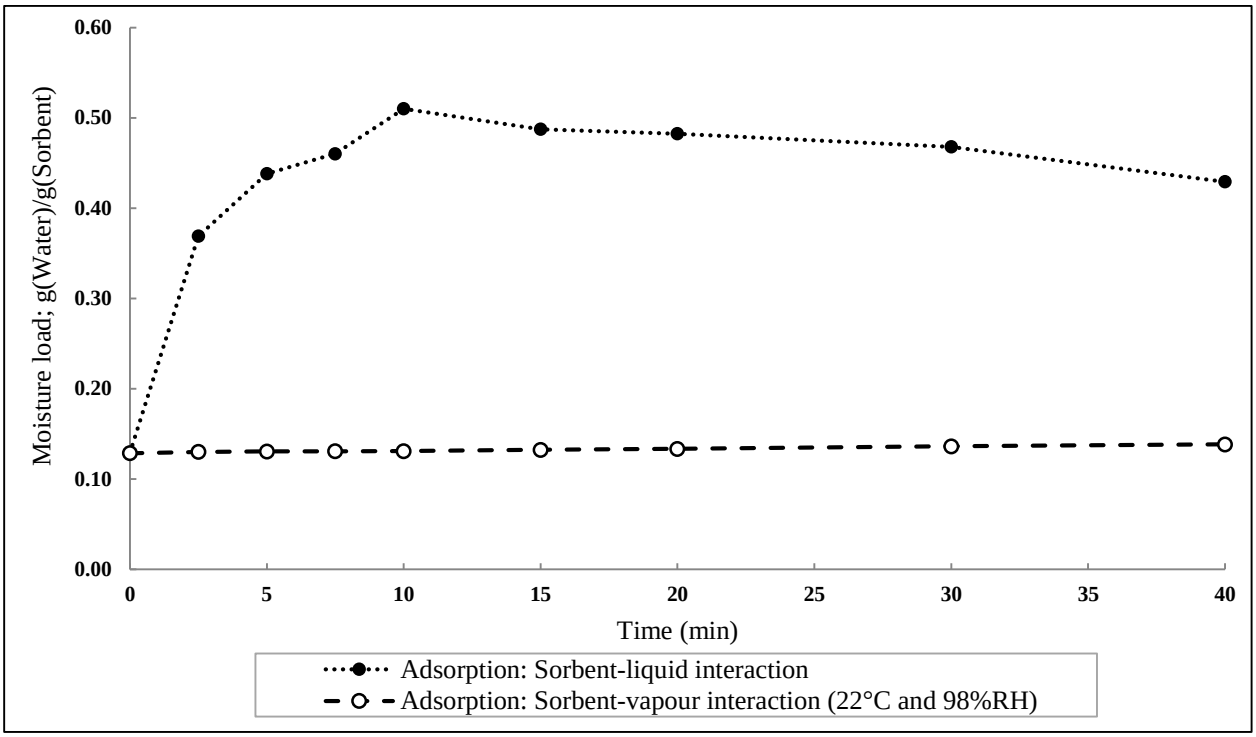


*Figure 6.2.5. Adsorption: Sorbent-liquid vs. sorbent-vapour interaction*

Figure 6.2.5 clearly shows that the sorbents submerged into liquid water were able to adsorb a much larger amount of moisture at a very high rate in relation to the ones exposed to the saturated air. After 40 minutes have elapsed, the submerged sorbents had a moisture content of 0.43g(water)/g(sorbent) as opposed to 0.14g(water)/g(sorbent) for the ones exposed to air. In a further effort to quantify the adsorbed liquid flow patterns, a single sorbent bead was inundated withwater that contained gentian violet pigment. When 40 minutes passed, the sorbent particle was removed, clotted and cut open. Highly magnified photographs were taken under a light electron microscope to examine the small physical properties of the particle. The micrographsshowed that water (indicated in darker colouring) was able to penetrate the sorbent, see Figure 6.2.6. Gentian voilet, being a water based pigment, illustrated that water in the liquid phase was able to penetrate to the core of the sorbent bead.

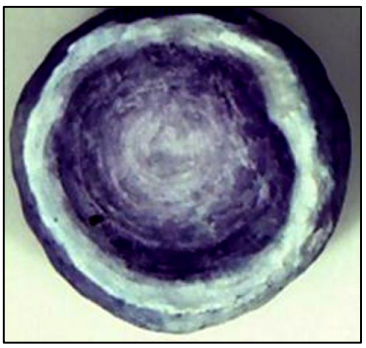

*Figure 6.2.6. Light electron microscope photograph of a sorbent particle*

*2.2. Coal: Desorption of liquid or vapour*

To determine the effect of vapour desorption on fine coal particles, setups 5 and 6, as shown in Figure 6.2.3, were used. Coal was placed in an open vessel at 22°C and 40% (dry) or 98% (saturated) relative humidity air. The aim was to measure the rate and total amount of moisture that desorbed from the coal particles due to evaporation at the two different conditions mentioned. Therefore, direct contact was the only available transport mechanism, as shown in setup 7 in Figure 6.2.3. The resultant moisture fluctuations are shown in Figure 6.2.7.

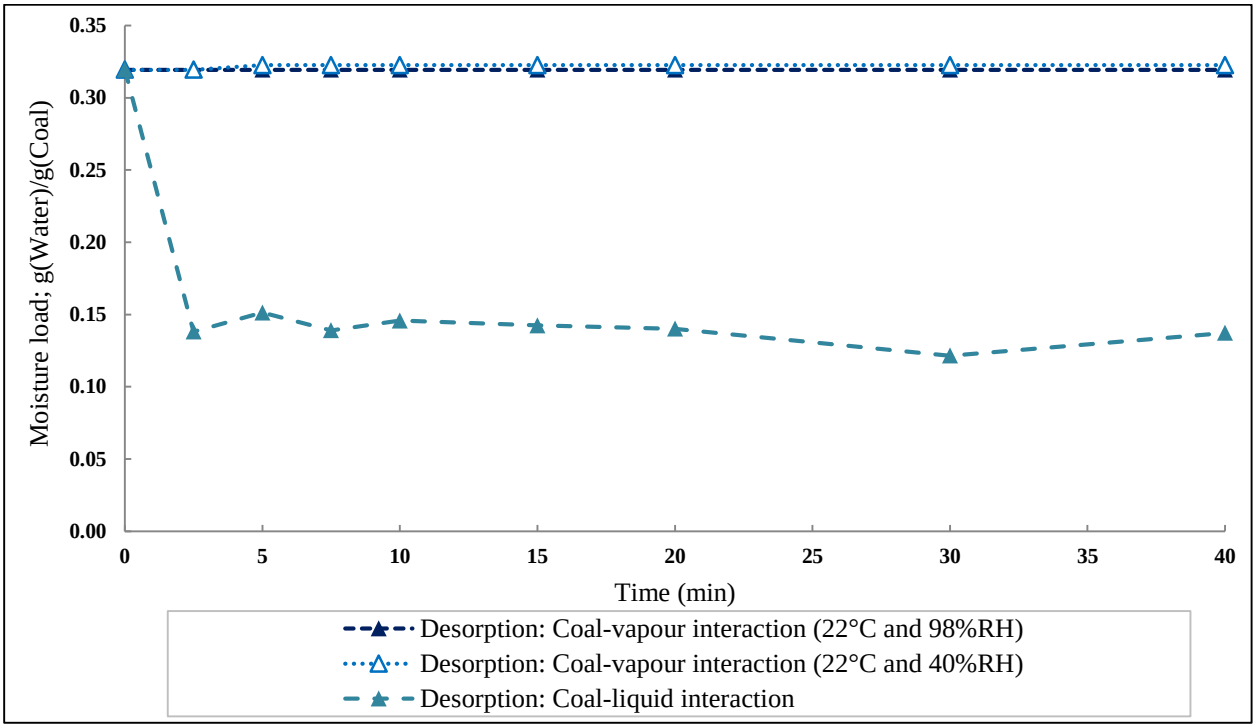


*Figure 6.2.7. Desorption: Coal-liquid vs. coal-vapour interaction*

In comparison, the direct contact moisture transport shows a significant decrease in coal moisture content, especially over the first 2.5 minutes where the coal moisture content more than halved. These tests clearly support the theory that direct liquid transfer between coal particles and the sorbents are the predominant transport mechanism.

*2.2. Vapour interaction between sorbent and coal*

One question regarding the behaviour of the moisture in the first two setups remained unanswered. The results from Figure 6.2.5 and Figure 6.2.7 indicated that no moisture was transferred in vapour phase. However, it is uncertain whether the moisture transfer is driven by a third external force when both the wet coal and dry sorbent material are placed in the same environment. In order to answer the question stated above, setup 8 as in Figure 6.2.3 was used. This setup allowed for moisture vapour phase transport only.

The results illustrated in Figure 6.2.8 showed stable masses for coal and sorbents over the 40 minute exposure time, which prove that moisture, is primarily transferred in liquid phase via direct contact between the coal and sorbents.

The unaccounted moisture loss or gain referred to in Figure 6.2.4 can for that reason not solely be attributed to the accumulation of water vapour in the open spaces in the vessels. This moisture may rather indicate a combination of inter-particulate moisture gathered between the samples or liquid droplets attaching to the sides of the vessel. However, it is a very small amount, and can therefore be regarded as negligible.

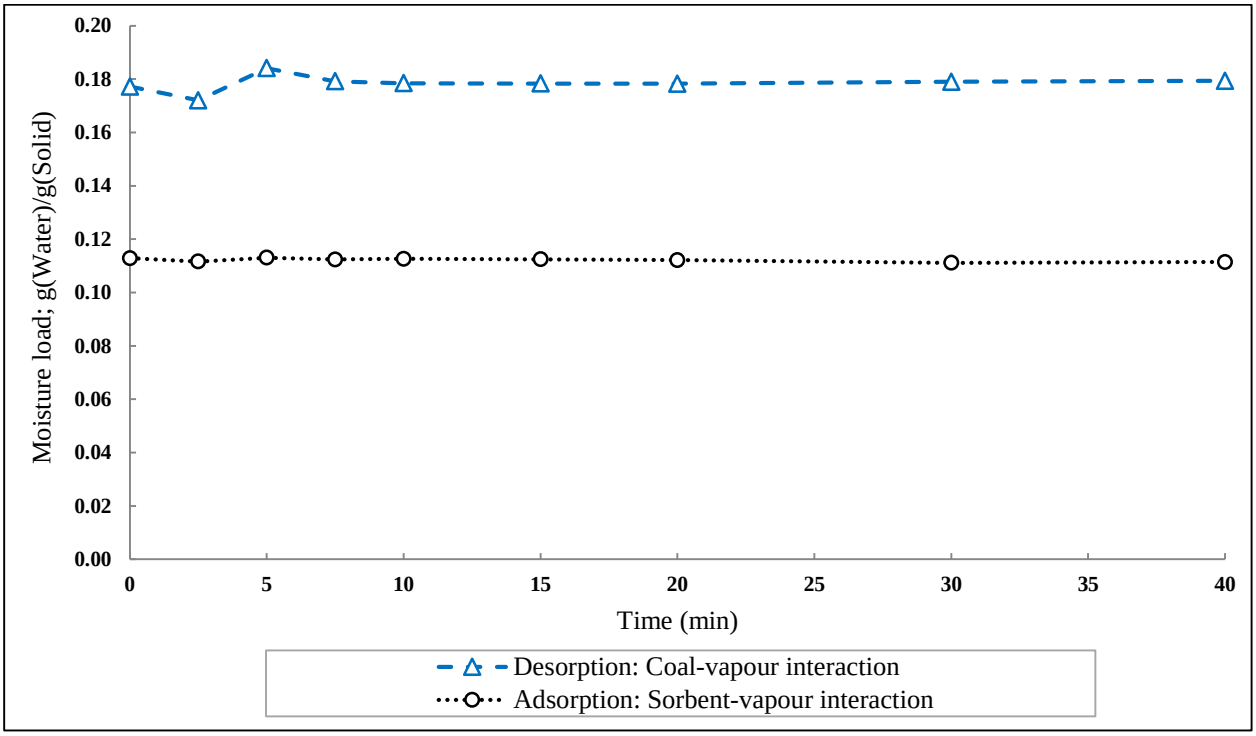


*Figure 6.2.8. Adsorption and desorption: Coal-vapour-sorbent interaction*

### *3. Description of liquid moisture transport*

After qualifying the transport mechanism, a series of adsorption tests were completed to compare the moisture transfer rate onto the sorbents in a typical contact sorption drying process against the adsorption transfer rate when a single or bulk amount of sorbents were submerged into pure water. A series of experiments were completed to determine possible influencers in the system that may hinder the liquid moisture transport. Setup 2 and setup 4 were used to investigate only the sorbent-liquid interaction. The sorbent-liquid-coal interaction was investigated for sorbent to coal mass ratios of 0.5:1, 0.75:1, 1:1, 2:1 and 3:1. These interactions are shown in Figure 6.2.9.

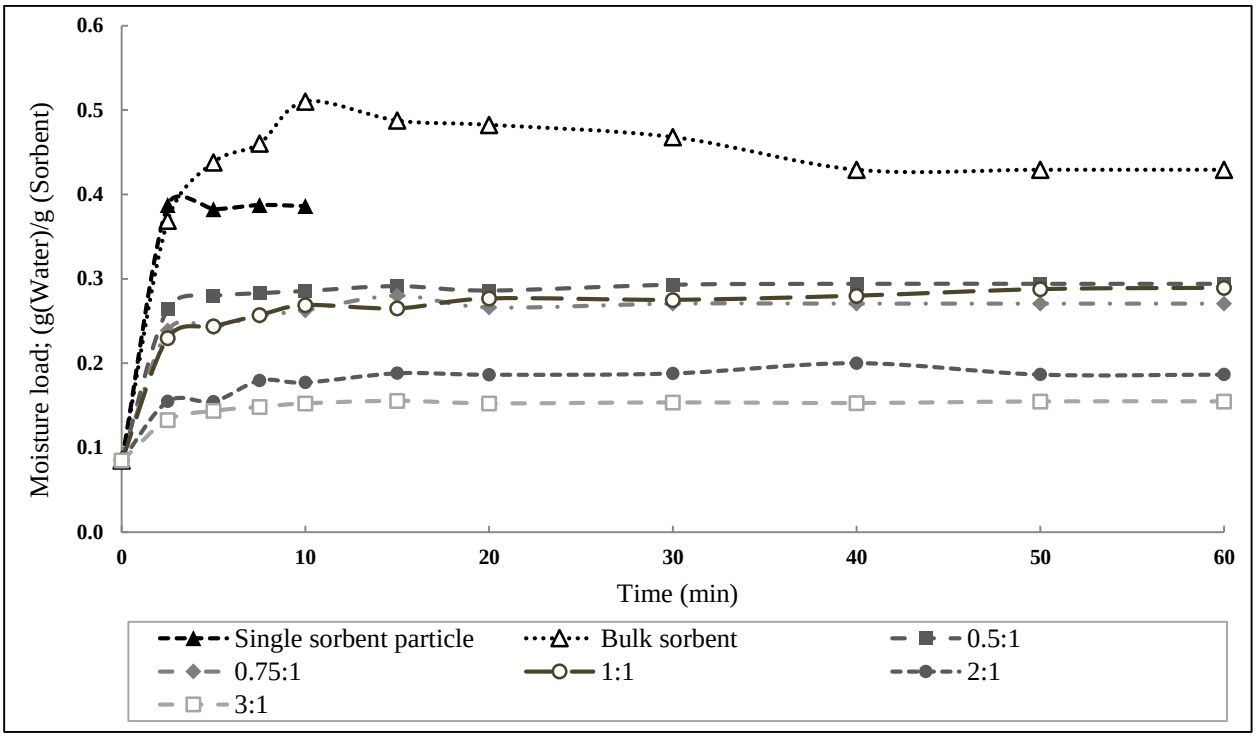


*Figure 6.2.9. Adsorption: Sorbent-liquid interaction vs. sorbent-liquid-coal interaction*

The single particle and bulk sorbent placed in pure water showed similar initial adsorption rates. The single particle reached a maximum moisture holding capacity of 0.39g(water)/g(sorbent) within 10 minutes, whereas the bulk sorbents continued to adsorb water until an equilibrium moisture load of 0.43g(water)/g(sorbent) was reached. This scenario indicates that sorbent material in bulk is able to adsorb and retain inter-particulate moisture as well, leading to a higher total moisture content. It usually reports as thin films on the surfaces of the single particles, or inside the contact angles formed between two adjacent particles.

Both the pure water setups yielded higher adsorption rates compared to the coal-sorbent mixtures. Furthermore, the addition of more sorbent material to the mixture decreased the initial adsorption rate per unit mass of sorbent material. Figure 6.2.9 shows a large decline on the adsorption rate when operating with sorbent to coal ratios of 2:1 and 3:1. This can be ascribed to the addition of sorbent material beyond the amount required for maximum adsorption. It requires additional time to share the moisture load among the coal and additional sorbent particles before equilibrium is reached. The slower drying rate is also ascribed to "blind spots" on the sorbents' outer surface where particles are in direct contact with neighbouring ones. Therefore, depending on the makeup of the load, resistances against liquid moisture transport in coal-sorbent mixtures may hinder the transfer of moisture and hence slow down the drying process.

*3.1. Resistance to liquid moisture transport*

The resistance was calculated using a generalised formula for capillary flow in a tube.

$$Q = -\frac{1}{R}(P_a - P_c) \qquad \textit{Equation 6.2.1}$$

Where$Q$in Equation 6.2.1 referred to the flow rate through the capillary length as a result of the difference between an estimated atmospheric pressure, $P_a$, of 1x10$^5$$Pa$ and the pressure due to capillary forces $P_c$. The volume flow rate for all the experiments were calculated with Equation 6.2.2.

$$Q\ (\frac{m^3}{s}) = \frac{m_{adsorbed}}{t}.\frac{1}{\rho} \qquad \textit{Equation 6.2.2}$$

The density, $\rho$, of water was used as 1000$\frac{kg}{m^3}$, while the experimental run time, $t$, was specified in seconds. The $m_{adsorbed}$, refers to the mass of water adsorbed in each experiment during the first 2.5minutes of the experimental run, when most of the moisture transfer took place.

The capillary pressure was calculated by using the Washburn Equation shown with Equation 6.2.3.

$$P_c = \frac{2\gamma}{r}\cos\theta \qquad \textit{Equation 6.2.3}$$

The surface tension, γ, of water is 0.07088$\frac{N}{m}$ at 22°C and the contact angle between water and hydrophilic activated alumina is approximately 48° (The Engineering Toolbox, 2004). The average pore radius equated to5.71x10$^9$ m, resulting in a capillary pressure of 1.66x10$^7$ $Pa$ and a pressure gradient of 1.65x10$^7$ $Pa$.

The resistance to flow was calculated for each contact sorption drying run completed with the 3 mm and 5 mm sorbent to dewater coal size fractions of +025mm-0.5mm, +0.5mm-1mm and +1mm-2mm. The experimental runs were completed at the same sorbent to coal mass ratios of 0.5:1, 0.75:1, 1:1, 2:1 and 3:1. These results were compared to the resistance of a single sorbent particle submerged in pure water. The summary of the resistance against liquid moisture transport for all the experimental runs completed with 3 mm sorbent is shown in Figure 6.2.10.

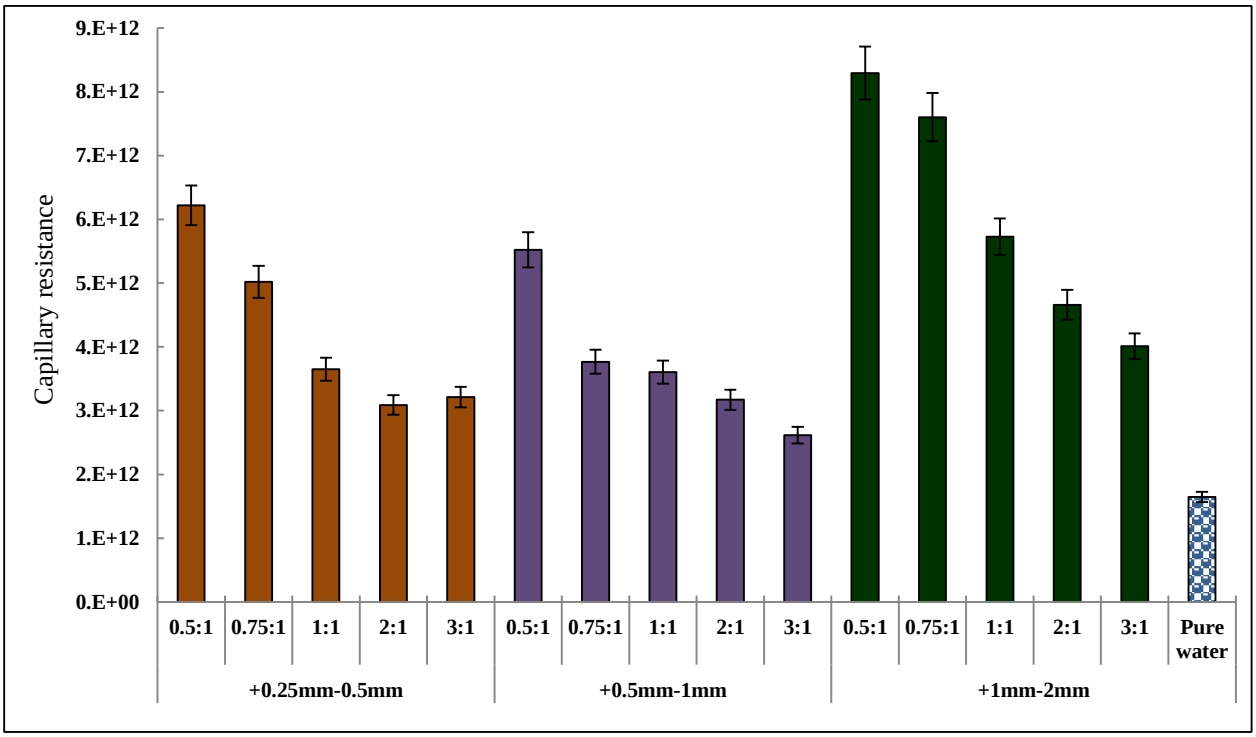


*Figure 6.2.10. Comparison of capillary resistance across a range experimental runs; 3mm sorbents*

Figure 6.2.10 shows that all the experimental runs had some degree of capillary resistance against liquid flow into the sorbent material. The results indicate that the resistance to liquid flow is lower for both the smaller particle size ranges of +025mm-0.5mm and +0.5mm-1mm, compared to the +1mm-2mm size range. The larger surface area of the finer coal fractions led to increased contact with the sorbent material to aid in the desorption of moisture from the coal fines. It should also be noted that the increased capillary tension and surface pressure of the finer coal fractions did not retain the moisture. Furthermore, an increase in the sorbent to coal ratio resulted in lower resistance and consequently allowed more moisture transport. Essentially, increasing the surface area available for adsorption allowed for added liquid flow. The experimental results of both the 3mm and 5mm sorbent material are compared in Figure 6.2.11.

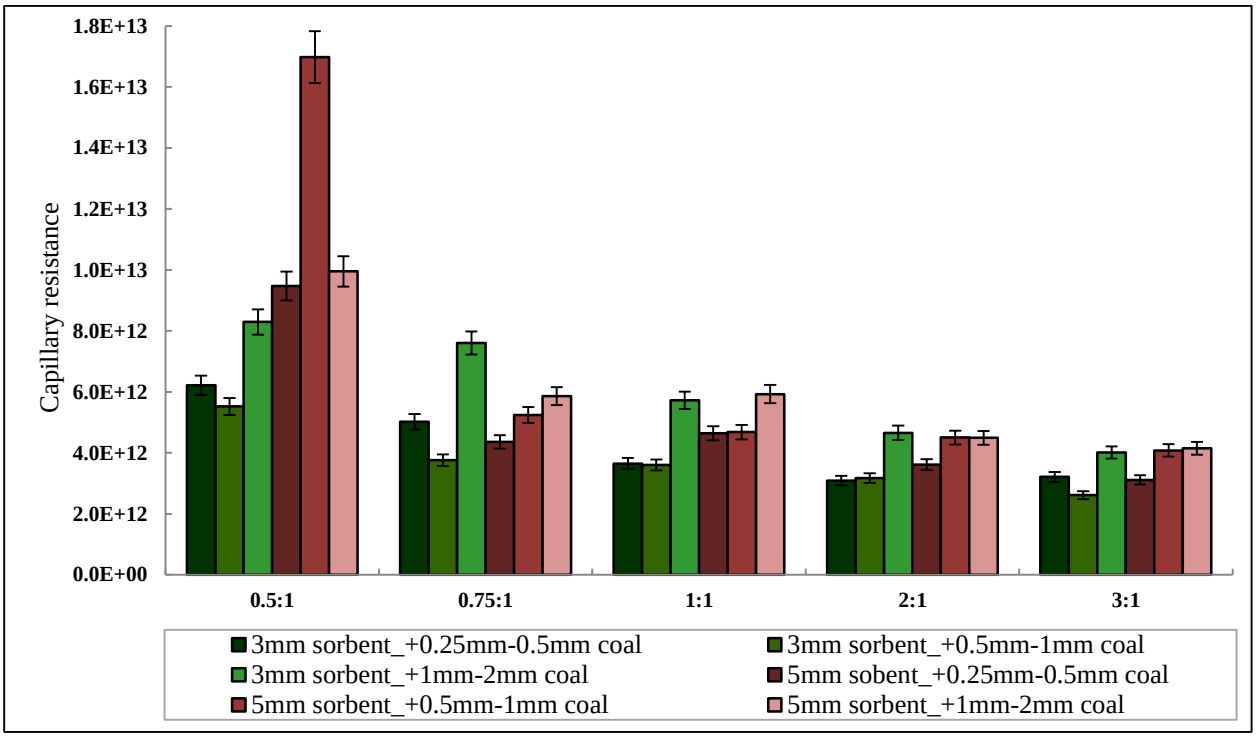


*Figure 6.2.11. Comparison of resistance to liquid moisture transport across a range experimental runs*

The results of resistance to liquid moisture transport were used to determine the statistical effect of sizes between the variables in each of the three groups: sorbent to coal ratio, coal size fraction and sorbent size. According to guidelines, an effect size of smaller than 0.25 will indicate that there is small difference between the results that the variables in a group deliver, whereas an effect size of larger than 0.8 would point to a significant difference in the results the variables deliver (Ellis & Steyn, 2003). Table 6.2.5 lists the effect sizes for each of the variables investigated.

*Table 6.2.5. Effect sizes; variables tested*

| **Sorbent to coal ratio** | | | | | **Coal size fraction** | | | **Sorbent size** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0.5:1** | **0.75:1** | **1:1** | **2:1** | | **+0.25mm-0.5mm** | **+0.5mm-1mm** | | **3mm** | **5mm** |
| **0.5:1** | - | - | - | - | **+0.25mm-0.5mm** | - | - | **3mm** | - | - |
| **0.75:1** | 1.52 | - | - | - | **+0.5mm-1mm** | 0.02 | | **5mm** | - | 0.15 |
| **1:1** | 1.83 | 0.45 | - | - | **+1mm-2mm** | 0.76 | 0.74 | - | - | - |
| **2:1** | 2.35 | 1.19 | 1.00 | - | - | - | - | - | - | - |
| **3:1** | 2.45 | 1.33 | 1.19 | 0.25 | - | - | - | - | - | - |

These ANOVA and T-test results correspond with the contact sorption drying results and capillary resistance values shown in Figure 6.2.10 and Figure 6.2.11. The effect sizes between the sorbent to coal mass ratios were quite high, indicating that there is a significant difference in the capillary resistance when

operating with different sorbent to coal ratios. It was found that using a higher sorbent to coal ratio increased the surface contact between particles, which resulted in a decreased resistance to liquid moisture transport and consequently faster dewatering. The only exception was the results found between the 2:1 and 3:1 mass ratios, which indicated that adding more sorbent to the system would not ensure more moisture flow.

The smaller particle size ranges of +025mm-0.5mm and +0.5mm-1mm had a lower resistance to liquid moisture transport compared to the larger fraction of +1 mm-2 mm. These results as shown in Figure 6.2.11 indicate that contact sorption is not only able to dry the finer coal fractions, but dewater these fines at a faster rate compared to larger fractions. This effect could be seen across the range of sorbent to coal ratios as well as sorbent sizes. The effect size between the three coal particle ranges also showed that the +025mm-0.5mm and +0.5mm-1mm resulted in similar capillary resistance values, contradictory to the +1mm-2mm.

The results illustrated in Figure 6.2.11 indicate that the capillary resistance between the 3 mm and 5 mm sorbent material was similar across the range of variables investigated. The exception was, however, when operating with a sorbent to coal mass ratio of 0.5:1. These results indicated that, when the amount of sorbents was the limiting factor, the 3mm sorbents with a larger surface area resulted in increased desorption. Looking at the sorbent to coal mass ratios of 0.75:1 to 3:1, it was clear that when sufficient sorbent material was available for adsorption, the size of the sorbent material did not play a key role in the desorption rate. It was found that the effect sizes between the 3mm and the 5mm sorbent were much smaller than 0.8, which means that there was no overall significant statistical difference found in the capillary resistance results.

### *Conclusion*

The drying mechanism for coal by means of sorbent material was controlled by liquid moisture transport. It was proven that desorption required direct contact between the coal and sorbent particles to facilitate the movement of the water. Optimised contact between the sorbent and coal resulted in decreased resistance to liquid moisture transport and therefore led to an increased desorption rate. The contact could be improved by increasing the sorbent to coal mass ratio in the system. Smaller coal particles with a larger surface area also showed improved contact with the sorbent material and could therefore benefit from this enhanced drying technology.

### *Acknowledgements*

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## 6.3. Additional information

Additional experiments were completed to firstly determine the influence of elevated temperatures on the moisture transport rate during adsorption assisted drying. Secondly, a series of tests were completed to determine if adsorption drying is suitable for the dewatering of ultra-fine coal of -0.212mm.

### *6.3.1. Operating conditions*

Additional experiments were conducted to determine whether an increase in temperature would increase the amount of moisture transported from the fine coal to the sorbent material. The experimental work was completed at 25°C, 40°C and 55°C for a particle size distribution of -2mm+0.5mm with ceramic spheres of between 6-10.5mm. Adsorption being an exothermic process does not require elevated temperatures for the process to be successful or to reach the target moisture. It was however established that a larger initial temperature gradient prompts slightly faster initial dewatering rate.

The adsorption results were used to determine the capillary resistance against liquid moisture transport. These results gave an indication to how these operating conditions might influence the moisture transport from the wet coal samples to the porous sorbent material. The capillary resistance was calculated using a generalised formula for capillary flow in a tube as shown in Equation 6.3.1. The same calculation methods were used as described in Section 6.2.

$$Q = -\frac{1}{R}(P_a - P_c) \qquad \textit{Equation 6.3.1}$$

The capillary pressure ($P_c$) was calculated by using the Washburn Equation shown with sub Equation 6.2.2.

$$P_c = \frac{2\gamma}{r} cos\theta \qquad \textit{Equation 6.2.2}$$

The surface tension ($\gamma$) of water was determined for each temperature and the calculated values are $0.072N/m$, $0.0696N/m$ and $0.0671N/m$ for 25°C, 40°C and 55°C respectively (The Engineering Toolbox, 2004). The results of the capillary resistance can be seen in Figure 6.3.1.

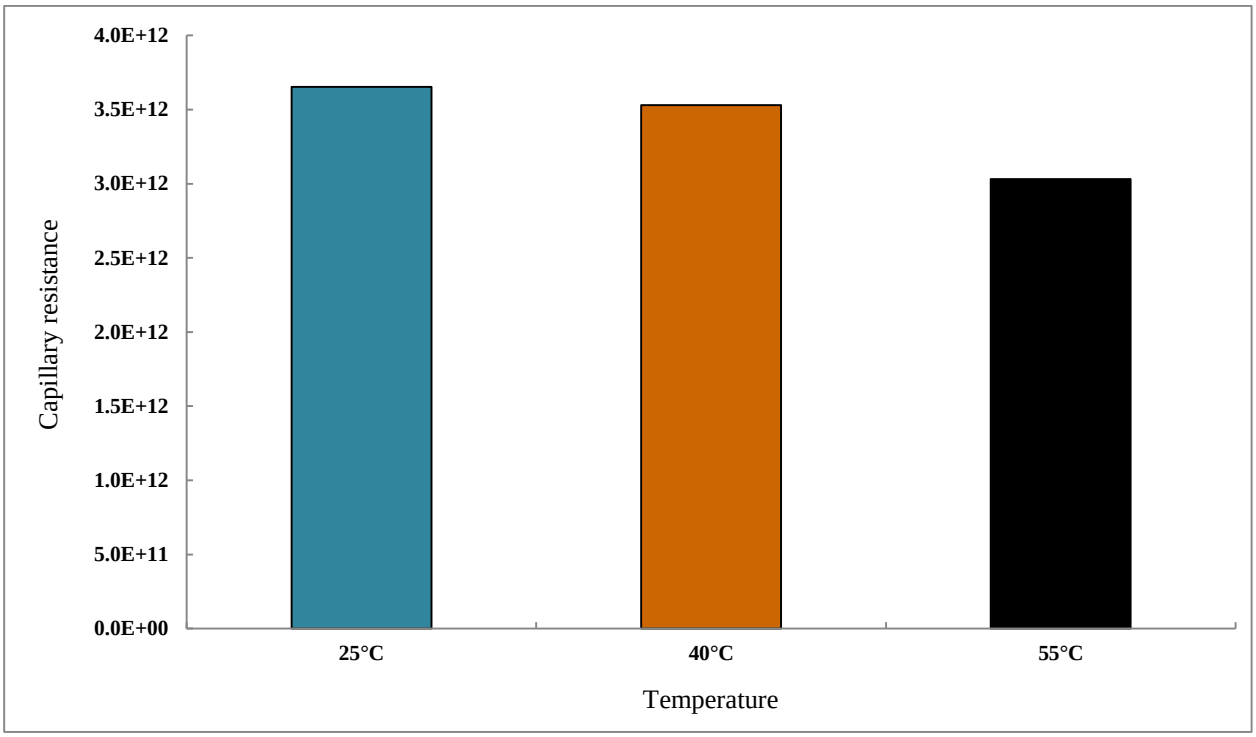


*Figure 6.3.1. Comparison of capillary resistance for 25°C, 40°C and 55°C*

Figure 6.3.1 shows that all the experiments completed at the specified temperatures had some degree of capillary resistance against liquid flow into the sorbent material. It was found that the capillary resistance was very similar for the experiments across the temperature range. Experiments completed at 25 °C, 40 °C and 55 °C delivered capillary resistance values of $3.65x10^{12}$, $3.53x10^{12}$ and $3.03x10^{12}$ respectively. This means that adsorption efficiency stayed relatively constant with an increase in temperature. These results are in accordance with Le Chatelier's principle that states that adsorption capabilities are not affected by an increase in temperature (Parashar, 2015; Bhaskar, 2014).

When the temperature is increased, more energy will be transferred to the moisture surrounding the coal particles. The increase in energy will cause an increase in the vapour pressure of this moisture content which makes this moisture available for transport as a result of the pressure gradient formed (Barbosa de Lima *et al*., 2016). However, this pressure gradient does not affect the adsorption rate as the adsorption do not adsorb vapour as proved in Paper 8. Adsorption rather relies on available open sites of the sorbent material for liquid moisture transport. Surface properties of the porous sorbent material will therefore regulate the adsorption rate (Parashar, 2015). It was determined and shown in Paper 8 that optimised contact between the sorbent material and coal particles resulted in decreased resistance to liquid moisture transport and therefore led to an increased adsorption rate. Optimisation can be implemented by using porous spheres with a larger surface area as well as by improving the contact in the system by mixing or operating with a higher sorbent to coal ratio. However, the addition of sorbent material should not exceed the optimum adsorption capacity, resulting in "blinding spots" and a decreased dewatering rate (Honeywell UOP, 2011; Kudra & Mujumdar, 2009).

### *6.3.2. Feed size distribution*

It was established in Chapter 4 that coal size fractions of +1mm-2mm, +0.5mm-1mm and +0.25mm-0.5mm could easily be dewatered to its equilibrium moisture content. However, drying of fines smaller than 0.212mm proved to be more challenging and could only be dewatered from a moisture content of about $30\%_{wt}$ to about $12\%_{wt}$ within 10 minutes.

The capillary resistance was calculated using Equation 6.3.1 where the same capillary pressure ($P_c$) was used as calculated by using the Washburn Equation in Chapter 4.

$$Q = -\frac{1}{R}(P_a - P_c) \qquad \textit{Equation 6.3.1}$$

The capillary resistance against liquid moisture flow was calculated for the various feed coal particle size distributions and the results are given in Figure 6.3.2.

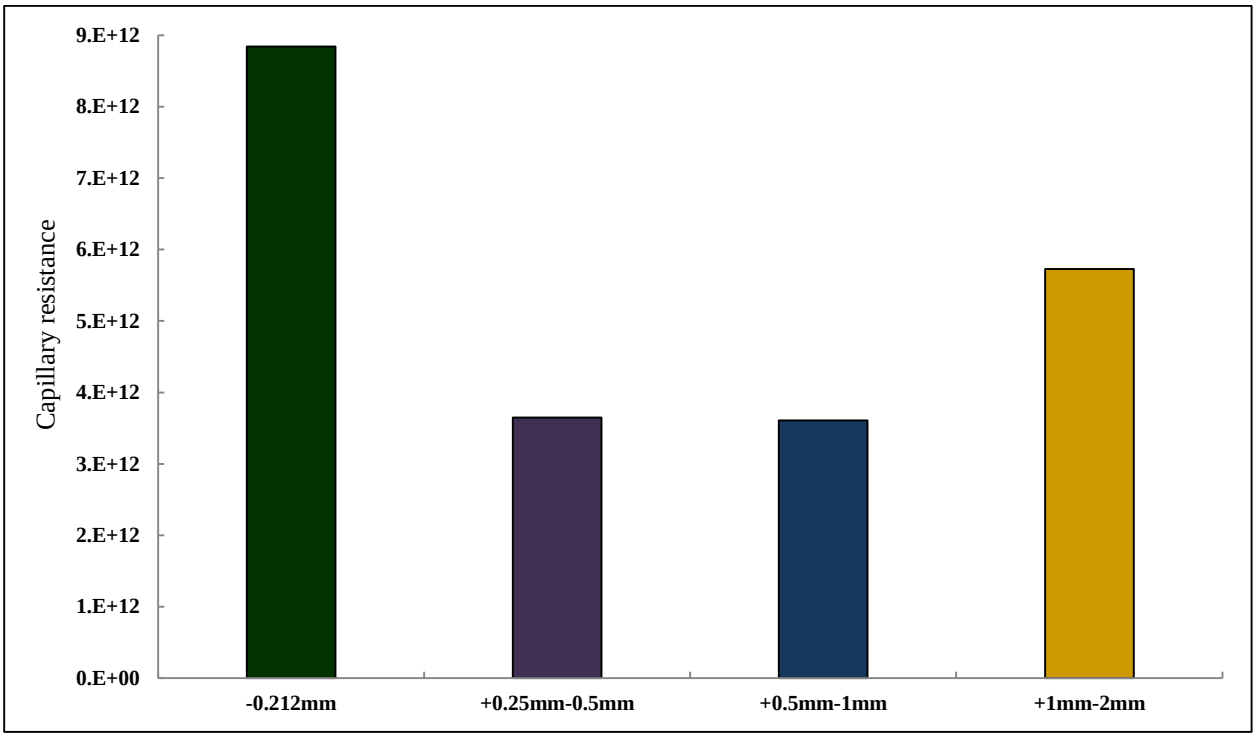


*Figure 6.3.2. Comparison of capillary resistance for various particle size distributions*

It was found that the ultra-fine coal showed the highest transfer resistance against moisture transport into the porous structure of the sorbent material. The main contributor to the higher resistance was the formation of agglomerates. When fines stick to one another to form larger pseudo particles, the effective surface of the agglomerate reduces drastically in relation to that of individual particles. The reduction in available surface decreases the water's ability to exit the agglomerate and transfer to the adsorbent (Pietsch, 2002).

The transfer resistance for the +0.5mm-1mm and +0.25mm-0.5mm size fractions was much lower. This phenomenon can be attributed to the large surface area of the finer particles which promotes contact with the sorbent material. While the ultra-fines smaller than 0.212mm formed agglomerates, the +0.5mm-1mm and +0.25mm-0.5mm and +1mm-2mm could easily be separated and mixed with the sorbent material. An increase in the particle size distribution to +1mm-2mm, resulted in a higher transfer resistance and lower moisture transport. The decrease in the total surface area available for moisture adsorption form the +1mm-2mm size range repressed the moisture flow to the sorbent material. Therefore, smaller coal particles with a larger surface area showed improved contact with the sorbent material and could, therefore, benefit from adsorption drying. However, this is only true there is a proper mix between the coal particles and sorbent beads and no agglomerates are formed. In the case of ultra-fine coal samples, a final moisture content of between $10\%_{wt}$ and $12\%_{wt}$ could easily be reached which is ideally suited for briquetting operations.

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# Chapter 7

## Conclusions and recommendations

This chapter serves as a final overview of this thesis. The main conclusions resulting from this study are emphasised and the contributions made by this thesis are identified. Recommendations regarding possible future work are identified in an effort to expand on the research described in the thesis. Recommendations are made to improve the comprehension of literature about and the technology development of adsorbent assisted drying of coal fines.

## 7.1. Conclusions

The main objective of this thesis is to propose a possible dewatering operation that can be implemented for fine coal drying. High airflow drying and adsorption assisted drying was investigated and evaluated to determine the most suitable dewatering operation for implementation on a larger scale. These findings led to a secondary aim, which was to define a moisture transport mechanism for adsorption assisted drying. Objectives were specified in Chapter 1, Section 3, to address the aims of this thesis. From these, the following conclusions were drawn:

1. It was evident from research depicted in Chapter 1, that fine and ultra-fine coal is a valuable resource that is currently underutilised in South Africa due to dewatering difficulties. Upgrading and dewatering these fines to a saleable product will definitely reduce environmental problems whilst increasing yield on coal beneficiation plants. It was concluded that current dewatering methods in conjunction with blending strategies, still leave voids in the industry for feasible and practical dewatering solutions, which is the principal motive for this study.
2. A laboratory scale unit of the high airflow fluidized bed was built and experimental work was completed to gain understanding of the technology. This technology was developed by defining the best operating conditions as discussed in Chapter 3, as well as by determining the operational difficulties, discussed in Chapter 5. It was concluded that a high airflow fluidized bed was able to dry coal fines to equilibrium moisture content around the inherent moisture levels of the coal as measured at 22°C and 40% relative humidity. This was achieved at or close to ambient conditions, indicating that the high airflow rate and lower relative humidity conditions of the fluidizing air contributed to an improved dewatering rate. These airflow conditions formed a large moisture concentration gradient which promoted faster dewatering rates of fine coal particles. Increased fluidizing air temperatures above 40°C did not improve the dewatering rate or the final equilibrium moisture content of the dewatered coal. When the vapour in the drying air comes in contact with the colder surface of the cylinder at a temperature below its saturation temperature, the vapour condenses to liquid unto the surface, which decreases the drying efficiency. It can be hypothesised that fluidizing air temperatures close to the boiling point of water will have a positive influence on the rate of fine coal dewatering. These elevated temperatures, however, would generate increased expenditure, which, with current coal prices, would not constitute a viable option.
3. A laboratory scale unit was built to test the possibility of drying wet coal fines with adsorption drying. Experimental work was completed on the rotary bed to determine the efficiency of the process, operational difficulties and best operating conditions. These results were discussed in Chapter 4 and Chapter 5. It indicated that transfer of moisture from coal to the sorbent was possible at ambient conditions. Although not reaching similar inherent moisture levels as high airflow drying, this process produced a coal product suitable for thermal and metallurgical use within 10 minutes retention time. In the case of ultra-fine coal samples, the final moisture content was between $10\%_{wt}$ and $12\%_{wt}$ which are ideally suited for briquetting operations. It is therefore safe to say this is an effective drying method

to dewater fine and ultra-fine coal at sorbent to coal feed ratios of 1:1 or 2:1. Effective regeneration of alumina-rich ceramic beads was possible using a packed bed operated with ambient air flow. It produced a sorbent bead that still contained between 5%$_{wt}$ and 10%$_{wt}$ moisture which was shown to operate similarly to the fresh sorbent feed containing a moisture content of 8%$_{wt}$. Repeated studies showed that reusing the regenerated sorbent consistently delivered low moisture levels at similar drying rates. This regeneration capability of the ceramic makes the process energy positive showing promise for implementation on a larger scale since the used sorbent material could easily be restored to its original state by using ambient airflow in a packed bed or when left in ambient conditions to dry. For this reason, the sorbent material could economically be regenerated and reused with repeatable efficient drying results.

4. The drying efficiency of both the high airflow drying and adsorbent assisted drying was investigated by focussing on the drying rate and the coal product moisture. The results were discussed fully in Chapter 3 and Chapter 4, while the efficiency of the two drying methods was compared in Chapter 5. It was concluded that high airflow could reduce the coal moisture to values lower than the inherent moisture content, whereas the sorbent material could only remove the surface moisture. However, it was established that adsorption assisted drying was more practical, efficient and feasible. Adsorption drying was easier to operate and the sorbent material could successfully be regenerated and reused with repeatable satisfactory drying results. When the energy consumption between airflow drying and adsorption drying with regeneration in a packed bed, is taken into account, even then, absorption drying proved to be superior. Adsorption assisted drying can, therefore, result in a significant energy gain, which can lead to increased revenue.
5. The moisture transport mechanism for adsorption assisted drying was investigated and described in Chapter 6. It was determined that the majority of the moisture transport took place in a very short time of 2.5 minutes. Furthermore, it was established that the moisture transport occurred in liquid form and accordingly, the optimised contact improved the adsorption drying rate. The moisture transport mechanism was described as a function of the resistance against liquid moisture transport in capillary tubes. All the experimental runs had a degree of capillary resistance against liquid flow into the sorbent material. The capillary resistance against liquid flow corresponded with the drying results and could be used as a method to determine the effect of parameters on the dewatering capabilities of the sorbent material. It was concluded that operating conditions improving the coal sorbent contact led to a decrease in capillary resistance and in return increased liquid moisture transfer. In addition, the larger surface area of the finer coal fractions led to increased contact with the sorbent material. Therefore, adsorption assisted drying, relying on the optimised contact between the wet coal fines and sorbent material, proved to be specifically beneficial for drying the finer coal fraction.

## 7.2. Contribution

The study of high airflow drying has led to the following papers either published in peer-reviewed journals or presented at conferences and accordingly published in conference proceedings:

1. Le Roux, M., Campbell, Q.P. & Van Rensburg, M.J. 2014. Fine coal dewatering using high airflow. *International Journal of Coal Preparation and Utilization*, 34:220-227.
2. Le Roux, M., Campbell, Q.P. & Van Rensburg, M.J. 2014. Drying of fine coal using air in a fluidized bed. (*In* Yianatos, J., *eds*. XXVII International Mineral Processing Congress, Santiago, Chile. Chile: Gecamin.
3. Le Roux, M., Campbell, Q.P., Van Rensburg, M.J., Peters, E.S. & Stiglingh, C. 2015. Air drying of fine coal in a fluidized bed. *Journal of the Southern African Institute of Mining and Metallurgy*, 115: 335-338.
4. Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & Peters, E.S. 2015. Drying of fine coal using warm air in a fluidized bed. Paper presented at the Southern African Coal Processing Society's conference, Secunda, South Africa.

The study of adsorption drying has led to the following papers either published in peer-reviewed journals or presented at conferences and accordingly published in conference proceedings:

1. Van Rensburg, M.J., Le Roux, M. & Campbell, Q.P. 2016. Drying of coal fines assisted by ceramic sorbents. (*In* Litvinenko, V., *eds*. XVIII International Coal Preparation Congress, Saint-Petersburg, Russia. Switzerland: Springer.
2. Peters, E.S., Le Roux, M., Campbell, Q.P. & Van Rensburg, M.J. 2017. Adsorbent assisted drying of fine coal. Paper presented at the Southern African Coal Processing Society's conference, Secunda, South Africa.
3. Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & Peters, E.S. 2018. Contact sorption: A method to reduce the moisture content of coal fines. *International Journal of Coal Preparation and Utilization*, 1-15.
4. Van Rensburg, M.J., Le Roux, M., Campbell, Q.P. & Peters, E.S. 2018. Moisture transport during contact sorption drying of coal fines. *International Journal of Coal Preparation and Utilization*, 1-16.

The following conclusions from this thesis contribute to the field of fine coal drying:

1. Compared to high airflow drying, adsorption assisted drying proved to result in lower energy consumption. An added benefit is that activated alumina sorbent material can successfully be regenerated without showing degradation. The regenerated sorbent can be reused and can achieve a similar drying rate and final coal product moisture content as the original sorbent material.

2. The loaded sorbent material can be regenerated with air instead of applying thermal techniques. The sorbent material can be dried with ambient airflow in a packed bed within 10 minutes. Otherwise, the sorbent material can be left in static atmospheric conditions and will within a reasonable time still revert to its initial moisture content.
3. It was proven that moisture transport occurred in the liquid phase, requiring direct contact between the coal and sorbent particles to initiate and sustain the movement of water. The moisture transport mechanism can be described by determining the capillary resistance against liquid flow. The moisture transport mechanism indicated that increasing sorbent surface area available for contact led to a decrease in capillary resistance, which allowed for added liquid flow.

## 7.3. Recommendations

The following recommendations are made for further research:

### *7.3.1. Literature recommendations*

1. This study presented a drying mechanism to describe the liquid flow for adsorbent assisted drying. The results should be verified by doing visual studies on the movement of moisture, using for example X-Ray Tomography. In addition, it is important to determine a drying model that will be able to predict the dewatering rate and product moisture at certain time intervals. It is suggested that this drying model should include the following parameters: coal particle size range, coal quality (proximate and maceral composition), sorbent size, sorbent porosity and sorbent to coal feed ratio.
2. The efficiency of the entire adsorption assisted drying process relies strongly on the regeneration of sorbent material. This study introduced the possibility of regenerating the sorbent with non-thermal methods. Future studies should focus on optimising the dewatering of the loaded sorbent material by investigating more experimental conditions and establishing a drying mechanism. A clearer understanding of the regeneration process would benefit the efficiency of adsorption assisted drying.

### *7.3.2. Technology development recommendations*

1. The construction of a pilot plant is highly recommended to test the feasibility of adsorption assisted drying on industry scale. Operating a continuous process with typical equipment and methods used in industry, would give insight into the optimisation of the process. A pilot plant would enable an improved technical and economic evaluation of the process based on energy consumption.
2. Additional work should be carried out to include ultra-fine filter cake mixed with coarser plant clean coal product to break down agglomerates formed by the cake.

3. Future work should focus on using sorbent material in dry beneficiation processes to dry run-off-mine coal to moisture levels where it can be used. Moisture plays an important role in dry beneficiation and needs to be below 8% for effective use.

4. The ceramic sorbent materials used in this study was predominately produced from alumina oxide and silica oxide. The sorbent material was specifically manufactured with an improved adsorption surface and capillary network. Adsorption assisted drying should be tested with beads produced from waste building material, also containing varying quantities of ceramic.

# Annexure

## Title pages

The Annexure contains the title pages of published papers in accredited journals or conference proceedings. Paper 1 to Paper 8 were published prior to submission of this thesis. Complete details of each paper can be found in the Preface as well as the corresponding chapters.

## Fine coal dewatering using high airflow (Paper 1)

International Journal of Coal Preparation and Utilization, 34:220–227, 2014

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# Fine Coal Dewatering Using High Airflow

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*Fluidized bed drying is currently receiving much attention as a dewatering option after the beneficiation of fine coal. Apart from concerns about safety and combustion, the operating costs can be high if very high gas or air temperatures are used. The aim of this study was to investigate the removal of moisture from fine coal by using air at a lower temperature (25°C – 40°C) within a controlled environment by lowering the relative humidity of air. It was firstly proven that fluidization has a major advantage over normal static beds when allowed to reach equilibrium. Hereafter, several parameters that influence the dewatering rate and final moisture content were tested, from which it was concluded that the relative humidity of air acts as the largest driving force for dewatering. It was, therefore, shown that this is a viable technology for the dewatering of fine coal.*

**Keywords** Dewatering; Drying; Fine coal; Fluidized bed; Warm air

## Introduction

Fine coal (defined in this article as between 1 mm and 2 mm) is difficult to dewater and can contain a total moisture content of higher than 25 wt% even after filtration [1]. This high-moisture content causes problems in handling as well as a decrease in the calorific value of the coal. An added disadvantage of a high-moisture content is an increase in transportation and port costs. The difficulty in dewatering often leads to fines being discarded onto discard dams or being blended, as is, to the course beneficiated fraction. Such a blend will decrease the quality of the final product by increasing the final product moisture. Developing feasible fine coal beneficiation processes can result in potential revenue and, at the same time, reduce environmental problems [2]. Fluidization is proving to be one such option in beneficiating fine coal. However, research conducted at North-West University found that elevated moisture content in the feed decreases the efficiency of the process [3].

There are several methods to reduce the moisture content in fine coal, for example, pressure filtration, centrifuging, and thermal drying. Thermal drying



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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/gcop.

# Drying of fine coal using air in a fluidized bed (Paper 2)

XXVII SANTIAGO • CHILE IMPC • 2014 | 20 - 24 October 2014, Hotel Sheraton, Santiago, Chile
impc2014.org | impc@impc2014.org | +56 2 2652 1528

ABSTRACT N675

## Drying of fine coal using air in a fluidized bed

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### ABSTRACT

Fluidised bed drying is currently receiving much attention as a dewatering option during the beneficiation of fine (defined here as between 1 mm and 2 mm particles) coal. Apart from concerns about safety and combustion, the operating costs can be high if very high gas or air temperatures are used. The aim of this study was to investigate the removal of moisture from fine coal by using air at a lower temperature (25 - 55°C) within a controlled environment by lowering of the relative humidity of the air. It was firstly proven that fluidization has a major advantage over non-fluidized beds, with regards to drying rate and final moisture content. Hereafter several parameters that influence the dewatering rate and final moisture content were tested, from which it was concluded that the relative humidity of air acts as the largest driving force for dewatering. Parameters tested included relative humidity, temperature and coal composition. Energy balances showed a positive nett energy increase in the dried coal during combustion when related to the energy input during drying. In comparison with thermal drying technologies, fluidized bed drying was proven to be less energy intensive. It was therefore shown that this is a viable technology for the dewatering of fine coal.

**Keywords:** Dewatering, Drying, Fine coal, Fluidization.

# Air drying of fine coal in a fluidized bed (Paper 3)

# Air drying of fine coal in a fluidized bed

by M. Le Roux*, Q.P. Campbell*, M.J. van Rensburg*, E.S. Peters*, and C. Stiglingh*

Paper written on project work carried out in partial fulfilment of Degree in Chemical Engineering (NWU) – Pursuing Masters in Coal Beneficiation

**Synopsis**

The demand for energy has continued to rise worldwide in line with population growth. The majority of South Africa's electricity is supplied by coal-fired power stations. The amount of fine coal (-2 mm) generated at coal processing plants has increased, due mainly to mechanized mining methods. Fine coal retains more water, which lowers its heating value.

Drying the coal is costly and it is difficult to achieve the required moisture content. Consequently, coal fines are often discarded. An estimated 8% of the total energy value of mined coal is lost[1].

Fluidized bed technology is often used to dry coal thermally, but this method is expensive and has an adverse environmental impact. The objective of this study was to investigate the removal of moisture from fine coal (<2 mm) in a fluidized bed operated with dry fluidizing air at moderate temperatures as the drying agent. The effects of different air temperatures and relative humidity levels were investigated in a controlled environment. The study further investigated the influence of coal particle size on moisture removal.

The drying rate was found to increase with increasing temperature. The relative humidity of the drying air had a more pronounced effect on the drying rate, even at temperatures as low as 25°C.. It became more challenging to remove moisture as the particle size decreased. The gain in calorific value was greater than the energy required to dry the coal samples, showing that a fluidized bed using moderately warm dry air is an energy-efficient drying technology. The energy efficiency of the fluidized bed compared favourably with other thermal drying methods.

**Keywords**

coal fines, drying, fluidized bed, energy efficiency.

## Introduction

The increased use of mechanized coal mining methods has resulted in greater amounts of coal fines being generated. Many operations report an estimated 6% of their ROM production to be in the -2 mm size range. Fine and ultra-fine size ranges constitute about 11% of the nominal product and retain the bulk of the moisture (SANEDI, 2011). Given the problems associated with moisture in fine coal, it is important to investigate and improve available moisture removal techniques. Coal constitutes the primary source of energy in South Africa and is a major contributor to the economy, and therefore improving coal quality will in effect maximize the quantity of usable coal (De Korte and Mangena, 2004). With the use of effective dewatering methods, fine coal can be beneficiated and added to the coarse particle circuits without compromising the quality of the product and hence substantially increasing the overall plant yield (Condie and Veal, 1998). Condie and Veal (1998) suggest that by rule of thumb, for every ton of moisture removed the clean coal product stream is supplemented with about 4 t of fine coal. This is a powerful incentive for developing advanced dewatering techniques for fine coal particles. Additionally, excessive moisture adds to the mass-based transport costs of coal. For this reason, developing advanced efficient fine coal drying techniques is beneficial from an economical point of view (Campbell, 2006).

Rowan (2010) states that coal preparation plants generally discard coal fines with size fractions below 150 µm into waste ponds. This poses a danger of spontaneous combustion, acid mine drainage, and dust release as the surface of the coal is exposed to ambient air and weathering conditions for long periods (De Korte and Mangena, 2004). Coal fines are more susceptible to water absorption than coarser coal and can contain up to 25 wt% total moisture after filtration (Le Roux, 2003). Thermal drying methods are more efficient than mechanical dewatering techniques (De Korte and Mangena, 2004), but the price of coal limits the use of these methods (SANEDI, 2011). Studies conducted at North-West University showed that drying of fine coal (-2 mm +1 mm) in a fluidized bed is possible at low temperatures between 25°C and 40°C.

Work by Le Roux *et al.* (2012) on vacuum filtration showed that intentionally damaging a filter cake improved the airflow infiltration, leading to a lower pressure differential across the cake but increasing the dewatering

[1] *Rowan, S.L. 2010. Analysis and scaling of a two-stage fluidized bed for drying of fine coal particles using shannon entropy, thermodynamic exergy and statistical methods. PhD dissertation, University of West Virginia, Morgantown WV.*

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# Drying of fine coal using warm air in a fluidized bed (Paper 4)

## DRYING OF FINE COAL USING WARM AIR IN A FLUIDISED BED

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**ABSTRACT**

Fluidised bed drying is currently receiving much attention as a dewatering option after the beneficiation of fine coal. The objective of this study was to investigate the removal of moisture from coal fines in a fluidised bed operating with air at moderate temperatures. The drying rate and energy consumption were determined for various operating parameters including relative humidity, temperature, airflow rate and particle size distribution. The overall energy consumption for the fluidised bed is lower than for all the dryer systems compared to and it compared favourably with other thermal drying technologies, proving to be a viable technology for the dewatering of fine coal.

*Keywords:* Dewatering; Drying; Fine Coal; Fluidised Bed; Warm Air

**INTRODUCTION**

According to Reddick *et al.* (2007) coal fines (defined in this report as smaller than 2mm) are produced as a result of mechanised mining methods. It was estimated by Mangena *et al.* (2003) that about 12% of South African mined coal is classified as fines. Fine coal is difficult to dewater and can contain a total moisture content of higher than 25%$_{wt}$ even after filtration (Le Roux, 2003). This high moisture content causes problems in handling as well as a decrease in the calorific value of the coal. An added disadvantage of high

# Drying of coal fines assisted by ceramic sorbents (Paper 5)

## Drying of coal fines assisted by ceramic sorbents

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**Abstract**

It is proposed to introduce contact sorption drying as a method to reduce the moisture content in coal fines. The aim of this study was to investigate the possibility of drying fine and ultra-fine coal using porous ceramic as the moisture sorbent. The main focus of this report is to define how the air temperature, particle size variations and mixing ratio would influence the contact between coal and ceramic for effective moisture adsorption. Drying of coal fines assisted by ceramic sorbents proved to be a viable concept as the ceramic was able to not only reduce the moisture content of fine coal, but of ultra-fine coal as well. The larger surface area of smaller ceramics allowed for efficient contact and consequently higher dewatering rates. The addition of more ceramic resulted in better contact with the wet coal and reduced the operating time quite significantly. Improved contact between the coal and ceramic therefore proved to be the main driving force during adsorption drying.

Keywords: Alumina; Ceramic; Coal; Drying; Fines; Moisture; Sorbent; Sorption

### Introduction

Mangena *et al*. (2003) estimated that about 12% of South Africa's mined coal can be classified as fine and ultra-fine coal. Due to its large surface area, the coal fine fraction retains the majority of the moisture in mined coal and can contain a moisture content of higher than 25% by weight (Le Roux, 2003). Compared to coarse coal, the fine and especially the ultra-fine fraction are far more difficult to dewater to an acceptable moisture content. As a result of the difficulty in dewatering, the fines are often dumped into discard dams or slurry ponds. Consequently these disposal methods leads to a series of environmental problems such as acid mine drainage, dust release, spontaneous combustion and it also occupies large areas of land. Aside from the environmental problems, the wasted coal fines have heating values comparable to the coarse coal fraction when dried (Reddick *et al*., 2007). It would then be sensible to investigate and implement cost effective and efficient drying methods to salvage the wasted fines and process the mined fine fraction. It is important to use coal wisely as it is the primary energy resource in South Africa (Fourie *et al*., 1980).

In fine coal processing the mechanical dewatering techniques are ineffective as these methods cannot reduce the moisture content to a desirable level. Dewatering of coal fines often relies strongly on thermal methods as coal fines are known to retain water (Le Roux & Campbell, 2003). There are several conventional thermal drying methods, however not all of these systems are ideal in terms of energy consumption and safety during operation (Kudra & Mujumdar, 2009).

It is proposed to introduce contact sorption drying as a method to reduce the moisture content in coal fines by creating a mass concentration gradient between the wet coal and dry sorbent. The aim of this study was to investigate the possibility to dry fine and ultra-fine coal using porous ceramic as moisture sorbent. The investigation focusses on defining how the temperature, particle size variations and mixing ratio will influence the contact between the coal and ceramic and consequently the moisture transfer. The efficiency of the contact drying technique would lay in the possibility of separating the coal and ceramic and furthermore regenerate the ceramic for re-use.



V. Litvinenko (ed.), *XVIII International Coal Preparation Congress*,
DOI 10.1007/978-3-319-40943-6_114

# Adsorbent assisted drying of fine coal (Paper 6)

## Adsorbent assisted drying of fine coal

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**ABSTRACT**

It is commonly found that fine coal (-0.5mm) and ultra-fine coal (-0.1mm), dewatered by mechanised methods, is still blended with coarse coal since it contains approximately 15-20%$_{wt}$ surface moisture (De Korte and Mangena, 2004). This high moisture levels poses a problem for utility companies as moisture retention lowers the effective heating value of the coal. Mohanty and Akbari (2012) remarked that by reducing the surface moisture levels of the fine coal product by 50%, the overall turnover of a typical colliery can potentially be improved by ±6%. Searches for innovative, cost efficient, and eco-friendly drying techniques have intensified (Bratton *et al.*, 2012). One such advanced dewatering process that was developed employs drying media to adsorb remaining surface moisture from the coal fines.

This investigation was primarily focussed on successfully, and feasibly employing adsorbent material to lower the surface moisture content of coal fines. It was found that the surface moisture levels of the fine coal was effectively reduced from ±0.30 g(moisture)/g(coal and moisture) to well-below 0.08 g(moisture)/g(coal and moisture) within 10 minutes. The cascading-bed drying technique consumed considerably less time than the fixed-bed drying technique. The best performing adsorbent to coal mass ratio was found to be 2:1, while the -2mm+1mm fine coal delivered the lowest product moisture levels and the -1mm+0.5mm produced the highest overall initial desorption rates during the cascading-bed drying technique. In addition, it was found that alumina and silica-based adsorbent yielded similar drying performances, whereas the 3mm adsorbents proved to have increased desorption rates over the 5mm adsorbents.

**Keywords:** *Adsorbents, fine coal; moisture content*

**INTRODUCTION**

Coal fines are generated by the increase in mechanization on coal mines and plants, and have the ability to retain large amounts of moisture due to its inherently large surface areas (Reddick et al., 2007). The bulk of the moisture is retained by fine (-1mm+0.1mm) and ultra-fine (-0.15mm)

**Contact sorption: A method to reduce the moisture content of coal fines (Paper 7)**

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https://doi.org/10.1080/19392699.2018.1541895

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# Contact sorption: a method to reduce the moisture content of coal fines

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**ABSTRACT**

This paper introduces contact sorption with ceramic sorbents as a method to reduce the moisture content of coal fines produced by coal processing plants. The proposed method was tested on laboratory scale where ceramic spheres with diameters of 3 mm and 5 mm were combined with wet coal fines of size fractions between 0.25 mm and 2 mm. The coal had an initial moisture content of 0.25 g(Water)/g(Coal and water), and was dewatered using contact sorption to an average moisture content of 0.13 g(Water)/g(Coal and water) after 2.5 minutes and 0.05 g(Water)/g(Coal and water) after 10 minutes, respectively. This paper focuses on identifying the solid phase conditions essential to improving the contact sorption drying technology, proving that contact between the coal and sorbent material is the main driving force behind this technology. Increasing the sorbent to coal mass ratio and using smaller sorbents with a larger surface area resulted in improved contact and consequently improved moisture mass transfer. The final coal moisture content that could be achieved was independent of coal particle size. Current studies show a reliance on thermal drying technologies to dry the saturated sorbent material, whereas this paper proves that drying with high airflow at low temperatures is sufficient to regenerate the sorbent material. The loaded sorbent material could easily be separated from the dried coal product by dry screening, and could be dried and regenerated afterwards in an air-blown packed bed within 10 minutes. The re-use of sorbent material showed no decrease in its dewatering efficiency, and it was shown to be possible to re-use the sorbents for a large number of cycles. Contact sorption can prove to be a cost-effective and efficient drying method to dewater coal fines in the industry.

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Coal beneficiation; fine coal dewatering; contact sorption drying

## Introduction

A significant portion of the mined coal in South Africa is often discarded in an effort to deliver a product meeting the requirements of the various industries (Department of Energy, Republic of South Africa 2017). The South African coal industry discarded around 2000 Mt of coal over the past 20 years (Department of Minerals Resources, South Africa 2014). About 50 Mt of discarded coal fine slurry is added every year because it is challenging to dry the coal fines (defined here as +0.15 mm–1 mm) and ultra-fines (–0.15 mm) since it retains a large fraction of water. Apart from occupying large areas of land, the discarded coal also creates a series of environmental problems such as acid

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# Moisture transport during contact sorption drying of coal fines (Paper 8)

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## Moisture transport during contact sorption drying of coal fines

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**ABSTRACT**

Studies have shown that contact sorption drying is a feasible technique to dewater fine (+0.15mm–0.5mm) and ultra-fine (–0.15 mm) coal. The aim of this article is to further investigate the drying mechanism involved. It could be shown that moisture transfer occurred primarily in the liquid phase, requiring direct contact between the coal and sorbent particles to facilitate the movement of the water. Moisture transfer was enhanced by operating with a higher sorbent to coal mass ratio. When drying smaller coal particle size ranges, the resistance to liquid transport decreased, leading to better desorption results. These improvements were mainly as a result of a greater contact area between the sorbent and coal particles.

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Activated alumina; fine coal; dewatering; contact sorption drying; moisture transport

### Introduction

Coal fines and ultra-fines are inevitably generated due to mechanized mining and processing methods (De Korte and Mangena 2004). Coal fines, defined here as +0.15 mm–0.5 mm, can adsorb and retain up to 25%$_{wt}$ of its weight in water (Bourgeois and Barton 2007). The ultra-fines, those particles smaller than 0.15 mm, can retain a total moisture content of more than 30%$_{wt}$ even after filtration. Consequently, it has become a common practice in the mining industry to blend as much as possible of these wet fine products with coarser, drier coal or otherwise dispose of these to prevent difficulties during handling and transportation, or avoid moisture penalties (Hand 2000). To date, the South African coal mining industry has produced and disposed of approximately 1 billion tonnes of wet fine coal. It is estimated that about 60 Mt of coal is added annually to the discarded fraction (SRK Consulting 2016). These fines may have calorific values comparable to coarser run-of-mine coal, making discarded fines a potentially valuable resource to be recovered (Reddick, Von Blottnitz, and Kothuis 2007).

Mechanical dewatering methods are only able to partially remove the surface moisture associated with coal, and are therefore insufficient when processing the finer fractions (Wakeman 1984). Thermal drying yields a drier final product, but its operation can be difficult, unsafe, and can involve great capital and operating costs (De Korte and Mangena 2004; Hand 2000). It was shown that contact sorption drying could reduce the moisture content of the fine coal fractions by removing much of the surface moisture (Van Rensburg et al. 2018). The aim of this article is to identify the mechanism of moisture transport during contact sorption drying of fine coal. The focus is to first determine

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