

Dewatering of Fine Coal with Flowing Air using Low Pressure Drop Systems

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Thesis submitted for the degree Philosophiae Doctor in Chemical Engineering
at the North-West University, South Africa

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July 2006

Declaration

I, **Quentin Peter Campbell**, hereby declare that this thesis entitled:

*Dewatering of Fine Coal with Flowing Air using Low
Pressure Drop Systems*

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. Relative contributions by the different authors are acknowledged in the relevant chapters.



Signed at Potchefstroom on 31 July 2006.

Preface

Format of this thesis

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Styles of numbering and referencing

It should be noted that the formatting, style of referencing, figure and table numbering and general outline of the six original articles, as required by the

various editors of the publications, were retained. No modifications to the original texts (apart from minor spelling or typographical errors) of the papers were made because the majority of these had been peer-reviewed, and all had been published. Because of the variety of journals and conferences, it may seem that an inconsistent reference style was used in the thesis. For clarity, all references used in all of the papers were listed again at the end of the thesis in the correct style, according to the guidelines of this University.

Figures and tables in the papers were re-formatted (without modification of the contents) to comply with the overall style of the thesis. Additions to clarify certain points in the papers are indicated by footnotes.

List of Publications

The publications presented in this thesis in accordance with rule A.12.2.2, are:

Journal articles (peer-reviewed)

LE ROUX, M. and CAMPBELL, Q.P. An Investigation into an Improved Method of Fine Coal Dewatering. Minerals Engineering, Vol. 16 (10), October 2003, pp. 999 – 1003.

LE ROUX, M., CAMPBELL, Q.P., WATERMEYER, M.S. & DE OLIVEIRA, S. The optimization of an improved method of fine coal dewatering. Minerals Engineering, 18. 2005. pp. 931 – 934.

VAN DER MERWE, D.C.S. and CAMPBELL Q.P. An Investigation into the Moisture Absorption Properties of Thermally Dried South African Fine Coal. Journal of the South African Institute of Mining and Metallurgy, Vol. 102, no.7 (October 2002), pp. 417 - 419.

Conference proceedings (peer-reviewed and published)

CAMPBELL, Q.P. 2000. Dewatering and De-saturation of Fine Coal. Annual SAICHE Conference. Secunda, South Africa. 8 - 12 October.

CAMPBELL, Q.P. 2002. The Influence of Coal Quality on the Dewatering of Fine Coal by Vacuum Filtration. XIV International Coal Preparation Congress. South African Institute of Mining and Metallurgy. Sandton, South Africa. 11 – 15 March.

CAMPBELL, Q.P., BLENKINSOP, M. and LE ROUX, M. De-saturation of fine coal: a different approach. 9th World Filtration Congress, New Orleans, 18 to 24 April 2004.

Statements from co-authors

Contributions from the following co-authors are recognised, and their statements follow:

M. Blenkinsop	<i>(page vii)</i>
M. le Roux	<i>(page viii)</i>
D.C.S. van der Merwe	<i>(page ix)</i>

Statement of consent: M. Blenkinsop

To whom it may concern,

I, **Michael Blenkinsop**, give my consent to **Quentin Peter Campbell**, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: ***Dewatering of Fine Coal with Flowing Air using Low Pressure Drop Systems***, the following publication, of which I am a co-author:

Campbell, Q.P., **Blenkinsop, M.** and Le Roux, M. De-saturation of fine coal: a different approach. 9th World Filtration Congress, New Orleans, 18 to 24 April 2004.

The relative contributions to the paper by the different authors are given in Chapter 7 (page 100).

This statement serves to comply with Rules A.12.2.1, A.11.5.4 and A.11.5.5 of the University.

Signed at Potchefstroom on 31 July 2006.



M. Blenkinsop

Statement of consent: M. le Roux

To whom it may concern,

I, **Marco le Roux**, give my consent to **Quentin Peter Campbell**, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: ***Dewatering of Fine Coal with Flowing Air using Low Pressure Drop Systems***, the following publications, of which I am a co-author:

Le Roux, M. and Campbell, Q.P. An Investigation into an Improved Method of Fine Coal Dewatering. *Minerals Engineering*, Vol. 16 (10), October 2003, pp. 999 – 1003.

Le Roux, M., Campbell, Q.P., Watermeyer, M.S. & De Oliveira, S. The optimization of an improved method of fine coal dewatering. *Minerals Engineering*, 18. 2005. pp. 931 – 934.

Campbell, Q.P., Blenkinsop, M. and **Le Roux, M.** De-saturation of fine coal: a different approach. 9th World Filtration Congress, New Orleans, 18 to 24 April 2004.

The relative contributions to the papers by the different authors are given in Chapter 4 (page 41), Chapter 5 (page 74) and Chapter 7 (page 100).

This statement serves to comply with Rules A.12.2.1, A.11.5.4 and A.11.5.5 of the University.

Signed at Potchefstroom on 31 July 2006.



M. le Roux

Statement of consent: D.C.S. van der Merwe

To whom it may concern,

I, **Daniël Charl Stephanus van der Merwe**, give my consent to **Quentin Peter Campbell**, candidate for the degree Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of the North-West University, to include in his thesis entitled: ***Dewatering of Fine Coal with Flowing Air using Low Pressure Drop Systems***, the following publication, of which I am a co-author:

Van der Merwe, D.C.S. and Campbell Q.P. An Investigation into the Moisture Absorption Properties of Thermally Dried South African Fine Coal. *Journal of the South African Institute of Mining and Metallurgy*, Vol. 102, no.7 (October 2002), pp. 417 - 419.

The relative contributions to the paper by the different authors are given in Chapter 6 (page 86).

This statement serves to comply with Rules A.12.2.1, A.11.5.4 and A.11.5.5 of the University.

Signed at Potchefstroom on 31 July 2006.



D.C.S. van der Merwe

Abstract

Successful dewatering and filtration of coal fines remain the major obstacles in preventing the extensive re-use of large reserves of high calorific quality coal fines as an additional energy source in South Africa. The high levels of final moisture in coal fines make it uneconomical to transport, handle and use. The industry is rapidly reaching the limit of current technology of mechanical dewatering; this limit is defined by fundamental coal properties, like amongst others, particle size, porosity and mineral content.

This thesis describes research investigating a shift in approach from high vacuum or pressure systems, to high air flow systems. Results from various projects at laboratory scale showed that it was possible to decrease the fine coal filter cake moisture to as low as 15%. This was obtained by allowing air to flow freely through a filter cake, even at ambient temperatures, and replacing the necessity for high applied vacuum levels. There was also an increase in the dewatering rate, as well as a lower breakthrough pressure. Such an approach can utilise existing equipment with minor modifications.

Other investigations showed that forced air-drying, both at ambient and elevated temperatures, could be used to overcome this mechanical limit. Again, an increased air flow rate at ambient pressure was used. Using air drying, moisture levels down to zero were possible.

These investigations led to the conclusion that increased air flow through a fine coal cake was more advantageous than an increase in the applied vacuum, or a longer dewatering time. This new approach to lowering the final moisture content in coal fines is crucial in any advancement of the use of this largely untapped energy source.

Opsomming

Ontwatering en filtrering van fyn steenkool is steeds die grootste struikelblok wat verhoed dat hoë kaloriewaarde fyn steenkool op groot skaal as 'n bykomende energiebron in Suid-Afrika benut word. Die hoë vlakke van uiteindelijke vog in fyn steenkool maak die vervoer, hantering en gebruik daarvan onekonomies. Die nywerheid bereik vinnig die limiete van die huidige tegnologie, gebaseer op meganiese ontwatering, wat bepaal word deur die fundamentele steenkooleienskappe, soos, onder andere, partikelgrootte, porositeit en mineraalinhoud.

Hierdie proefskrif beskryf navorsingsondersoeke na 'n verskuiwing vanaf hoogvakuum- of druksisteme na hoë lugvloeisisteme. Bevindings verkry uit verskeie laboratoriumskaalprojekte het getoon dat dit moontlik is om die voginhoud van fyn filterkoek tot so laag as 15% te verminder. Dit is vermag deur lug vrylik deur 'n filterkoek te laat vloei, selfs by omgewingstemperatuur, waardeur die gebruik van hoë toegepaste vakuumvlakke onnodig word. Daar was ook 'n toename in die ontwateringstempo, sowel as 'n laer deurbraakdruk. So 'n benadering maak die gebruik van bestaande toerusting, na klein aanpassings, moontlik.

Ander ondersoeke het getoon dat geforseerde lugdroging, beide by omgewings- en hoë temperatuur, gebruik kan word om hierdie meganiese limiet te bowe te kom. Weereens is 'n verhoogde lugvloei by omgewingsdruk gebruik. Deur lugdroging te gebruik, was vogvlakke tot by zero moontlik.

Hierdie ondersoek het tot die gevolgtrekking gelei dat verhoogde lugvloei deur fyn steenkoolkoek meer voordelig is as 'n toename in toegepaste vakuum, of 'n langer ontwateringstyd. Hierdie nuwe benadering om die uiteindelijke voginhoud van fyn steenkool te verlaag, is beslissend vir enige vooruitgang in die gebruik van hierdie grootliks-onbenutte energiebron.

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Chapter 1

Introduction

This thesis contains a collection of three accredited journal papers and three conference presentations published over the last five years on the topic of fine coal dewatering. These papers cover a range of related topics, from the fundamentals of dewatering, methods of dewatering, and finally to an argument for a new thinking in the technology of coal dewatering. Chapter 1 introduces the topic of coal and dewatering, and initiates the development of the new approach to fine dewatering.

Introduction and motivation

The flood of crude from fields around the world will ultimately top out, then dwindle. It could be 5 years from now or 30: No one knows for sure, and geologists and economists are embroiled in debate about just when the "oil peak" will be upon us. But few doubt that it is coming. "In our lifetime," says economist Robert K. Kaufmann of Boston University, who is 46, "we will have to deal with a peak in the supply of cheap oil." – National Geographic Magazine, June 2004.

Whether one accepts the above sentiment often featured in the popular press, or not, there can be no doubt that the future global energy picture is a bleak one. Considering petroleum and gas products (which make up about 62% of the world's energy sources), the estimates as shown in figure 1 illustrate the fact that this particular source of energy is fast approaching its maturity level.

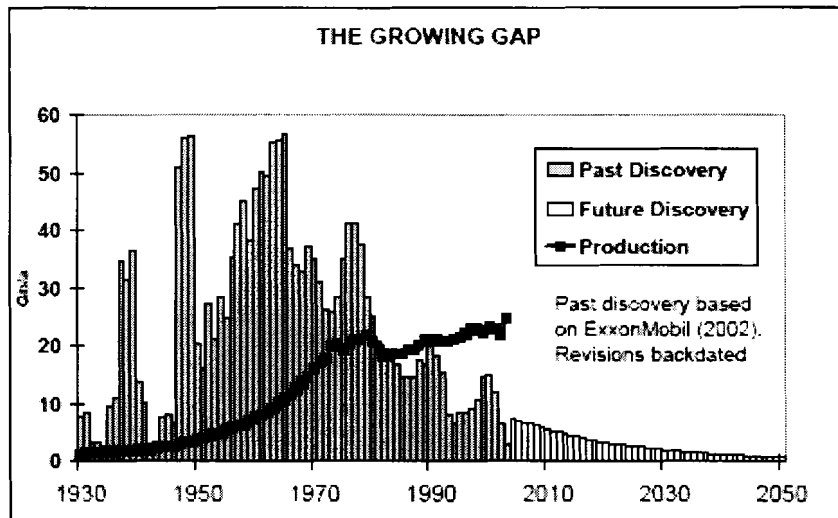


Figure 1: "The growing gap" showing the disparity between new global petroleum field discoveries and global consumption. (Association for the Study of Peak Oil and Gas Newsletter 28, December 2004. www.peakoil.net)

There is much debate about alternative or renewable energy sources. Technologies such as solar, wind, hydro and tidal energy are often presented as the solutions, but the facts are that, either through lack of current technology, or funding, or both, these technologies will not be able to sustain the energy demands of a future affluent world. Trainer (1996) stated, "Although renewable energy must be the sole source in a sustainable society, major difficulties become evident when conversions, storage and supply for high latitudes are considered. It is concluded that renewable energy sources will not be able to sustain present rich world levels of energy use ..."

The only reasonable future replacement for fossil fuel energy seems to be new generation nuclear energy (for example pebble bed reactors), but current political and environmental perceptions must first be overcome for this technology to be widely accepted.

In the interim, coal energy (currently contributing 26% of global energy needs – figure 2) is the only technology that is cheap, abundant and easy to use and transport. The current worldwide known coal reserves of 519 000 million tons (Department of Minerals and Energy, 2003) will be sufficient for our energy

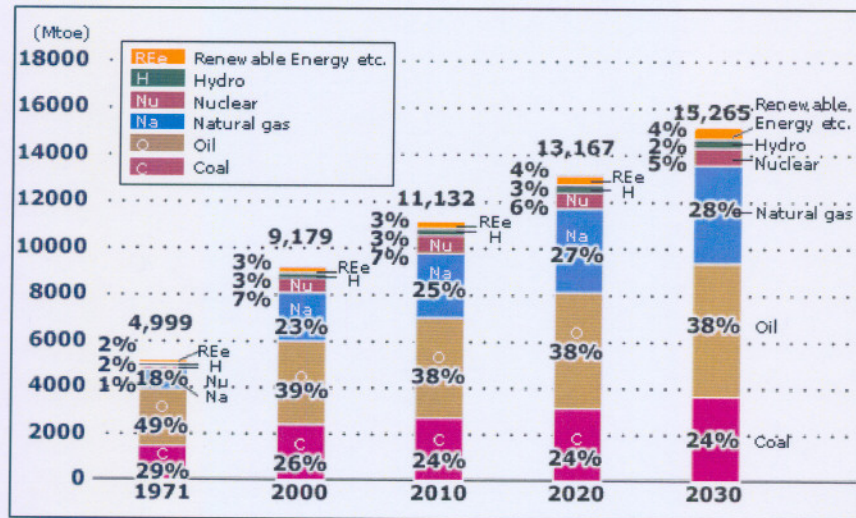


Figure 2: The future of global energy sources. (International Energy Agency, World Energy Outlook 2002, www.iea.org)

needs for another 130 years at current production levels*. While it is accepted that coal, like any other fossil fuel, does have a great negative affect on the environment (due to CO₂, NO_x and SO₂ emissions), there does not seem to be a suitable alternative for an energy source for the immediate future. With the advent of clean coal technologies, the short to medium term shortage in energy can be effectively filled using coal, provided it is well-managed and controlled from an environmental point of view. It is conceivable that at some time in the future, a truly safe and cheap renewable energy technology (probably nuclear) will have been established, but until then, we have to bridge the gap using coal to the best of our abilities.

The greatest challenge to energy researchers worldwide, and especially in South Africa, is to develop and maintain methods and technologies to optimise the current cheap coal resources to be used with the least possible impact on the environment.

* This figure is based on production tonnage only; diminishing quality was not considered.

The importance of coal as energy source in South Africa

South Africa is the world's 6th largest coal producer, with 220 million tons of saleable bituminous coal produced annually. Exports (mainly low ash coal) consist of 69 million tons. The estimated South African reserves are 55 000 million tons (Department of Minerals and Energy, 2003).

Power generation consumes 59% of local sales, with the remainder used for synthetic fuel conversion, metallurgical and other industrial uses (figure 3).

It is estimated that 12 to 14 percent of all run-of-mine coal produced in South Africa eventually reports to the fine fraction (Breed, 1992), defined in this thesis as material finer than 500 μm . The fines content in the produced coal has been increasing over the years due to the utilisation of mechanised mining methods.

Coal producers have a few options regarding the fines. In the past, economics dictated the practice of discarding fines and ultra-fines with the discard streams, or into tailings ponds. Since the high value of these fines had been recognised, it was either added to the product streams, or alternatively, upgraded and sold. The economic potential of coal fines has led to developments in fine coal beneficiation processes, like spirals and froth flotation. The major reason for not fully exploiting coal fines as an additional energy source was the high moisture levels found in the fine coal. Studies done on fine coal beneficiation plants showed it not to be uncommon for the coal to have a final moisture percentage

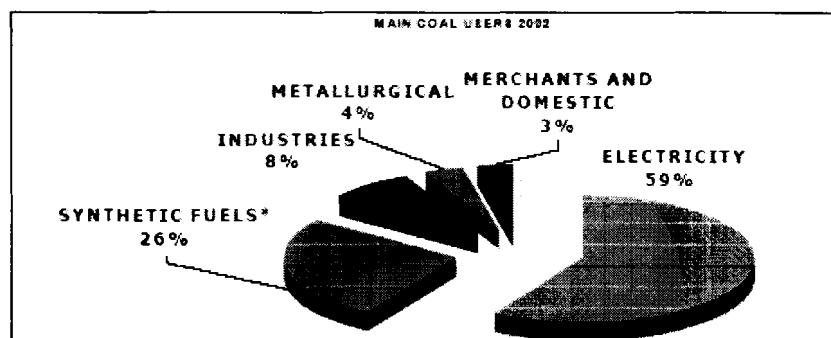


Figure 3: South African coal usage. (Department of Minerals and Energy, South Africa's Mineral Industry, 2002/2003)

(after dewatering) of up to 30 per cent, depending on the method of dewatering (De Korte, 2001).

By using an economical and technically effective dewatering technique, it is possible for the coal industry to turn this previous liability into an asset. The financial advantage is obvious, while added benefits include a positive impact on the environment and easier handling of the fine coal. This argument applies to both existing fines sources, as well as current arisings.

Moisture in coal

The water content of coal can originate from the coal bed (all of South Africa's mined coal seams lie below the water table) as well as from the beneficiation step. It is thus inevitable that water will be included in the final products. This moisture can have an adverse influence on meeting market specifications, it can cause problems with handling and will add to mass-based transport costs.

The nature of the moisture in coal is discussed in detail in the papers included in this thesis, but essentially moisture exists in coal as three identifiable states (Bourgeois et al., 1996; Rong, 1993).

- Free moisture refers to the water on the surface of a coal particle. This moisture accumulates in the inter-particulate voids of the porous cake. Most of this moisture can be removed from the filter cake by mechanical methods like filtration and centrifuging.
- The inherent or capillary moisture is the moisture within the pores of each individual particle. It consists of moisture held by the capillary forces in the smaller (meso and micro) pores. It is also known as intra-particulate moisture and can only be removed by using thermal methods.
- Finally, the chemically bound moisture is found in the chemical structure of the ash fraction of the coal, as crystal water for example. This moisture cannot be removed except by complete pyrolysis and thus, does not form part of the investigation and argument of this thesis.

While there are other classification systems for water in coal, (from fundamental thermodynamics, for example), these tend to be difficult to quantify because of the problems with analysis (Buckley & Nicol, 1995).

During the dewatering of any particulate bed of solids, one should distinguish between actual filtration step and the de-saturation step. The former entails the transport of a fluid through the bed and is well described by classical models such as Darcy's law. The latter starts once the supernatant water on top of a filter bed is removed and a two phase (air and water) flow occurs through the bed. The result of this is an overall reduction in the moisture content of the bed.

The capillary curve or de-saturation curve is a characteristic curve that describes mechanisms during the de-saturation of a porous substance. It is a plot of cake saturation (S) versus pressure drop (or applied vacuum) ΔP and an example is shown in figure 4.

According to Versluys (as cited by Buckley & Nicol, 1995), just before de-saturation starts (at complete saturation), moisture exists as inter-particulate

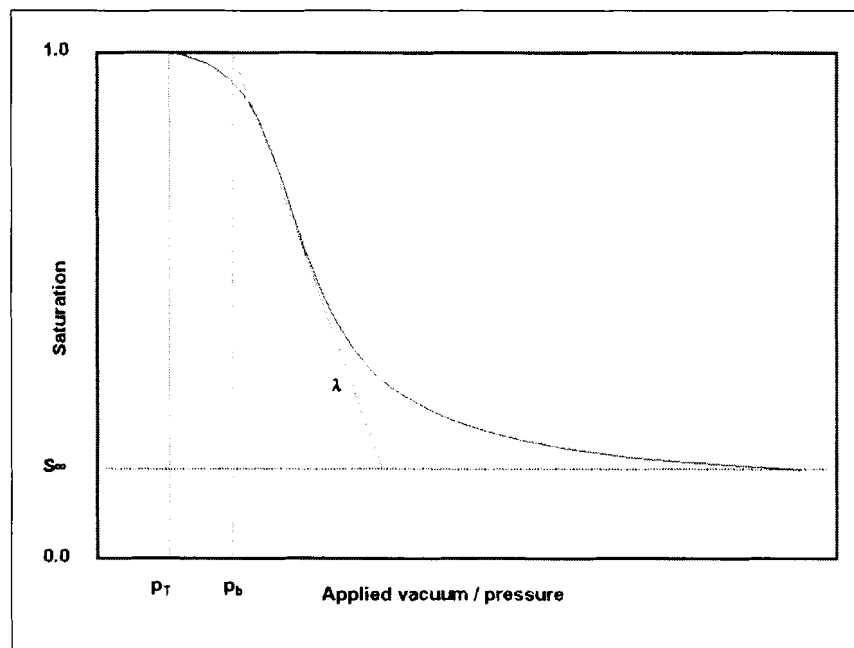


Figure 4: A typical de-saturation or capillary curve (Buckley and Nicol, 1995).

moisture in the *capillary state* and all the available inter-particulate spaces are completely filled with water. If air is introduced due to a driving force, like an applied vacuum or pressure, a threshold pressure difference, related to the capillary pressure, is needed to overcome resistance to flow of the water. The magnitude of this threshold is mainly due to surface tension forces, depending on the pore diameters. After this point, the rapid displacement of water by air occurs, and the *funicular state* is reached, where the air and water co-exist within the pore spaces. Water flows readily under the applied pressure or vacuum and is displaced at a high rate. This continues until all the funicular water is removed. At an even higher pressure, the *pendular state* is reached where liquid lenses of water exist at the inter-particle contact points, and this state represents the practical limit of mechanical dewatering. Moisture adheres to these points due to surface effects, and the contact angle of the water/solids system will determine the amount of retained liquid. Air simply passes through the pores without any further displacement of water. It is important to note that a higher vacuum or longer filtration time will not significantly reduce the saturation level beyond this point.

The research and results of the work described in this thesis will show that any future improvement in current mechanical fine coal dewatering techniques, like filtration, is unlikely to offer great benefits. Since current technology is very close to the limit of mechanical dewatering (as defined by the physical, chemical and thermodynamic factors describing the interaction of water on and inside fine coal particles), an alternative approach, such as thermal, or air blowing must be pursued.

Objectives of the study

The objectives of the study are discussed in each of the papers, but it can be summarised as follows:

- To investigate and understand the fundamental mechanisms by which moisture is held in coal;

- To investigate current de-watering technology, and establish the limits thereof;
- To investigate the effect of certain coal properties on the moisture content;
- To show that an alternative approach to dewatering is both possible and feasible at laboratory level;
- To investigate the details of the new approach and
- To demonstrate cases where the alternative approach has been implemented on a pilot scale.

Scope and contents of this thesis

In **Chapter 2**, an introduction is given to the topic of coal dewatering, particularly fine coal dewatering. The article, which was presented in 2000, gives an overview of the problems associated with the removal of moisture fine coal, and reviews the fundamental aspects regarding the nature of moisture in fine coal. The various states of dewatering (capillary, funicular, and pendular) are described and discussed. The Wakeman approach, using de-saturation curves, to develop a kinetic de-watering model is described, although the solution was not given due to the mathematical complexity of the problem. At the time that the paper was delivered, very little information and knowledge existed in the South African context, even though fine coal dewatering was shown to be one of the most important technical hurdles faced by the coal industry. An argument was thus made that much research was needed about this topic before any advances could be made.

In **Chapter 3**, the author addresses this plea by showing some initial results of a study on fundamental factors related to moisture in South African fine coal. The 2002 article investigates the relationship between the minimum attainable saturation level in a fine coal filter cake and some fundamental coal properties, like particle size and ash content.

After splitting coal samples into density and size ranges, saturation curves were determined for each coal size and density. From these, certain de-saturation properties, like maximum pore size (related to the breakthrough pressure), pore size distribution and the irreducible saturation, were deduced and related to particle size and density (essentially the ash content).

It was shown that coal quality played a major role in the moisture retention of fine coal. High ash coal contains less small pores, and this caused lower moisture retention. However, it was shown that particle size was the major factor influencing the residual moisture after vacuum filtration.

One very important result of the paper was a confirmation of a previously stated suggestion that cake structure played a greater part in the retention of moisture than surface effects (Rajan & Hogg, 1996).

Chapter 4 shows the results of a series of experiments leading to the first significant breakthrough in the study, and essentially the basis of the argument in this thesis. This paper, published in 2002, examines a phenomenon discovered earlier while performing routine capillary-curve determinations of various types of coal (as part of a continuation of the study described in Chapter 3, which was then suspended to pursue this new approach). It was observed that a sudden decrease and subsequent increase of the applied vacuum improved filtration performance significantly. Although the mechanism was not clearly understood at the time, indications were already there that some modification in cake structure (due to the sudden change in applied pressure) greatly improved the rate and efficiency of vacuum filtration. It was deduced that this modification gave rise to an improved airflow through the cake. The maintenance of a high and constant vacuum level was not as important as a higher airflow through the filter cake. A clear advantage was observed in using the approach where the flow rate of air through a filter cake was increased at the expense of applied vacuum.

A series of experiments where the applied vacuum was interrupted (i.e. the applied vacuum was stopped and released so that $\Delta P=0$) at various stages and

for different lengths of times, while capillary curves were being determined, confirmed that this was indeed what was happening. It was possible to decrease the final moisture percentage in a coal filter cake from 32 per cent, with no interruptions, down to 25 percent.* In addition, the rate of dewatering increased drastically, giving a drier final product in a much shorter time. The results showed that the drying time could effectively be reduced by approximately 60 per cent.

It was also shown that the effects were time-dependent. It was more advantageous to apply the structure modification during the funicular or middle stage of de-saturation. An optimum vacuum interruption stage was determined as 30 seconds into the dewatering cycle, lasting for 30 seconds.

To test whether the improvement was indeed due to a modification in cake structure, it was decided to deliberately damage the filter cake by using a metal spatula to make cuts in the cake surface. The results showed that a similar improvement in desaturation could be achieved, and that structural modification caused a higher airflow through the cake, which presumably displaced water more rapidly from the pores and channels in the cake.

This conclusion was pursued further and was the topic of the next paper (**Chapter 5**), that showed that mechanical damage to the surface of filter cake was indeed the cause of the increased airflow. A range of instruments, such as metal blades and rods were used to punch various patterns of perforations in the top layer of the cake while performing capillary-curve determinations. Significantly, it was found that it was only necessary to perforate the top 5 to 6 mm of the cake to achieve an increased airflow. This was probably due to a thin layer of fines at the top of the cake after natural sedimentation and deposition of particles during the formation of the cake. It was also shown that this top layer contained most of the fine material. This paper again confirmed the postulate, that increased airflow at a decreased applied vacuum improved

* Parekh (2006) mentioned that these filter cake moisture levels are more common with low ash coals, but this applies to US coals. According to the tests in this project, these moisture levels are achieved on high (45%) ash South African coals.

dewatering significantly. In this case, the final cake moisture level could be improved to 24% from about 30%.

The paper in **Chapter 6** was added to this thesis to illustrate other alternatives to mechanical dewatering, such as thermal drying. Although thermal drying was not a popular topic in South Africa at the time, it has been seriously reconsidered as a viable option lately, albeit on pilot scale. In this 2002 paper, the relationship between equilibrium moisture content and environmental relative humidity for thermally dried coal was studied and modelled. It was shown that thermally dried coal had a lower equilibrium moisture content than air-dried coal when exposed to the same ambient relative humidity and temperature. The tests were done for four coal types of different rank, although the range was limited due to the ranks available in South Africa.

This paper indicated that, while thermal drying was a potentially effective alternative fine coal dewatering method, there were still many problems associated with the technique. Some of the problems associated with thermal drying are dust explosions, high energy requirements, handling of wet material, and high capital requirements. Therefore, the inclusion of this paper does not reflect a view that thermal dewatering is a viable option, but rather to show that it was considered and rejected as an option.

Finally, all of the above information, findings and results are assimilated and used to present a case for a paradigm shift in considering the technology to use in fine coal de-saturation. This is done in the last paper (**chapter 7**). Building on the understanding, gained over the last five years of research, the arguments from the papers in chapters 3, 4 and 5 are presented here.

The limits of mechanical dewatering are real; in order to achieve lower final moistures, alternatives must be considered. The paper describes tests done during two case studies (of which one is on a pilot plant scale) that proved that fine coal could be more effectively dewatered by a high air-flow / low pressure drop system, rather than vice versa.

At high applied vacuum or pressure, the moisture in a packed bed exists in the pendular state. Due to the nature of the water in this state (under high pressure, as explained in Chapter 1), moisture in the pendular state is impossible to remove, except using thermal methods. This represents the limit of mechanical dewatering such as filtration. Any increase of vacuum (or pressure, for that matter) will not result in a significant improvement in moisture reduction.

If the state of moisture can be changed to the funicular state, at slightly lower applied vacuum or pressure, where water can be more rapidly displaced from the pores, a higher desaturation rate can be obtained. By modifying the cake structure, and simultaneously decreasing the applied vacuum, lower irreducible saturation levels can be attained.

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Chapter 2

Fundamentals of Moisture in Fine Coal

Dewatering and De-saturation of Fine Coal

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This paper was presented at the Annual SAICHE Conference held in Secunda, South Africa, from 8 - 12 October 2000, and was published in the conference proceedings. The article gives an overview of the problems associated with the removal of moisture in fine coal, and reviews the fundamental aspects regarding the nature of moisture in fine coal.

Dewatering and De-saturation of Fine Coal

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Abstract

The most important issue in coal processing today is the generation and handling of fines, both in the product and discard fractions. The dewatering of the fine coal fraction is of particular importance from operational, economic and environmental points of view. This paper describes the nature of water in fine coal and how it affects de-saturation by mechanical means. A fundamental kinetic filtration model is described, and is discussed in view of the current empirical dewatering and de-saturation filter sizing and design methods specific to a particular coal type and size. Work is being undertaken to reconcile these two extreme approaches by developing a usable model with easily determined parameters from physical coal properties.

Introduction

It is generally accepted that about 12% of the 280 million tons of ROM coal in South Africa (Department of Minerals and Energy, 1998) is smaller than 0,5 mm (defined as fine coal) and 2-3% is smaller than 0,1 mm (ultra-fine coal) (Breed, 1992). This figure had been increasing since the introduction of mechanised mining methods. Initially, fines and ultra-fines were dumped with the discard streams, but since the value of these fines had recognised, it has led to developments in fine coal beneficiation processes like spirals and froth flotation. The contribution of spiral products to annual exports has grown from nothing in 1985 to 8% in 1995 (Bunt, 1997).

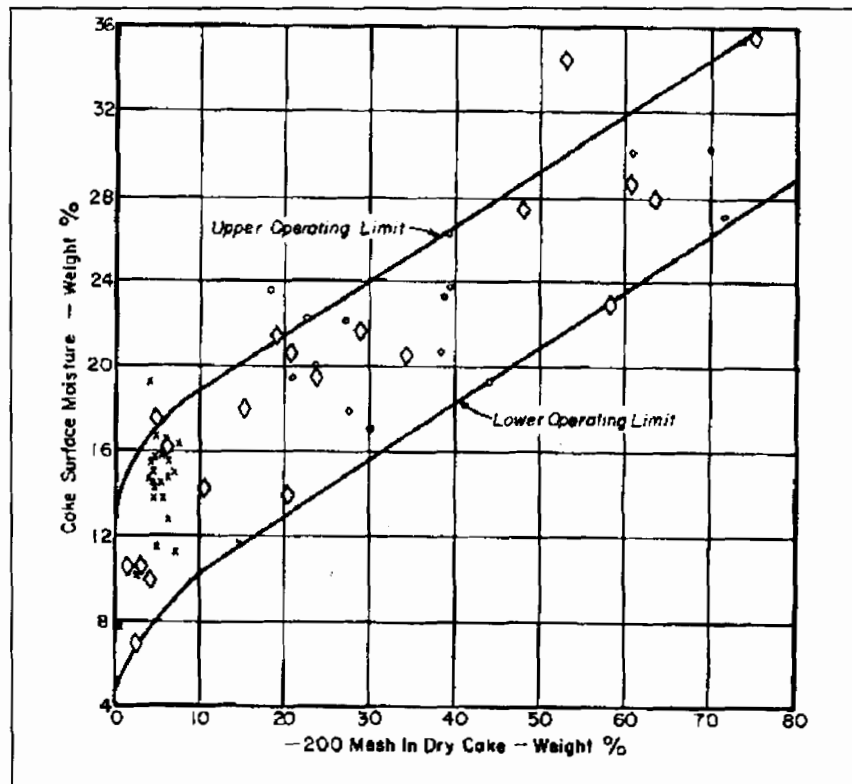


Figure 1: Filter cake moisture as a function of fines content (Parekh and Matoney, 1991).

Dewatering of coal is important because of the following factors: minimisation of transport costs, decreasing handling costs, increasing calorific values, and environmental restrictions. Quantification of these factors is difficult, but it is estimated that a 1% decrease in moisture increases the heating value by 1,4%. While total product moisture is between 2,5 and 4% (DME, 1999), the fine fraction can contain up to 25% moisture (Fourie & Wahl, 1998). Australian figures suggest that the fine and ultra-fine fractions contribute 50% of the total product moisture (Condie, Hinkel & Veal, 1996). It is well known that it is increasingly difficult to dewatering a coal product with a high proportion of fines (figure 1).

It is therefore surprising that so little fundamental research is being done in South Africa on the dewatering of fine coal. A literature search revealed only a few local publications on the topic, while more than 350 worldwide references were identified in a recent Australian study (Rong, 1993).

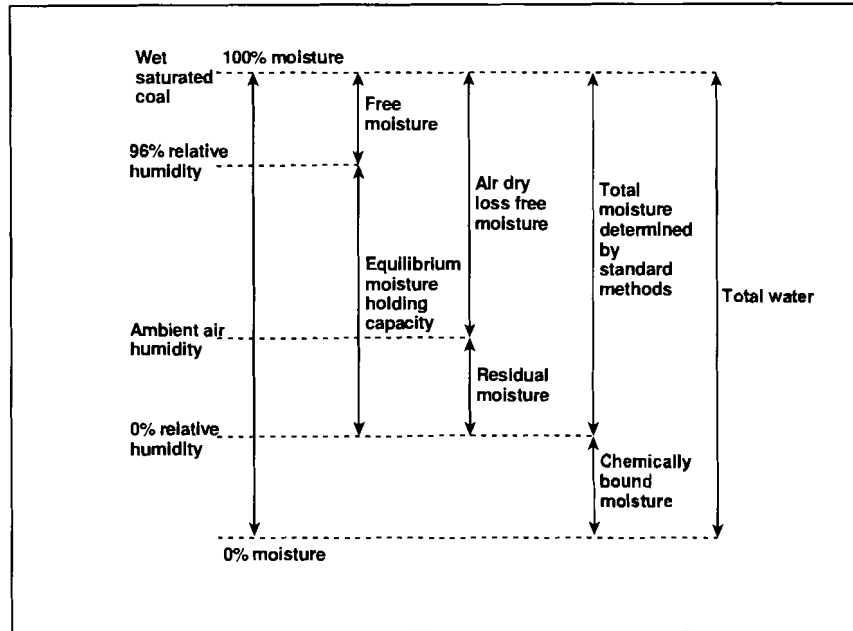


Figure 2: The nature of water in coal (Buckley and Nicol, 1995).

Current Dewatering Practices

Little data is available for the few South African operations that process fines, but an analysis of available data (DME, 1999) shows that spirals are used at 13 operations, and flotation at three plants (including anthracite producers). A description of the dewatering processes used at these plants is not readily available in the literature, and will be the topic of a future survey. In Australia, disc / drum vacuum filters and screen bowl centrifuges are the main dewatering techniques used, with product moisture contents of 21-25% and 14-17% respectively (Rong & Hitchins, 1993). For tailings dewatering, pressure filters were found to be superior. One interesting fact emerging from the Australian study was that the equilibrium moisture content (achievable by mechanical means under ideal conditions) was as low as 1,3 to 5,8%.

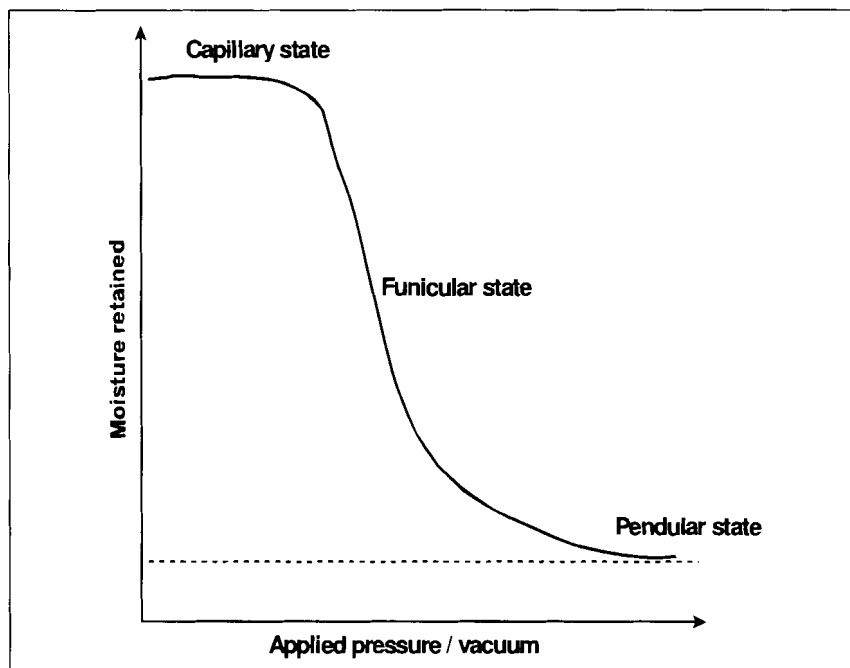


Figure 3: The relationship between cake moisture and applied pressure / vacuum (Buckley and Nicol, 1995).

The Nature of Water in Coal

The total water in coal can be, from fundamental thermodynamics, classified as *interacting moisture* and *non-interacting moisture*, but due to the difficulty in distinguishing this classification; it is more common to classify the type of moisture (somewhat arbitrarily) according to the relevant analysis standards (Buckley & Nicol, 1995). Figure 2 shows that a fraction of the total water in coal consists of *chemically bound* moisture, i.e. crystal water mainly associated with the adventitious mineral matter in the coal. This moisture can only be released by pyrolysis, and is, for practical purposes, excluded in any discussion on the mechanical or thermal dewatering. It is not considered part of the remaining *total moisture*, which can be analysed by standard methods. Total water consists of *air dry loss free moisture* (determined as the moisture lost by drying for three hours at 40°C) and *residual moisture* (determined by further drying to constant mass at 105° - 110°C). Another frequently used standard is the *moisture holding capacity* (the equilibrium moisture at 96% relative humidity)

and the remaining *free moisture*. Only this free moisture can be removed by mechanical means.

During filtration (and more specifically, de-saturation), free moisture exists as inter-particulate moisture in three states depending on the applied vacuum or pressure (Versluys, 1917) (see figure 3): water in the *capillary state* exists at low applied pressure or vacuum when all of the available inter-particulate spaces are saturated with water. Some pressure (capillary pressure) is needed to overcome resistance to flow of the water. At higher pressure or vacuum, and as the displacement of water by air proceeds, a *funicular state* is reached, where the air and water exist as a continuous network within the pore spaces. The water flows easily under applied pressure or vacuum, and is shown as a steep gradient of the line in figure 2. The *pendular state* is reached as discrete liquid lenses are formed in the inter-particle spaces, and this state represents the practical limit of mechanical dewatering. Air simply passes through the pores without any further displacement of water.

Modelling Dewatering and De-saturation

The modelling of filtration of any particulate material can be divided into two steps. During the first (or cake formation) stage, vacuum or pressure is applied to remove excess waters from the feed slurry to produce a saturated filter cake with all the inter-particulate pores filled with water in the capillary state. Provided the cake is incompressible, this step is easily and accurately described by Darcy's Law (Condie & Veal, 1998). Assuming that the resistance through the filter medium is negligible compared to the cake resistance, this law reduces to the well-known filtration equation:

$$\frac{t}{V} = \frac{K\eta}{2A^2\Delta P}V$$

where V is the volume of filtrate produced, t is the filtration time, K is the filter cake permeability, ΔP represents the applied pressure over the cake, η is the filtrate viscosity and A is the filter area.

The second stage of cake de-saturation starts when air is being drawn into the cake, displacing the filtrate from the pores and thus decreasing the overall saturation of the cake. Air breakthrough occurs near the end of this stage when a mixture of air and filtrate flows from the cake. Provided no cake cracking occurs, filtrate is then still being removed from the cake, but at a very low rate. The kinetics of the de-saturation stage depends mainly on the cake structure and particle size distribution, while coal surface properties have very little influence (Bourgeois et al, 1996). One attempt at modelling the kinetics of de-saturation assumes the cake to be a bundle of tubular capillaries of different diameters (Wakeman, 1976). The larger diameter capillaries would de-saturate at a higher rate, and would reach the pendular state first, while the smaller ones would follow. A particularly important experimental parameter is the pore size distribution index, which determines the ultimate equilibrium saturation. The relationship between the applied pressure and the capillary characteristics is given by:

$$S_R = \frac{S_e - S_\infty}{1 - S_\infty} = \left(\frac{P_b}{\Delta P} \right)^\lambda$$

where S_R is the reduced equilibrium saturation, S_e is the equilibrium saturation for a given pressure, S_∞ is the irreducible saturation at infinite pressure and time, λ is the pore size distribution index, ΔP is the applied pressure and P_b is the breakthrough pressure (at which point the capillary pressure of the pores are overcome to cause filtrate to start flowing from the cake).

The kinetics of de-saturation can be modelled by the simultaneous solution of four partial differential equations describing the material balance and flow of air and filtrate (Wakeman, 1979).

$$v_L^* = -S_R^{(2+3\lambda)/\lambda} \frac{\partial p_L^*}{\partial(x/L)}$$

$$v_a^* = -(1 - S_R)^2 (1 - S_R^{(2+\lambda)/\lambda}) \frac{\partial p_a^*}{\partial(x/L)}$$

$$\frac{\partial S_R}{\partial t} = -\frac{\partial v_L^*}{\partial(x/L)}$$

$$\frac{\partial \{\rho_a(1 - S_R)\}}{\partial t} = -\frac{\eta_L \partial(\rho_a v_a^*)}{\eta_a \partial(x/L)}$$

where p^* and v^* denote the reduced pressure and reduced volumetric flow rate of the air and water phases (denoted by the subscripts a and L respectively), L is the cake thickness, and x and t are distance and time dimensions.

The solutions to these equations are not trivial, and require complex numerical techniques.

The results of Wakeman's model does not describe the fine coal system very well, because of the complexity of the filter cake structure, and the difficulty of experimental determination of the parameters needed in the model. In particular, thin cakes and high vacuum conditions could not be adequately modelled (Condie, Hinkel & Veal, 1996).

The complexity of the model is in sharp contrast with the current filter sizing methods based exclusively on empirical data specific to each coal type and particle size (Bourgeois, 1999).

Future Research

A great advance will be made if the two modelling approaches can be combined to yield a more robust and widely applicable model of de-saturation. The kinetic description is important because, as was discussed earlier, filter plants operate very far from to the equilibrium cake saturation level (only achievable at very long filtration times under ideal conditions). The greatest benefit will be achieved by the improvement of filtration kinetics during the earlier stages of de-

saturation while in the funicular state. A better understanding of the governing factors like coal properties is needed to optimise this stage.

Acknowledgments

The author would like to thank the Director and staff at the Julius Kruttschnitt Mineral Research Centre in Brisbane, Australia, for assistance and access to information.

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Additional notes

It was clear from the literature research done for this paper, that the fundamental understanding of the nature of moisture absorbed into and adsorbed onto a complex structure such as coal, was the topic of many research projects. The models to describe the kinetics and equilibrium of moisture in coal are almost entirely empirical, which is indicative of the complexity of the problem.

The determination of the desaturation curve, as described in this paper, is probably the most useful way to understand the moisture desorption mechanism of a specific coal sample, and it is the basis of the Wakeman approach (Wakeman, 1979) to predict the desaturation behaviour of a moist filter cake. Unfortunately, the Wakeman equations have proved very difficult to solve. Subsequent work (Condie, Hinkel & Veal, 1996) was based on the digitization of the original published curves and then deriving kinetic models from these.

The inability to solve the Wakeman equations is not necessarily critical. Enough information can be obtained from desaturation curves to understand the kinetics of dewatering, even if it cannot be quantified. The determination of desaturation curves was the method used to generate most of the data used in subsequent work done for this thesis, and the entire argument presented in this thesis is based on data from desaturation curves.

Chapter 3

Effect of Coal Properties on Moisture in Fine Coal

The Influence of Coal Quality on the Dewatering of Fine Coal by Vacuum Filtration

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This peer-reviewed paper was presented at the XIV International Coal Preparation Congress held in Sandton, South Africa from 11 – 15 March 2002, by the South African Institute of Mining and Metallurgy and was published in the conference proceedings (pp. 199 – 202). The article investigated the relationship between the ultimate irreducible saturation level in a fine coal filter cake and some fundamental coal properties.

The Influence of Coal Quality on the Dewatering of Fine Coal by Vacuum Filtration

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Synopsis

Fine coal generation has increased over the years due to changing mining and handling methods, and newer beneficiation processes like flotation. Fine coal is more difficult to de-water than the coarse fraction by mechanical means, like vacuum filtration. While the effect of size is usually tested in traditional filtration test work, coal quality is usually expressed as feed ash by a single cumulative value. However, it makes use of a fraction of the information available in a washability table that would be particularly valuable for predicting performance that can be expected from various coal sources and blends. The relationship of the size and washability data to the de-saturation profiles of different coals could be used to extend existing fundamental two-phase flow models of vacuum filtration. The general objective of the study is to quantify the de-saturation characteristics of South African coals. This will be achieved by the characterisation of the de-saturation properties of different coals in their different size and washability classes. To date, coal from Sigma Colliery had been quantified in this way.

Introduction

It is estimated that about 12 percent of all ROM coal produced in South Africa reports to the 'fines' fraction,^{1,2} defined in this paper as material finer than 500 μm . This material is either sold untreated and blended into the product, or it is discarded to slimes and waste dumps.^{2,3} While a valuable resource is being wasted in this way, the difficulties of fine coal processing are well known.^{4,5} Of

these, the dewatering of the fine product to acceptable levels remains the greatest challenge. Dewatering of coal is important because of the following factors: minimisation of transport costs, decreasing handling costs, increasing calorific values, and environmental restrictions. While the total product moisture is between 2,5% to 4%, the fines fraction can contain up to 25% moisture.⁶

During de-saturation, free moisture exists as inter-particulate moisture in three distinct states depending on the applied vacuum or pressure:⁷ water in the capillary state exists at a low applied vacuum when all the available inter-particulate spaces are saturated with water. If air is to be introduced, some threshold pressure difference, related to the capillary pressure, is needed to overcome resistance to flow of the water. This pressure is mainly due to surface tension forces, and its magnitude depends on the pore diameter, as given by equation 3. At higher pressure or vacuum, and as the displacement of water by air proceeds, a funicular state is reached, where the air and water co-exist within the pore spaces. While in this state, water flows easily under applied pressure or vacuum, which is larger than the capillary pressure, and water is displaced at a great rate. At very high pressure, the pendular state is reached as liquid lenses of water exist at the inter-particle contact points, and this state represents the practical limit of mechanical dewatering. Moisture adheres to these points due to surface effects, and the contact angle of the water/solids system will determine the amount of retained liquid. Air simply passes through the pores without any further displacement of water. A higher vacuum or longer filtration time will not significantly reduce the saturation level beyond this point.

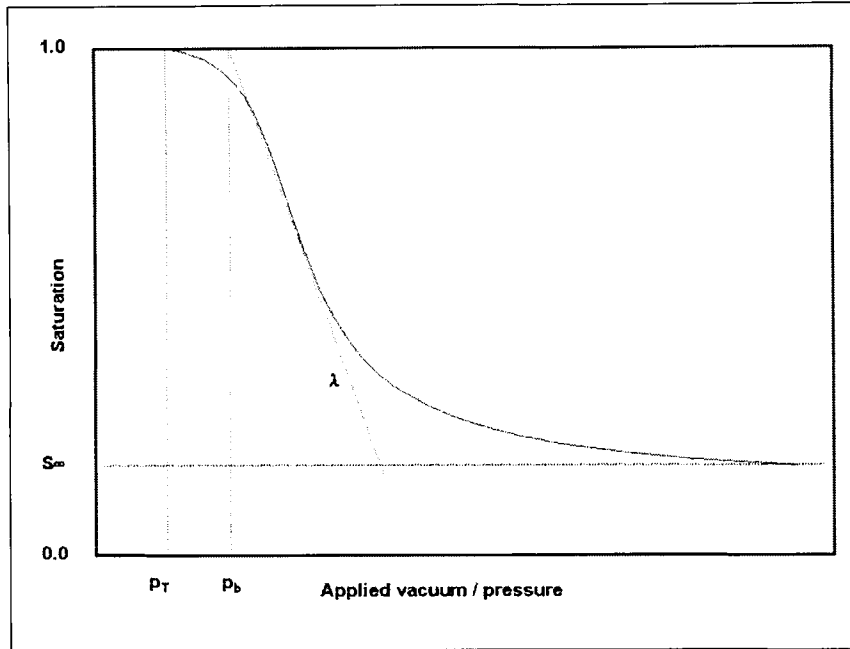


Figure1: A typical capillary curve

The de-saturation curve is a characteristic curve that describes the above states in a particulate cake with a distribution of pore sizes.^{8,9} It is a plot of cake saturation (S) versus pressure drop (or applied vacuum) ΔP , and an example is shown in Figure 1. The important features of the curve are: the threshold (p_t) and modified threshold pressures (p_b), the irreducible cake saturation S_∞ , and the slope λ . The curve can be described as:

$$S_R = \left(\frac{\Delta P}{p_b} \right)^{-\lambda} \quad [1]$$

where S_R , the reduced saturation, is a normalised saturation number using:

$$S_R = \frac{S - S_\infty}{1 - S_\infty} \quad [2]$$

The de-saturation curves contain a wealth of information regarding the de-watering of filter cakes. The breakthrough pressure (or modified threshold pressure) p_b and the pore size distribution index (λ) gives an indication of the largest pore diameter and the distribution of pore sizes, while the irreducible cake saturation represents the physical limit of de-saturation by mechanical means. Factors like particle surface characteristics, meso- and micropores, and mineral matter type can influence S_∞ .^{10,11}

Table I: Size and density fractions used in the test work.

Size fractions (μm)	Density fractions (g cm^{-3})
-100+710	+1,80
-710+500	-1,80+1,70
-500+355	-1,70+1,65
-355+212	-1,65+1,60
-212+150	-1,60+1,55
-150+75	-1,55+1,50
-75	-1,50+1,40
	-1,40

The most widely used de-saturation model, by Wakeman,^{12,13,14,15} makes use of the three parameters mentioned above as inputs. Any modelling of de-saturation must be preceded by the experimental determination of these parameters. Since these would vary widely depending on coal type, geographical origin, and particle size, some attempt was made to look for correlation with other physical data. One source of information is the size-washability data that is available for most coals.

It is hypothesised that by understanding the correlation contained within these size-washability tables, one can extrapolate a wealth of de-saturation data to aid the modelling and understanding of fine coal filtration.

Experimental Procedure

A dry fine coal sample of 'conveyer belt fines', originating from fines generated throughout the plant prior to washing, was obtained from Sigma Colliery. The samples were crushed and screened into seven different size fractions (Table I) using 450mm laboratory sieves. The three finest fractions (below 212 μm) had to be wet screened, filtered and dried in a furnace at 105 degrees for six hours.

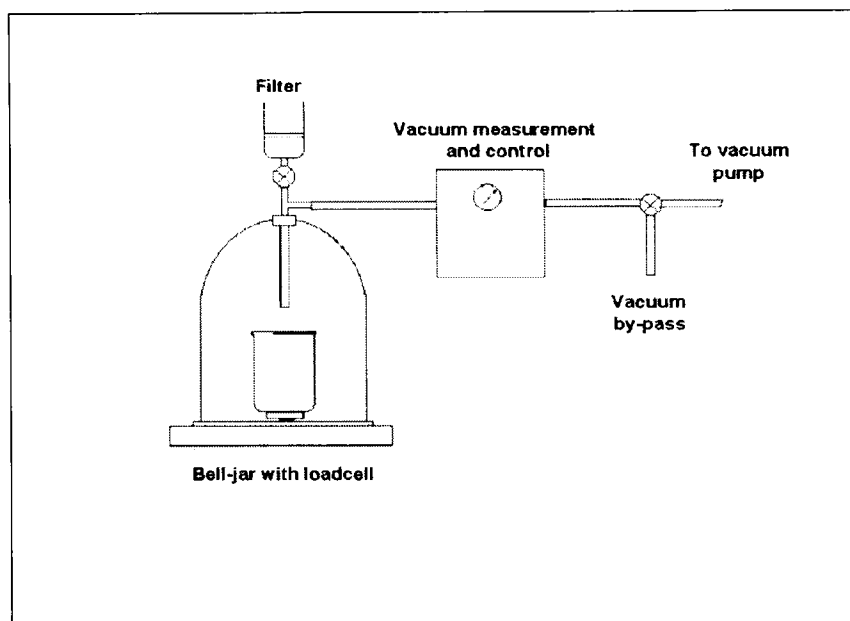


Figure 2: Experimental set-up

The dry sized coal samples were then divided into density fractions by adapting the standard float and sink procedure. A tetra-bromo-ethane (TBE) and toluene mixture was used as a dense medium in which the material was separated into eight density fractions (Table I). The products were thoroughly washed with water to remove most of the organic liquids, and then filtered and oven dried.

Figure 2 shows the filter test apparatus that was designed and built for the test work. A 47mm Millipore glass filter was mounted on a vacuum bell-jar that contained a filtrate receiver on a load cell. Millipore MF Disk MCE 0,1 μm filter membranes were used throughout. The vacuum driving force was applied, measured and controlled through a control panel connected to a vacuum pump. This meant that filtrate volume and vacuum readings could be logged on line.

Initial tests on clear water showed that the filter membranes became fouled very rapidly and hence the resistance increased during this time. For this reason each filter membrane was fouled intentionally by filtering potable water through the membrane at 40 kPa until the filtrate flow rate reached steady state (usually after about 30 minutes). This ensured a constant medium permeability.

About 20 grams of coal was thoroughly mixed in water to remove any air bubbles, introduced into the filter and allowed to settle under gravity for about 20 minutes to form a 'natural' cake structure. Vacuum was then applied at about 40 kPa and the supernatant water was filtered through the cake. Towards the end of the run, readings were taken to determine the Darcy permeability of the cake. The starting point of the capillary curve determination test (i.e. complete saturation or $S=1$) was taken to be the point where no visible supernatant water could be observed on top of the cake. At this point, the vacuum was set to a very low level (5 - 7 kPa). This level was maintained for five minutes, and the total volume of filtrate displaced during this time, was recorded. The interval was long enough to ensure that no further filtrate could be produced at the particular vacuum level. The vacuum was then increased in steps of about 5 kPa, and the same procedure was repeated until the vacuum reached about 75 kPa. The capillary curve could be determined by calculating the saturation in the cake at the end of each five-minute interval versus the corresponding vacuum setting. The residual saturation in the cake after dewatering at the highest vacuum level was determined by the mass difference before and after vacuum oven drying for at least 1,25 hours at 110°C.

Results and Discussion

For each data set, the model as given in equation [1] was fitted and the values for P_B , λ and S_∞ were determined. Figure 3 is one example of these curve fits, showing the experimental data as well as the fitted model. The relationships of the fitted parameters to the particle size and relative density of each sample are shown in figures 4 to 6. For clarity, only three of the size intervals are shown in the results.

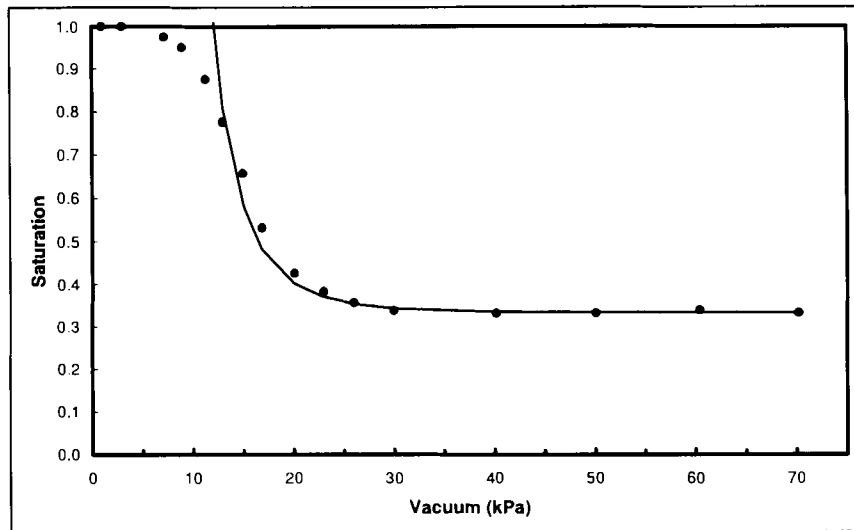


Figure 3: An example of an actual capillary curve with Equation [1] fitted to the data

Figure 4 shows that the breakthrough pressure is higher for fine coal only, and that the quality of coal has no influence. This was expected, because of the relationship of the breakthrough pressure to the diameter of the largest pores, as given by¹⁵

$$p_b = \frac{\alpha \gamma \cos \beta (1 - \epsilon)}{d_k \epsilon} \quad [3]$$

where γ and β are the air/liquid interfacial tension and the coal/water contact angle respectively, and ϵ is the cake porosity. The Kozeny pore diameter is given by d_k and α is a correction parameter, usually having the value 4.6.

Little information can be gained from figure 5 in terms of the pore size distribution. There seems to be no effect due to particle size, and differences in the three curves are within the estimated error of measurement and analysis. However, a downward trend in the value of λ with increasing relative density is apparent. As the mineral content of the coal becomes higher, the pores become more similar in size. This is due to the absence of the intra-particulate pores in minerals as opposed to coal particles. The value of λ for coal is usually assumed⁶ to be approximately 5, and this is confirmed by figure 5. The high λ values at RD 1.85 remain anomalous.

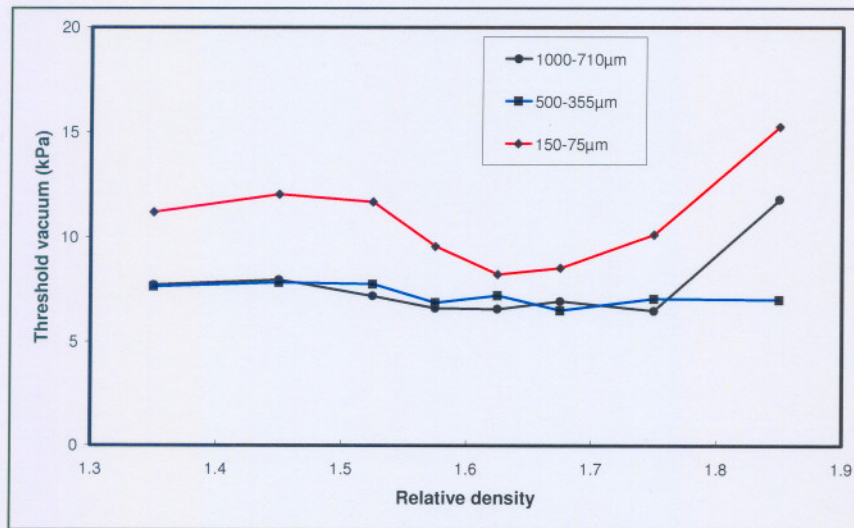


Figure 4: The breakthrough pressure as a function of particle size and relative density

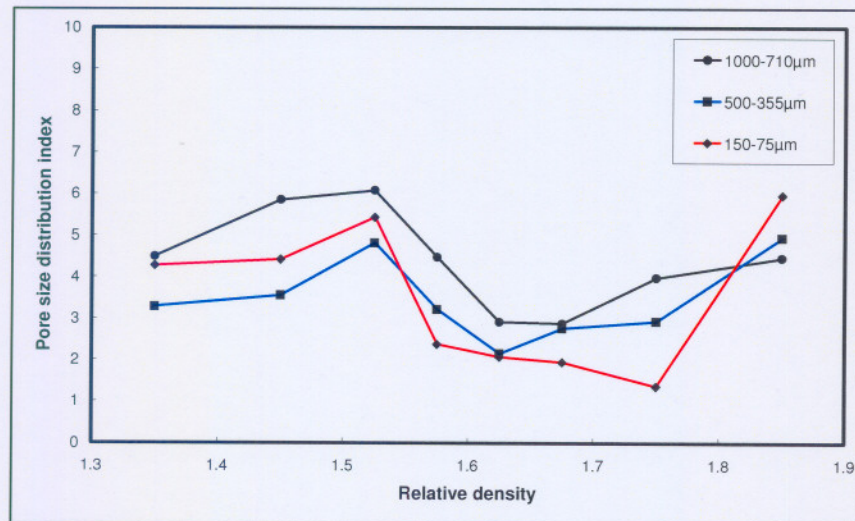


Figure 5: The pore size distribution index as a function of particle size and relative density

Figure 6 shows that the irreducible saturation depends on density only for the larger particles. The moisture represented by the irreducible saturation consists of a combination of inter-particle water in the pendular state and water contained in the very small intra-particulate pores. This type of curve does not yield much information on its own, since, by definition, saturation depends on structural factors like porosity. Figure 7, showing the final moisture content of the cakes, is more useful in trying to understand the type of water retention mechanism. It confirms that moisture retention after filtration is more size

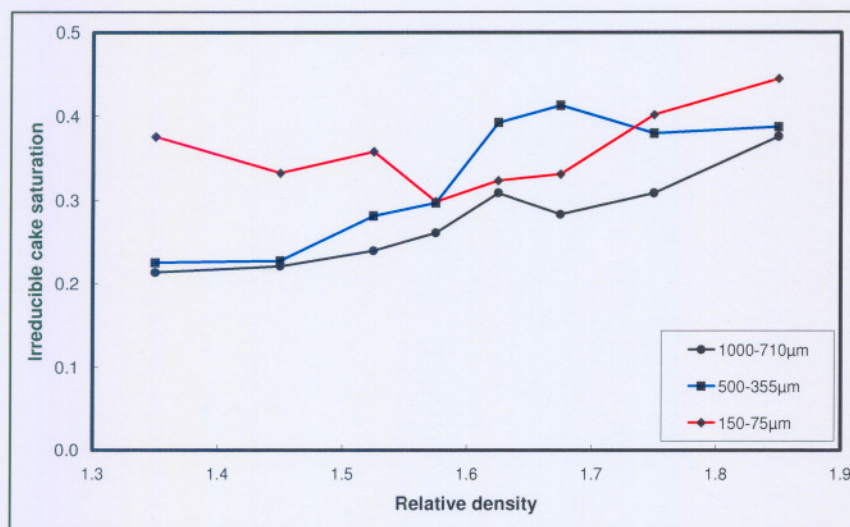


Figure 6: The irreducible cake saturation as a function of particle size and relative density

dependent for cleaner coals than for the high ash fraction. The intra-particulate pores are expected to exist in the cleaner coal fractions only, thus the moisture levels are slightly higher. Here, moisture is found in both the small intra-particulate pores as well as between particles, while at the high density moisture is in the pendular state only. Clearly, these will be affected by factors like cake porosity. The fact that cake structure, as opposed to surface and hydrophobic effects, is the major contributor to moisture retention had been shown with previous test work.¹⁶ Some manipulation of the data in figures 6 and 7 gives good insight into the porosity of the cake, but that discussion is beyond the scope of this article*.

Conclusions

The capillary curve is a useful method to determine parameters that can be used in the modelling of de-saturation processes. These parameters can also be interpreted to give useful information regarding the cake structure and pore sizes.

* The determination by calculation of the porosity is discussed in the notes on page 39.

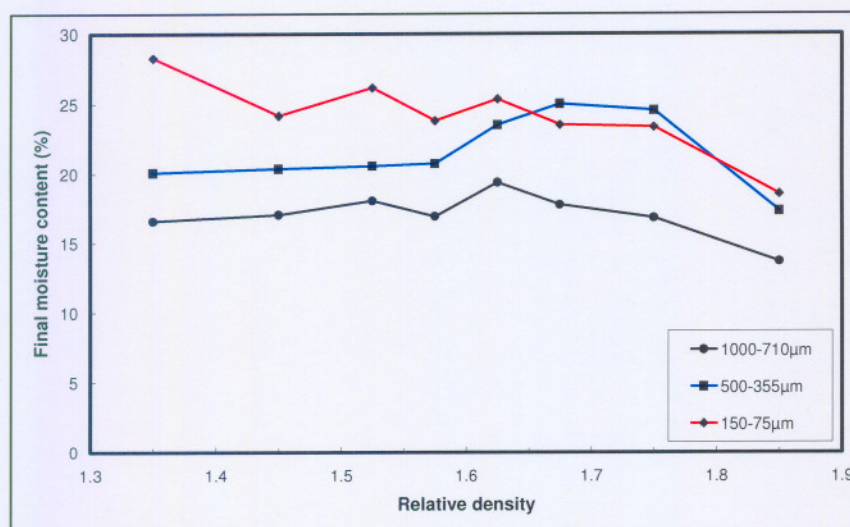


Figure 7: Final cake moisture as a function of particle size and relative density

It was shown that there was a difference in the moisture retention of fine coal depending of the coal quality. High ash coal contains less small pores, and the pore size distribution is more uniform. The distribution index value used in literature was confirmed. The absence of small pores in high ash coal also caused lower moisture retention.

Particle size is still the major factor influencing the residual moisture after vacuum filtration, but coal quality does have an influence as well. Size effects are more pronounced with particles smaller than 150 µm.

The collection of more data using different coals will enable researchers to clearly define the state of the residual water. Empirical information about the suitability of vacuum filtration can also be gained by using this type of analysis. This will be especially useful in the evaluation of possible dump re-treatment projects.

Future work will include accurate measurement of cake porosity and intra-particle porosity, and also proximate, ultimate and maceral analyses of the different coal fractions.

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Additional notes

After determining the usefulness of the desaturation curve determination in Chapter 2, this technique was applied here to generate information about which of the physical coal properties had an influence on desaturation.

It was found that the breakthrough pressure (related to the largest pore size) depended largely on the size of the coal particles, and not on the quality in terms of ash content (figure 4). The values obtained, showed that an applied vacuum of about 8 to 12 kPa was sufficient to initiate desaturation, and this was much lower than the values usually found in industry (more than 30 kPa). This fact strengthens the argument, made later in this thesis, that a lower applied vacuum will not necessarily negatively influence efficient desaturation (if associated with an increased airflow, of course).

The paper also confirmed the value of an irreducible saturation level of between 0,2 and 0,4 (figure 6) beyond which no increased application of any higher vacuum will show any effect. Figure 3.1 below shows a recalculation of the data on figure 6 to show final moisture content rather than saturation level. These results show about 15% residual moisture for the 1000 – 710 μm material, and 30% moisture for the 150 – 75 μm material, which is remarkably close to the

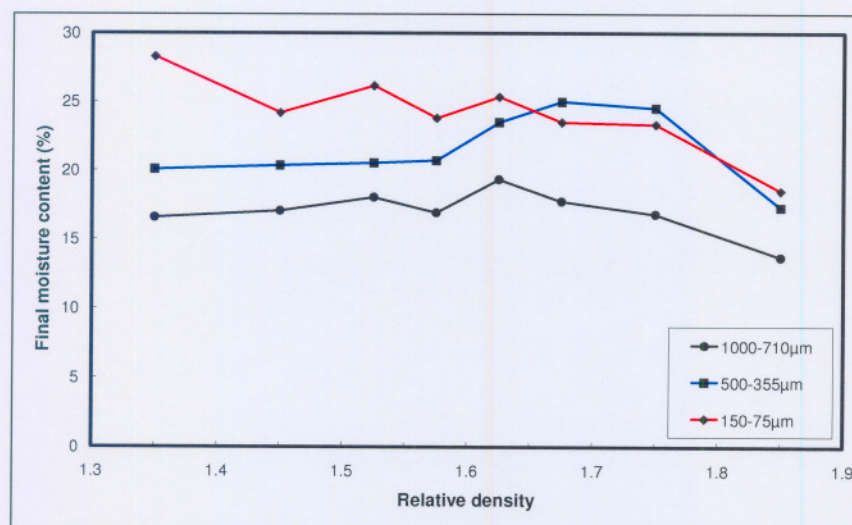


Figure 3.1: Final cake moisture as a function of particle size and relative density

limits currently experienced by vacuum filters in industry. This result confirms that any improvement in moisture levels cannot be attained by current mechanical techniques, even if a higher vacuum can be applied.

The results in this paper were obtained with material from one coal source (Sigma Colliery) only, but it was part of a planned study that would include other sources as well. It was during the determination of desaturation curves of other coal sources that the breakthrough came, as described in the next paper (Chapter 4). Because of the new approach taken after this breakthrough, further work on the relationship between desaturation parameters and physical coal properties was postponed. Planned investigations, like error analyses, analyses of pore sizes and ultimate and mineral analyses, were therefore not done.

An interesting (but unrelated) result of this work was the ability to calculate an estimate of the porosity of the filter cake from saturation and moisture data. By assuming that at $S=1$, all the available pores of all sizes are filled with water, and then back calculating the moisture content at that stage from the total volume of displaced filtrate measured during desaturation, one may deduce the volume of water filling the pores at $S=1$. Using the bulk cake volume (which is easily measured), the volume fraction of pores can then be calculated. Of

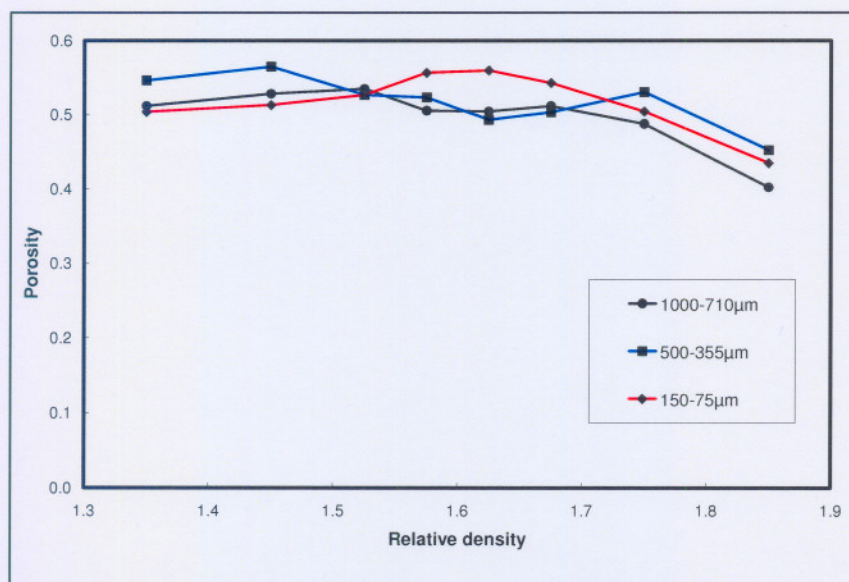


Figure 3.2: Calculated cake porosity as a function of particle size and relative density

course, the method is not very accurate, since visual observation determines the point $S=1$, but it was interesting that porosity values of between 0,4 and 0,6 were found, depending on the ash content of the cake (figure 3.2). High ash coal is expected to have less pore volume, because the ash component does not contain the same degree of meso and micropores as the coal itself.

The accuracy of the recorded filtrate mass data was estimated to be 10%, because the load cell had a range of 1 500 g, and was certified accurate to 0,001g. Vacuum measurements were made electronically to within the same error. The only inaccurate measurement in the experiment was the visual confirmation at which point 100% saturation occurs. However, this point will not influence the conclusions significantly, since it will only move the capillary curve up and down along the vertical axis.

More details about the experimental results, referred to in this paper, are given in Appendix A.

Chapter 4

Improving the De-Saturation of Fine Coal

An Investigation into an Improved Method of Fine Coal Dewatering

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This paper was presented at the Solid-Liquid Separation '02 Conference held in Falmouth, United Kingdom from 18 - 20 June 2002, and was subsequently peer reviewed and published in Minerals Engineering, Vol. 16 (10), October 2003, pp. 999 – 1003. The article describes a major advance made in the process of vacuum dewatering of fine coal.

Relative contributions by authors

M. le Roux was a postgraduate student working on this project under the leadership of Q.P. Campbell. The direction and scope of the study, planning of the parameters to be investigated experimentally, and the design of the experimental apparatus was the responsibility of Mr Campbell. Mr le Roux performed all the experiments, data recording and calculations. The conclusions about the reasons for the observed improvements resulted from long discussions between the authors. After Mr Campbell presented the data at an international conference, the paper was jointly written by le Roux and Campbell.

An Investigation into an Improved Method of Fine Coal Dewatering

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Synopsis

An improved method of dewatering fine coal ($-500\text{ }\mu\text{m}$) by vacuum filtration was developed. Tests on a bench scale vacuum filter showed that when the applied vacuum was interrupted during the dewatering cycle, a lower final moisture content could be achieved. There was also an increase in the dewatering rate, as well as a lower breakthrough pressure. Further investigation showed that if the filter cake was intentionally damaged (causing for an increased air flow rate, and a decrease in applied vacuum), a product with lower final moisture and an increase in the dewatering rate was obtained. This led to the conclusion that increased air flow through a filter cake was more advantageous than an increase in the applied vacuum.

Introduction

South Africa has large coal reserves, and is one of the world's leading producers and exporters of coal. The country currently produces approximately 290 million tons of ROM coal per annum. Of this, about 14 per cent is thought to be finer than $500\text{ }\mu\text{m}$ (defined as fine coal in this text) and 2-3 per cent finer than 100 microns (ultra-fine coal) (Breed, 1992). The fines content in the ROM had been increasing in recent years partly due to the introduction of mechanised mining methods. Coal producers have a few options as to what to do with the fines. Initially, fines and ultra-fines were dumped with the discard streams or tailings ponds, but since the value of these fines had been

recognised, it was either added to the product streams as is, or alternatively, upgraded and sold.

The economic potential of coal fines has led to developments in fine coal beneficiation processes, like spirals and froth flotation. The major reason for not fully exploiting coal fines as an additional energy source is the high moisture levels found in the fine fractions of coal. By using an economical dewatering technique, it is possible for the coal industry to turn this previous liability into an asset. The financial advantage is obvious, while added benefits include a positive impact on the environment, and easier handling of the fine coal.

Background

Moisture exists in coal as different states. This description was quantified by Rong (1993) while defining the different types of moisture as follows:

- Surface or free moisture refers to the water on the surface of a coal particle. Hence, when a filter cake is formed, the free moisture will accumulate in the pores of the filter cake (inter-particle moisture). Most of this moisture can be removed from the filter cake by mechanical means like filtration and centrifuging.
- Inherent or capillary moisture is the moisture allocated within the pores of each individual particle. It is also commonly known as intra-particle moisture, and can only be removed by using thermal methods.
- Chemically bound moisture is found in the chemical structure of the ash fraction of the coal, as crystal water for example. This moisture cannot be removed except by pyrolysis, and was found to be in the order of 3-8 per cent for bituminous coals (Bourgeois, 2000).

Studies done on fine coal beneficiation plants showed it not to be uncommon for the coal to have a final moisture percentage between 20-30 per cent after filtration, depending on the method of dewatering. This problem deserves attention for various reasons. Tao et al (2000) showed that a 1 per cent reduction in the moisture level of typical USA coal can lead to a 1.4 per cent

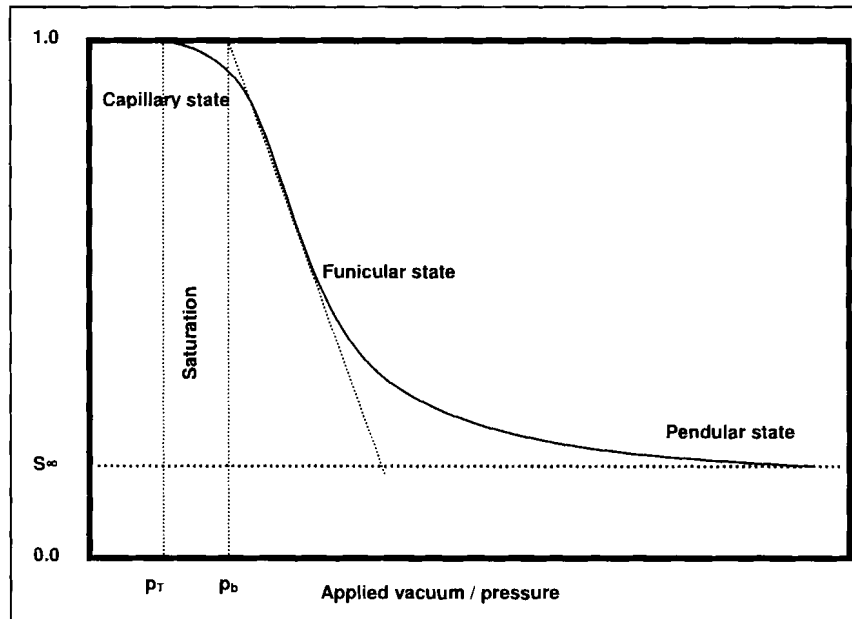


Figure 1: An example of a de-saturation curve showing the different states of dewatering

increase in the calorific value of the fuel available for combustion. In addition, environmental concerns and difficulty in handling are just two other problems that justify this research.

Capillary pressure- or de-saturation curves

The dewatering (or de-liquoring) process of any filter cake is described by a two phase flow of liquid and air through the cake. Capillary pressure curves are used to quantify and describe this process (Condie and Veal, 1998). These curves are obtained by performing filtration experiments at certain applied pressure (or vacuum) differentials on a filter cake until no more filtrate flows from the cake. The tests are then repeated at increasing pressure or vacuum differentials, and the resulting capillary pressure curve (figure 1) characterises the dewatering behaviour of the system.

The point at which the saturation is at 100% (or $S=1$), is the level where all the voids in the filter cake are completely filled with liquid prior to dewatering, without excess supernatant liquid present. The capillary stage is the first dewatering stage, where the applied pressure or vacuum is less than the

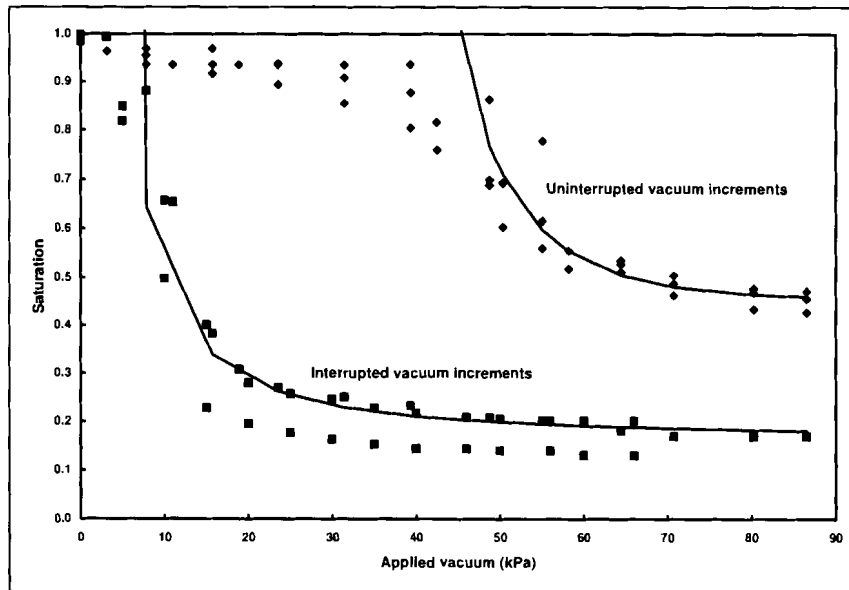


Figure 2: De-saturation curves showing the difference between continuous and interrupted vacuum increments (Le Roux, 2000)

threshold pressure P_T (related to the capillary pressure of the largest pores). This results in no flow of liquid from the filter cake. The second, or funicular stage, commences when the applied pressure or vacuum differential is greater than P_T . This is when most of the dewatering takes place. Liquid will flow rapidly from the filter cake until the third state, the pendular state, is reached. No further dewatering will take place here, and the remaining free moisture (at S_∞) will stay behind as small lenses on the surfaces of the particles, and in the micro pores of each individual particle as inherent moisture. In practice, P_T is difficult to determine due to a range of pore sizes in the cake, but can be approximated by the breakthrough pressure P_b .

While determining these de-saturation curves for a coal sample from the Waterberg coalfield, Le Roux (2000) discovered that instead of an uninterrupted application and stepwise increase to higher vacuum levels, if one reduced the vacuum application to atmospheric level momentarily (referred to as a vacuum break in the subsequent text) before re-application at the next higher vacuum level, yielded much better results. The results, shown in figure 2, showed a significantly lower breakthrough pressure, resulting in a lower final moisture percentage as well as a higher rate of dewatering (as seen from the slope of the

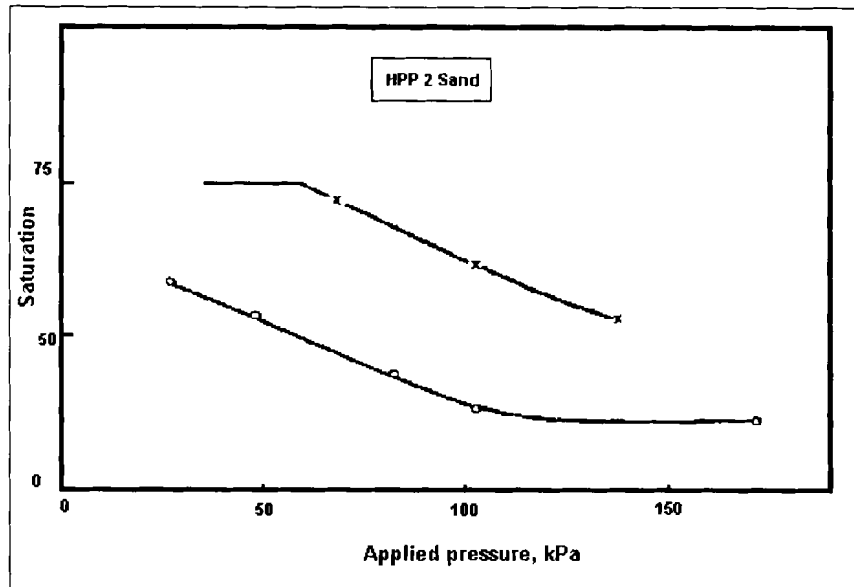


Figure 3: De-saturation curves compiled by Carleton and Mackay on HPP2 sand (1988)

curve). These findings were documented only once before in literature by Carleton and MacKay (1988) using glass beads and sands (Figure 3). This phenomenon was further investigated by the following test work.

Experimental setup

A fine coal sample was obtained from New Vaal Collieries (from the Free State coal field in South Africa), where the thickener underflow stream was sampled. The sample was first dewatered using pressure filters, then air dried for some time, sooner than the last moisture was removed in an oven at 60°C. Table I shows the proximate analysis of the coal, while a particle size analysis indicated the coal to be 100 per cent -600µm and 50 per cent -212µm. The coal samples

Table I: Proximate analyses of the coal.

% Moisture (SABS 924)	5.1%
% Ash (ISO 1171)	46.4%
% Volatile matter (ISO 562)	18.0%
% Fixed carbon	30.4%
Calorific value	12.7 MJ/kg ⁻¹

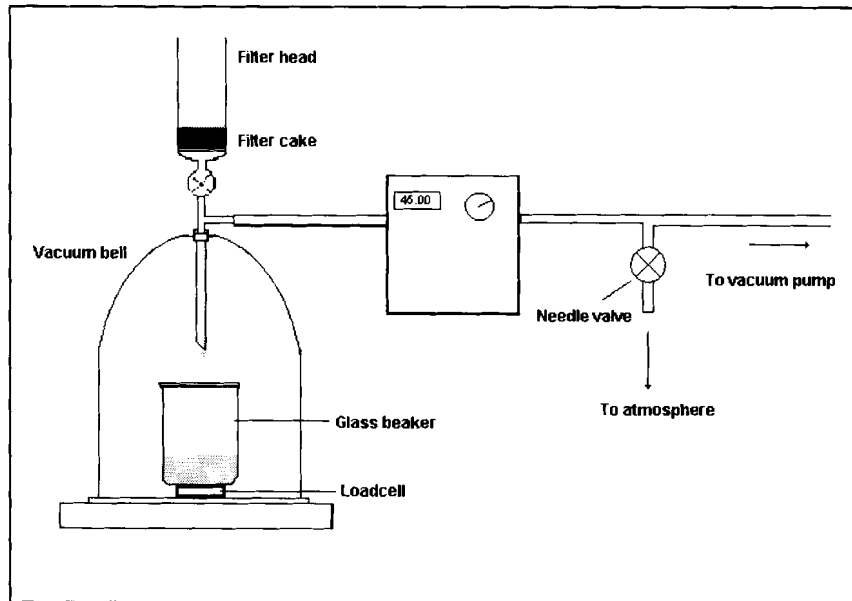


Figure 4: Schematic of the experimental apparatus

were then repulped to make up the feed to the de-saturation experiments.

The experiments were done on a bench scale filter. Operating conditions were chosen to emulate the belt filters currently operating at New Vaal Collieries, taking into account the type of coal, filter cake thickness and retention time on the filter, and also using the same filter cloth (Devtex 356). An applied vacuum difference of 45 kPa was used.

The filter system consisted of a glass bell jar that could be evacuated with a filter head fitted onto the top of the bell. A glass beaker, situated inside the bell jar on a load cell was used to collect the filtrate, and to measure the filtrate mass continuously. Data logging (time, applied vacuum, and filtrate mass) was done by a computer.

Each experiment was done under an applied vacuum of 45 kPa. The time for each test was approximately 300 seconds after the 100 per cent saturation point was reached. The cake thickness was about 15 mm, related to about 40g of dry coal per experiment. After each test the moisture in the cake was determined using the SABS 924 standard.

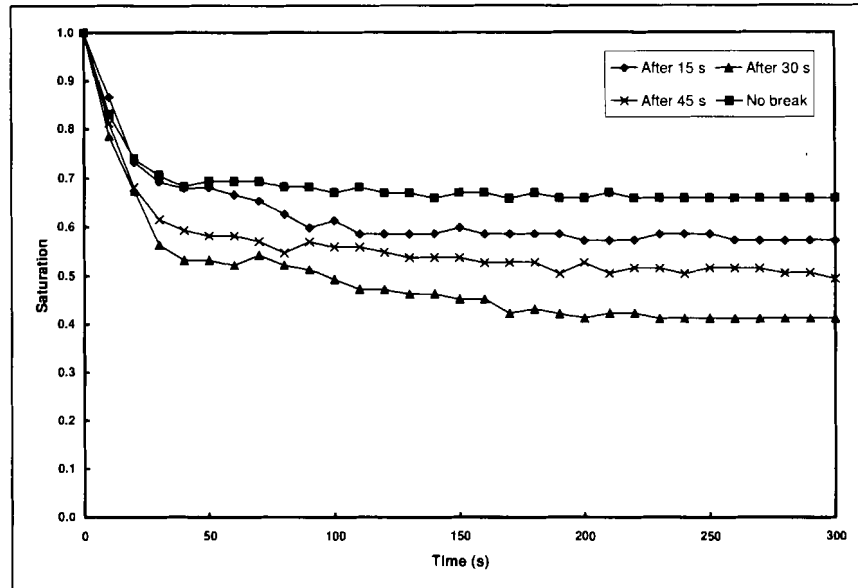


Figure 5: Comparative dewatering curves for a break lasting 30 s at different initial times. (Connecting lines are for readability purposes only.)

The time and duration of the interruption in the applied vacuum for each was varied. First, the break was made at 15 seconds after reaching the 100 per cent saturation level, and to last for either 15, 30 or 60 seconds. Subsequent tests had the break start at 30, 45 and 60 seconds, again using the same break duration times as above. Some tests were done without any breaks for comparative purposes. Finally, some tests were done using more than one break during the test.

Results and Discussion

Selected results* from the above tests are shown in figures 5 to 9. Figure 5 shows the experimental results for some of the tests done with a 30 second long break, at various initial break times, compared to one without any breaks. There was a significant increase in the dewatering rate for the experiments where the applied vacuum was interrupted, as well as a marked improvement in the final moisture levels. Similar trends were observed for tests with other initial breaking times as well. From the graph it seemed that the optimum time for the break was after 30 seconds.

* More detailed results are presented in appendix A.

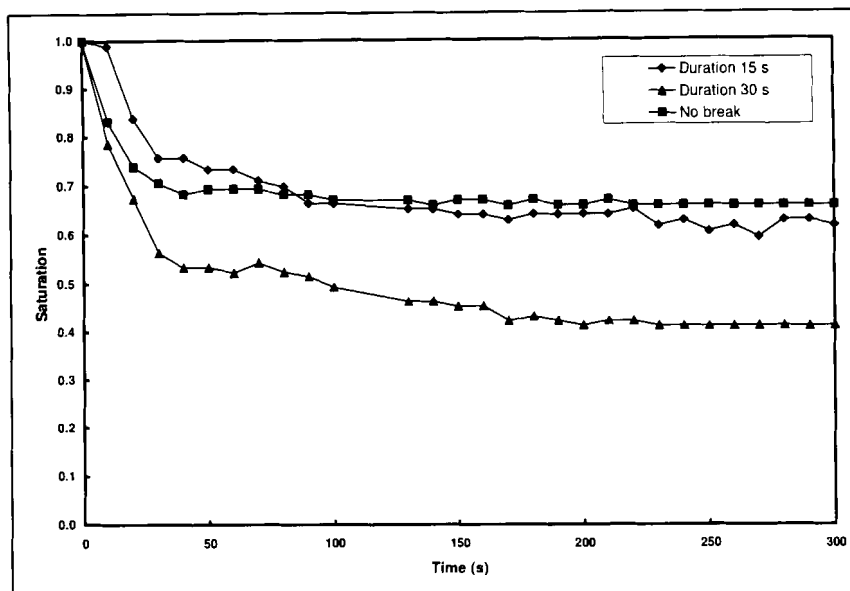


Figure 6: Comparative dewatering curves for a break starting after 30 s, at different durations. (Connecting lines are for readability purposes only.)

Figure 6 shows the results for experiments where the initial break occurred at 30 seconds, for different break duration times. Again similar trends were seen, with improving final moisture levels. A break duration of 30 seconds showed better results than for shorter times.

Figure 7 summarises all the results by plotting the final moisture levels for the different break initiation and duration times. It indicates an optimum condition for a break after 30 seconds lasting for another 30 seconds. This tends to suggest that the optimal break occurs during the funicular stage of dewatering. In this case, a final cake moisture of 25.2 per cent could be achieved, as compared to the standard filtration final moisture of 32.6 per cent.

The effect of repeated breaks were also studied, and the results showed that even though better rates of dewatering could be achieved, lower final moisture levels were not obtained. This suggested that the phenomenon occurred due to once-off modification, probably a structural change in the filter cake.

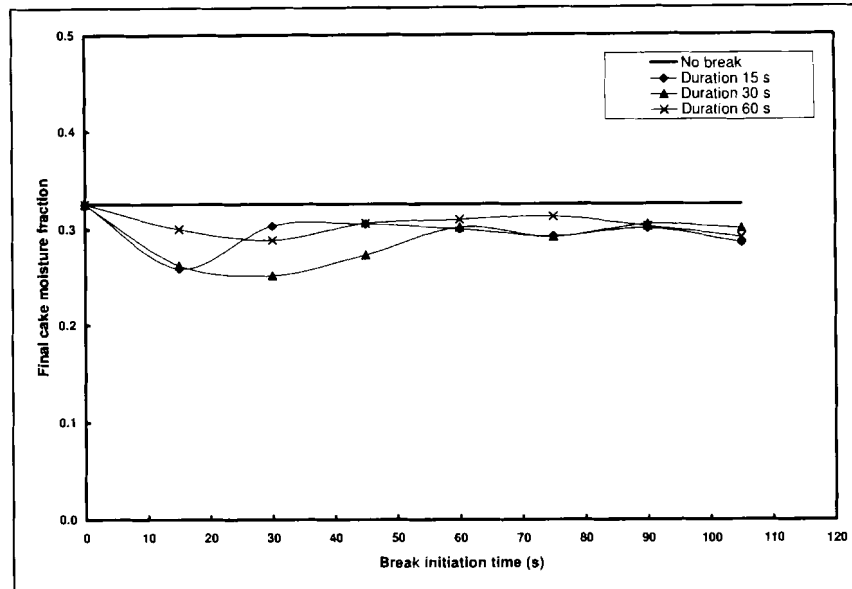


Figure 7: Summary of the final cake moistures achieved for breaks at different times and different durations, compared to the case where no break occurred. (Connecting lines are for readability purposes only.)

All the previous results showed a decrease in the breakthrough pressure of the filter cake, which suggested a change in pore size due to a changing cake structure. This structural change was not due to compression of the filter cake, because an earlier test for the compressibility of coal filter cakes by Kukard (2001) showed that an insignificantly small compressibility factor existed, a fact that could be confirmed by literature as well. (Gala et al, 1981)

An alternative explanation how the apparent size of the pores in the filter cake could have increased was by the occurrence of cracks at the bottom of the filter cake during the dewatering cycle, caused by the interruption in the applied vacuum. This will lead to an increase in the air flow rate through the filter cake. To test this hypothesis it was decided to deliberately damage the filter cake after 30 seconds into the dewatering cycle, using two parallel cuts made by a spatula as indicated in Figure 8.

The results of this test are compared with that of the optimum condition of the first set of tests, as well as with the normal filtration (figure 9). A final saturation level of 0.52 was obtained in this case – an improvement over the standard 0.66. The cuts in the filter cake also caused a decrease in applied vacuum from

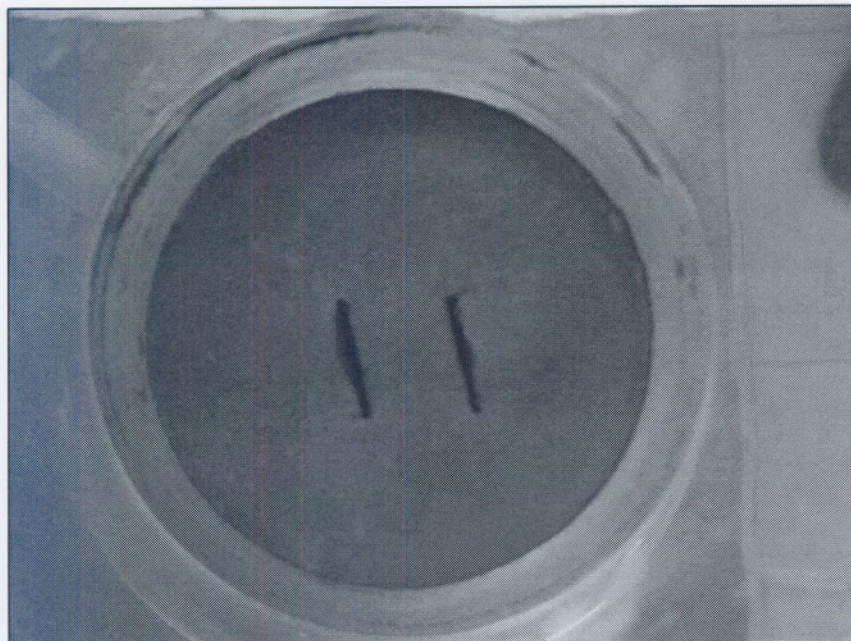


Figure 8: Top view of the filter cake showing two parallel cuts made using a spatula.

45 kPa to 29 kPa, and despite this, there was an increase in the rate of dewatering in comparison to the best previous conditions.

These results suggest a change in the usual paradigm on vacuum filtration: it may be more advantageous to increase the air flow through the cake rather than increasing the pressure differential. The increased air flow will aid in the withdrawal of moisture that would under normal circumstances be trapped as inherent moisture. It is still unclear as to the exact mechanism how this occurs.

Conclusions

A clear advantage was observed in using the approach where the air flow rate through a filter cake was increased at the expense of applied vacuum. It was possible to decrease the final moisture percentage in a coal filter cake from 32 per cent down to 25 percent. Also, the rate of dewatering increased drastically, giving a drier final product in a much shorter time. The results showed that the drying time could effectively be reduced by approximately 60 per cent.

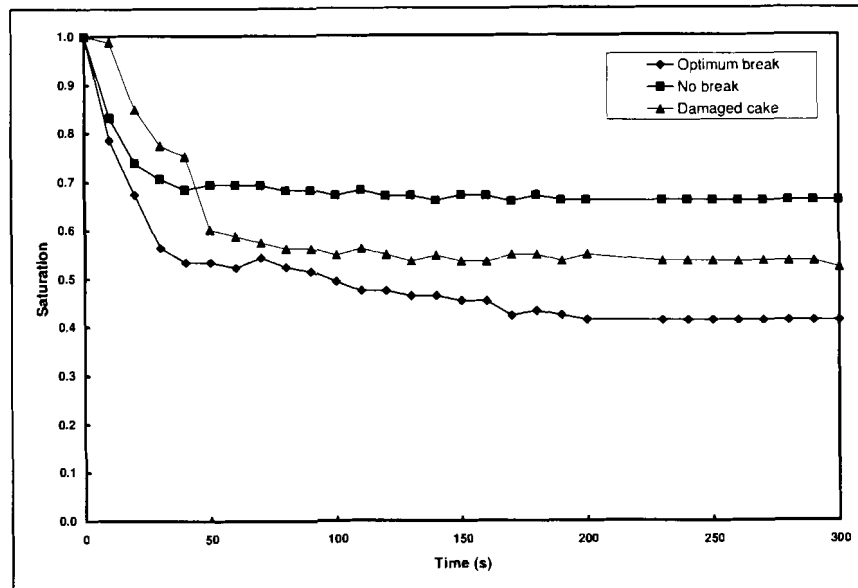


Figure 9: Comparative dewatering curves for the optimum vacuum break condition, as well as or the damaged cake. (Connecting lines are for readability purposes only.)

It was also shown the effects were time dependent. It was more advantageous to apply the vacuum break during the funicular, or middle stage of de-saturation. An optimum vacuum interruption point was determined as 30 seconds into the dewatering cycle, lasting for 30 seconds.

The flow of air through a filter cake plays an integral part in the dewatering. Increasing the airflow through a filter cake by deliberate damage to the cake resulted in a much drier final product under the conditions investigated. More effective de-saturation could be achieved at a lower pressure differential across the filter cake.

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- Coaltech 2020
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Additional notes

The duration of the tests (about 300s) was chosen to simulate conditions on a horizontal belt filter. There were no disk and drum filters (with retention times of about 60 to 90 seconds) operating in South Africa in a coal application at that time (De Korte, 2001).

While performing routine desaturation curve determinations as a continuation of the work described in the previous chapter, a discovery was made that changed the entire approach to dewatering research. It was found that if, instead of a stepwise increase in applied vacuum (say from 20 kPa to 40 kPa), one reduced the applied vacuum momentarily to zero before re-applying it to the next incremented level, significant changes occurred in the desaturation response, as characterised by the desaturation curve. The irreducible desaturation level decreased significantly and, even more importantly, the rate of desaturation improved.

At first, experimental error was suspected and this effect was tested again, with the same results. While this paper only describes the behaviour of one coal type, le Roux (2002) confirmed this effect while working with other coals (even including Australian coals) and vacuum filtration systems. Figure 4.1 shows

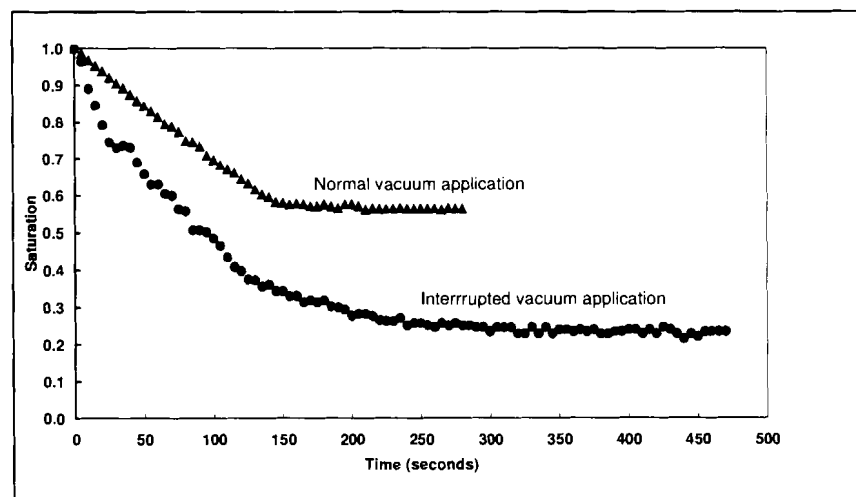


Figure 4.1: Results of desaturation tests on -500 µm Waterberg coal, using both methods of vacuum application.

results of this test using -500 μm Grooteegeluk fine coal from the Waterberg coal field in South Africa. The vacuum was kept at 45 kPa, with vacuum breaks at regular intervals. The tests were repeated at the JKMRC in Australia on their Single Leaf Filter Test Rig, with similar results (Figure 4.2). The coal used was -500 μm Peak Downs coal, filtered at 40 kPa. It was shown that this phenomenon was independent of coal source, filter type and filter medium. The only literature reference to this type of desaturation behaviour was in the 1988 paper by Carleton and MacKay. No explanation was given there.

While this effect was only later ascribed to, and subsequently proven to be due to, very fine cracking of the filter cake (due to the sudden shock of vacuum application), the significance of the finding was that a much lower breakthrough vacuum was required to initiate dewatering. While the air flow rate through the cakes could not be measured at the time, it was obvious that the rate had increased. An instrument capable of measuring such low air flow rates at varying pressure was expensive, and such installations were not done.

This paper also describes investigations into the duration and application time of these 'rest periods' during which the applied vacuum equals zero. The

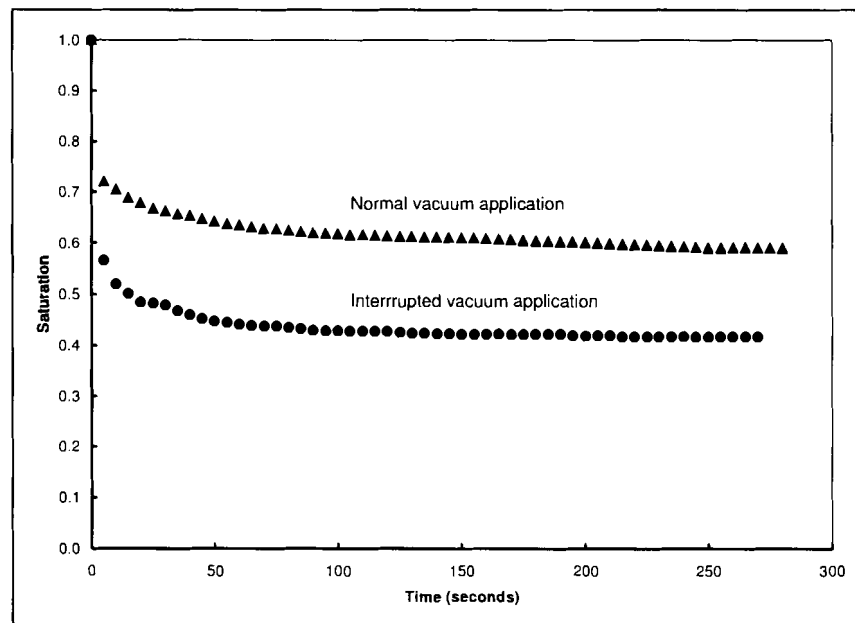


Figure 4.2: Results of desaturation tests on -500 μm Peak Downs coal, using both methods of vacuum application on the SLFT

optimum point at 30 seconds after the onset of desaturation falls within the funicular stage.

Finally, the paper describes a single test done by deliberately damaging the cake by cutting the top half of the cake with a metal spatula (Figure 8 in the paper). While this action is contrary to common vacuum dewatering practice where care is taken not to damage the cake to ensure the highest possible applied vacuum, it was confirmed that the increased air flow at a compromised applied vacuum level improved desaturation.

The action of damaging the cake was provisionally patented, but the application was withdrawn after a 1975 US patent (Carmel & Lundh, 1975) was found to employ a 'ploughing' of the cake on a moving belt to improve filtration. The idea is described as a "Method and apparatus for separating a liquid-solid mixture employing a filter means, suction means, a plurality of rotary disrupting disks located above the filter and which are positioned to create a plurality of parallel ditches and ridges, and roller means for subsequently smoothing out said ditches and ridges into a layer of uniform thickness". The patent further describes the set of rotary disks, at an oblique angle, disrupting the top layer of the filter cake. It is presumed that this type of damage to the cake has the same effect as described in the above paper.

In a US patent, Muralidhara *et al.* (1985) proposed the possible advantages of an electro-acoustic dewatering method, where applying an acoustical field to a solid-liquid suspension at a frequency and amplitude adapted to separate water bound to suspended particles in the suspension. A similar mechanism may have been involved, but the patent describes only the separation of water from the surface of the solids. The improvement of dewatering is not necessarily due to the formation of cracks in the particulate bed.

It is important to note that since the samples were dried at elevated temperatures in air before the experiments (in these and all subsequent tests), the coal surface was almost certainly modified by oxidation. This, however, probably did not influence the degree of dewatering obtained significantly,

because it was shown earlier in Chapter 2 (Rajan & Hogg, 1996) that surface affects contributed much less to dewatering than structural effects, like the particle size distribution of a filter cake.

More details about the experimental results, referred to in this paper, are given in Appendix A.

Chapter 5

Optimising the New Method of Fine Coal Dewatering

The Optimization of an Improved Method of Fine Coal Dewatering

By M. le Roux, Q.P. Campbell, M.S. Watermeyer and S. de Oliveira

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This peer-reviewed paper was published in Minerals Engineering 18 (2005) pp. 931 – 934, after being presented at the Solid-Liquid Separation '04 Conference in Cape Town in November 2004. The article further investigates the techniques of fine coal dewatering described in previous chapters. More results are generated and the process is optimised.

Relative contributions by authors

M. le Roux was originally a postgraduate student under the leadership of Q.P. Campbell. After being appointed as a staff member, he continued to work on researching the same topic together with Mr Campbell, and they both acted as study leaders for the then final year students: M.S. Watermeyer, and S. De Oliveira. The experimental data in the paper was generated by the latter two students during their final year laboratory projects. The apparatus used was the same as that used in the previous papers. Data recording and calculations were done and checked by both Messrs Campbell and le Roux. The paper was jointly written by Le Roux and Campbell.

The Optimization of an Improved Method of Fine Coal Dewatering

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Abstract

An improved method of dewatering fine coal ($-500\text{ }\mu\text{m}$) by vacuum filtration was developed and optimized. Tests on a bench scale vacuum filter showed that when a filter cake was deliberately damaged, causing the airflow through the cake to increase and the applied vacuum to decrease, a lower final moisture content could be achieved as well as a higher rate of dewatering.

This method was optimized, taking into account the optimum time to inflict the damage to the filter cake during a single dewatering cycle. The amount and character of the inflicted damage to the filter cake was also investigated. It was found that the optimum time to inflict the damage was as soon as possible after the point of 100% saturation, decreasing the final moisture percentage from 29% to 24%. The configuration of the damage had no significant influence to the final moisture content of the filter cake. This led to believe that the air flow through the cake during dewatering is mainly hindered by a layer of ultra fine coal that will form at the top of a filter cake. Further investigation showed this layer to be approximately a third from the top of the filter cake, relating to a particle size of between 120 and 130 μm .

Introduction

South Africa is currently listed as the 6th largest coal producer in the world, supplying approximately 285 ton of ROM coal per annum (DME, 2003). Of this, about 14% report as fine coal (smaller than 500 μm) and up to 2–3% can be classified as ultra-fine coal (finer than 100 μm) (Breed, 1992). This amounts to about 30 million tons of fines being produced annually.

Since coal washing is a wet process, this fine fraction is in slurry form, or at best, a very moist solids stream. Coal producers have a few options as to what to do with the fines. Initially, fines and ultra-fines were dumped with the discard streams, but since the value of these fines had been recognised, it was either added to the product streams as is, or alternatively, it was upgraded, dried and sold. The economic potential of coal fines has led to developments in fine coal beneficiation processes, like spirals and froth flotation plants. The main reason for not fully exploiting this energy source is the high levels of moisture associated with the fines fraction of coal. Efficient removal of this moisture will yield definite benefits in finances and handling of the fine coal, while it will also have a positive impact on the environment.

Background

Rong (1993) defined the three types of moisture in coal to be surface or free moisture, inherent or capillary moisture and chemically bound moisture. Of these three, only the surface moisture can be removed from the filter cake by mechanical means like filtration and centrifuging. Further studies done on fine coal showed it not to be uncommon for the coal to have a final moisture content of up to 30% after filtration.

A 2001 survey of South African coal beneficiation plants showed that of the then 24 operations, some 18 plants employed processes for fine coal beneficiation (De Korte, 2001). At seven of these plants, the ultra-fine slurries were dewatered using centrifuges or filters. With Tao et al. (2000) showing that a 1% decrease in the final moisture of 3 million tons of clean coal can lead to a saving

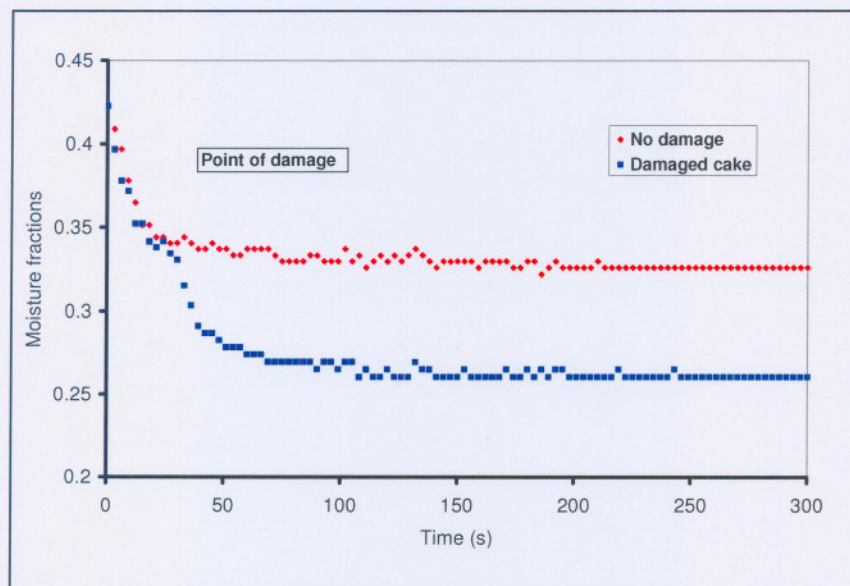


Fig. 1. Results where the filter cake was deliberately damaged as found by Le Roux (2002).

of US\$ 300,000, these amounts of moisture left in the fines are adding up to become a big financial liability.

Le Roux and Campbell (2003) showed that by deliberately damaging a fine coal filter cake, thereby increasing the air flow through the cake at the expense of a lower pressure differential across the cake, will yield a final product with much lower moisture content. It also increased the rate of dewatering and decreased the breakthrough pressure. This phenomenon is shown in Fig. 1.

Fig. 1 clearly shows a rapid increase in the dewatering rate after the filter cake was damaged. The end result yielded a cake that was about 5% drier than for the standard filtration test. To be applicable in industry, this process needs to be optimized with regards to time and method of applying the damage.

Experimental setup

Two fine coal samples were obtained from New Vaal Collieries (from the Free State coal field in South Africa), where the thickener underflow stream was sampled. The samples were first dewatered using pressure filters, then air dried for some time, before the remaining moisture was removed in an oven at 60 °C.

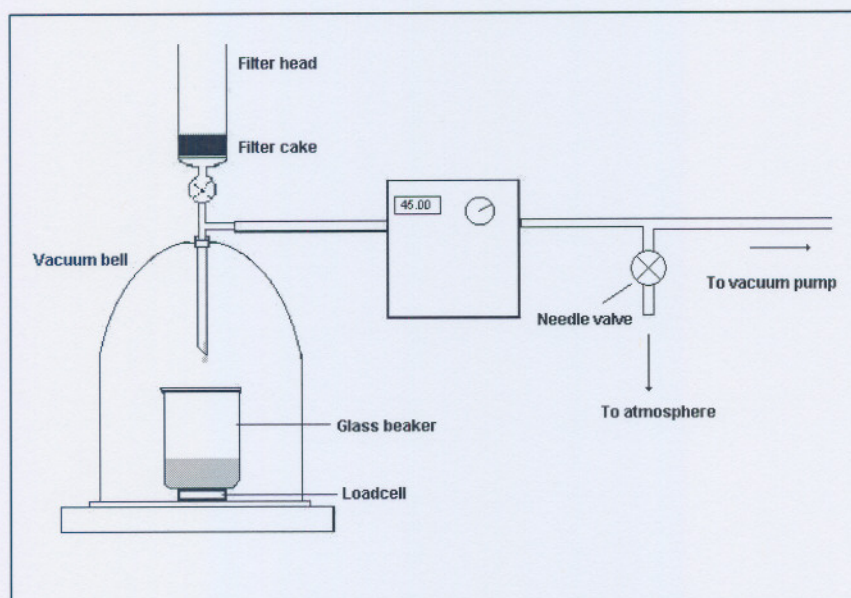


Fig. 2. Schematic of the experimental apparatus.

Table 1 shows the proximate analysis of the coal, while a particle size analysis indicated the coal to be 95%—600 μm and 50%—212 μm . The coal samples were then repulped to make up the feed to the desaturation experiments.

The experiments were done on a bench scale filter. Operating conditions were chosen to emulate the belt filters currently in use at New Vaal Collieries, taking into account the type of coal, filter cake thickness and retention time on the filter, and also using the same filter cloth (Devtex 356). An applied vacuum difference of 45 kPa was used.

The filter system consisted of a glass bell jar that could be evacuated with a filter head fitted onto the top of the bell. A glass beaker, situated inside the bell

Table 1: Proximate analysis of the different coal samples from New Vaal

	Sample 1	Sample 2
% Moisture (SABS 924)	4.74%	5.04%
% Ash (ISO 1171)	52.60%	43.99%
% Volatile matter (ISO 562)	16.78%	18.53%
% Fixed carbon	25.88%	32.44%
Calorific value	11.20 MJ/kg	14.75 MJ/kg

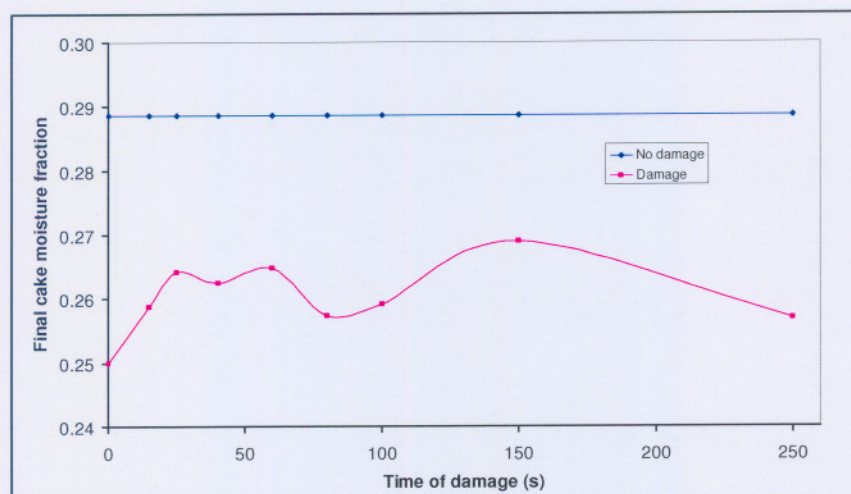


Fig. 3. Summary of final cake moistures achieved for different damage times.

jar on a load cell was used to collect the filtrate, and to measure the filtrate mass continuously. Data logging (time, applied vacuum, and filtrate mass) was done by a computer (Fig. 2).

The first sample was used to determine the optimum time during the dewatering cycle to damage the filter cake, as well as to establish the ideal configuration of the damage. This was done under an applied vacuum of 45 kPa. The retention time for each test was 300 s after the point of 100% saturation was reached. The cake thickness was 15 mm, relating to 60 g of dry coal per experiment. After each test the moisture in the cake was determined using the SABS 924 standard.

A test was done without damaging the cake. This served as a control for later comparisons. In all the subsequent tests the filter cake was damaged at different times during the dewatering cycle, punching apertures into the cake using an array of implements.

The second sample was used to determine if there was a certain depth that a filter cake has to be damaged to obtain optimum airflow through the cake. The tests were carried out at the same conditions as for the first sample, but the damage that was inflicted onto the cakes differed in depth.

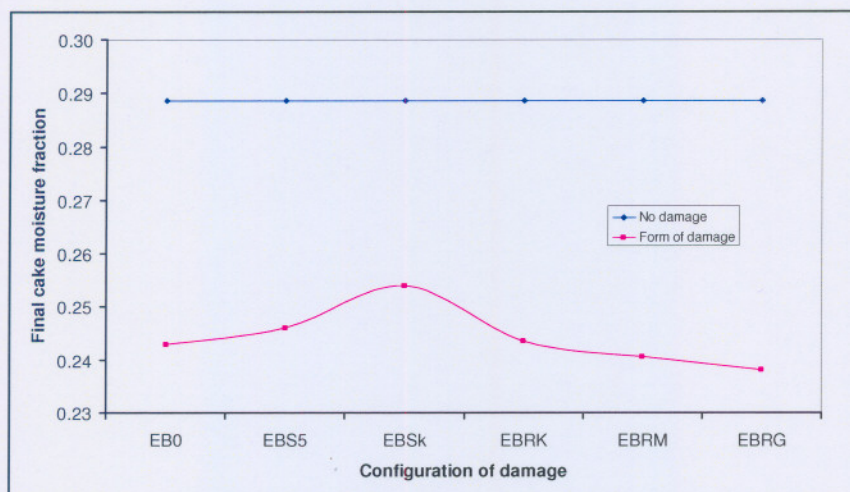


Fig. 4. Summary of final cake moistures for different implements used to damage the cake.

Results and discussion

Selected results from the above tests are shown in Fig. 3, Fig. 4 and Fig. 5. Fig. 3 shows a summary of results for the tests done where the damage was inflicted at different times during the dewatering cycle. It can be seen that the optimum final cake moisture occurred when damage occurred the point of 100% saturation, i.e. where all inter- and intra-particle voids are totally filled with water, without any excess water on top of the filter cake. It yielded a final moisture percentage of 25% compared to 29% final moisture for the standard filtration test. Each of the tests was repeated three times which gave an average standard deviation of less than 1%. For clarity sake this is not added in the following graphs.

The optimum configuration of implements used to perforate the cake was tested

Table 2: Meaning of abbreviations used in Fig. 4

Abbreviation	Meaning
Eb0	2 Holes—spatula
EBRK	20 Holes—2 mm iron rod
EBS5	5 Holes—spatula
EBRM	8 Holes—6 mm glass rod
EBSk	2 Continuous cuts
EBRG	8 Holes—9 mm glass rod

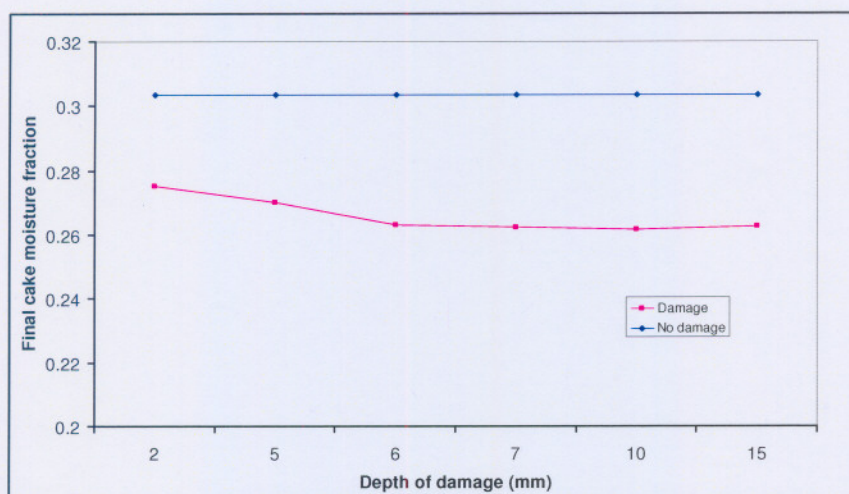


Fig. 5. Summary of final cake moistures achieved with varying depth of inflicted damage.

by using a variety of laboratory accessories. These included different sized glass rods and flat steel pins. It was found that there was no real advantage in using different implements to apply the damage, and thus the shape of the perforation. The only observation that was made was to apply the damage in such a manner that it promoted the maximum amount of natural cracking to occur in the filter cake. A summary of these results are shown in Fig. 4. The horizontal axis on the graph gives abbreviations for the different implements. The meaning of these abbreviations can be found in Table 2.

Fig. 5 shows the results for experiments where the damage was inflicted up to a certain depth in the filter cake. It can be seen that applied damage of even 2 mm deep already gives an improvement on the final moisture content of the filter cake. However, the optimum depth was found to be 6 mm for a 15 mm thick filter cake.

A particle size analysis was done on the top third part of the filter cake, using a Malvern Mastersizer. As shown in Fig. 6 it yielded a d_{90} of 122 μm . This is an indication of the way a filter cake forms inside the funnel. The top layer consists of ultra fine coal particulate, hence resulting in a much dense packing of the filter cake. This directly hinders the flow of air through the filter cake, preventing dewatering. Therefore creating artificial channels to a predetermined depth

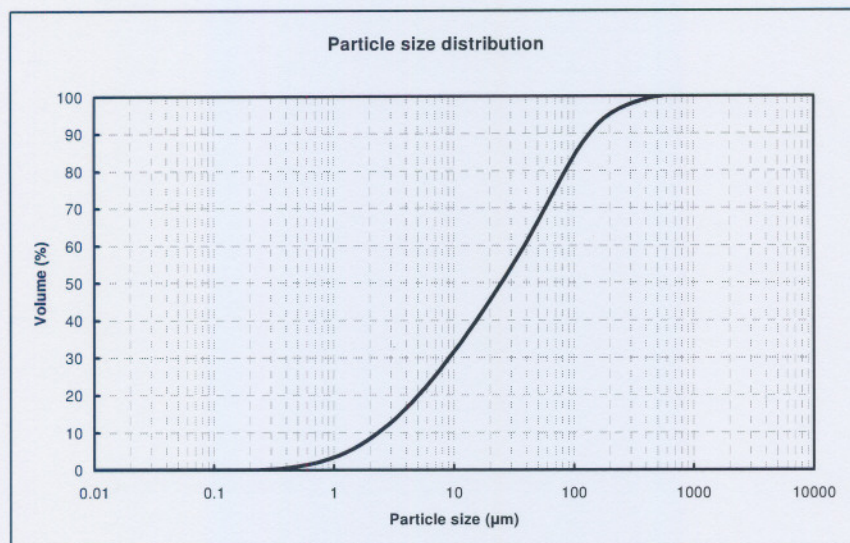


Fig. 6. Particle size analysis of the top part of the filter cake.

where the 125 μm particles are less abundant will aid in the flow of air through the remaining part of the filter cake, drying it more quickly and efficiently.

Conclusions

An approach of increasing airflow through a filter cake during dewatering, at the expense of applied vacuum, yields a definite advantage in the field of deliquoring. It was possible to reduce the final moisture content of a fine coal filter cake by about 5% points while also increasing the rate of dewatering to the extent that the retention time could be reduced by as much as 60%.

It was also shown that the optimal time during a dewatering cycle to create the artificial airflow channels is at 100% saturation, or as close to it as possible. This can be done with any instrument that would promote further natural cracking of the cake. The critical particle size for a high ash bituminous coal was found to be 125 μm. The artificial channels should be created to a depth just below the point where 90% of these particles are bridged. This will cancel out the water retention effect of the ultra fine coal particles, and will result in an optimum air flow through the cake to assist in the dewatering process.

Acknowledgements

The authors would like to acknowledge the following organisations for their contribution to this project, financially or otherwise.

- Coaltech 2020.
- Anglocoal, particularly New Vaal Collieries.
- IST-Delkor.

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Additional notes

The concept of intentional damage to a filter cake in order to increase the airflow is further investigated in this paper. The following questions were addressed in the paper:

- When (in the dewatering cycle) must the cake be damaged?
- Is the shape of the instrument causing the damage important?
- How deep must the perforations penetrate the filter cake?
- What are the benefits from this action?

In Chapter 4, it was shown that the best time to inflict the damage and thus to increase the air flow, was in the funicular stage (about 30 seconds after the onset of desaturation). This paper confirmed that the optimum point was in the funicular stage, but it was shown here that the optimum was closer to the onset of desaturation. It is suspected that at this point the cake is not yet compressed or blinded with fines carried into the structure, and thus more air flows through the cake if the top fines layer is cracked. While it was shown by Kukard (2001) that fine coal filter cakes were essentially incompressible, it may be possible for the cakes to undergo an initial re-arrangement directly after the application of a high applied vacuum. Unfortunately, it was not possible to measure the porosity of the filter cakes at any stage, because the methods to determine this employed high pressures, which would in turn change the structure again. Further work may be done to investigate this phenomenon, possibly microscopically.

The parallel spatula cuts employed in the first series of tests, proved the least effective of all the shapes of perforations tested. Round or square holes, made by using blunt objects, were more effective, probably because it caused secondary fine cracking radiating out from around the hole. This caused a higher air flow rate through the cake. Although it was not possible to observe this fine cracking, it seems to be a feasible explanation.

Most significantly, it was found that it was only necessary to damage the top layer (2mm to 6 mm, in this case) to cause improvement. Size analyses of different layers in the cake showed that the coarser particles were settled at the bottom, with the finer particles at the top. This was because before filtration, the cake was allowed to form by natural settling from the feed slurry. Thus, it was only necessary to 'break' the tight layer of fines on top of the cake to increase airflow. The porosity of the cake in the lower layers was sufficient to allow for this increased air flow rate. While the segregation of particles according to size is easily achievable in a laboratory, because of the method used, this should be verified in practice on a real belt filter, where more turbulence exists while forming the cake.

The results showed that desaturation time could be reduced by as much as 60% when a higher air flow rate was used. This was in line with all the other results obtained thus far.

The previous three papers showed that in most industrial fine coal filtration applications, the limit to dewatering was already reached. Further optimisation of the process would not yield any significant improvement. What was needed, was a totally different approach to address this limit.

More details about the experimental results, referred to in this paper, are given in Appendix A.

Chapter 6

Thermal Dewatering of Fine Coal

An Investigation into the Moisture Absorption Properties of Thermally Dried South African Fine Coal

By D.C.S. van der Merwe and Q.P. Campbell

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This peer-reviewed paper was presented at the XIV International Coal Preparation Congress held in Sandton, South Africa, from 11 to 15 March 2002, by the South African Institute of Mining and Metallurgy, and was published in the conference proceedings. The article subsequently appeared in the Journal of the South African Institute of Mining and Metallurgy, Vol. 102, no.7 (October 2002), pp. 417 - 419. The article investigated the possibility of the utilisation of thermal dewatering on South African coals. The purpose of the work was to investigate the water absorption properties of the coal after thermal drying.

Relative contributions by authors

D.C.S. van der Merwe was a postgraduate student working on this project under the leadership of Q.P. Campbell. The direction and scope of the study, planning of the parameters to be investigated experimentally and the design of the experimental apparatus was the responsibility of Mr Campbell. Mr van der Merwe performed all the experiments, data recording and calculations. The paper was jointly written by Van der Merwe and Campbell.

An Investigation into the Moisture Absorption Properties of Thermally Dried South African Fine Coal

D.C.S. van der Merwe and Q.P. Campbell

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Synopsis

The aim of this research was to study the absorption characteristics of thermally dried fine coal from South African collieries. All samples were wet milled to - 150µm in a ceramic ball mill. It was dewatered in a pressure filter before being either thermally dried at 150°C or air dried. Directly after drying the samples were put into a climate box at 28°C and three different relative humidities, namely 30, 60 or 94 percent. It was found that the equilibrium moisture content of thermally dried coal at a specific relative humidity is lower than that of air dried coal. The relationship between the equilibrium moisture content and relative humidity is described by $1 - RH = \exp(-KTM_e)^n$. There seems to be no relationship between the volatile matter content and equilibrium moisture content, whereas with an increase in mineral content there seems to be an increase in the equilibrium moisture content of the coal. A model is also discussed that fits the experimental data and gives a good prediction for changes in the conditions. The moisture uptake rate increases with an increase in temperature and a decrease in particle size. From the static drainage test it was found that the drainage rate decreased with the addition of air dried fines to a normal colliery product.

Introduction

Water, while being the workhorse of mineral processing, is also one of the most undesirable components in the final product. Not only does the high moisture content have an adverse influence on meeting market specifications, it can also be a nuisance in handling and add on to the expensive freight cost. Up to 50% of the moisture in a coal plant product can be present in the ultra fine fraction ($-5\text{ }\mu\text{m}$), even after being filtered. There are several ways to consider reducing the moisture content of the product like reducing the amount of fines, increasing the efficiency of the dewatering device, changing the surface chemistry of the fine coal or thermal drying.¹

Although a number of dewatering and drying technologies exist and are being practised commercially, the general perception exists in the South African coal industry that thermal drying is impractical, unsafe and/or uneconomical. The fine coal that is generated during the coal mining and processing operations has traditionally been pumped as slimes to co-disposal discard dumps. This fine coal constitutes about 10-15 percent of annual run of mine tonnage². Economically viable techniques to dewater the fine coal may result in this coal being included in the saleable fraction. This will turn a liability into an asset and could improve the income earned from coal sales by the South African industry substantially.

Background

According to Rong³ three types of moisture can be distinguished in coal, namely:

- Surface or free water which lies on the surface of the coal particle;
- Inherent or capillary water which is absorbed into the capillary structure of individual coal particles, and;
- Chemical water which is chemically bound with the coal or tailings.

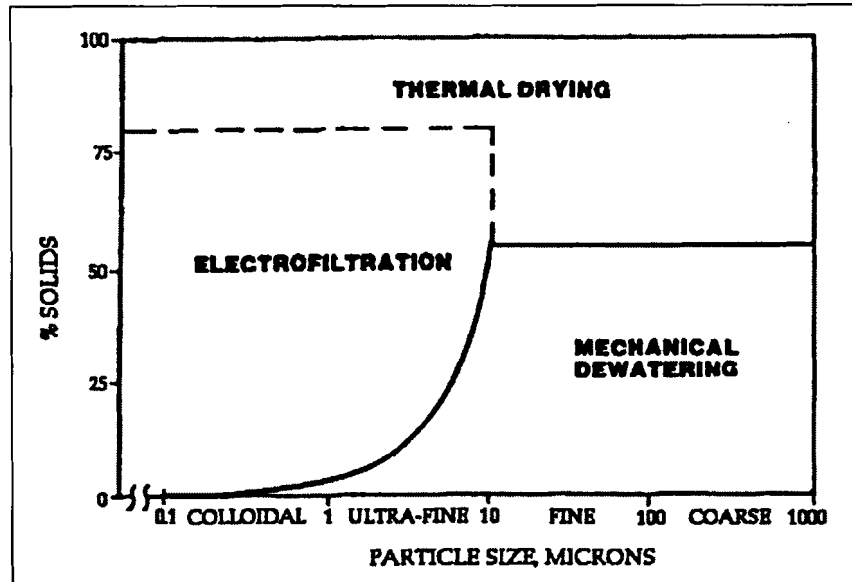


Figure 1: Effective dewatering techniques in relation to particle size⁴.

While the surface moisture of a solid depends on the shape and the extent of the external surface, coal being a porous material contains moisture in its sub microscopic pores. Water micro-capillaries (which are mostly intra-particle) has been quantified by nuclear magnetic resonance and gravimetric sorption techniques and shown to be in the range of 3 - 8 percent for bituminous coals. It is coal dependent and this moisture cannot be removed by mechanical means.⁴ This is supported by figure 1 which shows effective dewatering techniques for coal.

The relationship between relative humidity (RH) and equilibrium moisture content (M_e) for both the thermally dried and air dried samples are described by:

$$1 - RH = \exp(-KTM_e)^n \quad [1]$$

with T as temperature (K), K and n as material specific factors. This relationship corresponds with part of a model as described by Shadle⁵.

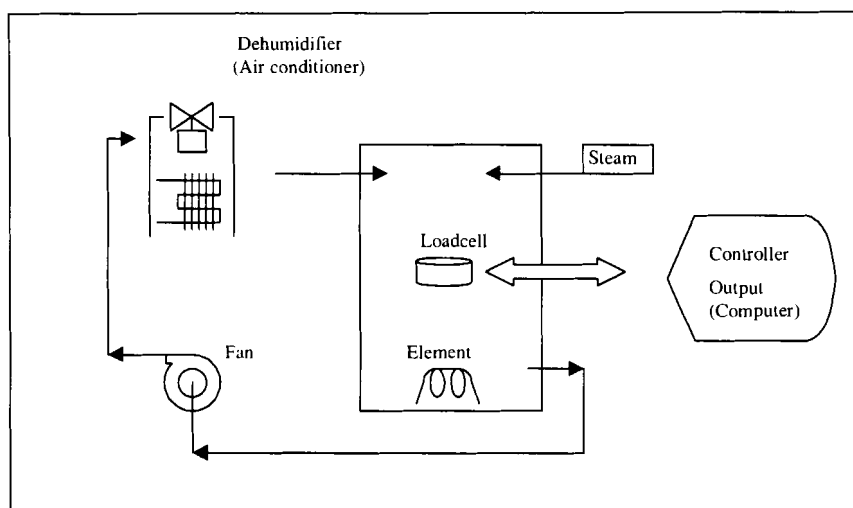


Figure 2: Diagram of experimental set-up (climate box).

Experimental Setup

Coal from four different South African collieries was used for the absorption experiments. Goedehoop colliery's coal was used for the static drainage test. Table I shows the proximate analysis for the different coals.

For the constant humidity experiments a climate box was used. A load cell measured the mass of the sample in the climate box. The temperature and relative humidity were computer controlled and the mass recorded every second. Figure 2 is a diagram of the experimental setup.

The coal samples were milled in a ceramic ball mill and the $-150\mu\text{m}$ fraction was removed with wet screening. The samples were dewatered in a pressure filtered to give a filter cake of about 0.5cm thick. The filter cake was thermally dried in a

Table I: Proximate analysis results for coal samples used in experiments.

Colliery	Bank	Sigma	Tavistock	Zululand Anthracite
Moisture (%)	2.6	7	3.3	2.1
Ash (%)	22	28.8	19.9	18.2
Volatile matter	22.7	21.5	24.9	8.7
Fixed carbon	52.7	42.7	51.9	71
Total Sulphur	0.54	0.38	0.89	0.89

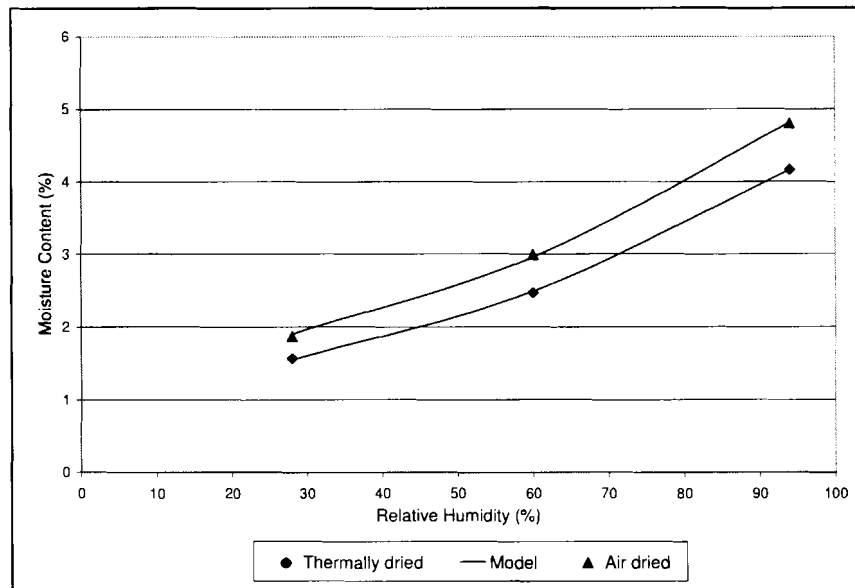


Figure 3: Comparison between experimental and theoretical values for coal from Tavistock.

laboratory oven at 150 °C or air dried at atmospheric conditions before going to the climate box. A control sample also went directly from the filter to the climate box.

The temperature in the climate box was 28 °C. Coal from each colliery was kept at 28, 60 and 94 percent relative humidity respectively. The mass increase of the sample was recorded over time and used to calculate the moisture content of the sample.

Results

Figure 3 shows the experimental data for coal from Tavistock and the theoretical values as described by equation 1.

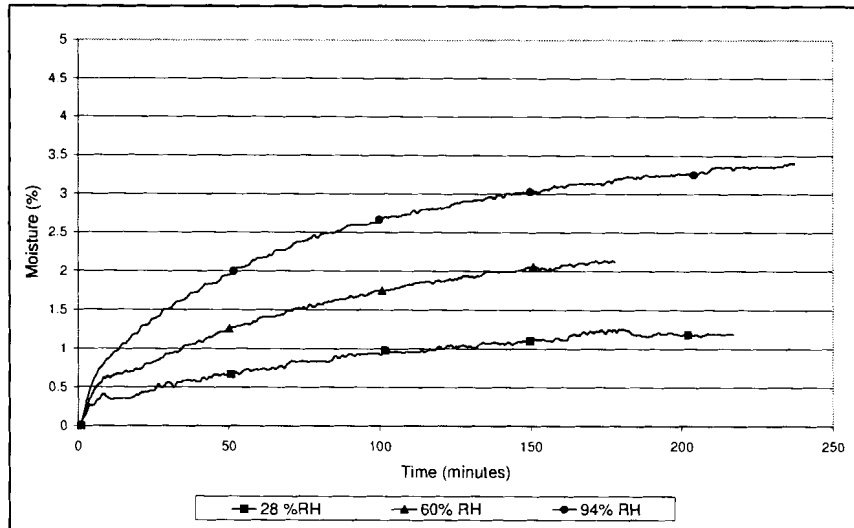


Figure 4: Moisture uptake rates for thermally dried coal from Bank colliery at different relative humidities.

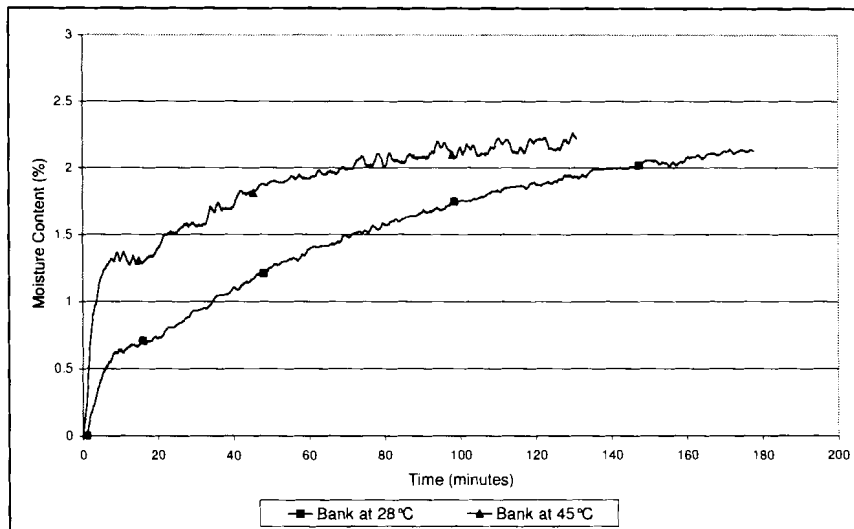


Figure 5: Influence of temperature on moisture uptake rate for coal from Bank Colliery at 94 percent relative humidity

Figure 4 shows the different moisture uptake curves for coal from Bank colliery at different relative humidities. This behaviour is expected and mentioned by Suuberg and Devi⁶. Due to the higher humidity, the partial pressure of the water vapour is higher and more moisture can be absorbed. The same trend was displayed by the other coal samples.

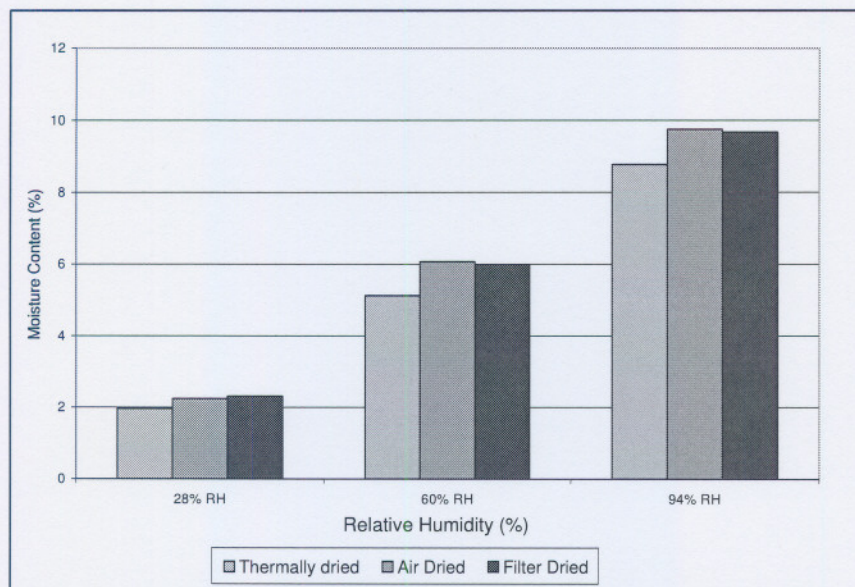


Figure 6: Comparison between different drying methods for Sigma coals.

An increase in temperature increases the moisture uptake rate but does not increase the equilibrium moisture content as can be seen from figure 5.

There was a small difference in the equilibrium moisture content between thermally dried coal and air dried coal for all the samples. At the same relative humidity, the thermally dried coal displayed a lower equilibrium moisture content than the air dried samples. This was most evident for Sigma's coals as shown in figure 6. This may be due to a collapse of the micropores in the coal during thermal drying^{7,8}.

No relationship could be observed between the volatile matter content and equilibrium moisture content but with an increase in mineral matter the equilibrium moisture increased as well. A model described by Shadle fits the experimental data fairly good (figure 7). It also predicted the change in moisture uptake rate with an increase in temperature.

Conclusions

The relationship between equilibrium moisture content and relative humidity for the coal studied can be described by equation 1. Thermally dried coal has a

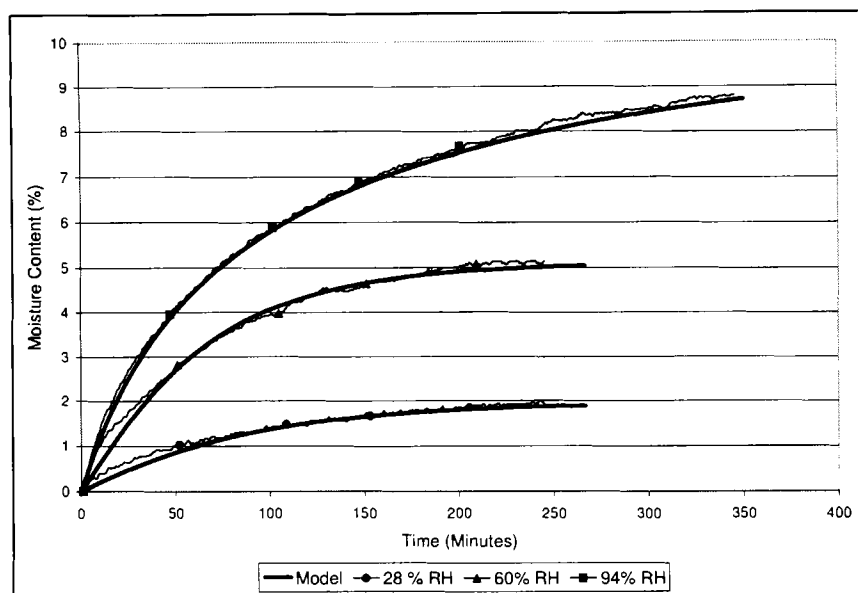


Figure 7: Model compared to experimental data for thermally dried Sigma coal.

lower equilibrium moisture content than air dried coal at the same relative humidity. Coal from Sigma has a much higher equilibrium moisture content than the other coals. This may be due to its higher mineral contents. Literature suggests that mineral matter acts as a hydrophilic site and that water readily absorbs into mineral matter's pores as well.

The model described by Shadle fits the experimental data fairly good and may be used to predict the behaviour of the coal during moisture uptake. Fine coal negatively influences the drainage characteristics of a coal bed, although more research is needed. Things like stockpile size and shape, size distribution of the coal on the stockpile and type of moisture should be investigated.

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Additional notes

As was shown in Chapters 3 to 5, the limit to mechanical fine coal dewatering had been reached, and alternatives had to be employed for further improvement. This paper describes the first project in a series to re-evaluate thermal dewatering as a viable option.

Coal samples were dried at 150°C and the results were successfully modelled. The subsequent re-adsorption of moisture was also investigated, and it was found that thermal dried coal had a lower equilibrium moisture level. It was at first thought that this could be due to structural (pore size) changes caused by heating, but subsequent test work showed such changes will only occur at higher temperatures (around 350°C – 450°C). The real reason could therefore be due to lower temperature effects such as volatile losses or changes in the oxidation properties of the coal surface. This is yet to be further investigated.

The important consequence of this work was that desaturation could be obtained at moderately low temperatures, in this case 150°C. This led the researchers to pursue the idea that even lower temperatures, if accompanied by high air flow (see the previous chapters), would suffice in effective dewatering. This is addressed in the next paper.



Figure 4: The FCP at Hendrina Power Station.

& Management (Pty) Ltd (WERM) and built at Hendrina Power Station in South Africa, such that one mill could be supplied with 50% of its feedstock as recovered fine coal.

The results of the tests showed that fine coal could be successfully dried in large quantities using flue gas as a drying medium.

The one surprising result was the relatively low flue gas temperature required for drying. Temperatures as low as 70°C in the dryer still resulted in significant reduction of moisture. This differed significantly from conventional thermal drying where the boiling point of water should be exceeded, and the most important variables were those related to the flow and heat properties of the flue gas, rather than temperature. Again, this suggested that the principle of a high flow / low pressure system performed better in fine coal dewatering.

Conclusion

The results from the above two projects illustrate the principle that fine coal can be more effectively dewatered by a high air-flow / low pressure drop system,

Paper 3 (Chapter 4) experimental data

This section describes additional information and data that did not appear in the original paper in Chapter 4 (page 41).

Photographs of the test equipment



Figure A.2.1: Single leaf filter test rig at JKMRC



Figure A.2.2: Filter test rig at North West University



Figure A.3.2: Six spatula cuts in the surface of a filter cake



Figure A.3.3: Example of damage by a 2 mm rod (20 holes)



Figure A.3.4: Implements used to damage the filter cake

