

Development and manufacturing of a prototype pulverized fuel feeder for a micro burner

DJ Botha
20577540

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Supervisor: Mr CP Kloppers

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Abstract

Existing coal fired power stations could be improved by increasing the efficiency of the combustion process. The combustion process is incorrectly set up since inaccurate calorific values (CV) for the pulverized fuel is used in the calculations. These inaccurate calorific values are the result of there not currently being a way to correctly measure the energy released during fuel combustion. Hence, current calorific measuring devices cannot simulate the conditions found inside the combustion chamber of a power station.

A microburner should be built that is capable of simulating the combustion chamber environment and allow for correct measurements of calorific values of the pulverized fuel (PF). During operation of the microburner, the initial combustion of the powder inside of the combustion chamber is done by using propane gas. Thereafter, the microburner has to solely rely on the PF flow into the microburner to keep the flames ignited. As a result, this continual flow of PF into the microburner is of great importance for the operation of the burner.

In this study, a prototype pulverized fuel feeder was designed and build that fulfils the requirements needed for a microburner. Various tests were conducted with the prototype pulverized fuel feeder and these tests can be divided into four distinct phases. The first two phases tested the feeder's functionality and was used to alter the design of the pulverized fuel feeder. Also, the proper method to attach measuring devices to the feeder was studied in these two phases. In the last two phases the repeatability, accuracy and possibility of a set flow rate of the feeder was tested.

The results obtained showed that the current design of the prototype PF feeder is incapable of successfully delivering a specific constant flow rate. However, the feeder is capable of delivering flow rates within the required range if some requirements were met. These requirements are: PF should contain no moisture, operational sizes should be small and more pre-test should be done to predict operational size to adjust gas input accordingly.

In conclusion, several types of bridge formations was identified and classified based on their strength and how they influence the feeder's performance. Therefore, the prototype feeder design can be improved with the knowledge obtained in this study.

Keywords: coal fired power station, efficiency, combustion, calorific value, pulverized fuel, feeder, flow rate, moisture, bridge formations.

Preface

This dissertation consists of a list of contents, a list of figures, a list of tables, a nomenclature and five chapters.

Chapter 1: The chapter gives an introduction, a background of methods to calculate the energy level found in pulverized coal, the problem statement, the project goal, deliverables and the scope.

Chapter 2: Chapter 2 is a detailed literature study on the subjects pertaining to pulverized coal feeder.

Chapter 3: This chapter includes preliminary feeder testing and the concept and detailed design of the pulverized fuel feeder.

Chapter 4: Chapter 4 consists of the design of the auger and gear box with the mathematical equations to calculate the design parameters. The ultimate analyses of the air to fuel ratio are also included.

Chapter 5: This chapter describes the testing and evaluation of the PF feeder design, including the numerous changes made to the design.

Chapter 6: Chapter 6 presents the results obtained on the pulverized fuel feeder and modifications to be made to increase the efficiency of the feeder.

Chapter 7: This chapter discusses the conclusion of the results and offers a number of recommendations.

References: Contains a list of the resources that was used for the completion of this project.

Appendix: Includes additional information necessary for the Project.

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Nomenclature

PF	- Pulverized fuel
CV	- Calorific value
NCV	-Nett calorific value
(NCVp)	- Nett calorific value at constant pressure
(NCVv)	- Nett calorific value at constant volume
GCV	-Gross calorific value
(GCVp)	- Gross calorific value at constant pressure
(GCVv)	- Gross calorific value at constant volume

Chapter 1: Introduction

It is almost impossible to imagine today's world without electricity. With a growing population, the demand for electrical power constantly increases, putting strain on the power producing infrastructure of a country. It is expensive and time consuming to build new power stations. Therefore, possible improvement on existing infrastructure and technologies can help increase the efficiency of these systems.

The increased efficiency of a power station could increase generation capacity, reduce fuel waste and reduce overall production cost. Increasing the available electrical supply of the power station decreases the cost of power generation, making electricity more affordable. In order to improve the efficiency of a coal power station, the efficiency of the combustion process of the pulverized coal in the power station must be improved.

1.1. Background

Coal is categorized into two different ranks, high rank and the low rank coals. Low ranked coal consists mainly of lignite and sub-bituminous coals that have high moisture levels with low carbon content. These low-ranked coals are generally fragile and are a softer material with a dull earthy appearance.

Higher-ranked coals consist mainly of anthracite coal, which have a high carbon content and low moisture levels. These high-ranked coals can be identified by their hard, strong material with a glossy shine. The high-ranked coal produces substantially more energy than the low-ranked coal. However, they are too expensive to use for producing energy. Due to the high monetary value of the high-ranked coal, it is exported to other countries, leaving the low rank coals for local use.

Coal fired power stations in South Africa are usually built next to or in close proximity to collieries as it is more cost effective than to transport it by road or rail and ensures a constant supply of coal. The coal power stations are usually designed to use the rank of coal of the collieries next to the station. However, if the coal is depleted or the mined coal is low, alternative coal must be imported from another coalfield. Moreover, if this occurs, the coal

brought to the power station could be of a different rank of coal than what the station was designed for.

Notably, if a different rank of coal is used in a power station it could lower the efficiency of the boiler as the combustion process will not occur at optimal conditions. This could potentially lead to the production of greenhouse gasses and coal being wasted. Additionally, it could even have adverse effects on the equipment of the power station, leading to a shut down for repairs.

It is of the utmost importance for a power station to know the exact amount of energy that will be released when burning a specific rank of coal. The reason is that the right air–fuel ratio has to be determined for the specific rank of coal to ensure optimal combustion conditions in the boiler. This is done by controlling both the amount and the rate at which pulverized fuel (PF) and air enters the boiler.

The calorific value (CV) of coal is the amount of energy released when burnt, while the gross calorific value (GCV) is the total amount of energy released during the complete combustion. The calorific meter used to determine the GCV depends on the physical state of the fuel. The fuel can be in various states, such as a solid, liquid or a gas. A bomb calorimeter is used for solid and liquid fuels while a boys gas calorie meter is used for gasses. A bomb calorimeter is operated under constant volume, while the boys gas calorie meter is operated under constant pressure. Thus, depending on the state of the fuel, the GCV is donated either as (GCV_v) or (GCV_p) .

Coal fire power stations use the net calorific value (NCV_v) for their calculations for optimal coal combustion in boilers. The NCV is calculated from the GCV by subtracting the latent heat from water formed during combustion of the fuel. However, the use of (NCV_v) is not a true representation of the energy that is released during the combustion process in the combustion chamber as the combustion chamber operates at a constant pressure and not at a constant volume. In addition, the energy released for (NCV_p) is typically more than that of (NCV_v) and as a result, not all energy released during combustion is used effectively. Overall, coal-fired power stations could potentially operate at a much higher efficiency if (NCV_p) were used instead of (NCV_v) .

1.2. Problem statement

Coal power stations do not use all their resources as effective as they should. First, coal power stations use the NCV_v calorific values instead of the NCV_p calorific values. The use of the wrong calorific values leads to a loss in energy, efficiency and cost. The reason for the use of the wrong calorific values is that there is no calorific meter capable to determine the NCV_p of coal at a constant pressure. This is because there is no calorific meter that is able to replicate the conditions found inside a power station's combustion chamber.

A net calorific meter that is capable of simulating the working conditions inside a power stations combustion chamber must be built to measure the calorific value of the coal correctly. However, this new calorific meter, also called an NCV_p microburner, requires a PF feeder to feed the PF reliably at a desired rate. The size of the combustion chamber is dependent on the flow rate of the PF entering the combustion chamber. The air–fuel ratio is dependent on the rate at which the PF enters the combustion chamber. The air–fuel ratio must be burned at an optimal air–fuel ratio so that optimal or complete combustion can be achieved. The optimal or complete combustion is so that the optimal energy can be achieved from the combustion process.

1.3. Aims and objectives

The aim of this project is to design and build a PF feeder that is capable of feeding PF accurately and reliably to a microburner. Therefore, the prototype PF feeder must comply with the requirements received from the microburner design parameters. The requirements are, the feeder must be able to deliver a flow rate within a specific range as needed for the microburner to operate correctly. Also, if possible the feeder must be able to deliver a desired flow rate at a constant rate within this specific flow range.

Secondly, the prototype PF feeder must be capable of operating at a specific elevated temperature for extended periods of time. Thus, the feeder must be built with materials that can withstand the elevated temperature.

Lastly, it is required that the supplied 10 litre Pyrex glass bottle be implemented into the design of the PF feeder. This is to make it possible to visually observe the powder level in the bottle including any structural formations that may obstruct flow.

The objectives of this project are the following:

- The prototype PF feeder must be able to deliver a flow rate within a specified range.
- The design of the feeder must be checked to see if it is capable of delivering a specific constant flow rate.
- Design an auger capable to feed the PF so that the PF bed is kept in constant motion to prevent formation of bridges and rat holes.
- Calculate the flow rate of the PF feeder by measuring the loss of PF in the container.
- Design and build a container, auger, gearbox, volute, support frame and plenum.
- Obtain measuring equipment that includes load cells (with program) and pressure sensors.
- Test and modify of designs.

1.4. Scope

The scope of the project only included those items mentioned in the aim and objectives above and did not include the following:

- The design, manufacturing and testing of the microburner.
- The optimization of microburner test bed.
- The integration of the PF feeder and the microburner.
- Any change to the optimized air–fuel ratio, as only sub-stoichiometric air–fuel ratio is needed for the PF feeder.

Chapter 2: Literature Study

2.1. Introduction

The necessary literature to obtain sufficient knowledge and background on designing a PF feeder was studied in this chapter.

An in depth look into how important the hopper shape is in allowing bulk materials such as grains, sands and powders to flow freely from it. Also, as the powder may spend a period of time stored inside the hopper between testing, it is necessary to study the effect that storing will have on its flow ability.

Some general characteristics of powders were studied in order to understand how it could potentially influence its own degree of flow ability. These characteristics could be physical (particle shape and size), environmental (temperature and humidity) or even internal forces between particles (particle-particle and particle-surface forces).

Methods to help improve the poor flow ability of powders were studied. This could be done by altering the physical properties of the powder or by simply applying an external force.

A realistic example of an existing PF feeder was studied to help avoid any unnecessary and avoidable problems from occurring, and to ensure that no unnecessary additions were added to the design.

Firstly, some basic definitions are important (Thompson, 1997):

- **Bin:** A bin is an upright standing container that is used to store powders or any other bulk solids.
- **Silo:** A silo is a tall bin with a height that is 1,5 times greater than its diameter, $H > 1,5D$.
- **Bunker:** A bunker is a shallow bin with a height that is 1,5 times smaller than its diameter, $H < 1,5 D$.
- **Hopper:** Is an independent part attached to the bottom of the silo that has a converging sloped wall
- **Solid flow patterns:** Are the boundaries that are formed between flowing and non-flowing regions of the solids in the bin.

2.2. Common flow patterns in bins and hoppers

According to Jenike (1964), there are three basic types of flow patterns in bins and hoppers. These flow patterns are funnel flow, mass flow and expanded flow.

2.2.1. Funnel Flow

Funnel flow, also called core flow, occurs predominantly in bins that have a flat bottom design and in hoppers that have very shallow sloped angles with a rough surface finish (Thompson, 1997). In Figure 1, the typical designs for funnel flow bins are shown as described by Chase (s.a.).

Funnel flow is commonly found in industrial applications where the storage bins are designed with only the storage capacity in mind without considering the discharge ability of the stored bulk solid (Thompson, 1997).

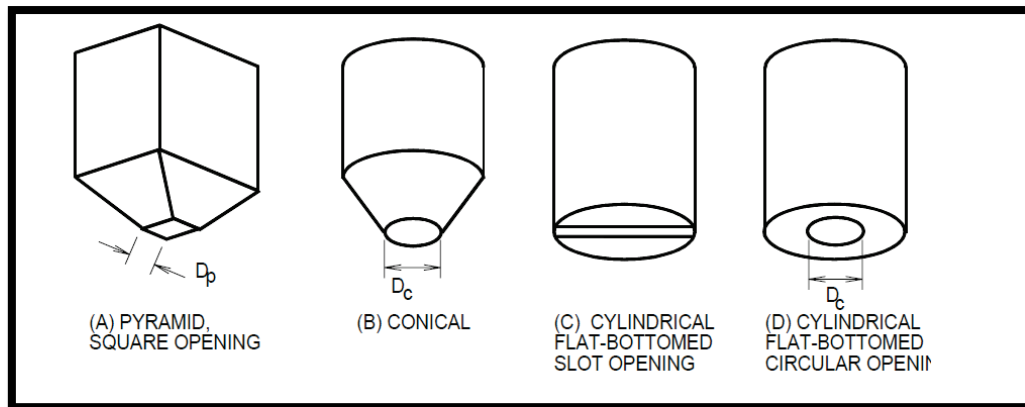


Figure 1: Common designs for funnel flow bins (Chase, s.a.)

Two separate regions form when the bulk solid is extracted from the bin, namely the active region and the stagnant region, as shown in Figure 2. The active region is formed when only the middle region of the bulk solid is in motion, while the region closer to the wall remains stationary, forming the stagnant region. This stagnant region causes the bin to discharge less material than it was designed for (Thompson, 1997).

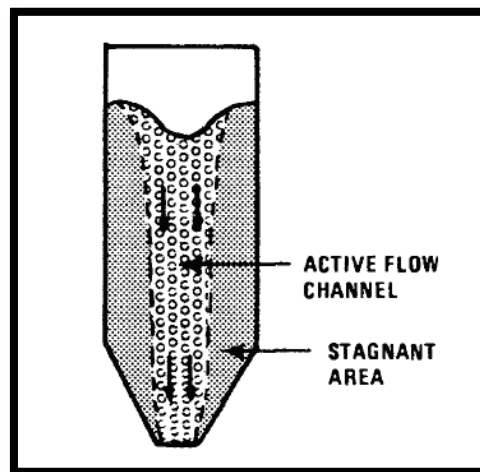


Figure 2: Funnel flow with active and stagnant flow regions (Thompson, 1997).

Storing solid material for a period of time leads to degrading or caking into a solid mass due to the stresses and binding mechanism working on it (Thompson, 1997). In addition, if the bulk solid in the stagnant region is left undisturbed, hardening of the solid mass occurs. It becomes stable enough to form a conical shaped hole known more commonly as a rat hole (Thompson, 1997). However, if the stagnant region is disturbed it will become unstable and collapse into the channel, causing a pulsating type of flow from the bin exit (Thompson, 1997).

Discharge of bulk solids in the funnel flow bins are usually erratic due to the formation and collapsing of bridges near the bin exit. Furthermore, the discharge rate can become uncontrollable when discharging fine powder as it easily becomes aerated when the bridge or rat hole collapses, causing it to flush from the bin (Thompson, 1997).

Bulk solids stored in funnel flow bins are vulnerable to time consolidated effects such as degrading, caking and segregation, gradually worsening as time goes on (Thompson, 1997). Time consolidation has a large effect on the funnel flow bins. When the bin is filled with new material, the new material is the last to exit the bin (first in last out). Consequently, the bulk solid remains inside the bin longer than it should (Thompson, 1997).

2.2.2. Mass flow

Mass flow typically occurs in hoppers that have sufficiently smooth surface finish and steeply sloped angles (Thompson, 1997) as shown in Figure 3, adapted from Chase (s.a.).

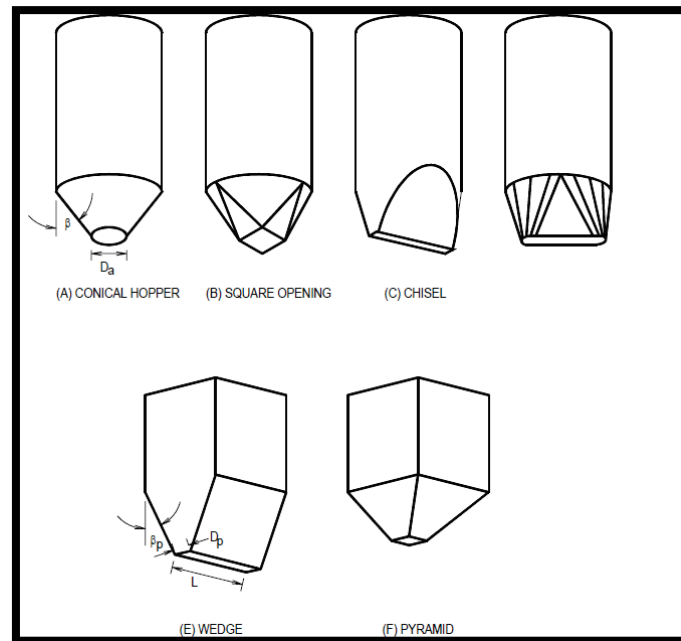


Figure 3: Common designs for mass flow bins (Chase, s.a.)

In mass flow, all regions of the bulk solid are in constant motion, albeit at various velocities. This eliminates flow problems such as rat holing; flooding and erratic flows that occur with funnel flow (Thompson, 1997). Since the bulk solids are in a constant motion, no regions of stagnant flow occur, allowing the bin to be completely emptied.

Furthermore, time consolidated effects are minimized in mass flow bins since the first material to enter the bin is the first out. As a result, the bulk solid does not spend more time in the bin than is necessary (Thompson, 1997). Also, the flow out of the hopper is uniform and does not pulsate as with funnel flow. The extraction rate of the bulk solid out of the bin is therefore more controllable than funnel flow (Thompson, 1997).

2.2.3. Expanded flow

Expanded flow is a combination of mass flow and funnel flow (Thompson, 1997). However, it is not always feasible for industries to change from existing funnel flow bins to mass flow bins due to high cost. In addition, mass flow bins have physical restrictions such as height (Thompson, 1997).

Figure 4 is an example of an expanded flow bin. In Figure 4, the mass flow hopper (conical or transitional-slot hopper) is fitted underneath the existing funnel flow bins to improve the existing bins without having to replace them. The mass flow hopper allows for uniform discharge and for better control of the discharge rate of the bulk solid (Thompson, 1997).

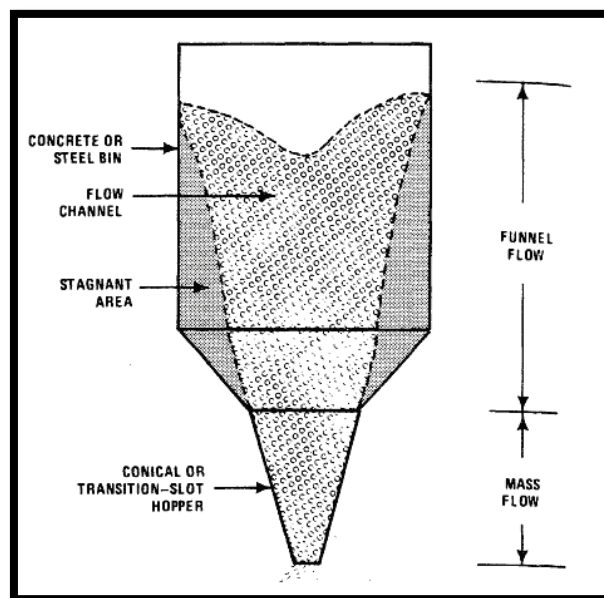


Figure 4: Expanded flow (Thompson, 1997).

2.3. Factors that influence the flow properties during bin storage

2.3.1. Impact during loading

The impact occurs when the bin is filled with new bulk solid while there is still old bulk solid left in the bin. As the new bulk solid is added to the bin, it falls onto the old bulk solid. The impact of the newly added bulk solid onto a single stress point compresses the old bulk solid. As a result, the bulk solid over the exit starts to compact (Thompson, 1997).

However, the stress caused by the impact of the powder can be reduced by installing a deflector plate. The deflector plate causes the powder to spread over a wider area evenly (Thompson, 1997).

2.3.2. Temperature and chemical changes

The temperature inside the storage bin influences the bulk solid that is stored inside the bin. High temperatures can cause the solids to agglomerate or soften. With lower temperatures a possible phase change can occur (Thompson, 1997).

These physical changes to the solids have a significant effect on their flow ability due to the temperature changes (Thompson, 1997).

2.3.3. Moisture

Moisture can be absorbed into the bulk solid through absorption of moisture in the atmosphere if the solid is exposed to the elements. However, the amount of moisture in the bulk solid can be eliminated by drying it. Therefore, great thought should go into how the bulk solid should be stored. Moisture can enter the storage bin if airtight containers are not used (Thompson, 1997).

The moisture in the bulk solid affects the yield strength of the bulk solid. Thus, it can undergo more plastic deformation before it starts to break up. Friction between particles and bin surfaces increases, affecting the flow ability of the bulk solid (Thompson, 1997).

The moisture also increases solid-wall adhesion between the bulk solid and bin surfaces, causing the powder to stick to the bin surface (Thompson, 1997).

2.3.4. Particle size

As the particles size starts to decrease, the flow ability of the bulk solid also starts to decrease, with wall friction tending to increase (Thompson, 1997). Another result of decreasing particle size is the decrease of permeability of the bulk solid, which could increase the possibility of flooding (Thompson, 1997). Low permeability may cause flow limitation out of the hopper exit, possibly due to lowering in pressure in the hopper. This creates a vacuum inside the bin that prevents further flow (Thompson, 1997).

2.3.5. Vibration

Vibrations tend to cause compacting in many bulk solids and cause flow stoppages in solids that have high instantaneous flow function. Vibration while the bulk solids are stored in the bin should be avoided at all times (Thompson, 1997).

2.3.6. The effects on PF during bin storage.

Storing PF for a long period of time should be avoided if possible due to its hygroscopic properties, compacting and the tendency to spontaneously combust (American Society of Heating Ventilating Engineers, 2013:252-253).

Also, the hygroscopic nature of the PF powder causes the particles to physically rearrange themselves over a period of two to three days while in storage, forming a hard and densely packed powder bed (Eastop & MacConkey, 1998).

2.4. Agglomeration

Powder particles can bind with each other to form larger particles known as agglomerates, which can make the flow of the bulk solids difficult, if not impossible. Chase (s.a.) defines these binding mechanisms as follows:

2.4.1. Solid bridges

- Mineral bridges
- Chemical reactions
- Particle melting
- Binder hardening
- Crystallization of dissolved substances

2.4.2. Adhesion and cohesion forces

Adhesion and cohesion are both forces that act between the particles-particles and particles-surfaces, altering the flow ability of the powdered material (Chase, s.a.). Adhesion is defined as the interaction between a particle and a non-homogenous particles, surface or substrate. The perfect example for adhesion is water droplets that adhere to the surface of a glass after the water has been poured from it (Chase, s.a.).

Adhesion properties can also be found in solids. Small particles, usually in powdered form, display adhesion properties (Chase, s.a.). Cohesion is defined as the interaction between homogenous particles to form an aggregate that is deformed or disintegrated when an external force is applied (Chase, s.a.). It is important to note that a frictional force is a resistance force that acts against an external force that tries to move the particles adhering to a surface along its length (Chase, s.a.).

2.4.3. Interfacial forces

Interfacial forces are liquid bridges and capillary forces that act between particles. They are caused by the contact surfaces between phases (solid, liquid and gas) and interfacial tensions (Chase, s.a.).

2.4.4. Attractive forces

It can be short-ranged intermolecular forces such as van der Waals forces, and longer ranged forces act as electrostatic and magnetic forces. Short-ranged repulsive forces are also present, but if the particles are close enough to each other, the attractive forces will be stronger (Chase, s.a.).

2.4.5. Interlocking

Interlocking occurs to the geometry of the particles and happens when the powder comes in contact with a fibrous material where it then becomes entangled in it (Chase, s.a.).

2.5. *Types of powder flow*

Some powders do not have good flow ability properties and for this reason, it is sometimes necessary to apply an external force on the powder to induce flow. According to Hayakawa (1973), there are several types of induced flow.

2.5.1. Gravitational flow

Gravitational flow is using only gravity to make the powder flow out of a hopper, without using any flow aids. Not all powders are able to flow by only using gravity and require some type of external force or flow aid to improve the flow ability of the powder (Hayakawa, 1973).

2.5.2. Mechanically forced flow

This can include any method of physically stirring or moving the powder by mechanical means to improve the flow of the powder (Hayakawa, 1973).

2.5.3. Compression flow

The powder bed is compressed by applying a force directly to the entire surface, forcing the powder out of the bin or container exit (Hayakawa, 1973).

2.5.4. Vibration flow

Vibration flow entails using vibration as a means of improve the powder flow. The problem is that this can also induce mechanical interlocking between irregular shaped particles, which causes the formation of an interlocking arch, making the flow ability of the powder even worse (Hayakawa, 1973).

2.5.5. Fluidized flow

With fluidized flow, a gas or liquid is pumped into the powder bed to fluidize it. This means that the powder bed expands, making particle-to-particle interaction less, thereby improving the flow ability of the powder. Some powder, however, are hard to fluidize due to the strong inter particle forces between them (Hayakawa, 1973).

2.6. *How to improve the flow ability of bulk solids*

The flow ability of powders can potentially be improved by changing some of the physical properties of the powder. These physical properties include lowering the moisture content and changing the particle shape and size (Masuda *et al.*, 2006).

Fluidity can further be increased through air aeration to fluidize the powder, increasing the distance between particles and making interaction between particles less (Masuda *et al.*, 2006).¹

The fluidity is also improved by altering the dynamic contact of particles, making use of pulsation of air pressure (Masuda *et al.*, 2006).

In order to meet distribution and feeding requirements of the PF, it should be kept dry and in constant motion (Nifuku & Katoh, 2003). Furthermore, an increase in relative humidity will increases the electrical conductivity of both the particles and the contact surface, while reducing the resulting electrical charge received on both the contact particles and the surface (Nifuku & Katoh, 2003).

2.5.1 Flow aids

A flow aid is a device that can be used to help improve the flow of a powder out of a hopper and can be any one of the following (Jenike & Johanson, 2016):

- Pneumatic hammers
- Air cannons
- Fluidization pads
- Fluidization nozzles

Not every flow aid can be used for fine powders as they might have the opposite effect, hampering flow.

Air cannons are effective for initiating material flow, especially when the material has been sitting idle for a time. However, if the powder has cohesive properties, the air cannons are ineffective, as it has to fire continuously to maintain flow of the material (Jenike & Johanson, 2016).

While air cannons are effective to break bridges in silos, they are ineffective when trying to break up rat holes (Jenike & Johanson, 2016).

Vibrators tend to cause the powder particles to segregate and form stratification layers of different particle sizes (Jenike & Johanson, 2016). Additionally, they may produce high levels of noise and could cause structural damage to the hopper if not properly installed (Jenike & Johanson, 2016).

2.7. Splitting powders into groups

Powders were first divided into different groups by Geldart (1973) and were done so according to the degree of difficulty in fluidizing the powder bed, which can be seen in Figure 5 below.

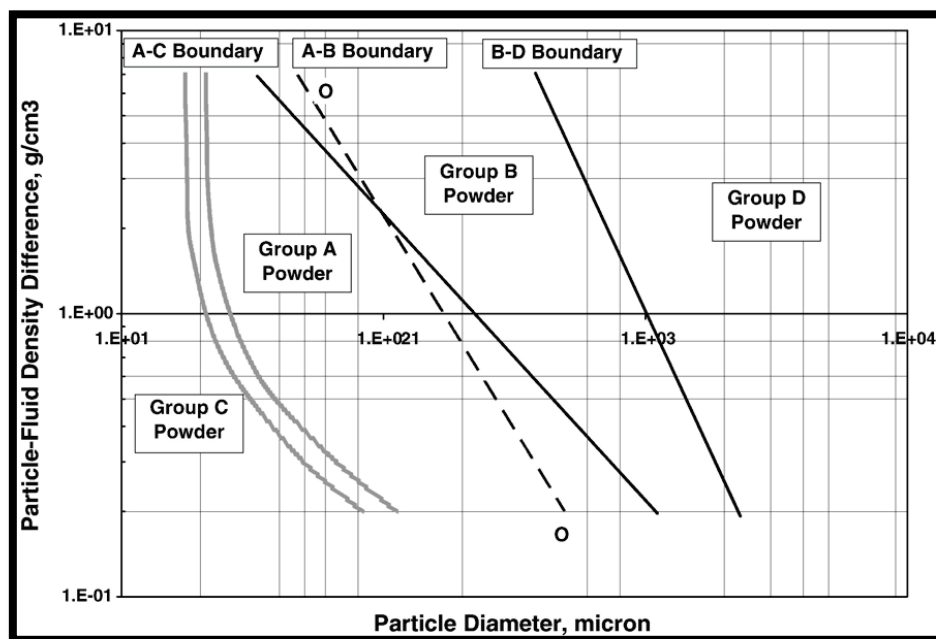


Figure 5: Geldart's classification of powders for fluidization by air (Geldart, 1973).

2.7.1. Group A powders

Group A powders are typically very small particles with low particle density, typically less than 1.4 g/cm^3 (Geldart, 1973).

When the powder bed is aerated, it expands considerably before any bubbling of the bed starts to occur. When the aeration gas is suddenly turned off, the bed collapses very slowly at a typical rate of $0.3 - 0.6 \text{ cm/s}$ (Geldart, 1973).

Air bubbles smaller than 4cm rise more quickly than the interstitial gas velocity at about 30-40 cm/s, regardless of the bubble size and it is assumed that the bubble rise velocity is controlled by the rate at which the powder is mixing. It is possible to mix the powder thoroughly with a low amount of aeration (Geldart, 1973). Bubble size can be reduced by having a powder bed that has a wide particle size distribution or has a distribution of small mean sized particles (Geldart, 1973).

2.7.2. Group B powders

Group B powders range in particle sizes of 40 μ m to 500 μ m, with particle densities between 4g/cm³ and 1.4g/cm³. Sand is a typical example of group B powders (Geldart, 1973).

When the powder bed is aerated, it only expands by a small amount and collapses rapidly when aeration is stopped. Bubbles start to form in the powder only when the aeration velocity is slightly above the minimum fluidization velocity (Geldart, 1973).

There is little or almost no mixing of the powder bed, with bubble size increasing linearly with bed height and excess gas velocity (Geldart, 1973).

2.7.3. Group C powders

Group C powders consist of small sized particles that have strong cohesive properties and a tendency to form agglomerates. These powders are hard to fluidize and tend to form stable channels when aerated (Geldart, 1973).

When aerated at the correct velocity, the powder bed expands, but when the air forms a stable channel through the powder bed it starts to collapse and is impossible to expand the bed once more (Geldart, 1973).

Mixing of particles during aeration is even poorer than that of A and B grouped powders (Geldart, 1973). The fluidization properties of this group of powders can be improved by using mechanical stirrers or vibrators to break up the stable channels that are formed during aeration (Geldart, 1973).

2.7.4. Group D powders

Group D powders are powders that contain large particles with high particle densities. Bubbles formed through aeration tend to rise very slowly in the powder. These powders are unable to be fluidized as the gas only creates a spout on the bed surface (Geldart, 1973).

2.8. Permeability and flow rate of powders

The flow rate of the powder is of great importance to this project therefore, it is necessary to determine if it was possible to predict the flow rate.

Every bulk material has a specific maximum rate at which it discharges from the hopper with a specific sized hopper exit. (Carson *et al.*, 2013) gives a mathematical approximation that can be used to calculate the maximum discharge rate for a free-flowing and coarse bulk material with particle sizes of 3mm or larger can be seen in the equation below:

$$Q = \gamma A \left\{ \frac{Bg}{2(1+m)\tan\theta} \right\}^{\frac{1}{2}}$$

Here Q is the maximum steady discharge rate, γ is the bulk density of the bulk materials, A is the area of the hopper exit, B is the exit diameter of the hopper, g is the gravitational acceleration, θ is the angle of the hopper sides in degrees (measured vertically) in degrees. The value of m is 1 if the hopper exit has a circular shape and 0 if it is slotted. However, this equation cannot be used for bulk solids that have small particles such as fine powders (Carson *et al.*, 2013).

Controlling the discharge rate of fine powders is difficult for funnel flow bins as the subsequent created flow channels are typically not stable. As a result the shape and size of the flow channel continues to vary as the channel either expands or collapses entirely resulting in flow rates that vary between no flow conditions and complete flooding. However, the flow of fine powders can be easily managed using a mass flow bin as all of the powder is in motion and the resulting flow channel is more stable (Carson *et al.*, 2013).

It should be noted that the maximum flow rate of fine powders through the outlet of a mass flow bin is much slower when compared to larger and courser bulk materials. During the flow

of fine materials the expansions and contractions of voids, create an upward air pressure gradient at the exit of the mass flow bin. This air pressure gradient works against the force of gravity, pushing down on the material, and as a result reduces the discharge rate of the mass flow bin. On the contrary, when courser particles materials are used pressure gradients do not usually form. This is because the courser materials are more permeable than those of the fine powders and allows air to move more freely in and out of voids as they expand and contract (Carson *et al.*, 2013).

As mass flow bins have stable and predictable flow patterns it is possible to use permeability values to calculate steady state discharge rates from the hopper (Carson *et al.*, 2013).

2.8.1. Variables Affecting Flow Rate

The variables that affect the flow rate characteristics of a powder are interparticle friction, particle shape and size, type of materials, environmental factors and weight of the bulk. Additionally, particle surface oxides and lubricant films also affect the flow characteristics as they alter the friction between particles and help increase flow rate (Carson *et al.*, 2013).

Reduced flow rates in powders are typically encountered when they have one or more of the following characteristics: low specific gravity, low apparent density, high friction coefficient of the fine particles, high specific surface area, a complex blend of different materials and high moisture content (Carson *et al.*, 2013).

2.8.1.1. Interparticle friction

It is primarily where one particle either directly or indirectly restricts the free movement of another particle in a specific region during discharge. The degree in which these particles affect one another is determined by the interparticle friction coefficient. Also, other factors which may prevent particles from moving freely is that they may temporarily cling to the surface of the bin and to one another. They may also interlock with each other if the particles have irregular shapes. As a result, these form clusters which occupy a considerable amount of volume (Carson *et al.*, 2013).

The flow rate of the powder varies greatly depending on the size and shape of the particle as the formation of clusters form more easily in some powders than in others (Carson *et al.*, 2013).

2.8.1.2. Particle size and shape

Sub sieve powders (powders that have particle sizes less than 44 micron), typically have very poor flow rates compared to larger sized particles (Carson *et al.*, 2013).

2.8.1.3. Type of material

The theoretical density of the powder plays a major role in the flow of different materials as for example copper, aluminium and iron. Additionally, characteristics such as the adhesive and cohesive properties of the material as well as magnetic or electrostatic interactions have an effect on the flow rate (Carson *et al.*, 2013).

2.8.1.4. Environmental factors

Environmental factors such as humidity have a direct effect on the flow rate of powder. When a powder is exposed to humid air the particle surface absorbs the moisture from the air and results in the flow rate being reduced. At the same time, agglomerates form in most powders when the moisture content of the powder starts to increase. This formation of agglomerates increases the permeability of the powder which results in the increase of the flow rate and settling rates (Carson *et al.*, 2013).

2.8.1.5. Weight of the bulk

The specific gravity of the bulk material affects the flow rate. A powder with a lower specific gravity such as aluminium generally has a slower flow rate than compared to a powder that has a higher specific flow rate such as iron. However, the larger the apparent density of the powder the faster the powder will flow (Carson *et al.*, 2013).

2.9. Discharge experiments

As the coal feeder is essential for the project, it is of absolute importance to understand the mechanics of aeration of powders in hoppers. For this reason, the experiments done by Lu *et al.* (2012) are studied in detail. The experimental set-up of their Perspex is illustrated in Figure 6.

The experiments show the rate at which the aeration air enters the hopper to fluidize the powder bed and the pressure that is developed in the hopper. This is important as this can have an effect on the discharge rate of the powder out of the hopper (Lu *et al.*, 2012).

The flow rate of powder particles greatly depends on its size, shape, water content, and coherence and adherence properties. The size of the particle plays an important role in the flow of the powder out of a hopper. If the particle has a diameter smaller than 100 microns, the flow out of the hopper will be hindered by the development of interstitial pressure gradients caused by the relative motion between the powder particles and the airflow (Lu *et al.*, 2012).

The smaller the diameter of the powder particle, the bigger the interstitial pressure gradients will be, as it is commonly assumed that the pressure gradient is proportional to the square of the particle diameter. The cohesive forces of the powder also play a bigger role as the powder particle becomes smaller, leading to the formation of aggregates and cohesive arches that cause discontinues flow or no flow at all (Lu *et al.*, 2012).

An aggregate is formed when the powder particles stick to each other to form lumps or clumps. This means that the powder does not flow as individual powder particles, but as lumps of particles that can cause blockage during flow (Lu *et al.*, 2012).

Mechanical vibration and air aeration are some of the techniques used in industry to promote powder flow discharge that is steady and constant. Aeration when compared to mechanical vibration is cheaper, simpler and makes less noise (Lu *et al.*, 2012).

Fluidization is necessary for powders that do not have good flow ability out of a hopper without the use of external forces such as vibration or aeration. Fluidizing these powders

makes it possible to not only discharge them at a consistent rate, but it also makes it possible to control the discharge rate of the powder out of the hopper (Lu *et al.*, 2012).

Air aeration causes the powder particles to separate from each other causing the powder to become more like a liquid. This helps increase the discharge rate of the powder (Lu *et al.*, 2012).

As powdered coal falls under the Group C powders, it will not flow out of a hopper without the assistance of aeration airflow. The discharge rate of these powders can be controlled by varying the flow rate of the air used to aerate the powder (Lu *et al.*, 2012).

Aeration velocity is plotted against discharge rate for each time they ran the experiment in a Perspex hopper. It is possible to observe that with the increase of aeration velocity, not only does the discharge rate improve, but the discharge rate also becomes more stable. However, there is a point where the aeration velocity becomes too high with the result that the discharge rate will start to decline (Lu *et al.*, 2012).

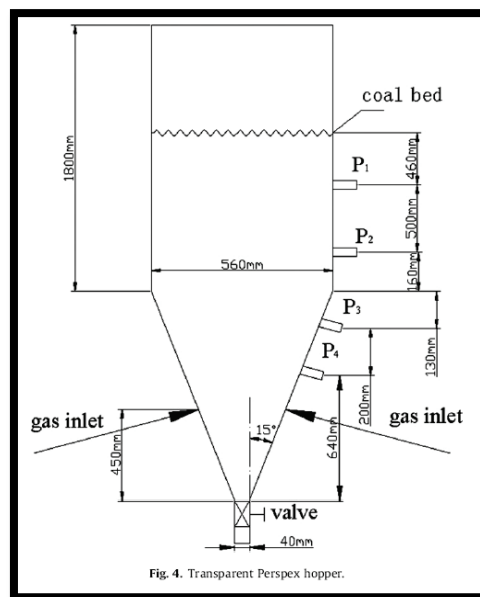


Figure 6: Perspex Hopper Design (Lu *et al.*, 2012).

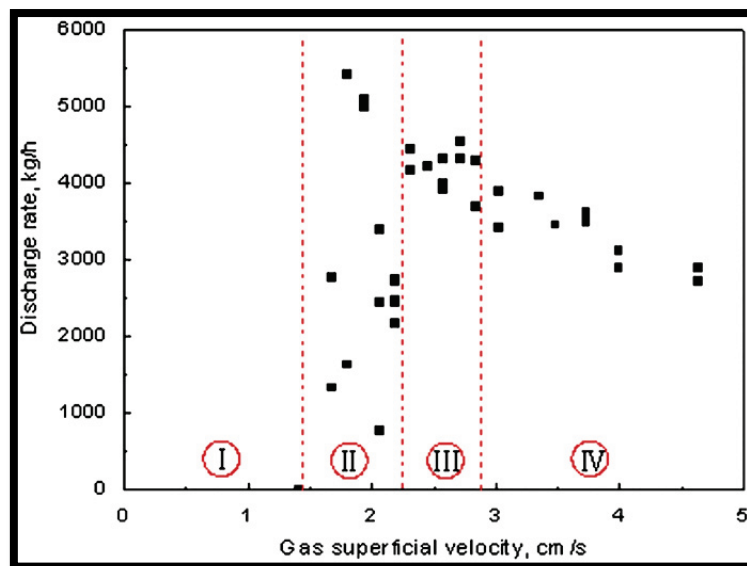


Figure 7: Discharge Rate as a Function of Aeration Rate (Lu *et al.*, 2012).

Table 2 Discharge regions of pulverized coal.				
Region	U_g (cm/s)	Flow pattern	Characteristics	Bed state
I	< 1.4	Blocking	Stable arch, cannot discharge	Fixed
II	[1.4, 2.2]	Funnel flow	Intermittent and unstable discharge	Partial fluidized
III	[2.2, 2.8]	Mass flow	Stable discharge with good reproducibility	Pseudo-full fluidized
IV	> 2.8	Mass or funnel flow	Restrained discharge	Bubbled

Figure 8: Discharge Regions of Pulverized Coal (Lu *et al.*, 2012).

2.9.1. Region 1

First, when the hopper was not aerated there was no powder flow out of the hopper as a powder arch formed almost immediately blocking the hopper exit. When the hopper was aerated with a small air velocity, it did almost nothing to increase the flow ability of the powder with no change to the discharge rate (Lu *et al.*, 2012).

After continuously increasing the air velocity, a point was reached at 1.4 cm/s where it was just enough to help increase the discharge rate of the powder. However, the discharge rate

was inconsistent and unstable. This means that an aeration velocity smaller than 1.4 cm/s is not able to change the state of the powder bed as it remains fixed with no bed expansion (Lu *et al.*, 2012).

A fixed bed with no bed expansion means that the aeration velocity is not enough to increase the flow ability of the powder as the discharge rate and reliability of hopper discharge remains unchanged due to the hopper exit becoming blocked by the formation of an arch (Lu *et al.*, 2012).

However, when the aeration velocity reaches 1.4 cm/s, this causes the bed to become partially fluidized with some bed expansion, resulting in a small increase in the flow ability of the powder (Lu *et al.*, 2012).

The weight of the powder causes the powder arch to become compressed, making it stronger. This means that more energy from the injected air is needed to break the arch. When the aeration velocity is very low it is not capable of breaking the arch formed by the powder. However, when it reaches a specific velocity, in this case 1.4 cm/s, it is capable of breaking the arch, allowing the powder to flow freely (Lu *et al.*, 2012).

As coal powder has high cohesive interparticle forces it tends to form agglomerates. The geometric shape of the coal particles and that of the formed agglomerates are usually very irregular, which increases friction and the chance of mechanical interlocking between particles or agglomerates to form an interlocking arch. By injecting air into the hopper breaks the agglomerate into smaller pieces reducing friction and lowers the chance for mechanical interlocking (Lu *et al.*, 2012).

Donsi *et al.* (2004), believed that all materials do have a certain degree of cohesiveness, but this could be overcome with the addition of sufficient amounts of energy to loosen the particles from each other and promote the flow ability of the powder (Lu *et al.*, 2012).

When they later tried the same experiment on a bigger carbon steel hopper, it was found that the minimum aeration velocity of 1.4 cm/s was insufficient to promote powder flow out of the hopper. This means that the minimum aeration velocity depends on the hopper design and that the data collected from one are not applicable to another. The four regions described, however, are found in all tests and are shown in Figure 7 and Figure 8 (Lu *et al.*, 2012).

2.9.2. Region 2

Region 2 in this case is found between the aeration velocities of 1.4 and 2.2 cm/s. The discharge rate of the hopper is varied and unstable as it is hard to repeat the same discharge rate for a specific aeration velocity (Lu *et al.*, 2012).

This can be attributed to funnel flow like patterns in the hopper where the top layers of powder flows quickly through a funnel like structure out of the hopper exit (Lu *et al.*, 2012).

Nedderman (1992) observed that the flow of fine powders is usually irregular and intermittent with normal operations having a typically slow flow rate (Lu *et al.*, 2012).

Donsi *et al.* (2004) noted that when powder beds are aerated with small aeration velocities they produce rat holing and funnel flow with small discharge rates. Flooding also occurs when the rat hole becomes unstable and collapses on itself (Lu *et al.*, 2012).

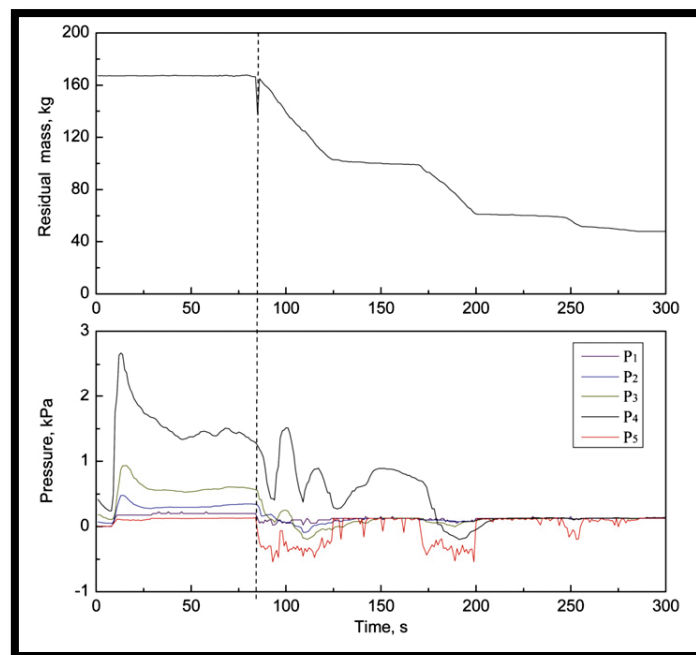


Figure 9: Discharge Curves for Aeration Velocity at 1.7 cm/s (Lu *et al.*, 2012).

When the powder bed is aerated at a velocity of 1.7 cm/s, as shown in Figure 9 above, the discharge weight profile of the hopper takes on a ladder like shape. The ladder like shape is caused by the formation and subsequent collapse of these arches, this it means that the discharge rate is dependent on the cycle of formation and destruction of these arches which varies greatly (Lu *et al.*, 2012).

The pressures of P1 – P4 continually forms peaks during the whole of the discharge and this is probable caused by the continual forming and breaking of the arches (Lu *et al.*, 2012).

2.9.3. Region 3

Region 3 is between the aeration velocities of 2.2 and 2.8 cm/s. This region has the unique characteristic of having very stable and repeatable discharge rates compared to the previous regions (Lu *et al.*, 2012).

It is different from the previous regions as channelling, arching and flooding are absent in this region, which contributes to the reliability and repeatability of the discharge flow (Lu *et al.*, 2012). This means that the flow inside the hopper becomes a mass flow type as result of the powder bed inside the hopper being completely fluidized (Lu *et al.*, 2012).

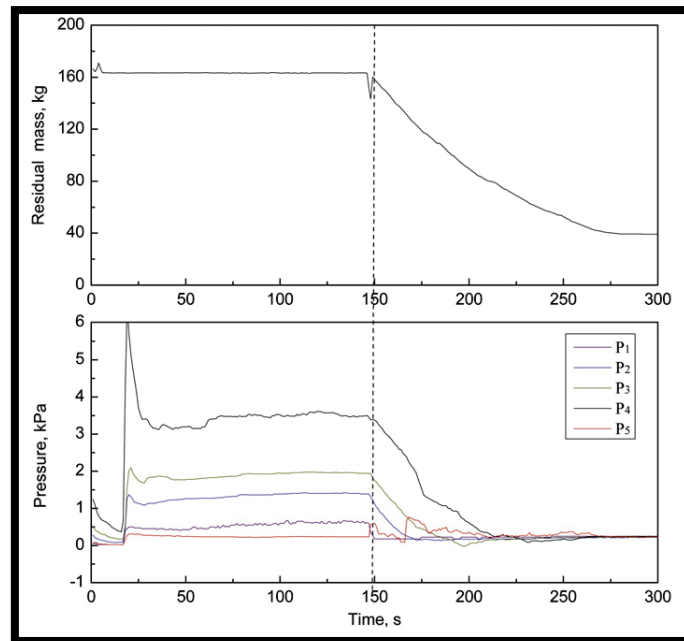


Figure 10: Discharge Curves for Aeration Velocity at 2.5 cm/s (Lu *et al.*, 2012).

As can be seen from the Figure 10 when the hopper is aerated with a velocity of 2.5 cm/s, the weight of the powder gradually decreases when the outlet is opened. The discharge rate, however, is not constant as the discharge rate decreases over time (Lu *et al.*, 2012).

This means that the discharge rate is also dependent on the pressure inside the hopper and the pressure created by the weight of the powder. The change in powder discharge rate with the decrease in bed height can probably be attributed to the aeration air escaping through the outlet (Lu *et al.*, 2012).

The flow of aerated air was considered by Altiner (1983), as occurring in two distinct directions namely with one moving upwards and one downwards. The discharge rate of the powder is seen as to be proportional to the down flow, which decreases with bed height. As the discharge rate of the powder only changes a little, the pressure is not the only parameter determining the discharge rate (Lu *et al.*, 2012).

2.9.4. Region 4

Region 4, which in this case starts when the aeration velocity is greater than 2.8 cm/s, shows that the continual increase of the aeration velocity does not necessarily continue to improve the flow ability of a powder (Lu *et al.*, 2012).

Aeration normally decreases the density of the powder bed to improve the flow ability, but it is possible that when the density becomes too low due to the increase of the aeration velocity, the air will actually blow the powder upwards and away from the hopper outlet creating what is known as a gas-balanced arch (Huang *et al.*, 2009; Zheng *et al.*, 2007). When a gas-balanced arch forms, the discharge rate would typically become lower and more variable (Lu *et al.*, 2012).

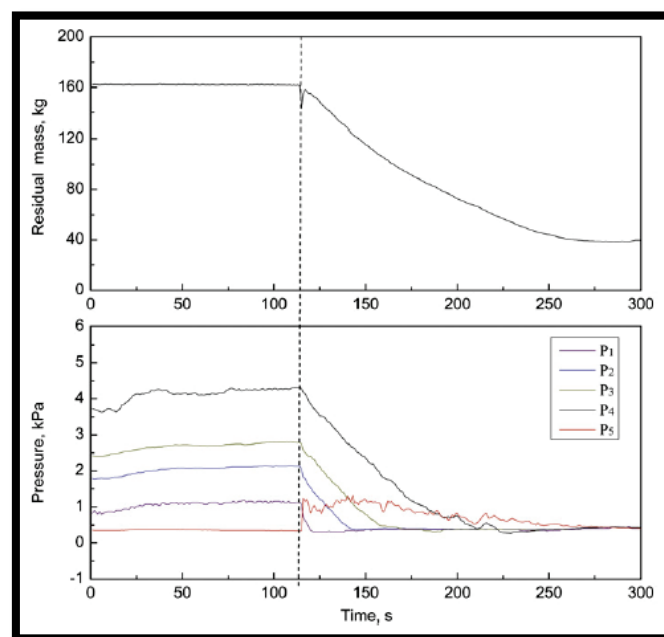


Figure 11: Discharge Curves for Aeration Velocity at 3.7 cm/s (Lu *et al.*, 2012).

Here the hopper is aerated with a velocity of 3.7 cm/s, as seen in Figure 11. It shows a discharge curve very similar to that of Figure 10, making it possible to assume that the flow in the hopper is also a mass flow (Lu *et al.*, 2012).

2.9.5. Mechanism of aerated discharge

Many studies and experiments have been done on improving the powder discharge rate from hoppers by using aeration, but the precise mechanism that improves the powder flow is not known (Lu *et al.*, 2012).

Aeration has the following three effects on powder beds (Lu *et al.*, 2012):

- It positively increases the interstitial pressure between powder particles, which are normally negative if not aerated (gravitational flow).
- Increased aeration velocities may increase the total volume that the powder occupies in a hopper due to bed expansion.
- Aeration provides the necessary energy to overcoming the interparticle interactions to improve the flow ability of the powder.

2.9.5.1. First effect

The first effect can be seen by comparing the pressure inside a hopper between a purely gravity discharge to an aerated assisted discharge (Lu *et al.*, 2012).

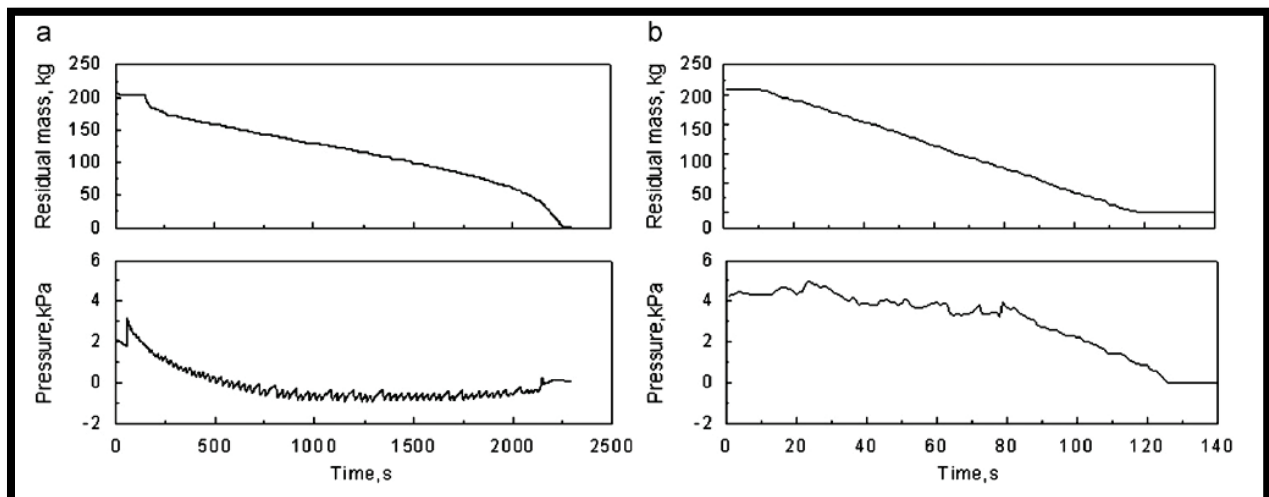


Figure 12: Discharge Curves for Aeration Velocity at (a) 0 cm/s and (b) 2.0 cm/s with pressure curve included (Lu *et al.*, 2012).

Figure 12 shows both the measured mass flow and pressure (P4) for (a) gravity discharge and (b) aerated discharge (Lu *et al.*, 2012). The pressure at P4 is mostly negative due to the negative interstitial pressure created during powder discharge. As the powder leaves the hopper it creates a negative pressure due to the increase of volume, but no air can get in as the powder blocks airflow in to the hopper (Lu *et al.*, 2012).

When aerated the pressure P4 is positive, increasing the discharge rate and shortening the time it takes to completely empty the hopper (Lu *et al.*, 2012). The smaller the particle diameter, the greater the negative pressure P4 will be and the bigger the need for aeration to discharge the powder from the hopper (Lu *et al.*, 2012).

2.9.5.2. Second effect

The dotted line in Figure 7 shows at which velocity the state of the bed starts to change (Lu *et al.*, 2012).

The three lines dividing the regions are classified as the following (Lu *et al.*, 2012):

- The first line between regions 1 and 2 is known as the partial fluidization velocity (U_{pf}).
- The second line between regions 2 and 3 is known as the full fluidization velocity (U_{ff}).
- The third line between regions 3 and 4 is known as the incipient bubbling point (U_{mb}).

Region 1

Aerodynamic drag on particles are small when the aeration velocity is less than the partial fluidizing velocity ($U_g < U_{pf}$). This means that the drag of the bubbles that move upwards during aeration is not strong enough to change the state of the fixed powder bed and loosens the powder to improve the discharge (Lu *et al.*, 2012).

Region 2

The aerodynamic drag forces started to overcome the gravitational forces acting on the particles when the aeration velocity becomes greater than that of the partial fluidizing velocity ($U_g > U_{pf}$). As a result the particles loosens from each other, causing the powder bed to expand and discharge to improve (Lu *et al.*, 2012).

Some powders like pulverized coal have strong cohesive forces between the particles and tend to form agglomerates. These agglomerates cause unstable and non-uniform bed expansion due to the formation of channels through the powder bed (Lu *et al.*, 2012).

A study did by Donsi and Ferrari (1991) on the aeration of group A powders shows that there is a relationship between aeration velocity and discharge rate. As the aeration velocity increases, the discharge rate also increases.

This relationship is not as apparent for group C powders as the bed only becomes partially fluidized with the discharge rate being highly variable at any given aeration velocity (Lu *et al.*, 2012).

Region 3

The powder bed becomes pseudo-full fluidized when the aeration velocity is greater than the pseudo-full fluidizing velocity ($U_g > U_{ff}$). Full fluidization is defined by Bell and Ferrari (1991) as the maximum limit of aeration possible to improve the discharge rate of a powder (Lu *et al.*, 2012).

The height of the powder bed also has an effect on the discharge rate of the powder. The discharge rate of the powder normally decreases with the decrease of the bed height. However, it does not affect the average discharge rate (Lu *et al.*, 2012).

Region 4

When the aeration velocity is greater than the incipient bubbling point ($U_g > U_{mb}$) the powder bed starts to boil vigorously with the excess air actually hampering the discharge rate, causing it to decrease (Lu *et al.*, 2012).

2.9.5.3. Third effect

Aeration provides the energy necessary to overcome the interparticle forces such as van der Waals, capillary (liquid bridge), sintering, electrostatic, and frictional forces. Aeration of powder even at the lowest injected velocity is enough to increase the discharge rate according to Bell and Ferrari (1991).

The energy needed to separate the particles and aggregates to enable flow depends on both the physical properties of the particles and the porosity of the powdered bed as stated by Donsi and Ferrari (1991).

The energy from aeration needed to overcome interparticle forces dissipates at a constant rate per unit solid weight. Increasing the aeration rate will improve the discharge rate. When the aeration velocity is greater than the incipient bubbling point, however, the energy is too much, reducing the discharge rate (Lu *et al.*, 2012).

A powder that has strong cohesive forces like group C powders aggregate readily and need far more energy to loosen the particles and aggregates from each other. This is one of the reasons why they are so difficult to discharge from hoppers (Lu *et al.*, 2012).

2.9.6. The fluidization process of coal powder

Aeration velocity is expressed as U_g and is determined by the following equation (Lu *et al.*, 2012).

$$U_g = \frac{4Q}{\pi d_m^2}$$

Q is the flow rate of the air being injected through an injection pipe with a diameter of d_m at a specific point on the cone section of the hopper (Lu *et al.*, 2012).

The theoretical minimum velocity (U_{mf}) needed to fluidize pulverized coal can be determined by the equation (Lu *et al.*, 2012).

$$U_{mf} = \frac{d_p^2(\rho_p - \rho_g)}{1650\mu} g$$

Where d_p is the mean particle size, ρ_p is the particle density, ρ_g is the gas density, and μ is the gas viscosity (Lu *et al.*, 2012).

The coal bed remains fixed at low aeration velocity due to the strong cohesive forces acting between the particles and formed agglomerates, with air bubbles forming channels through the bed where it moves up towards the bed surface (Lu *et al.*, 2012).

By increasing the aeration velocity gradually, the coal bed will start to expand, but not homogeneously like it will do with Group A powders for example (Lu *et al.*, 2012).

Increasing the aeration velocity further will result in the coal bed starting to boil and later the coal particles will be blown upwards, dispersing it into the empty air space of the hopper where it then adheres to the walls. Fluidization, according to Song *et al.* (2004), can be divided into three different stages, namely fixed bed, fluidized bed and pneumatic conveying (Lu *et al.*, 2012).

Designing a hopper for pulverized coal is difficult due to its cohesive properties. Most hopper designs today are based on Jenike's design method (Jenike, 1961) as this hopper design allows for mass flow of powder out of a hopper by using only gravity. This design method, however, is limited and only works best for non-cohesive powders as cohesive powders need flow aids to increase the flow ability of the powder (Lu *et al.*, 2012).

2.10. Summary

Powdered coal or PF is categorized as a group C powder, meaning that it will not be able to flow freely from the hopper and that an external force will be required. Powder group C consists of small irregular shaped particles, which are highly abrasive and tend to cause mechanical interlocking bridges near the exit of hoppers.

Furthermore, there are strong cohesive forces between the particles that result in the formation of agglomerates. Equally important, the small size of the particles will also substantially lower the gas permeability of the powder bed, which could cause a pressure differences in the feeder during feeding.

It should be noted that PF must not be stored in the feeder for any extended period of time due to its hygroscopic properties, its ability to compact the powder bed and the tendency to spontaneously combust.

Chapter 3: Analysis model

3.1. Introduction

The design of the microburner and its components is heavily depended on the ability of the feeder to successfully provide a small flow rate. A list of requirements is shown in Appendix D Table D1, where the relevant data of the feeder is highlighted in yellow. The reasoning for these requirements necessity is discussed below.

The PF flow rate is important to the microburner since it determines the size of the microburner. The feed rate which the feeder is capable of delivering to the microburner determines the size of the microburner and also its other components such as combustion chamber, heat exchanger etc. Therefore, the flow rate of PF needs to be small in order to keep the size of the microburner as small as possible.

Heat from the heat exchanger is used to heat up the primary air entering the bottle of the PF feeder. This hot primary air is necessary to heat up the PF before it enters the combustion chamber in order to lower the energy necessary to ignite the PF. Also, the hot air also helps dry the powder of any moisture which it may have absorbed.

The bunker size is important for the microburner since it has to be able to continuously operate for an extended period of time to acquire sufficient data. Therefore, the size of the bunker or the size of the feeder bin has to be sufficiently large enough to allow for continuously operation of the burner while also delivering PF within the required range.

The first part focuses on ensuring that no combustion of the PF can take place inside the bottle by calculating the stoichiometric air-fuel ratio of the coal. Therefore, the optimal stoichiometric air-fuel ratio for the specific coal used was determined, using the same ultimate analysis data used in the microburner project.

The second part focuses on the calculations of the gearbox design, which will be integrating a motor into the prototype PF feeder design. The output of the gearbox is important as it is meant to reduce the speed at which the auger turns while simultaneously increasing the

torque, allowing for improved rotation in the powder. This design for the gearbox is also meant to help reduce the strain on the motor and help prevent it from overheating.

The last part of this chapter is meant to show the calculations for the auger since the auger was originally meant to feed both the PF and keep the powder bed in constant motion. However, due to the literature study and the results of the preliminary analysis it was decided not to use the auger to feed the PF.

3.2. *Determining the Stoichiometric air-fuel ratio of coal*

The following section determines the air-fuel ratio that is necessary for the coal powder to burn. These calculations are important to determine if the coal powder inside the bottle will be able to burn, which must be avoided for safety reasons.

3.2.1. **Ultimate analysis**

The ultimate analysis is a quantitative analysis of various elements present in the coal sample. The ultimate analysis data shown in Table 1 was obtained from INGM 427 course class notes while the equations were found in the following book: Applied Thermo-dynamics for engineering Technologists (Eastop & MacConkey, 1998). The as-received data were used as it was the most relevant for the experimentation that without drying the powder.

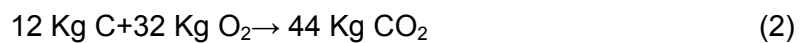
Table 1: Ultimate analysis of a coal sample (Storm, s.a.).

Ultimate Analysis		
Contents	Air Dried	As Received
N	2%	1.88%
O	8%	7.5202%
C	45%	42.301%
A	38%	35.72%
S	1%	0.94%
H	2%	1.88%
Mi	4%	3.76%

4.1.2 Combustion equations

The following equations, are found in were used to determine the stoichiometric constants to calculate the mass oxygen needed to burn 1 kg of coal.

Carbon (C):



$$\text{Oxygen required} = \left(\frac{32 \text{ Kg}}{12 \text{ Kg}} \right) \times 0.42301 = \frac{1.128 \text{ Kg O}_2}{1 \text{ Kg Coal}} \quad (3)$$

$$\text{Carbon produced} = \left(\frac{44 \text{ Kg}}{12 \text{ Kg}} \right) \times 0.42301 = \frac{1.155 \text{ Kg CO}_2}{1 \text{ Kg Coal}} \quad (4)$$

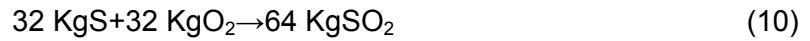
Hydrogen (H):



$$\text{Oxygen required} = \left(\frac{16 \text{ Kg}}{2 \text{ Kg}} \right) \times 0.0188 = \frac{0.1504 \text{ Kg O}_2}{1 \text{ Kg coal}} \quad (7)$$

$$\text{Steam Produced} = \left(\frac{18 \text{ Kg}}{2 \text{ Kg}} \right) \times 0.0188 = \frac{0.1692 \text{ Kg H}_2\text{O (steam)}}{1 \text{ Kg coal}} \quad (8)$$

Sulphur (S):



$$\text{Oxygen required} = \left(\frac{32 \text{ Kg}}{32 \text{ Kg}} \right) \times 0.0094 = \frac{0.0094 \text{ Kg O}_2}{1 \text{ Kg coal}} \quad (11)$$

$$\text{Sulphur dioxide} = \left(\frac{64 \text{ Kg}}{32 \text{ Kg}} \right) \times 0.0094 = \frac{0.0188 \text{ Kg SO}_2}{1 \text{ Kg coal}} \quad (12)$$

The following calculations are the calculated total amount of oxygen required to burn 1 kg of coal. According to the ultimate analysis, the coal contains 7.5% oxygen, which was calculated for 1 kg of coal.

Oxygen available in coal:

$$\text{Oxygen available} = \frac{0.075202 \text{ Kg O}_2}{1 \text{ Kg coal}} \quad (13)$$

Determining total amount of oxygen required:

$$\text{Total oxygen required} = 1.128 \text{ Kg O}_2 + 0.1504 \text{ Kg O}_2 + 0.0094 \text{ Kg O}_2 - 0.075202 \text{ Kg O}_2 \quad (14)$$

$$\text{Total oxygen required} = \frac{1.212598 \text{ Kg O}_2}{1 \text{ Kg coal}} \quad (15)$$

Determining the amount of air required

In order to calculate the air–fuel ratio, the amount of air required is calculated from the percentage of oxygen in air. The percentage of oxygen in the air is 23.3%.

$$\text{Total air required} = \frac{1.212598 \text{ Kg O}_2}{0.233} \quad (16)$$

$$\text{Total air required} = \frac{5.204 \text{ Kg Air}}{1 \text{ Kg coal}} \quad (17)$$

The stoichiometric air–fuel ratio for this specific coal rank is 5.204. This means that 5.204 Kg of air is needed to burn 1 Kg of coal.

3.3. Safety calculations

A 10L Pyrex bottle was donated for use as the main body for the PF feeder. The air–fuel ratio inside the bottle should be well below the stoichiometric air–fuel ratio. This is to ensure that the coal powder inside the bottle will not combust when the bottle is connected to the PF burner. The following equation is used to calculate the amount of air inside the empty bottle.

$$\rho_{\text{dry}} = \frac{P}{RT} \quad (18)$$

Where,

ρ_{dry} = density dry air ($\frac{\text{Kg}}{\text{M}^3}$),

P = Air pressure(Pa),

R = Specific gas constant (dry air $287.05 \frac{\text{J}}{\text{Kg. K}}$),

T = Temperature (K)

The density of air (ρ_{dry}) calculated at atmospheric pressure of 87 kPa and a temperature of 23 °C.

$$\rho_{\text{dry}} = \frac{87 \times 10^3}{(287.05)(296)}$$

$$\rho_{\text{dry}} = 1.023 \frac{\text{Kg}}{\text{m}^3}$$

The total mass of air inside the 10L bottle (where $V = 10\text{L} = 0.01\text{m}^3$):

$$\rho = \frac{m}{V} \quad (19)$$

$$m = \rho V \quad (20)$$

$$m = \left(1.023 \frac{\text{Kg}}{\text{m}^3}\right) (0.01\text{m}^3)$$

$$m = 0.01023 \text{ Kg Air}$$

This means that there is not enough air available inside the 10L bottle for combustion to take place. Not even enough for 1 kg of PF.

Two additional factors that may increase the air density is the bottle pressure and air temperature.

1. Increase of pressure inside the bottle of 10Kpa.

$$\rho_{\text{dry}} = \frac{(87 \times 10^3) + (10 \times 10^3)}{(287.05)(296)} \quad (21)$$

$$\rho_{\text{dry}} = 1.141622 \frac{\text{Kg}}{\text{m}^3}$$

$$m = (1.141622)(0.01)$$

$$m = 0.01141622 \text{ Kg}$$

2. Increase of air temperature to 70 ° C.

$$\rho_{\text{dry}} = \frac{(87 \times 10^3)}{(287.05)(343)}$$

$$\rho_{\text{dry}} = 0.883624159 \frac{\text{kg}}{\text{m}^3}$$

$$m = (0.883624159)(0.01)$$

$$m = 0.883624159 \text{ Kg}$$

In conclusion, there is no fear that the PF will combust inside the bottle, as there is not enough air inside the volume to promote combustion.

3.4. Gearbox design calculations

This section is a detailed discussion of the calculations used to calculate the design of the gearbox. The equations can be found in the Juvinall & Marshek (2006). The following Figure 31 is a representation of the layout of the gearbox. In Figure 13, the interaction between the gears is shown. There are two sets of gears, pinion gear (P) which is driven by the motor that interacts with the second gear (g1.1). The gear (g1.2) is fixed onto gear (g1.1) on the same shaft, which in turn drives the final gear (g2).

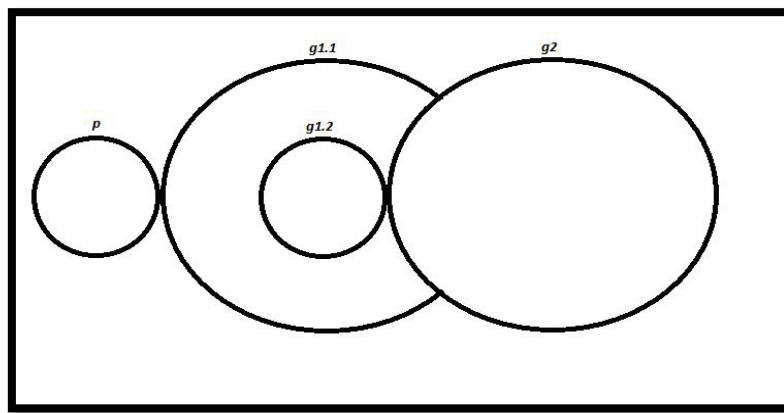


Figure 13: Gear configuration.

The initial values for the gears

The following values were chosen as the best values from numerous values for the design of the gears. The d represents the diameter for each of the gears, P_{RPM} is the revolution of the pinion, m is the modulus that is kept constant at 2, and P_P is the power of the motor.

$$d_p = 36 \text{ mm}$$

$$dg_{1.1} = 98 \text{ mm}$$

$$dg_{1.2} = 38 \text{ mm}$$

$$dg_2 = 120 \text{ mm}$$

$$P_{RPM} = 108 \text{ RPM}$$

$$P_P = 50 \text{ W}$$

Determining the RPM for each gear

$$\frac{\omega_P}{\omega_g} = -\frac{d_g}{d_P} \quad (22)$$

$$\omega_{g1.1} = -\frac{\omega_P d_P}{d_{g1.1}} \quad (23)$$

$$\omega_{g1.1} = 39.679 \text{ RPM}$$

In addition, since gear ($g_{1.2}$) is attached to gear ($g_{1.1}$), the rotational speed is the same.

$$\omega_{g1.2} = \omega_{g1.1} \quad (24)$$

$$\omega_{g1.2} = 39.673 \text{ RPM}_1$$

$$\omega_{g2} = \frac{\omega_{g1.2} d_{g1.2}}{d_{g2}} \quad (25)$$

$$\omega_{g2} = \frac{(39.673)(38)}{120}$$

$$\omega_{g2} = 12.56 \text{ RPM}$$

Calculating the centre distance for each gear pair

$$C = \frac{d_P + d_g}{2} \quad (26)$$

$$C_1 = \frac{d_P + d_{g1.1}}{2} \quad (27)$$

$$C_2 = \frac{d_{g1.1} + d_{g2}}{2} \quad (28)$$

$$C_1 = \frac{36+98}{2}$$

$$C_2 = \frac{38+120}{2}$$

$$C_1 = 67 \text{ mm}$$

$$C_2 = 79 \text{ mm}$$

Calculating the number of gear teeth for both sets of gears

$$m = \frac{d}{N} \quad (29)$$

$$N_p = \frac{d_p}{m} \quad (m = 2) \quad (30)$$

$$N_p = 18$$

$$N_{g1.1} = 49$$

$$N_{g1.2} = 19$$

$$N_{g2} = 60$$

Determining addendum radius of gears

$$r_a = r + a, \text{ where } a = 2 \text{ mm} \quad (31)$$

$$r_{ap} = r_p + a = 20 \text{ mm} \quad (32)$$

$$r_{ag1.1} = r_{g1.1} + a = 51 \text{ mm} \quad (33)$$

$$r_{ag1.2} = 21 \text{ mm}$$

$$r_{ag2} = 62 \text{ mm}$$

Determining the diameter of base circle and base pitch (P_b)

ϕ =pressure angle=20 °

$$r_b = r \cos \phi \quad (34)$$

$$P_b = \frac{\pi d_b}{N} \quad (35)$$

$$r_{bP} = 18 \cos 20 = 16.91 \text{ mm} \quad (36)$$

$$r_{bg1.1} = 46.04 \text{ mm}$$

$$r_{bg1.2} = 17.85 \text{ mm}$$

$$r_{bg2} = 56.38 \text{ mm}$$

Determining the contact ratio of the meshing gear pair

$$CR = \frac{\sqrt{r_{ap}^2 - r_{bp}^2} + \sqrt{r_{ag}^2 - r_{bg}^2} - c \sin \phi}{P_b} \quad (37)$$

The first pair of gears (p and $g_{1.1}$)

$$CP_1 = \frac{\sqrt{r_{ap}^2 - r_{bp}^2} + \sqrt{r_{ag1.1}^2 - r_{bg1.1}^2} - c_1 \sin \phi}{P_b} \quad (38)$$

$$CP_1 = \frac{\sqrt{20^2 - 16.91^2} + \sqrt{51^2 - 46.04^2} - 67 \sin \phi}{5.90}$$

$$CP_1 = 1.64$$

The second pair of gears ($g_{1.2}$ and g_2)

$$CP_2 = \frac{\sqrt{r_{ag1.2}^2 - r_{bg1.2}^2} + \sqrt{r_{ag2}^2 - r_{bg2}^2} - c_2 \sin 20}{5.90} \quad (39)$$

$$CP_2 = \frac{\sqrt{21^2 - 17.85^2} + \sqrt{62^2 - 56.38^2} - 79 \sin 20}{5.90}$$

$$CP_2 = 1.66$$

Determining the force acting on the gears through force analysis

$$F_r = F_t \tan \phi \quad (40)$$

Where F_r = force along the radical direction that tends to punch the gear apart and F_t = force along the tangential direction that turns the gears.

The velocity tangent has to be calculated first to obtain the needed tangential force.

$$v = \frac{\pi d_n}{60\,000} \quad (41)$$

$$v_{tP} = \frac{\pi d_P n_P}{60\,000} \quad (42)$$

$$v_{tP} = \frac{\pi(36)108}{60\,000}$$

$$v_{tP} = 0.20 \text{ m/s}$$

$$v_{tg1.1} = \frac{\pi(98)39.673}{60\,000}$$

$$v_{tg1.1} = 0.20 \text{ m/s}$$

$$v_{tg1.2} = \frac{\pi(38)39.673}{60\,000}$$

$$v_{tg1.2} = 0.08 \text{ m/s}$$

$$v_{tg2} = \frac{\pi(120)12.56}{60\,000}$$

$$v_{tg2} = 0.08 \text{ m/s}$$

The tangential force (F_t) is calculated from the tangential velocity values obtained in the previous equation (40). In addition the power of the motor (W) is 50 W.

$$F_t = \frac{W}{V} \quad (43)$$

$$F_{tP} = \frac{50}{0.2035} = 245 \text{ N}$$

$$F_{tg1.2} = \frac{50}{0.07893639} = 633.42 \text{ N}$$

$$F_{tg1.1} = \frac{50}{0.2035} = 245 \text{ N}$$

$$F_{tg2} = \frac{50}{0.07893639} = 633.42 \text{ N}$$

The produced gear torque is calculated from the tangential force (F_t) values.

$$T = r \times F_t \quad (44)$$

$$T_p = (0.018)(245)$$

$$T_p = 4.41 \text{ N.m}$$

$$T_{g1.1} = (0.049)(245)$$

$$T_{g1.1} = 12 \text{ N.m}$$

$$T_{g1.2} = (0.019)(633.42)$$

$$T_{g1.2} = 12 \text{ N.m}$$

$$T_{g2} = (0.06)(633.42)$$

$$T_{g2} = 38 \text{ N.m}$$

3.5. Auger screw design calculation

According to Roberts (2001), the auger can be designed using the following equations:

Calculating the volumetric flow rate of the new auger design

$$Q = Q_t \eta_v \text{ (m}^3/\text{s)} \quad (45)$$

$$Q_t = \Gamma \omega D^3 \text{ (m}^3/\text{s)} \quad (46)$$

$$\Gamma = \frac{1}{8} \left[\left(1 + 2 \left(\frac{C}{D} \right) \right)^2 - \left(\frac{D_c}{D} \right)^2 \right] \left[\frac{p}{D} - \frac{t_s}{D} \right] \text{ (-)} \quad (47)$$

Where Q_t = theoretical maximum volumetric flow rate when running at 100% full capacity,

η_v = volumetric efficiency, D = Screw diameter (m), p = Pitch (m), C = Radial clearance (m), D_c = Core or shaft diameter (m), ω = angular velocity of screw (rev/s) and t_s = thickness of screw blade.

Calculating the mass flow rate of an auger

$$Q_m = \rho Q = \rho Q_t \eta_v \quad (48)$$

Where Q_m = theoretical mass flow (kg/s) and ρ = bulk density (kg/m³). The following ρ and η_v values were taken as $\rho = 829 \text{ kg/m}^3$ and $\eta_v = 1$.

Mathematical model of auger

A mathematical model of the auger was made in excel (using equations 45 – 48) where the goal seek function was used to determine what the pitch (p) of the auger must be, to obtain the desired flow rate of 2 g/s. Also, the goal seek function was used to determine the pitch size for both a minimum and a maximum flow rate. The results of these goal seek functions are shown in Figure 14.

Auger Design Variables		
Screw_ss		
D_screw	53.6	mm
Screw_thickness	3	mm
Clearance	1	mm
D_Shift	30	mm
ηV	1	-
Input		
PF Powder		
Density_wet	829.4	Kg/m ³
Motor/Gear		
RPM	12.563	RPM
P	50	W
ω	0.21	rev/s
Small Cylinder		
D_ss_id	55.6	mm
L_ss	45.16	mm
Output		
Output at Minimum flow rate		
Q_t	2.05E-06	m ³ /s
Q_m	1.70	g/s
r	0.06	-
Number of turns	1.17	-
Pitch_Screw	38.74	mm
Output at Maximum flow rate		
Q_t	3.26E-06	m ³ /s
Q_m	2.70	g/s
r	0.10	-
Number of turns	0.76	-
Pitch_Screw	59.76	mm
Output at Desired flow rate		
Q_t	2.41E-06	m ³ /s
Q_m	2.00	g/s
r	0.07	-
Number of turns	1.00	-
Pitch_Screw	45.04	mm

Figure 14 Auger program screenshot.

Calculating the desired flow rate of the auger

The following shows how the flow rate of the auger was calculated by using the goal seek function to determine the correct pitch size. The additional values were measured from the design specs of the auger, as shown in Figure 14.

$$D = 0.0536\text{m}$$

$$p = 0.045\text{m}$$

$$C = 0.001\text{m}$$

$$D_c = 0.03\text{m}$$

$$\omega = 0.20938333 \text{ rev/s (12.56 RPM)}$$

$$t_s = 0.003\text{m}$$

Inputting the values into the previous equations

Firstly, equation 47 is solved using the known values:

$$\Gamma = \frac{1}{8} \times \left[\left(1 + 2 \left(\frac{C}{D} \right) \right)^2 - \left(\frac{D_c}{D} \right)^2 \right] \times \left[\frac{p}{D} - \frac{t_s}{D} \right]$$

$$\Gamma = \frac{1}{8} \times \left[\left(1 + 2 \left(\frac{0.001}{0.0536} \right) \right)^2 - \left(\frac{0.03}{0.0536} \right)^2 \right] \times \left[\frac{0.045}{0.0536} - \frac{0.003}{0.0536} \right]$$

$$\Gamma = 0.075 \text{ (-)}$$

Determining the volumetric flow rate of an auger

Using equation 45, the volumetric flow rate of the auger can be calculated as follows:

$$Q_t = \pi \omega D^3$$

$$Q_t = (0.074709987) \times (0.20938333) \times (0.0536)^3$$

$$Q_t = 2.41 \times 10^{-6} \text{ m}^3/\text{s}$$

Determining the mass flow rate of an auger

The mass flow of the auger is then determined by using equation 46:

$$Q_m = (829) \times (2.41 \times 10^{-6}) \times (1)$$

$$Q_m = 0.00199789 \text{ kg/s}$$

$$Q_m = 2 \text{ g/s}$$

Overall, the desired flow rate can be determined by adjusting the pitch size through using the goal seek function.

Chapter 4: Designing the PF Feeder

4.1. Introduction

Mass flow of the powder out of the hopper would be the most desirable option for any feeder design working with PF. However, it is not possible for the current design of the prototype feeder since the design of the hopper is limited to using a glass bottle as visual inspections inside the hopper was deemed necessary.

This means that the use of external forces will be needed to help force the PF to flow from the bottle. This force flow method could be done mechanically, using stirrers or augers, or through fluidization, injecting a gas directly into the powder bed in order to fluidize it. Alternatively, force flow using vibrations was also a viable option, however due to the small irregular shapes of the PF particles this would cause mechanical interlocking inside the bottle.

Therefore, choosing the correct force flow method is important as the bottle cannot be modified to the correct shape, mentioned in the literature, and the number of modifications that can be made to the bottle is limited. However, improving the flow ability of the PF could at least help with extracting the powder from the bottle. Thus, the flow ability of the powder can be improved by lowering the moisture content of the powder.

A preliminary analysis was done to test some of the acquired concepts from the literature study namely, the flow ability of C group powders and the use of external forces to induce flow.

The concept and detailed design of the prototype PF feeder was done using the knowledge gained from the literature study including the result of the preliminary analysis. In addition, several key components were identified during the concept design phase, as seen in Figure 21, which plays a significant role in the functionality of the PF feeder.

4.2. Pre-design practical experimentation

In this section, the flow ability of the PF powder and the use of external forced to induce powder flow was tested.

4.2.1. Preliminary Analysis

It is necessary to know what type of mechanisms (screws, pedals, air jets etc.) would function correctly to promote the flow of PF before any designs can be considered for the PF feeder.

In order to do this preliminary analysis, a simple mock-up was used. This simple mock-up consists of a rain meter with a hole drilled in the bottom. The rain meter is supported by a steel frame to hold it upright during testing and acts as a support for a small motor to be fitted on top of the frame. This simple mock-up was used to determine if it was possible for the PF to flow freely without any external input. It was found that the PF bed tended to form a bridge near the exit, which completely blocked the PF flow.

4.2.1.1. Mechanical induced flow

The bridge that was formed near the exit of the rain meter could be broken by applying an external force. The external force was applied by using a piece of wire to stir the powder near the exit, therefore, breaking the bridge and allowing the PF to flow. However, when the external force was removed the PF bed formed another bridge. Consequently, the PF bed has to be continually agitated by an external force to prevent the formation of bridges. A simple auger design is shown in Figure 15. The auger shown in Figure 15 was manufactured through 3d printing which is quicker, easier and more cost effective than traditional means. The 3d printing material used to print the auger was ABS plastic.

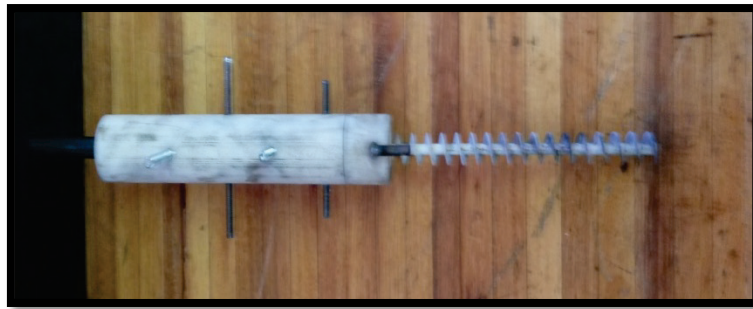


Figure 15: Simple Auger.

The auger was directly connected to a small windscreen motor that was used to turn the auger in the PF. The frame was modified to support the small motor and the auger configuration as shown in Figure 16.



Figure 16: Simple Auger Test.

Numerous test runs revealed that the auger prevented bridges from forming. However, rat holing started to occur in the PF bed. A stagnant region of PF was formed between the auger and the rain meter wall. It was strong enough to prohibit it from collapsing into the rat hole,

preventing flow. Furthermore, lightly tapping the side of the rain meter caused the stagnant region to be disturbed, resulting in it collapsing. The formed rat hole clinging to the side of the rain meter is shown in Figure 17.

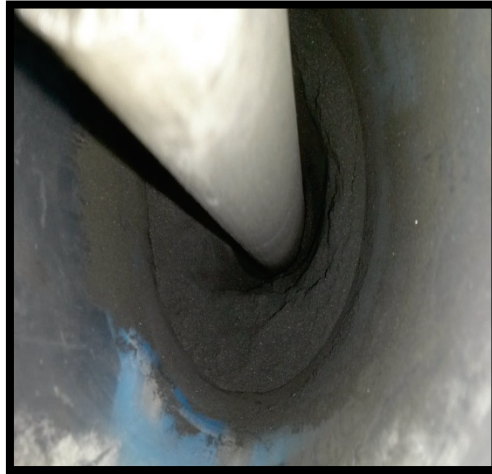


Figure 17: PF rat holing.

An attempt to collapse the formed stagnant region of PF was made by attaching small rods to the auger shaft. However, the small rods did not collapse the stagnant region as only grooves were cut into the PF without causing a collapse as shown in Figure 18.



Figure 18: PF grooves cut.

Alternatively, a gas such as air can also be used as an external force to agitate the PF bed to prevent formation of bridges and promote flow. The simple mock-up was modified so that air can be used as an external force.

4.2.1.2. Pneumatic induced flow

The use of air as an alternative external force changed the nature of the powder bed. The injection of air enables fluidization of the powder bed, causing the bed to act more like a fluid than powder. A draw back with this method is that it could potentially distribute a large amount of the PF into the surrounding air, posing a possible fire risk. As a result, the PF was substituted with cement powder since it has similar fluidization characteristics. In Figure 19, the air was injected into the bottom of the rain meter through four points to fluidize the cement powder.

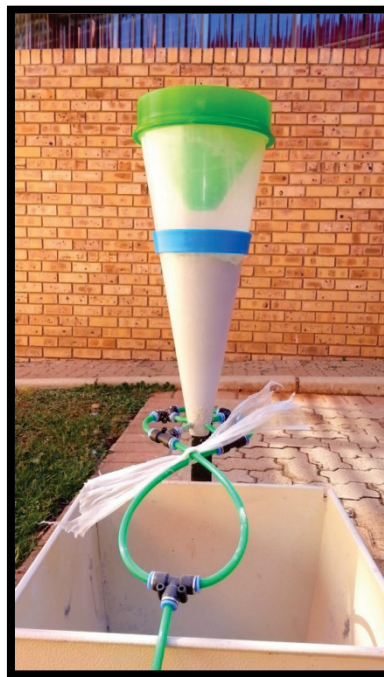


Figure 19: Fluidization test.

The air that was injected into the rain meter loosened the powder surrounding the exit of the rain meter, inducing flow of the cement powder only around the exit. Consequently, a bridge

formed above the injection points, halting the flow of the cement powder. The formed bridge prevented the injecting air to penetrate the cement powder above the bridge. Therefore, the injected air followed the path of least resistance and flowed out from the exit. If the exit of the rain meter is blocked, the injected air bubbled upwards towards the surface, giving the powder bed a boiling like appearance. However, when the blockage from the exit was removed, the powder bed immediately collapsed and a bridge was formed again.

In Figure 20, the rain meter was sealed with a plastic bag to see if pressure inside the rain meter would improve the powder flow. The exit of the rain meter was blocked, which caused the powder bed to bubble. Subsequently, inflating the plastic bag and increasing the pressure. After the blockage from the exit was removed, the powder was forced from the exit as an effect of the pressure inside the rain meter. This occurrence can be related to an effect known as flushing (Chapter 2.2.1). Flushing occurs when the bubbling from the powder bed aerates the cement powder, causing the cement bed to be less dense. The air flowing through the cement powder increases the distance between the cement particles. This less dense (aerated) cement powder prevents the formation of rat holes and bridges, therefore inducing flow from the exit. Decreasing pressure in the rain meter and the plastic bag resulted in a decrease of flow.



Figure 20: Fluidized flow utilizing pressure.

In conclusion, PF is not capable of flowing freely on its own due to its tendency to form both bridges and rat holes. In consequence, the PF feeder should use force flow by utilizing a mixture of both mechanical and pneumatic means.

An auger was chosen for the mechanical means since the auger's shape can easily be altered to match the inside profile of the bottle. Also, rat holing and the formation of bridges can be prevented by the large surface area of the auger on the powder bed. However, it is not feasible to use circular rods or rectangular blades to disrupt the entire powder bed since the interaction surface is too small.

Additionally, the PF flow from the hopper will be controlled pneumatically by means of pressurizing the hopper so that the agitated powder bed will be forced out of the hopper. What is more, it is not feasible to use air to fluidize the powder as it may create a dangerous air rich environment inside the hopper, which could potentially catch fire or even explode.

4.2.2. Design considerations

The design considerations have a direct impact on the overall design of the PF feeder. There are some requirements that have to be met, which places some limitations on the design.

4.2.2.1. Requirements

The PF feeder had to meet following requirements for the hopper (bottle) the airflow and the PF feeder.

Visual inspection was required to observe the interaction between the PF bed and the auger, monitoring the PF powder level in the bottle and to study how the PF flows inside the bottle while the feeder is in operation. Therefore, a 10L glass Pyrex bottle was used as the hopper for the PF Feeder. All attachments to the bottle had to be made from glass to study the flow of PF from the PF Feeder.

The PF Feeder should provide a uniform mass flow rate within a required range and if possible a constant desired flow rate. In addition, the airflow into the bottle must be low enough to ensure that the stoichiometric air–fuel ratio in the bottle stays well below the optimum ratio to ensure safe operation.

Furthermore, all of the parts that make contact with the PF powder bed and glass bottle should be made from materials that can withstand temperatures up to 70 °C without deformation occurring.

4.2.2.2. Limitations

According to literature, the best design for the hopper is the one that utilizes the mass flow design since it gives a steady and predictable flow rate. Unfortunately, the requirement for this project was to use a glass Pyrex bottle, which influenced the hopper design for the prototype PF feeder. Therefore, this severely limits the predictability and flow rate of the PF since it has to rely on the use of external forces to extract the powder from the hopper.

Pyrex is a tempered glass. It is therefore stronger and more resistant to heat than ordinary glass. However, Pyrex, like original glass, is still fragile and this limits the number of

modifications that can be made to the Pyrex bottle used in the design. Similarly, the design complexity of the additional glass attachments is severely limited by both the workability of the glass and the skill of the glassblower.

Furthermore, the type of material used to manufacture the auger will be limited. The material needed for the auger should be strong enough not to break as it is turned in the powder bed and hard enough so that the bottle is not damaged. The material should be able to withstand temperatures up to 70 °C as mentioned in the requirements.

A further requirement was to incorporate a 50W (windshield) motor into the design of the PF feeder to power the auger. Therefore, the gearbox had to be specifically designed for the motor in order to control the amount of torque delivered to the auger and the speed at which it rotates.

4.3. Concept design of PF feeder

A concept design for the PF feeder was designed based on the results of the preliminary analysis, the requirements and the limitations of the PF feeder. The concept design is shown in Figure 21. In Figure 21 there are several components (A-F) when designing the PF Feeder.

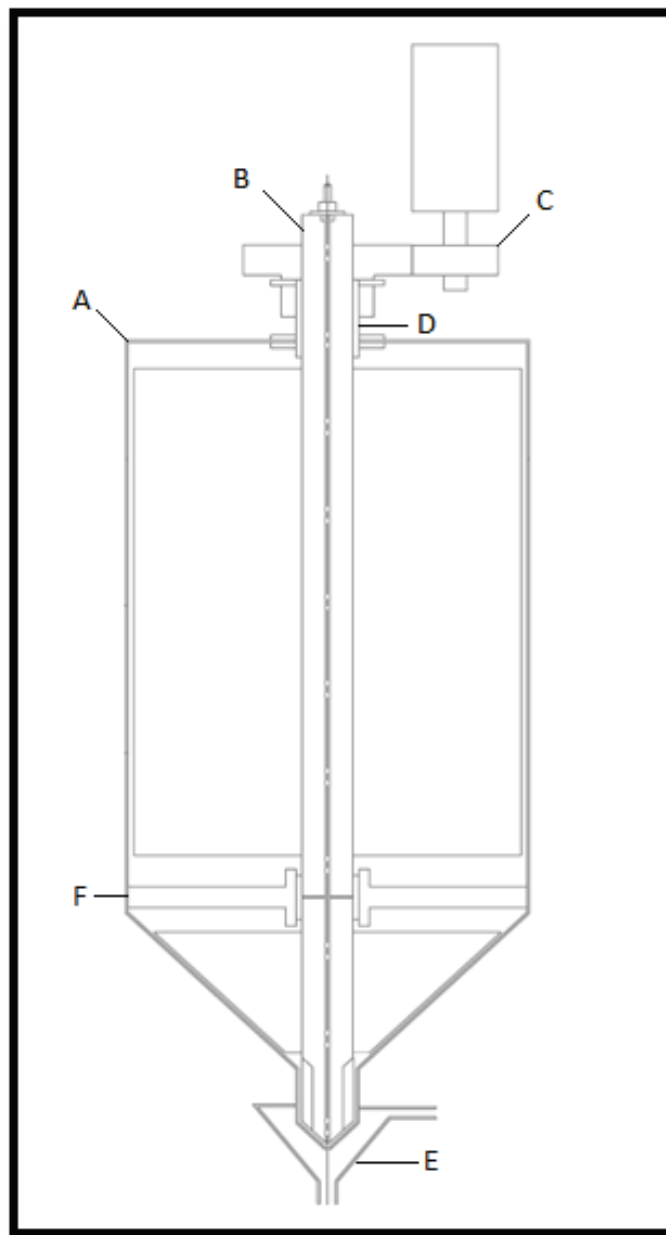


Figure 21: Concept design of the PF feeder.

4.3.1. Components of PF feeder

The following components should be considered when designing the PF feeder, since these components have an impact on the functionality of the PF feeder.

4.3.1.1. The bottle (A)

- The bottle should be refillable.
- The bottle exit should be narrowed to a smaller diameter.
- The support for the auger and gearbox should be fixed to the top of the bottle.
- There should be a point where the air enters the bottle.
- The bottle must be able to seal well to allow it to be pressurized.
- The auger should be placed into the bottle.

4.3.1.2. The auger (B)

- The auger must be in total contact with the powder bed to agitate it successfully.
- The auger must have a jet at its bottom to break up any possible bridges at bottle exit.
- Holes must be placed into the auger surface to allow PF to fall back to the lower sections of the auger.

4.3.1.3. The motor and gearbox (C)

- The auger is powered by the same 50W windscreen wiper motor used in the preliminary analysis as it has sufficient torque.
- Torque is transferred to the auger by the motor by connecting it directly or by using a simple gearbox to better transfer the power.
- The motor turns at a maximum rpm of 108 rpm, so it was useful to design a gearbox that can reduce the speed and increase the possible torque.
- Space is an issue, so the gearbox had to be as compact as possible.

4.3.1.4. Auger support and elevation control (D)

- The auger must have the ability to be lifted up and away from the bottle exit to increase flow area near the exit.
- The auger must be able to fasten to the bottle for support.
- The auger must be able to support the both the gearbox and motor.

4.3.1.5. The volute (E)

- The volute should lower the pressure at the bottle exit to help suck out PF.
- It must be able to help mix air and PF more uniformly as necessary for the burner.
- The volute should allow additional air into the system if needed.

4.4. Detail design of the PF feeder

4.4.1. Pyrex bottle modifications

The Pyrex bottle had to be modified for use as the hopper for the PF feeder. The Pyrex bottle was turned upside down so that the top of the bottle could be used as the exit for the PF while the bottom of the bottle becomes the top where the auger is inserted into the bottle.

A number of holes were cut into the lid to make place for the auger shaft support (middle hole), the refill point (outer hole). A third hole was made on the side of the lid so that air can be inserted to allow the bottle to be pressurized as shown in Figure 22.



Figure 22: Bottle lid.

The bottle top, which is now the exit of the bottle, was tapered to a smaller size to decrease the exit hole diameter to the required size. This alteration can be seen in Figure 23 below.

The smoothness of the glass and shape of the auger prevented any build-up of PF on the tapered sections. Additionally, the taper angle of the bottle top is greater than the angle of repose of the PF, helping to prevent PF build-up.



Figure 23: Bottle exit.

Furthermore, both the bottle and the lid was heat treated after the modifications were made to alleviate any internal stresses that may have formed during the cutting and flame-forming process. The bottle was sealed by using a rubber gasket along with silicon so that the bottle can be pressurized.

Lastly, a simple frame was built to support the bottle as shown in Figure 24 below. This bottle support frame was built to support the now upside down bottle and as a means to fasten the lid to the bottle top by using a Perspex support. Additionally, to prevent the glass bottle from coming in direct contact with the steel frame, which could damage the bottle, it was necessary to cover the steel rings with rubber tubing.

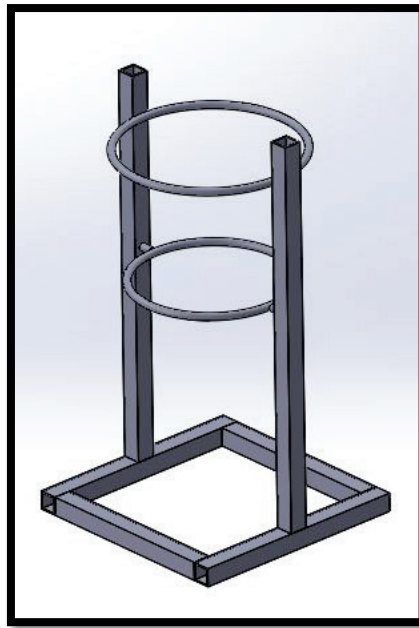


Figure 24: Bottle support frame.

4.4.2. Volute Design

The volute is a glass piece attached to the bottle exit. The volute was designed to lower the pressure at the bottle exit and to help distribute the PF particles evenly in the transporting air heading towards the burner. The volute also serves as a means of adding additional air to what would later make up the primary air for the burner. Similarly, as with the bottle, the stoichiometric air to fuel ratio of the volute should remain well below optimum ratio to avoid premature combustion.

The volute was designed to create a low pressure point at the bottle exit by using compressed air that enters at the outside radius of its cone-shaped geometry to create a vortex. The local pressure drop at the bottle exit allows for lower bottle pressure necessary to allow flow as it helps pull out the PF from the bottle.

The volute is fixed to the underside of the bottle near the exit (Figure 25) by using epoxy glue made specifically to glue pieces of glass together. However, if the volute ever had to be removed, it could easily be done by placing it into the auto clave at a high temperature to burn off the epoxy glue.



Figure 25: Fixing volute to bottle.

4.4.3. Auger Design

The results of preliminary analysis showed that the auger should have a large surface area that comes into contact with the powder bed to agitate the whole powder bed, avoiding the formation of both rat holes and bridging. For this reason, the auger was designed to follow the inside profile of the bottle as seen in Figure 26.

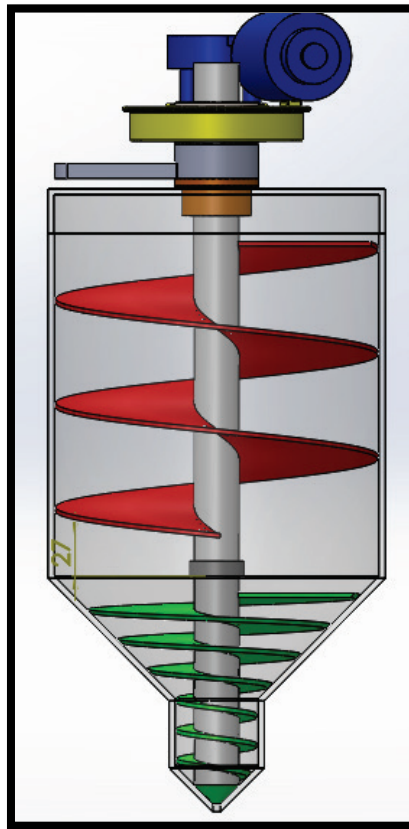


Figure 26: Auger in bottle profile.

The auger will not feed the PF downwards towards the bottle exit, as this will only compact the PF near the bottle exit due to the narrowing. Therefore, the PF will instead be fed upwards.

Large holes were made into the larger auger (red auger), as seen in Figure 27, to allow the PF to easily move down to the lower sections of the auger and to prevent transporting all the PF away from the bottle exit. Finally, it helps ensure better distribution of the PF in the bottle after refilling.

These larger holes were also designed to act as scoops, scooping up powder from lower levels to ensure that the powder does not compact under the auger blade. This allows the auger moves more freely through the powder bed as shown in Figure 27.

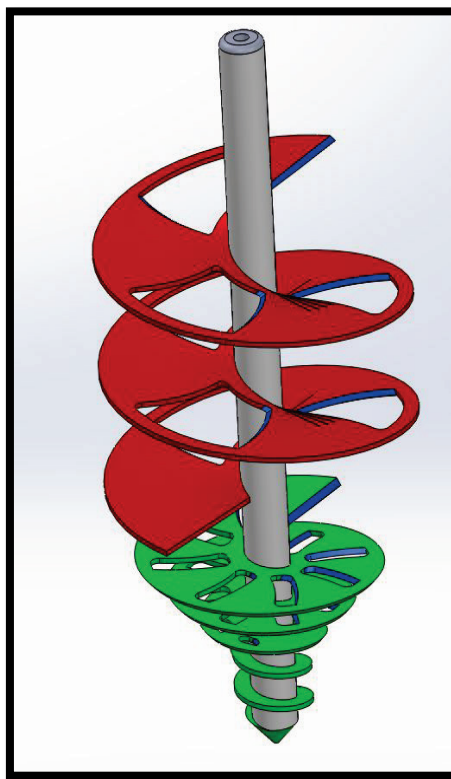


Figure 27: Detail design of the auger.

The shaft was made hollow with a small hole at the bottom to provide additional airflow straight through to the exit of the bottle. The small hole at the bottom of the auger shaft will act as a nozzle, blowing a steady jet of air out of the bottle exit to keep it clear from any potential PF blockages and to help assist the volute increasing the lower pressure point.

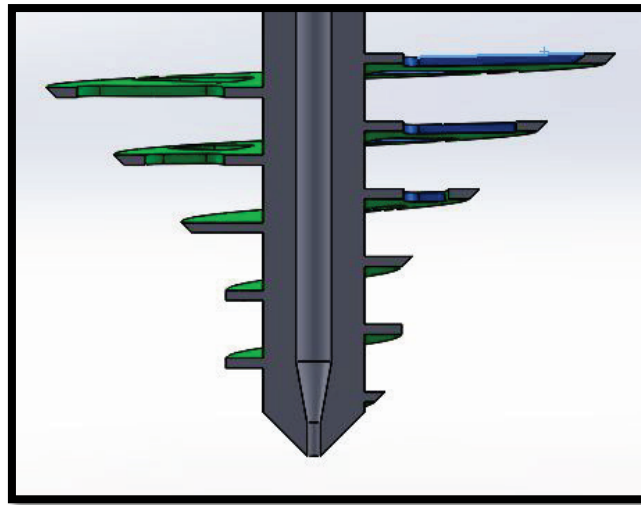


Figure 28: Jet nozzle.

Methods available to manufacture the auger by traditional means were limited by both the complexity of the design and the possible workability problems of any material chosen to construct the auger. Additionally, the cost of manufacturing the auger would have been unacceptable high, especially since the auger was only meant to be one of many possible designs to be produced in the near future.

Therefore, the auger was instead manufactured using a large industrial 3D printer that could print the part from ABS plastic quickly and easily. The plastic is soft enough not to damage the glass, but is still strong enough not to break while moving through the PF powder bed and can also withstand temperatures of 70°C without deforming.

4.4.4. Gearbox design

The gearbox was designed based on the knowledge gained from designing, building and testing a simple prototype gearbox to determine the correct design needed for the gearbox. The design of the prototype gearbox is included in this document and can be found in Appendix B for further study.

The gearbox was made to be compact as the available space on top of bottle is limited. It has to be light as it will rest on top of the glass bottle. Therefore, a two-stage reduction gearbox configuration was used. For this design the auger rotational speed had to be reduced to 12,5 RPM to raise the maximum torque available to 34,2 Nm, increasing the available torque by a factor of 2.3 times that of the prototype gearbox. Additionally, the goal of this design was to reduce the temperature rise of the motor by lowering its workload, thereby extending the operational time of the feeder. The gearbox is designed to allow the main gear to move vertically while still in contact with the other gears that are transferring the power. This allows the auger to be lifted or lowered as needed.

The second stage reduction gearbox works on the same principal as a first stage reduction gearbox in that a smaller and faster pinion gear (p) is used to turn a larger gear to generate an increase in torque at a relatively slower speed. This can be seen in Figure 29 below. In this case, the torque and rotational speed generated by the large middle gear (g1.1) is transferred directly to the smaller middle gear (g1.2) as they are fixed directly to each other. The smaller middle gear (g1.2) now has much more torque than the pinion gear (p) and is capable of increasing the torque of the main gear (g2).

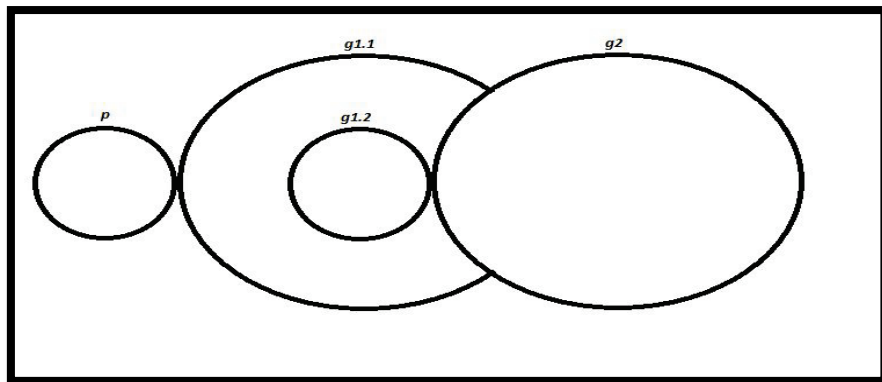


Figure 29: Second stage reduction gearbox.

The gears of the new gearbox cannot be made from ABS plastic like with the prototype gearbox, but has to be made from stronger materials instead. Furthermore, the ABS gears were already nearing their limit when the final testing of the prototype gearbox was concluded.

To ensure that the gear will be able to cope with this increase of torque and ensure a longer operational lifetime, 6mm mild steel was used for the new gears. This time the gears were manufactured using more traditional means as the gears were laser cut from 6mm mild steel, giving them more strength and greatly reducing the likelihood of gear failure.

In addition to the gears, new steel shaft also had to be manufactured to support the gears and to allow them to turn within the new gearbox housing. Two pairs of essential ball bearing were added to this new design to help keep the shafts aligned and seated within the gearbox housing. Shafts for the gears had to be designed and manufactured to allow the now steel gears to turn, resulting in a complete redesign of the gearbox housing.

Since steel gears, shafts and a sealed ball bearing were used for this new gearbox, it was unnecessary to enclose the gearbox fully to prevent the PF from entering it. Therefore, the housing of the new gearbox consisted of two separate 10mm Perspex pieces that were laser cut to the necessary size required. The seats for the ball bearing were machined into the Perspex pieces using a CNC machine.

The two Perspex pieces are kept in place by threaded rod making it possible to adjust the distance between the pieces quickly and easily if needed. Additionally, the threaded rod makes it easier to take the gearbox apart for maintenance quickly. A benefit to keeping the housing open is that it makes it much easier to keep the inside of the gearbox clean by using compressed air.

The gearbox was designed to be fixed to a gearbox support, which has a built-in lifting mechanism to lift the auger shaft. The main gear had to be lifted to avoid the large middle gear and to come in to contact with the smaller middle gear. The width of the smaller middle gear had to be increased to allow the main gear to remain in contact with it as the auger was to be either lifted or lowered. The gearbox is shown in Figure 30.

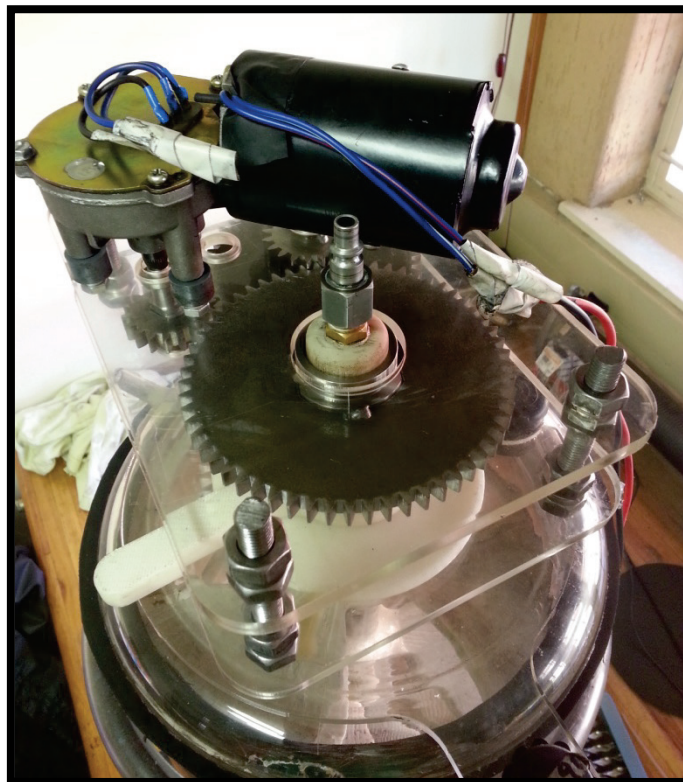


Figure 30: The Detail gearbox design.

In addition, a gearbox support was built to form the base of the gearbox. It helps to keep the gearbox fixed on top of the bottle as shown in Figure 31.

The gearbox support also supports the auger by keeping it aligned with the bottle exit and allows for dry lubrication through a cylinder bush made from Nylatron. An elevation mechanism was built into the gearbox support to allow the auger to be lifted upwards by sliding the lever over a surface that inclines at a specific angle, which then pushes up the main gear and as a result forces up the auger.

Lifting the auger increases the gap between the auger and tapered bottle bottom, allowing more FP to enter this gap resulting in the subsequent increase of the mass flow. In addition, a disk of Nylatron was inserted between the level handle and main gear for both gearboxes to allow the gear to turn without turning the level handle due to friction.

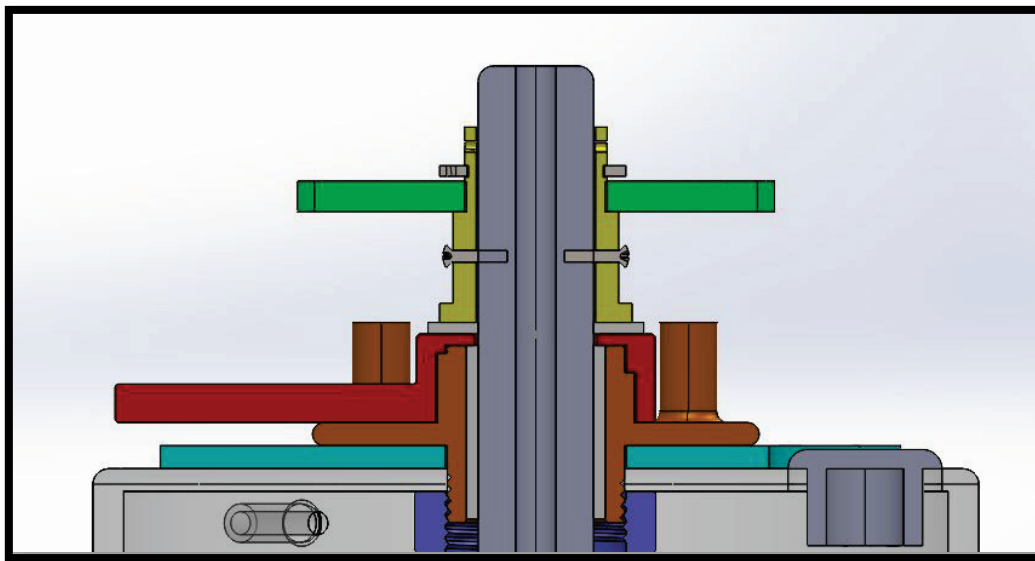


Figure 31: Auger lifting mechanism.

4.4.5. The plenum

The flow of the PF out of the feeder was uneven and contained clumps of agglomerates. This was of concern for the burner, as the PF was not adequately distributed with the primary air coming from the feeder. This could have an adverse effect on the ability of the burner to stay lit, which may result in a flame-out. Additionally, if the burner was able to stay lit it may cause incomplete combustion of the PF due to the encountered air–fuel ratio being outside of the design parameters of the burner. Therefore, the plenum as seen in Figure 32 below was designed and built in an attempt to correct this problem.

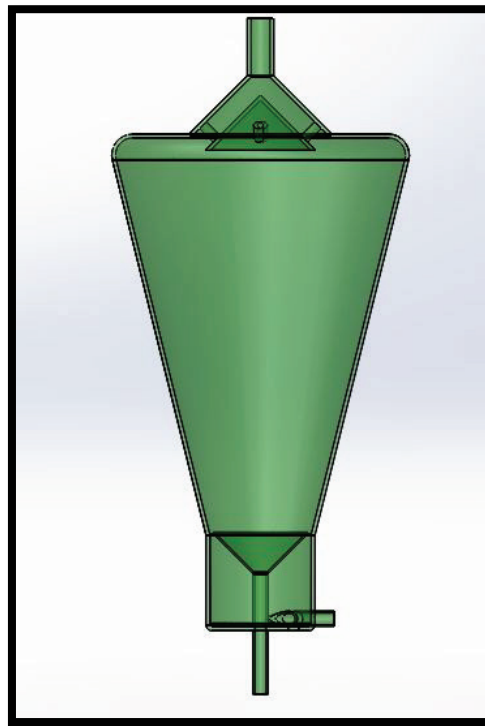


Figure 32: The plenum.

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The PF enters the plenum from the top where it then hits a distribution plate to break up the agglomerates and distribute it more evenly throughout the volume of the plenum. A vortex is created inside the plenum by injecting secondary air at an angle at the bottom of the plenum to keep the PF in suspension and to help improve the distribution before it goes to the burner.

The volume of the plenum is also smaller than that of the PF feeder at about 2 litres to keep the PF in suspension and to increase the pressure of the air–fuel mixture to 16Kpa as needed for the burner.

Chapter 5: Testing and evaluation of PF feeder

5.1. Introduction

An in-depth overview of the prototype PF feeder's development is discussed in this chapter where possible solutions to the problems encountered during testing were assessed.

The development of the prototype PF feeder can be divided into four separate phases. These phases are based on the degree of complexity, method of testing and how the test data for the prototype PF feeder was measured.

Overall, phases 1 and 2 were intended to test the working ability of the prototype PF feeder whereas, phase 3 and 4 was intended to provide useful data of the working prototype PF feeder. As a result, the data collected from these two phases were used to study the effectiveness of the feeder design and check if it meets the requirements.

5.2. Phase 1 (Simple preliminary testing phase)

Phase 1 is the earliest part of the project where simple methods were used to test the PF feeder to see how the PF feeder performs and if the PF can be adjusted to flow reliably at a specific rate using this design. Therefore, tests were conducted by running the PF feeder while adding compressed air to the bottle, nozzle and volute. The flow of the compressed air to each of these parts (bottle, nozzle and the volute) was controlled through a set of ball valves fixed to a piece of cardboard that was marked to show how much the valves were opened (Figure 33). The compressed air was supplied from one of the workshop compressed air lines. However, the pressure of the compressed lines had to be reduced significantly since the compressed air lines operate at a pressure of 8 bar. Therefore, a flow regulator was used since the regulator can control the pressure of the air supply. In Figure 33, the air supply to the feeder was controlled with the main valve (Blue Tab), whereas the supply to the bottle, nozzle and volute was controlled by the three valves with red tabs.

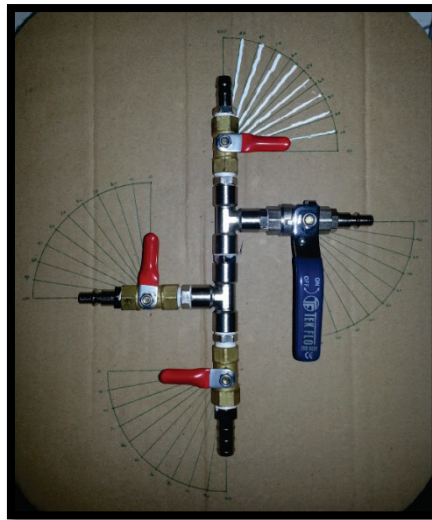


Figure 33: Control valves for air supply.

The flow rate of the PF feeder was determined by collecting the amount of PF discharged after each test and then weighing it on a sensitive laboratory scale. Thereafter, the average flow rate for each test was calculated from the weight of each sample and divided by the amount of time it took to conduct each test.

$$\text{mass flow} = \frac{\text{mass measured}}{\text{test duration}}$$

The testing was performed outside since it is hazardous to work with PF in a confined space and PF is messy to work with. However, after several tests it was discovered that the flow rate determined on different days did not match, even though the test parameters were kept constant for each test. Therefore, to obtain the same flow rate, the test parameters had to be changed each day by either increasing or decreasing the air entering into the system. Also, the PF did not flow uniformly out of the feeder and even started to puff from the outlet. It was noted that after consecutive tests, the amount of PF had to be increased, the test times increased and the motor started to have difficulties turning the auger through the PF. The speed of the motor started to decrease, straining noises were heard and the amount of time needed for the motor to heat up decreased. Consequently, the 3D printed gears were ruined (Figure 34) by the increased strain that the auger put on the gears. Therefore, a new gearbox

had to be designed that could provide more torque to the auger and lower the load put on the motor to prevent it from overheating.



Figure 34: 3D printed gear destruction.

5.3. Phase 2 (Complex preliminary testing phase)

The testing methods in Phase 2 were more complex than those used in Phase 1 due to the addition of pressure (air pressure) and load sensors. In addition, the newly designed gearbox and plenum were added to this phase and used to conduct tests. The PF feeder and any additional testing equipment were attached to the support frame as previously described. The PF feeder was connected to a load cell making it possible to observe and record the flow rate during testing so that the true mass flow rate could be determined.

A high degree of accuracy is important when measuring the small mass flow. Therefore, a load cell with a maximum measuring range close to the weight of the PF feeder was used to note small weight changes. Moreover, the PF Feeder weighs approximately 18 Kg when filled with PF.

Two separate 10 Kg load cells were first used to measure the discharge rate of the PF out of the bottle. The load cells were mounted across from each other on top of the support frame with the feeder frame, and then fixed on top of them.

However, the placement of the load cells caused an unforeseen problem, as they were too sensitive and made difficult to distinguish between the PF flow rate and noise caused by the

vibration of the motor, the jet air line and the movement of the auger. Various ways to mount the load cell to the PF feeder were explored to see if the amount of vibration picked up by the load cell can be reduced. Hanging the feeder from the load cell cancelled out the most of the noise, therefore, allowing the flow to be observed. Tests were performed with this configuration before the flow sensitivity of the measuring system was reduced by replacing the two 10 Kg load cells with a single 50 Kg load cell that greatly improved the flow rate accuracy.

The volute was removed and replaced with a newly designed plenum chamber, as it was not capable of eliminating the "puff flow" observed during Phase 1. The plenum was designed to be fitted underneath the bottle to eliminate or reduce the "puff flow" and allow for a steadier PF flow rate to the burner.

Mechanical pressure gauges were added to both the bottle and the plenum to monitor its pressure and the effect it has on flow rate. However, mechanical gauges were replaced with electronic pressure after a couple of tests had been performed. The pressure in the bottle was significantly lower than expected. Therefore, the mechanical gauges were obsolete in accurately measuring the pressure. The sensors made it possible to monitor the pressure in the nozzle. In addition, the rapid pressure fluctuations inside the bottle and the plenum made the slow reacting mechanical pressure gauges worthless. However, the electronic pressure sensor made it possible to observe the fluctuating pressure and to collect data for studying mass flow rate versus bottle–plenum pressure.

Further testing showed that the jet could be removed as no bridges were formed near the PF feeder exit and with the volute removed, it no longer served a purpose in helping to create the lower pressure point at the bottle exit. Vibrations picked up by the load cell were further reduced by removing the jet air supply, which was known to amplify vibrations caused by the motor.

Furthermore, there was a manufacturing error that caused the tapering near the bottle exit not to be completely uniform in shape, resulting in a small gap forming between the tapered bottle exit. Additionally, this gap prevents the complete closure of the bottle exit and unfortunately this small gap is also large enough to allow PF flow rates larger than is required if a sufficient amount of pressure is allowed to build up inside of the bottle. As a result, the

shaft level mechanism was deemed unnecessary and removed, making it easier to seal the bottle and allow for greater bottle pressures.

One of the biggest problems encountered with the plenum was that a surge would occur when the airflow to the bottle and/or plenum was too high. This surge increases the pressure in the plenum and increases the difficulty to control the mass flow rate.

It was theorized that the air inside of the plenum does not move through the plenum exit, but would instead move up into the bottle, increasing its pressure. This increase in pressure generates a larger force working on the PF bed increasing the flow rate of the PF out of the bottle and into the plenum causing it to flood. The flooding of the PF decreases the internal volume of the plenum and further increases its pressure along with the additional air from the bottle repeating the cycle.

The data and visual inspection revealed that the required outlet diameter of the plenum that was needed for the burner was too small and did not allow the air–PF mixture to escape fast enough. When the plenum was swamped by PF from the bottle, it quickly decreased the volume of the plenum leading to the rapid increase of pressure.

5.4. Phase 3 (Final development of PF feeder and first test)

During Phase 3 a small crack had developed on the glass lid that could not be fixed with either glue or epoxy resin, as shown in Figure 35. Therefore, the bottle lid had to be redesigned for safety reasons and to ensure a better fit for both bottle and auger shaft. To distribute the forces acting on the bottle lid evenly and to ensure a better seal, the fastening of the lid to the bottle and PF Feeder frame was redesigned. Redesigning the bottle lid improved the sealing of the bottle more effectively (better increase in bottle pressure) than in the earlier phases. In the earlier phases, the bottle was not completely sealed due to a design flaw that led to small gaps between the auger shaft and the support bush.



Figure 35: Failure of the bottle lid.

In addition, the ball valve regulating air to the bottle was replaced with a more sensitive gate valve. This is so that the airflow could be controlled more accurately since the valve to the plenum was left fully open to avoid PF settling on the bottom of the plenum. This was done to see if the plenum surge could be avoided by having more control on the PF mass flow out of the bottle. However, even with the effective seal on the bottle the plenum surge worsened, even at a lower bottle pressure. Overall, the surging was not improved even when the airflow to the plenum was continually reduced.

Therefore, the plenum was removed and tests were performed with only the bottle since the required PF mass flow rate was not achieved with the plenum attached. The "puff" that had occurred, had to be solved some other way. In the tests without the plenum, compressed air was used to minimize external factors that may play part in influencing the mass flow and to study what effect the bottle pressure has on the mass flow rate of the PF powder. Even so, the "puffing" still occurred after the plenum was removed. However, the first set of test without the plenum showed that it was possible to control the PF mass flow rate.

At that point, the PF powder collected at the beginning of the year was used up. Therefore, new PF had to be collected from Eskom's R&D facilities in Rocherville. The mass flow obtained with the new PF was an improvement to the previous PF used in the tests.

The "puffing" tendency previously observed was also greatly reduced. However, as time passed, the mass flow started to worsen until it was the same in as the earlier test. In short, the PF powder collected from Rocherville was dryer than the PF used in the previous tests. Therefore, the dry powder had better flow ability while the moist powder had a tendency to clump together, which caused the flow ability of the PF to worsen. In addition, the moisture in the PF caused the formation of bridges as the particle–particle forces increased.

Alternatively, silica gel pellets were used to remove the moisture from the PF powder in an attempt to dry the PF and improve the flow ability once more. First, the silica gel was placed into an oven for 3 hours at 150°C to remove any moisture absorbed and left for another 19 hours at 30°C to cool off. Thereafter, the dried silica gel was placed in nylon stockings as shown in Figure 36, to ensure that mixing with the PF would not occur. The silica stocking was placed together with the PF into an airtight container where it was left for two days to dry.



Figure 36: Drying the PF powder with silica gel.

As a result, the flow ability of the dried PF improved. However, the flow ability of the PF was still not close to the ones collected previously from Rocherville. In fact, it worsened more quickly, even when the drying procedure with silica gel was repeated. The PF was still absorbing moisture even after drying had occurred. It was discovered that the compressed air used in the tests contained moisture as a large amount of moisture was collecting in the

moisture filter of the pressure regulator. Therefore, the wet air coming from the compressed air line was continuously wetting the PF as the tests were being conducted, worsening its flow ability. Nitrogen gas was used instead of trying to get a dryer for the compressed air to see if there will be any improvement in PF flow ability. Once again, the PF powder and the silica were dried by using the oven for 3 hours at 100°C. Thereafter, the silica gel and the PF powder were left for another 18 hours at 50°C. The oven was switched off thereafter, but both the silica gel and the PF was kept inside in the oven to cool down for approximately four hours to room temperature before it was transferred to an airtight container.

Overall, the flow ability improved, becoming more reliable with the mass flow now and the "puffing" occurrence seldom appearing. However, the flow rate still varies from day to day and the gas flow to the bottle must be changed each time to get the necessary mass flow rate required.

5.5. Phase 4 (Test observations and Second test)

One observation throughout months of testing was that flow rate was dependant on the humidity. The flow rate tended to vary more on warm humid days than dry cold days. The tests that were conducted in the winter months resulted in better flow characteristics for the PF and a large amount of static electricity was produced. However, tests conducted during the spring and summer months resulted in low PF flow and little to no static electricity produced. Figure 37 shows how the PF particles cling to the edge of the plenum's dispersal piece, indicating the presence of static electricity within the plenum.



Figure 37: Presence of static electricity.

Also, conducting tests in the winter was less difficult since the PF flowed without much effort and few problems occurred. On the other hand, flow test conducted during the spring and summer months were difficult. There were times that the PF refused to flow and when it flowed, it was not as separate particles, but instead as groups of agglomerates. Therefore, humidity can be a possible factor in the performance of the feeder, since the feeder performance varied between different days with different atmospheric conditions. Therefore, the PF could possibly be hygroscopic, causing the PF to absorb moisture out of the atmosphere, wetting the PF as a result. In conclusion, the change in humidity explains the forming of agglomerates even though the PF was dried in an oven and nitrogen gas was used in the place of compressed air. Similarly, it explains the presence and the lack of static electricity in various seasons. The moisture in the air helps dissipate the static charge formed the feeders surface. Finally, it also explains why water was present in the compressed air line.

As a result, the PF feeder was moved indoors to limit exposure to atmospheric conditions. The method of storing the PF powder was also changed. The PF was heated in the oven for several hours, after this it would then be stored with silica gel in an airtight container until it had cooled down to room temperature. Additionally, the time for the PF loading into the PF feeder and testing were decreased to limit the time of atmospheric exposure.



Figure 38: PF feeder moved indoors.

Chapter 6: Results and discussions

6.1. Introduction

The goal of testing in phase 3 was to determine if the feeder could successfully operate within the required range. Also, another goal was to determine if it was at all possible to acquire a specific desired flow rate of 2g/s by altering only the gas flow into the feeder.

In phase 3, the tests are divided into several different groups based on factors such as: the dryness of the powder, days left to dry, location of test, the gas used and lastly the technique used to dry the PF before testing.

In phase 4, the goal was to find the cause of the varying PF flow changes that occurred between the daily tests and to try ways of preventing it. Furthermore, to investigate this variation the same test was done over three consecutive days with the gas flow rate and other inputs remaining the same.

6.2. Phase 3 testing

The goal of Phase 3 was to limit the number of possible variables that may be influencing the accuracy and repeatability of the PF feeder. Furthermore, the test aimed to determine if it is possible to operate the feeder in the required range between 1.7 – 2.7 g/s while, also determining if it was possible to acquire a specific flow rate of 2 g/s.

It was, however, necessary to remove the plenum as it was hard to acquire any specific flow rate and even harder to get any repeatability of the flow rate due to the surging, as described in section 5.3 and section 5.4. Additionally, as mentioned in section 5.4, it was suspected that moisture, either from the atmosphere or from the compressed air line, may be having a greater effect on the PF than previously thought.

After checking the pipe supplying the compressed air it was found that the inside of the pipe was indeed wet, confirming the presence of moisture in the supplied air. Therefore, nitrogen was used as an alternative because it is inert, un-reactive to PF, does not carry any moisture and can be used to lower the relative humidity in the bottle by forcing out air that may be carrying moisture.

6.2.1. Phase 3 test procedure

A small number of pre-tests had to be conducted each day before any testing could take place. The correct gas flow to the bottle had to be acquired to get the required feeder flow rate of 2 g/s. However, the number of tests that could be conducted for each day was limited by the size of the sealed container used to dry and store the PF. Therefore it was important to limit the number of pre-test so that the relevant data could be recorded. Only the data gathered when the flow rate was close to the desired flow rate were taken and not that of the pre-tests, as the settings from thereon stayed constant for the duration of the day's test.

The results of Phase 3 are divided into five different groups depending on changes made to the testing process. These changes included the method used to dry the PF, the amount of time given for the PF to dry, whether the test were conducted inside or outside a building and the type of gas used for the day's experiment. Additionally, only PF collected from Eskom's research and development facility in Rocherville was used for testing in Phase 3. The preparation for each group was as follows:

6.2.1.1. Group 1

The PF was used just as it was collected from Rocherville still inside the sealed plastic bags without any additional drying taking place. There was no change in gas type as air supplied by the compressed air line was used and testing was conducted outside of the building.

6.2.1.2. Group 2

This was the first group where the PF was dried by using only Silica gel. First, to ensure that the silica gel contained no moisture and to increase the overall effectiveness of the silica gel, it was dried in an oven at a temperature of 150°C for 3 hours and later the temperature was

turned down to a 30°C and the silica gel was left for an additional 17 hours to cool down and prevent exposure to moisture.

Second, the silica gel was placed inside silk stockings to prevent it from mixing with PF and placed along with the PF inside of a sealed container, leaving it to absorb the moisture from the PF for a period of 2 days. Lastly, the compressed air was replaced with nitrogen supplied from a large nitrogen bottle. As with group 1 tests, tests were conducted outside.

6.2.1.3. Group 3

The drying method of the silica gel and PF, including the gas used for testing, remains the same as that previously mentioned in group 2. However, the time given for the PF to dry in the sealed container was shortened to only one day and testing was conducted inside of a building.

6.2.1.4. Group 4

The drying method of the silica gel and PF, the gas used for testing and the location of the tests remained the same as that of group 3. However, in contrast to both groups 2 and 3, the PF was allowed to dry for a period of three days.

6.2.1.5. Group 5

The drying method of the PF was changed and the PF was dried along with the silica gel inside of an oven at temperatures of 70°C for 17 hours. Furthermore, after 17 hours the oven was turned and the PF was left to cool down for an hour to make it possible to handle the PF and silica gel. Afterward, both the PF and silica gel was placed into the sealed container and left for 3 hours to cool down to room temperature. As with groups 3 and 4, nitrogen was used and tests were conducted inside of a building.

6.2.2. Phase 3 test results

Table 2 shows the collected data for each separate day of testing where the feeder was required to reach a required flow rate of 2 g/s. This table includes the degree at which the valve is opened for the gas flow, including the deviation between the minimum and maximum flow rates for each day of testing. Additionally, the table also includes the deviation from the average flow rate (DFA) and the average deviation from 2 g/s (ADFG).

Table 2: Phase 3 test results.

Phase 3 Results							
Group	Date	Valve (°)	Max (g/s)	Min (g/s)	Average (g/s)	DFA (%)	ADFG (%)
Group 1	2015-11-04	270	3,16	2,37	2,76	± 14,39%	38,13%
	2015-11-05	270	2,82	2,21	2,51	± 12,15%	25,50%
Group 2	2015-11-10	90	1,96	0,61	1,28	± 52,79%	-35,93%
	2015-11-12	270	4,22	0,68	2,45	± 72,44%	22,45%
Group 3	2015-11-13	270	6,15	2,06	4,10	± 49,75%	105,18%
Group 4	2015-11-16	135	3,35	2,37	2,86	± 17,20%	43,00%
	2015-11-17	100	2,19	1,43	1,81	± 21,01%	-9,55%
Group 5	2015-11-19	145	2,15	1,72	1,94	± 11,19%	-3,22%
DFA = Deviation from average flow rate							
ADFG = Average deviation from 2 g/s							

Studying the results shown in table 2, it is clear that the prototype PF feeder is not capable of delivering a specific constant flow rate. Instead, the feeder tends to deliver a flow rate that varies largely between the minimum and maximum flow rate which from this point on will be referred to as the operational range of the feeder.

The deviation from the average flow rate (DFA) seen in table 2 is used to help illustrate the size for each operational ranges. It should be noted, that it's easier for the feeder to come close to delivering the desired flow rate and also stay within the required flow rate, using pre-tests settings, when the size of the operational range was small.

The average deviation from 2 g/s (ADFG) shown in table 2 is the deviation between the average flow rate and the desired flow rate of 2 g/s for each test. The data from the 17 November and 19 November shows that if the operational range is small enough and if the desired flow rate is within the operational range, it was possible to get the an average flow rate that was very close to the desired flow rate.

The performance of the feeder can be determined by comparing the size of the resulting operational ranges. In table 2, it is shown that the feeder gave the worst performance during the testing of groups 2 and 3 due to the large size of their operational ranges. In contrast, the feeder gave its best performance for groups 1, 4 and 5, and shows that the feeder is capable of giving a good performance.

It was suspected that the poor performance delivered by the feeder could be contributed to the method used to dry the PF powder as both these groups 2 and 3 were dried using only the silica gel. As a consequence, the absorption rate of the silica gel was much slower than previously expected, meaning that the PF was not given a sufficient amount of time to dry. The powder of group 4 was prepared in the exact same way as groups 2 and 3 but the drying period was extended. As a result, the performance of the feeder increased drastically. Therefore, the moisture content of the PF has a large effect on the performance of the feeder since feeders performance tended to improve when the moisture content was removed.

The operational ranges of the tests and the required flow range do not completely overlap as shown in table 2. This is due to the limits of using pre-tests as only a small number could be done and they were influenced by the size of the resulting operational ranges. It must also be noted that due to the small flow rate required, any small change made to the gas input would have a large effect on the resulting flow rate. Therefore, the pre-tests were only intended to adjust the feeders input to get a flow rate as close as possible to the desired flow rate as possible

In conclusion, although the feeder was incapable of delivering a constant desired flow rate of 2 g/s, the data shows that it is possible for the feeder to deliver within the required flow range of 1.7 to 2.7 g/s. However, some conditions must first be met such as: the powder has to be completely dry and contain no moisture; the operational range for each test has to remain small and the numbers of pre-tests have to be increased to better help predict the size of the operational ranges and adjust the gas input accordingly.

The results from the tests performed are displayed in Figure 39 below, illustrating the variations in flow rates for each test conducted. Additionally, it is clearly apparent that there is a great deal of variation between the daily flow rates even though they were set to deliver the same required flow rate of 2 g/s.

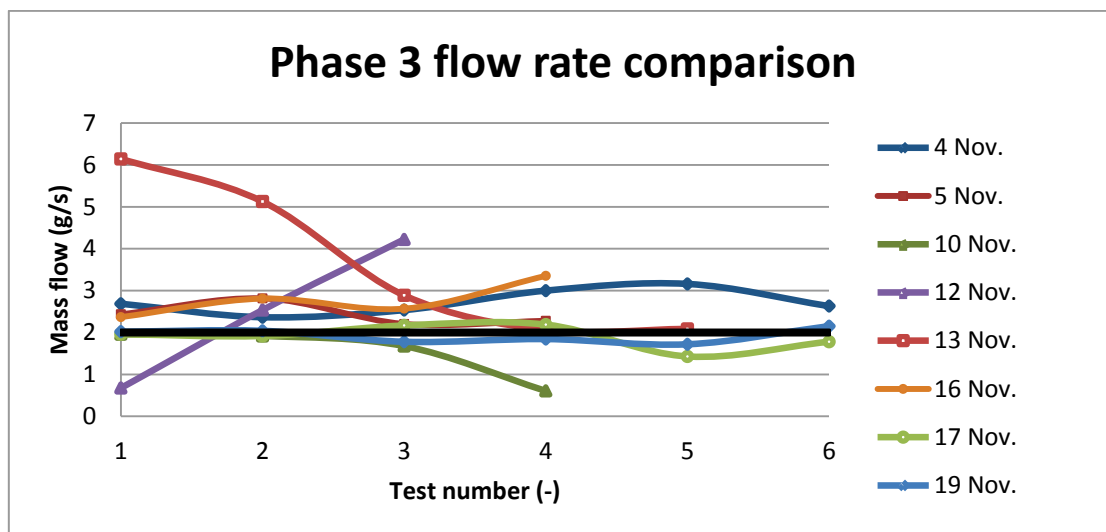


Figure 39: Phase 3 flow rate comparison.

The flow rates of 17 and 19 November delivered the best flow rates as the deviation between the minimum and maximum flow rates, including the average deviation from the desired flow rate, is relatively small compared to the other tests. The results for the best performing flows rates are displayed in Figure 40 below.

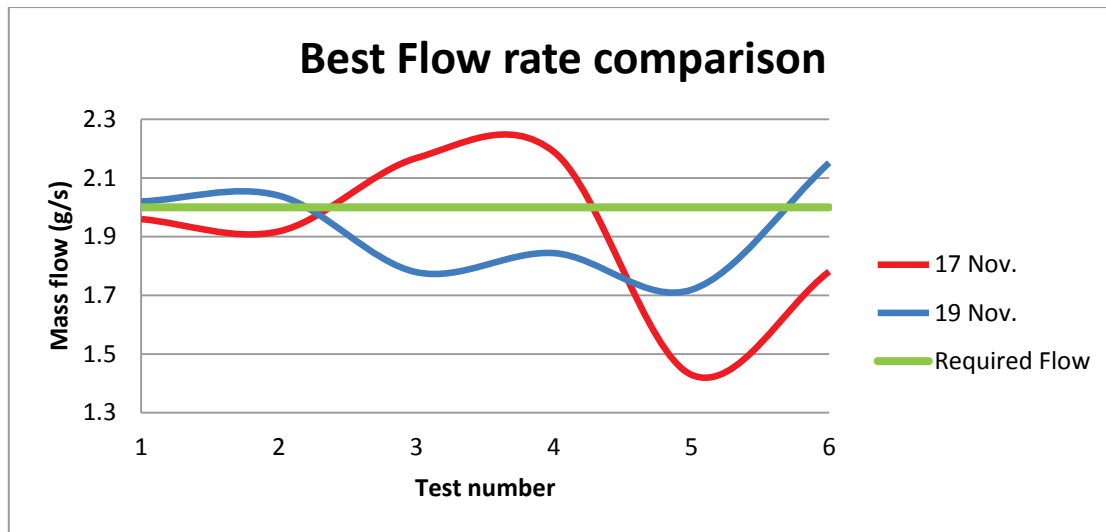


Figure 40: Best flow rate comparison.

6.2.3. Best and worst performing flow rates of Phase 3 testing

The following graphs show the pressure and flow rate data collected for the best and worst tests that were collected during the completion of Phase 3 testing. For each graph, blue represents the maximum flow rate of the feeder that was obtained during the specific day's testing, while red represents the minimum flow rate. Furthermore, the green line in the flow graphs represents the required flow rate of 2 g/s that was needed for each test.

6.2.3.1. The best performing flow rates

The pressure graph for 17 November shows considerable formations and destruction of bridges, resulting in a spiky appearance of the bottle pressure graph. Therefore, the sudden rise in pressure inside the bottle seen in both the minimum and maximum flow rates is an indication that the gas cannot escape the bottle due to the formation of bridges. Similarly, the sudden loss in pressure can be attributed to the opposite happening, in this case the destruction of the bridges allowing the gas/PF mixture to exit the bottle.

The width of each pressure peak also differs between the minimum and maximum flow rate as the width of the maximum flow rate tends to be narrower than that of the minimum flow rate, which typically tends to be a bit wider.

As the bridges break up more easily for the maximum flow rate this could mean that the gas/PF mixture passes out of the bottle with greater ease compared to the minimum flow, allowing for an increased flow rate. Therefore, more time is spent flowing for the maximum than that of the minimum, which can clearly be seen in the 17 November flow rate graph.

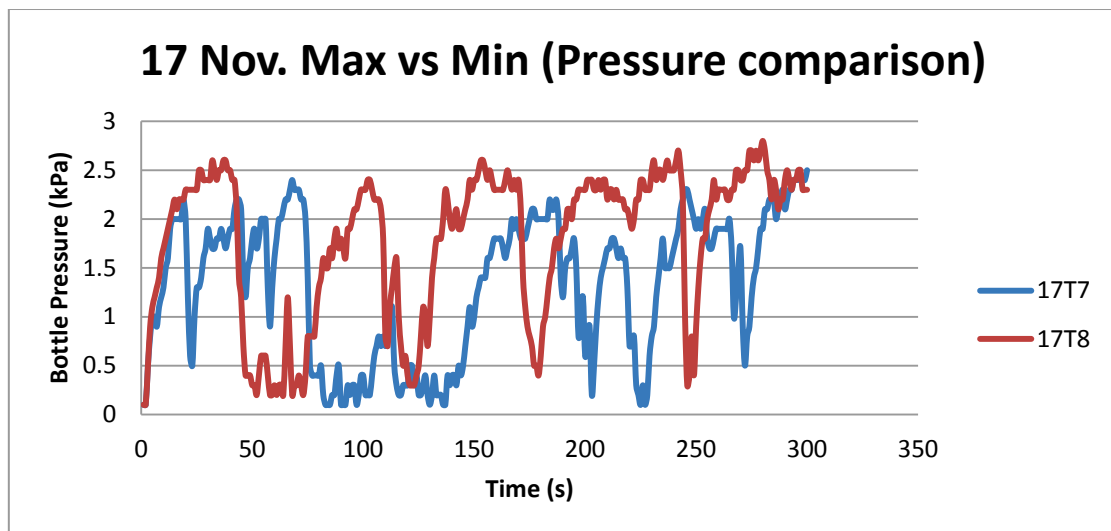


Figure 41: 17 November max. vs. min. pressure comparison.

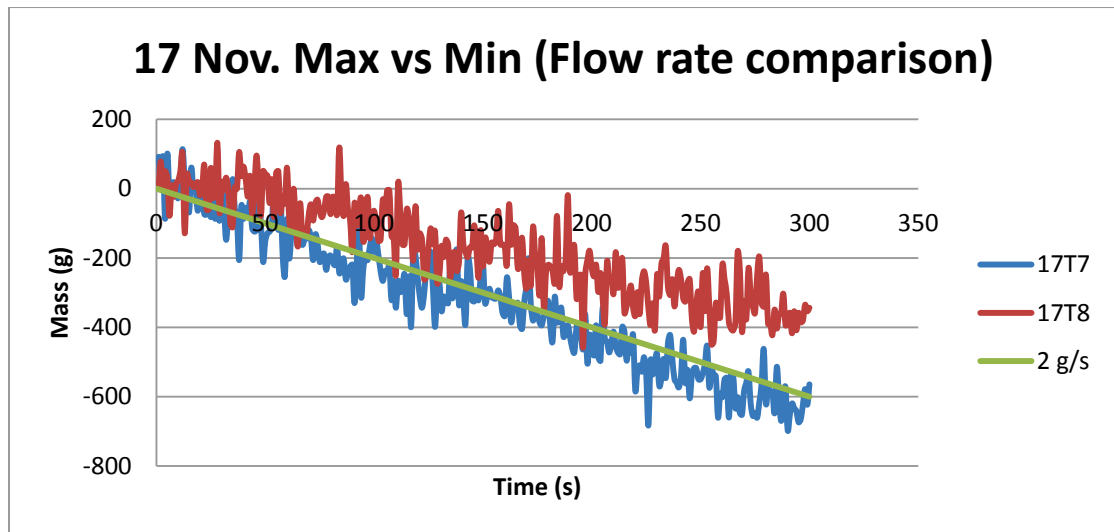


Figure 42: 17 November max. vs. min. flow rate comparison.

For the pressure graph of 19 November, the bridges formed for the minimum flow rate were much stronger than that of the maximum flow rate as the flow was only capable of destroying small number of bridges, which quickly reformed after destruction. In contrast, the maximum flow rate had much weaker bridges, which were easily destroyed, allowing uninterrupted flow of gas/PF out of the feeder. What is also interesting to note is that once the bridges were destroyed, only a small drop in pressure was recorded for the minimum flow rate when compared to both the maximum and minimum flow rates of 17 November.

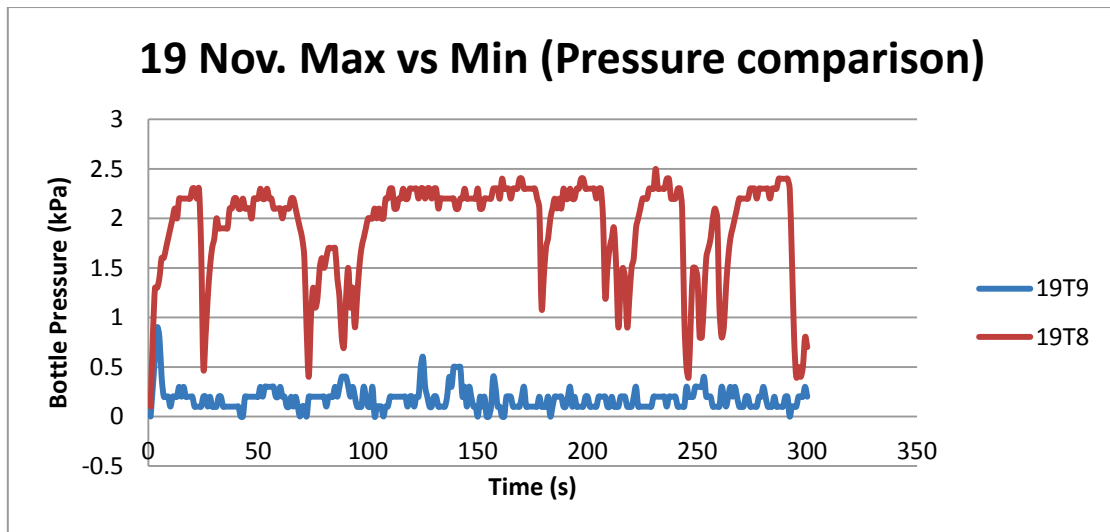


Figure 43: 19 November max. vs. min. pressure comparison.

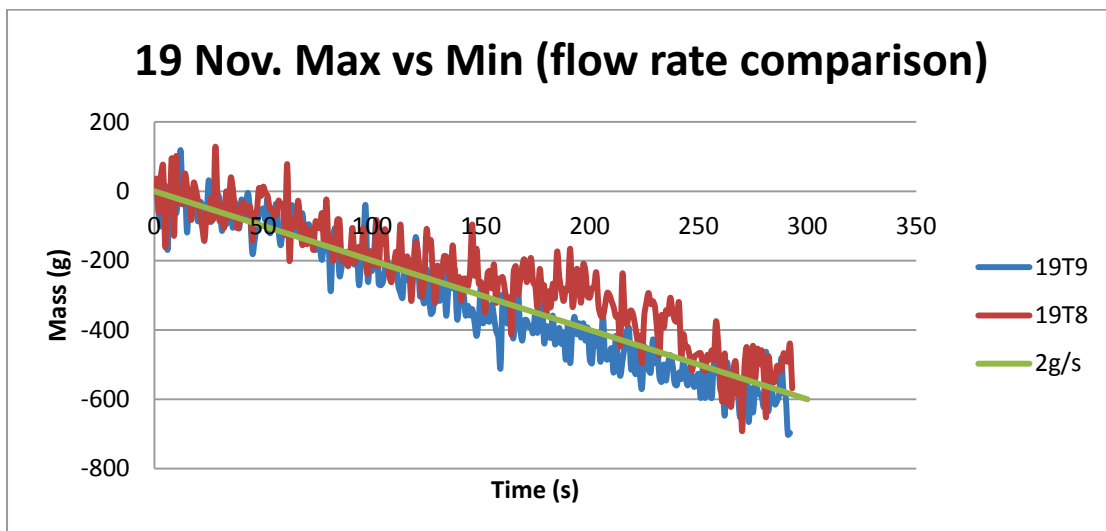


Figure 44: 19November max. vs. min. flow rate comparison.

6.2.3.2. Worst performing flow rates of Phase 3 testing

The pressure graph of 10 November shows that relatively weak bridges were formed for both the minimum and maximum flow rates and these were broken up very easily as well. When the pressure graphs of both that of the 10 and 19 of November are compared with each other, it seemed to have a similar appearance, but the flow rate of the PF differed greatly.

However, this difference in flow rate can be attributed to the difference in gas flow rates between the two tests, with the test having the greater gas flow resulting in a higher PF flow rate. The difference between the minimum and maximum flow rates can be attributed to the weak bridges being formed as the bridges of the minimum flow may be just a bit stronger than that of the maximum flow as can be seen in the small pressure difference between the two.

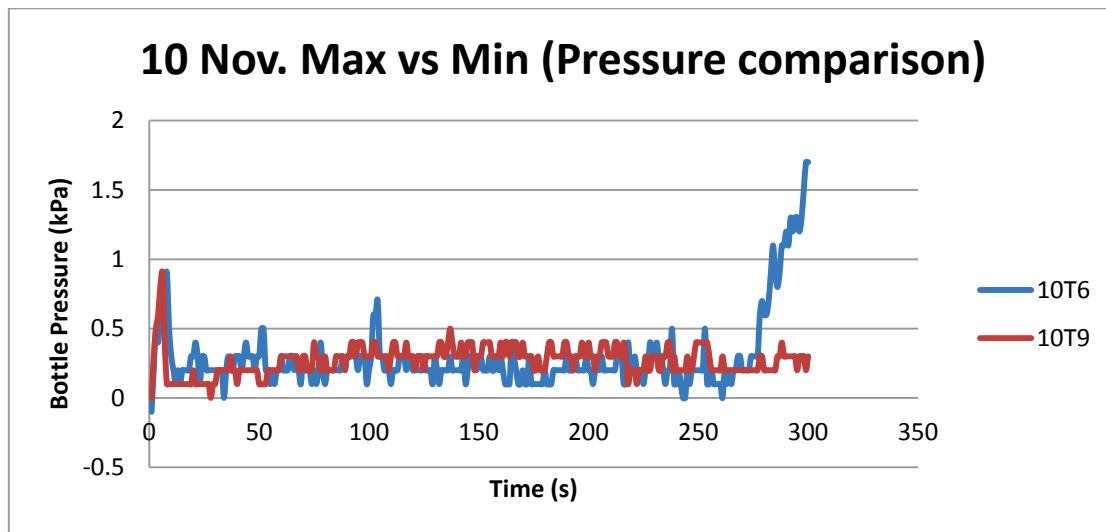


Figure 45: 10 November max. vs. min. pressure comparison.

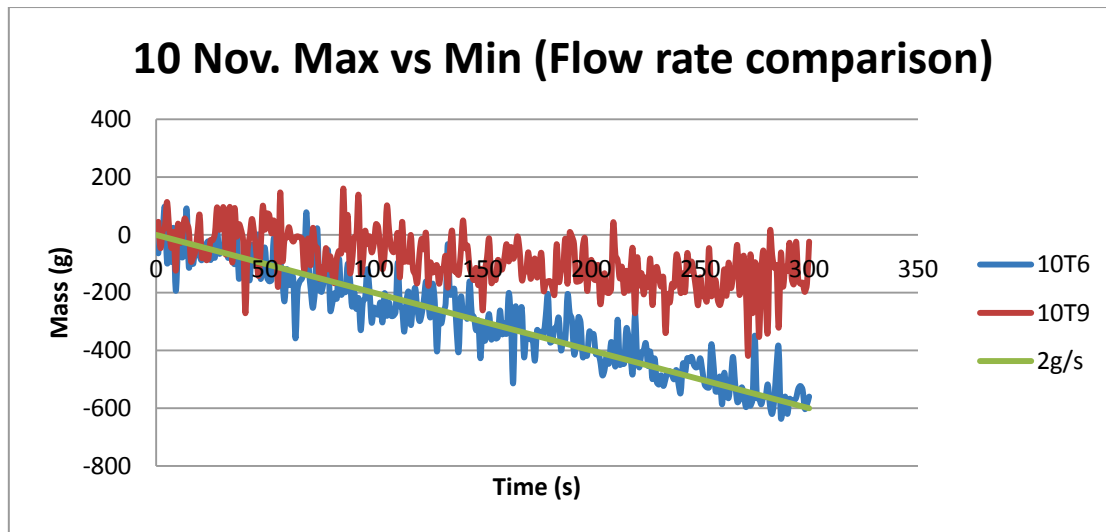


Figure 46: 10 November max. vs. min. flow rate comparison.

In the pressure graph of 13 November, Figure 47, the large discharge rate of the maximum flow rate can be attributed to the quick formation and destruction of bridges with the subsequent large discharge of pressure after the destruction of each bridge. On the other hand, when the bridge became weaker as shown in the pressure graph, between 120 and 230 seconds, the flow rate of the PF started to slow down significantly, which can be seen in the flow graph as the change in gradient of the flow line.

The minimum flow line on the pressure graph is a perfect example where the bridges are sufficiently weak enough to be easily destroyed and where the gas flow into the bottle is ideal to get the required flow rate. The effect that this sudden weak formation of bridges has on the flow rate of the maximum flow rate can be seen in Figure 48.

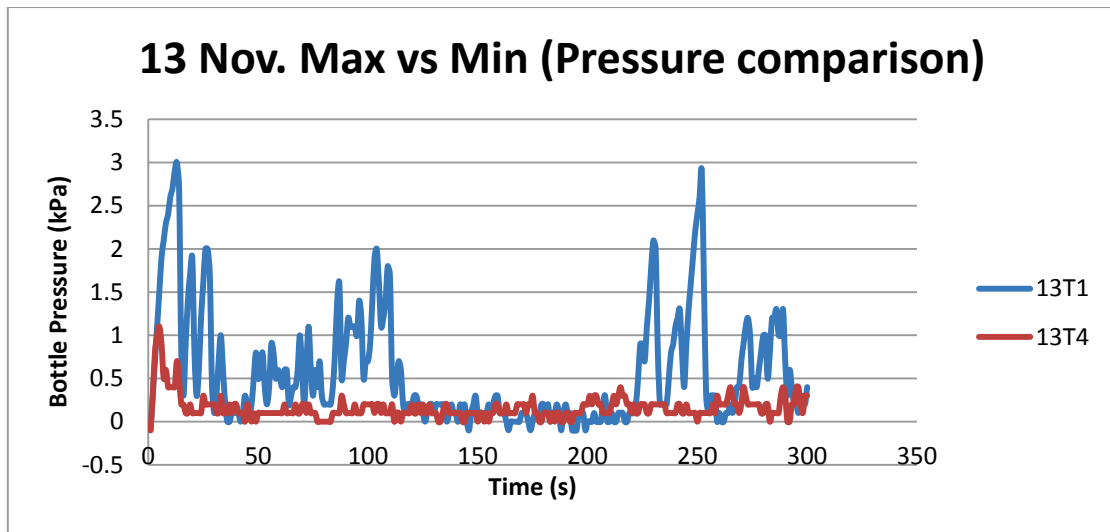


Figure 47: 13 November max. vs. min. pressure comparison.

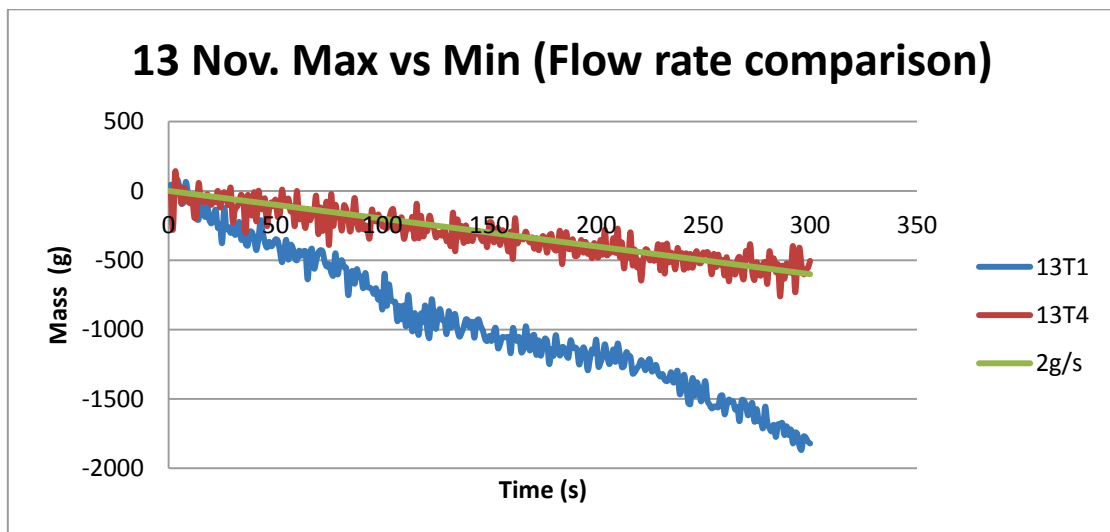


Figure 48: 13 November max. vs. min. flow rate comparison.

6.3. Phase 4 testing

In phase 3, a number of pre-tests were performed daily before the actual testing was conducted. This was done to correctly adjust the gas input into the bottle in order to deliver a desired flow rate within the required range.

The goal of Phase 4 testing was to investigate the cause of the PF flow changes on a daily basis and find ways to prevent or better manage it. Furthermore, investigation of the problem was done by doing the same test over three consecutive days with the exact same gas flow rate and other inputs to see how the flow rate will differ.

6.3.1. Test procedure

The PF and silica gel was placed in the oven for 17 hours at a temperature of 70 °C to rid the PF from any moisture absorbed during its exposure to atmosphere. Thereafter, the PF was left to cool off for an hour in the oven. The PF was then moved to an airtight container where it was left for 3 hours to cool off to room temperature before testing. In addition, the feeder was cleaned daily and any PF in the feeder from the previous day's testing was removed to prevent contamination.

Additional steps were taken to improve the accuracy of the measuring devices. The load cell was insulated from load frame by using insulation tape. All monitoring equipment was activated and zeroed an hour before testing. Furthermore, nitrogen gas was used instead of compressed air as explained during the fourth stage of Chapter 4 and previously in this chapter during the testing of Phase 3. The initial pressure in the pipeline was set at 100 kPa with the main valve closed. The valve leading to the bottle was opened to 145 degrees, which allowed a nitrogen flow rate of 0.0414 l/s entering the bottle.

The duration for each test was made 5 minutes to allow more tests each day. The Rpm of the auger was measured for each test to see how it would affect the mass flow rate. The mass of PF used each test was made constant at 5.5kg to ensure that this could not affect the data gathered.

6.3.2. Test results

Table 3, Table 4 and Table 5, contains the data collected for each of the three consecutive days, including important variables such as mass flow, bottle pressure and Rpm. In addition, the average and the deviation from the average (DFA) for each test was calculated and shown in Table 6.

In table 6, the DFA values differed greatly from one another even though the drying methods and gas input was the same for the three days. Thus, pressure plots were plotted so that reasoning can be obtained for the varying data.

Table 3: Phase 4 Test 1.

Phase 4 Test 1			
Date		25/11/2015	
Test Number	Mass flow (g/s)	Average Pressure (kPa)	RPM
1	3.59	2.95	11.5
2	1.88	3.48	11.5
3	1.02	3.62	11.5
4	0.96	3.67	10.75
5	0.52	3.67	10.2
6	0.34	3.74	10
7	0.35	3.77	10

Table 4: Phase 4 Test 2.

Phase 4 Test 2			
Date		26/11/2015	
Test Number	Mass flow (g/s)	Average Pressure (kPa)	RPM
1	2.47	2.50	10.00
2	1.18	3.24	10.00
3	0.95	3.20	10.25
4	1.14	3.30	10.25
5	1.09	3.34	10.25
6	1.04	3.53	10.75
7	1.26	3.56	10.25

Table 5: Phase 4 Test 3.

Phase 4 Test 3			
Date	27/11/2015		
Test Number	Mass flow (g/s)	Average Pressure (kPa)	RPM
1	4.01	0.90	10.25
2	4.36	0.92	10.50
3	4.89	1.34	10.50
4	3.54	2.66	10.50
5	5.32	1.68	10.50
6	3.97	1.22	10.25
7	3.96	2.45	10.50

Table 6: Phase 4 Test Results.

Phase 4 Results				
Test date	Max. (g/s)	Min. (g/s)	Average. (g/s)	DFA (%)
25-Nov	3,59	0,34	1,96	± 82,93%
26-Nov	2,47	0,95	1,71	± 44,41%
27-Nov	5,32	3,54	4,43	± 20,10%
DFA = Deviation from average				

Plotting the flow rates of each day as seen in Figure 49 below offers a clear visual representation of the variation between each of the separate day's flow rates. This may mean that something other than just the moisture in the PF may be influencing the flow rate, resulting in the daily deviation seen in table 6.

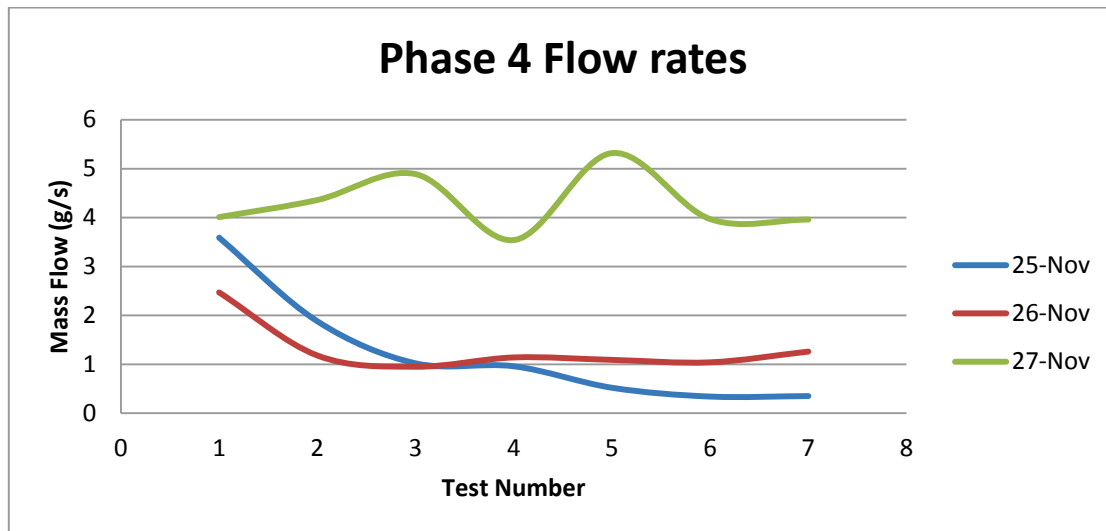


Figure 49: Phase 4 flow rate comparison.

6.3.3. Phase 4 pressure and PF flow rate comparison

The maximum and minimum flow rates of Table 3, Table 4 and Table 5 are shown below with the maximum flow rate indicated with the blue line and minimum flow with the red. Additionally, a green line is added to the flow rate graphs to indicate a flow rate of 2 g/s and is used as a measuring stick to see how far the flow rates are from the desired flow rate if the feeder was pre-tested as previously done in Phase 3.

Even with the same settings and procedures, it is clear that the flow rate varies greatly when compared on a daily basis. The pressure graphs, as seen in the testing of Phase 3, gives a better indication of what is going on inside the bottle during feeder operation. In Figure 50, Figure 52 and Figure 54 the bottle pressure of the minimum flow rate is typically higher and more constant when compared to that of the maximum flow.

The bottle pressure for maximum flow is almost identical to that of the minimum flow in Figure 50 and Figure 52, except that in one more bridges are destroyed, resulting in a few sudden drops in pressures that quickly recovers after the formation of a new bridge.

Figure 54 shows something entirely different with bottle pressure for both maximum and minimum flow rates fluctuating more than in the previous tests. The minimum flow rate started to stabilize due to the formation of a relatively strong bridge. However, it lasted for approximately 120 seconds before weak bridges once again start to form.

When comparing the largest maximum flow rate and smallest minimum flow rate achieved during the testing of Phase 4 it is clear to see that something external may be affecting the ability of the PF powder to break up, allowing the flow of gas out of the bottle.

The pressure graph for the maximum flow rate of Figure 50 shows the formation and destruction of multiple bridges, while the minimum flow rate shows that it was incapable of destroying the initial bridge that formed at the start of the test.

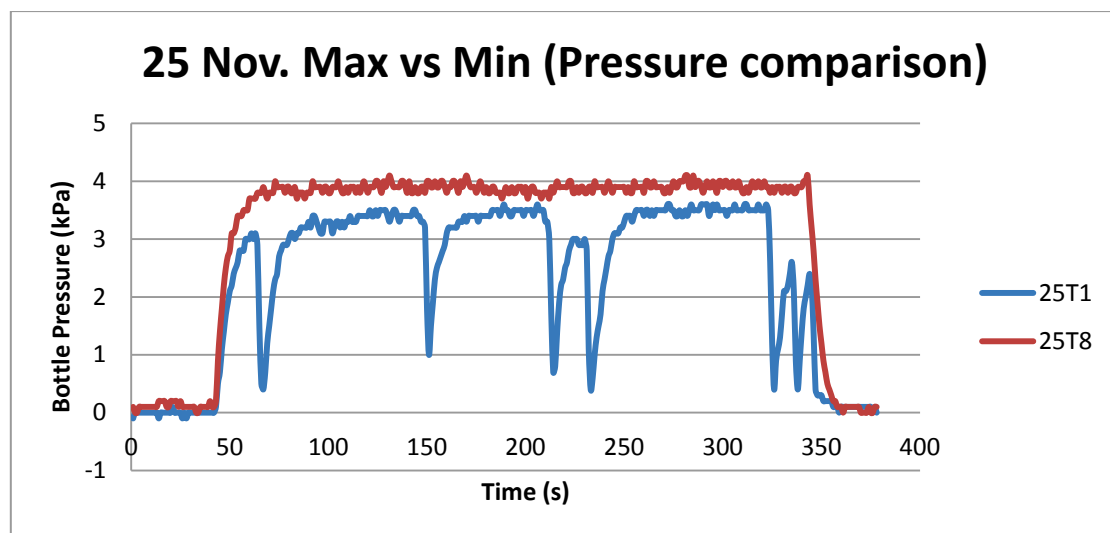


Figure 50: 25 November max. vs. min. pressure comparison.

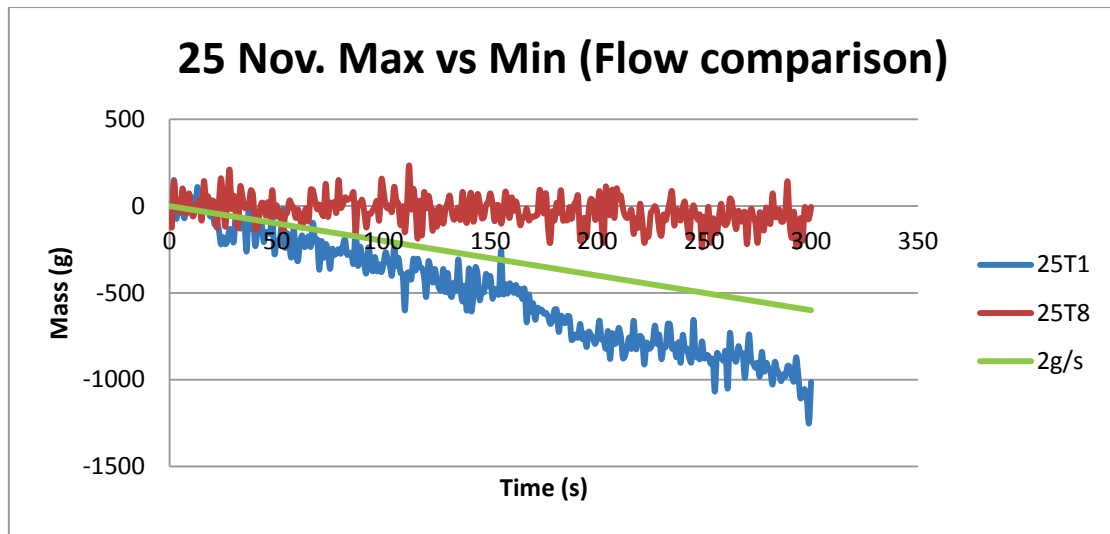


Figure 51: 25 November max. vs. min. flow rate comparison.

The maximum flow rate of Figure 52 was somewhat capable of breaking the bridges that formed and each time the bridge was destroyed, it allowed the discharge of a large amount of bottle pressure. Additionally, it is interesting to note that while the pressure graphs for 25 and 26 November look similar, their bottle pressures are much different with one being more than the other.

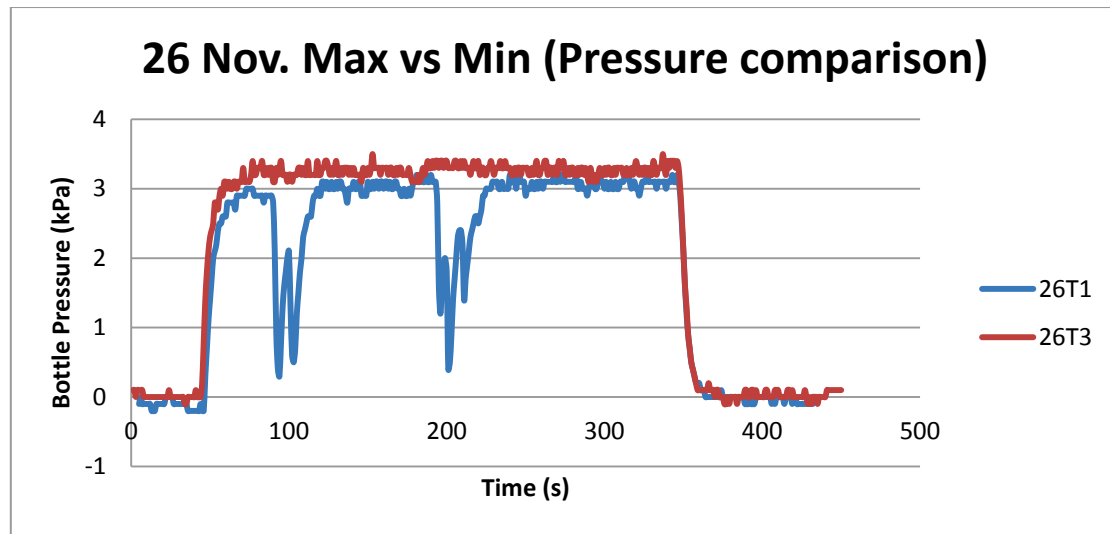


Figure 52: 26 November max. vs. min. pressure comparison.

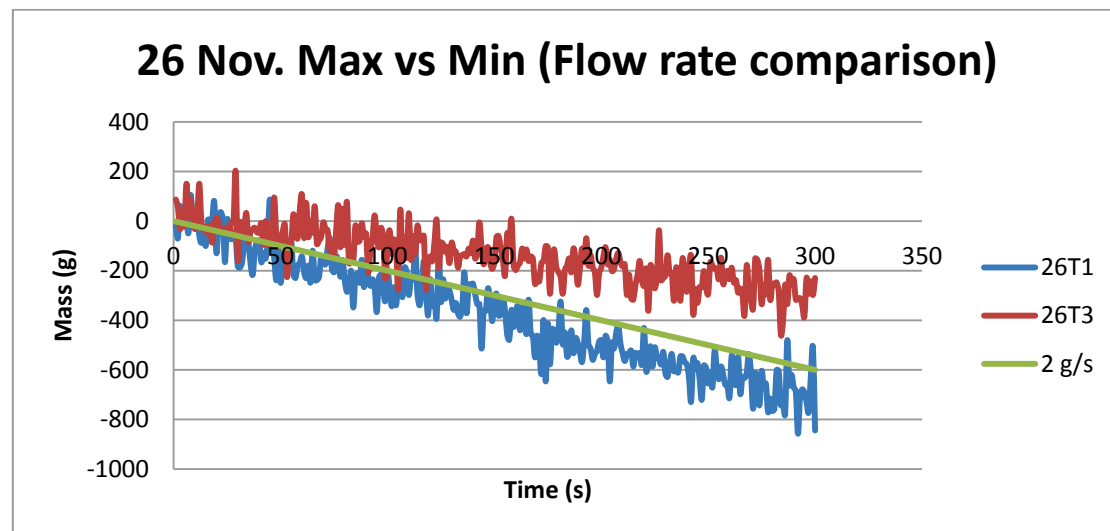


Figure 53: 26 November max. vs. min. flow rate comparison.

This pressure difference could be attributed to the ability of the gas to penetrate the PF bed. For instance, one day the gas is capable of easily penetrating the PF bed, effectively lowering the bottle pressure and ensuring PF flow. On the other hand, the opposite may also be true as the gas may not be able to penetrate the PF bed as easily, causing a pressure build up inside the bottle, which then results in lowering the PF flow rate.

As mentioned in (chapter 5 section 5.5) it is possible that the PF is highly hygroscopic in nature, causing it to absorb moisture from the surrounding atmosphere. The powder absorbs moisture until equilibrium between the two is reached, resulting in the wetting of the powder. This could explain why the test results in table 6 vary from day to day since the atmospheric conditions do not remain constant.

In Figure 54 the pressure graphs for both the minimum and maximum flow rates initially look very similar as they were both able to destroy numerous bridges and for some time gave almost the same PF feed rate. However, the minimum flow rate soon diverged as it was incapable of quickly destroying a new stronger bridge that formed, which ultimately resulted in the change of the PF flow rate as seen in Figure 55.

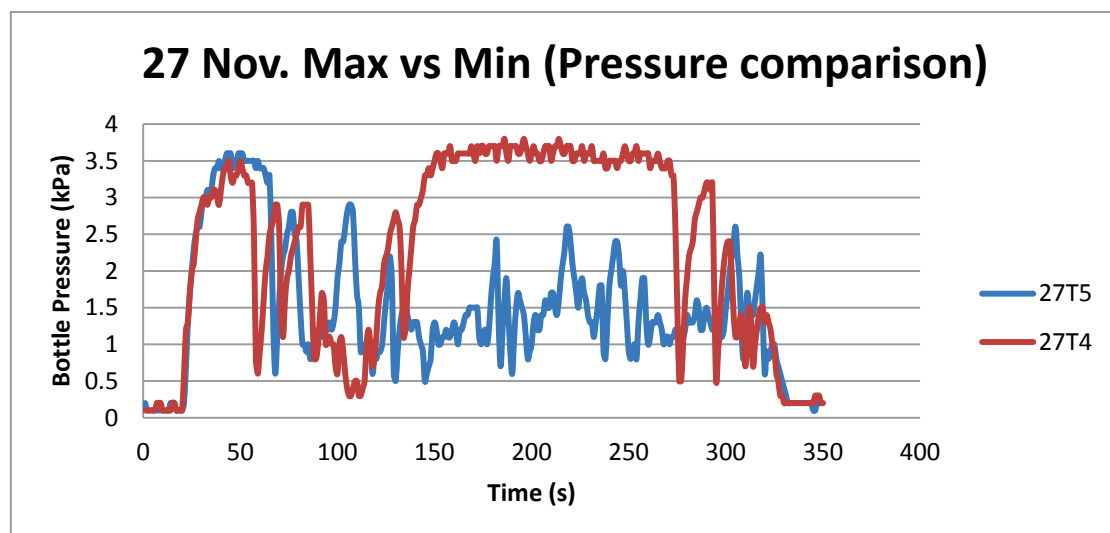


Figure 54: 27 November max. vs. min. pressure comparison.

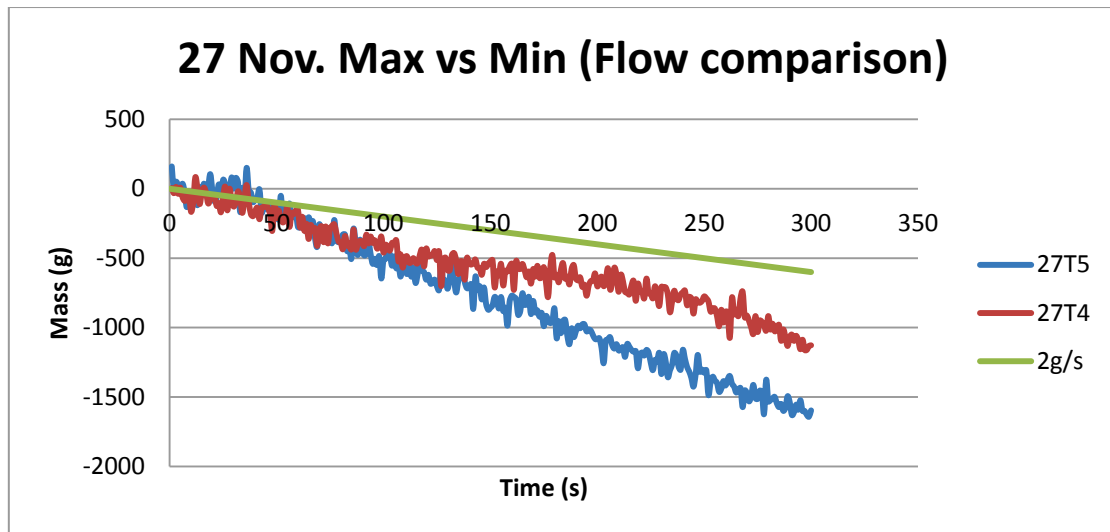


Figure 55: 27 November max. vs. min. flow rate comparison.

6.4. Verification and validation

The equations used in designing the auger, section 3.5, were used to create a mathematical model of the feeder. This was done to help predict the flow rate of the feeder and ensure that the feeder would deliver a flow rate within the required range as needed. The auger was designed using this model to deliver a specific constant flow rate as mentioned in the requirements.

In Chapter 2, it was mentioned that the PF powder has several factors that influence its flow ability and the resulting flow rate. These factors, which are mentioned below, do not allow the powder to freely flow from a bin and needs to be forced to flow by applying an external force.

The PF powder falls under the group C powders which have strong cohesive properties between the particles and also has a tendency to form agglomerates. Additionally, the powder consists of small irregular shaped particles which cause them to mechanically interlock.

The hygroscopic properties of PF allow the powder to absorb moisture directly from the atmosphere when the humidity is sufficiently high enough. The degree at which the powder absorbs moisture depends on the dryness of the powder and the level of humidity for the specific day. This absorption of moisture causes the powder to become “wet” which ultimately affects the resulting flow rate that can be achieved. Alternatively, when the humidity was low and there was not any moisture in the powder, the discharge of PF out of the feeder would cause static electricity to be generated. This generated static electricity would cause the PF particles to cling to the surface of the glass bottle as mentioned in (Chapter 5.5).

Unfortunately, the equations do not factor in the influences acting on the PF and as a result the mathematical model cannot be used to accurately predict the flow behaviour of the feeder. Currently, there is no singular analytical equation that can be used to accurately model the behaviour of PF powder.

The use of CFD programs to predict the behaviour of the PF feeder is also not possible as they also do not factor in any influences that may act on a powder. They can however only be used, like the mathematical model, to predict the behaviours for free flowing powders.

As the flow rate of the feeder cannot be predicted using either a mathematical model or CFD, it is therefore necessary to study the effects that these variables have on the behaviour of the PF feeder. Additionally, it is also important to show how the different factors change the behaviour of the PF feeder compared to the mathematical model used to design the auger.

The effect that each one of these different factors has on the behaviour of PF flow is not easily distinguishable from each other in the collected data. However, the results of phase 3 and 4 showed that it was possible to identify one of these factors, namely moisture.

In phase 3, it was discussed that during the testing of groups 1, 4 and 5, the feeder gave the best test results whereas groups 2 and 3 gave the worst results. Therefore, the assumption is that the difference in the results is due to the moisture content in the PF.

The behaviours of each groups of phase 3 is compared to the desired flow rate of 2 g/s of the mathematical model shown in the figures below.

By comparing the different groups to each other, it is possible to see from the behaviour of the flow rates that the “dry” powders of groups 1, 4 and 5, tends to oscillate within a specific range. This specific range was called the operational range of the feeder during the discussion of the results in chapter 6. On the other hand, the “wet” powder in groups 2 and 3, do not oscillate at all and in fact does not seem form any real pattern since the flow rates deviates from the oscillation pattern with each test.

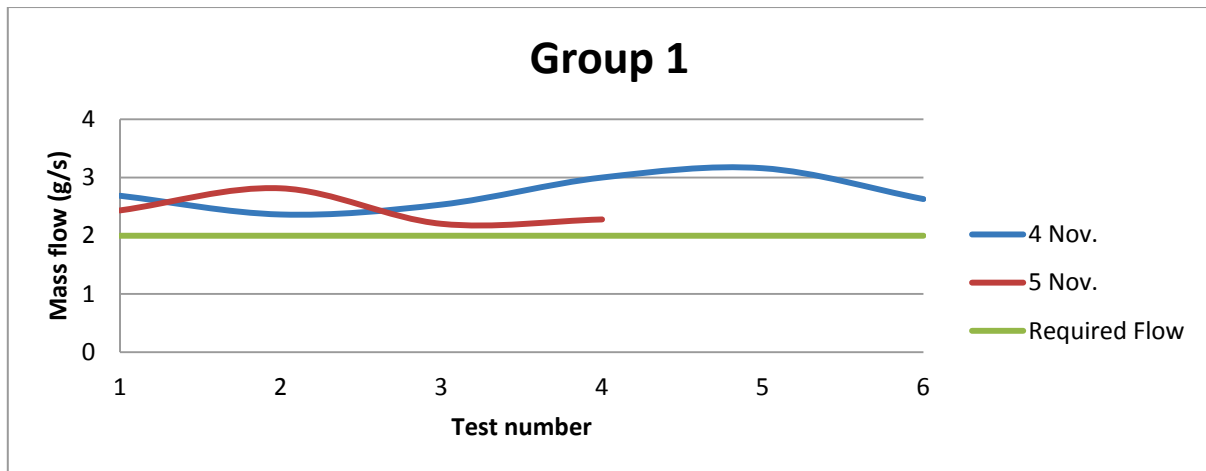


Figure 56 Comparison of flow behaviours between group 1 and auger design flow rate.

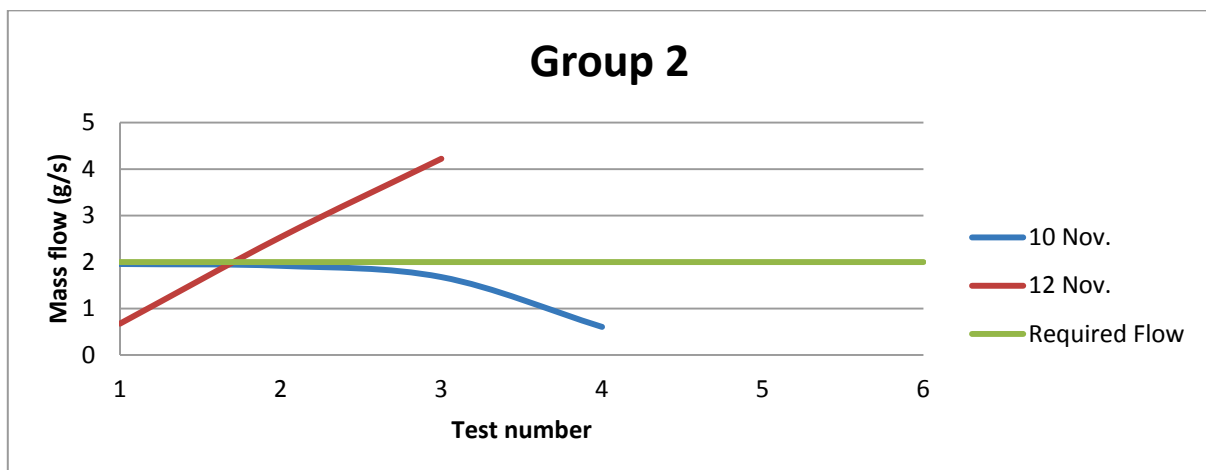


Figure 57 Comparison of flow behaviours between group 2 and auger design flow rate.

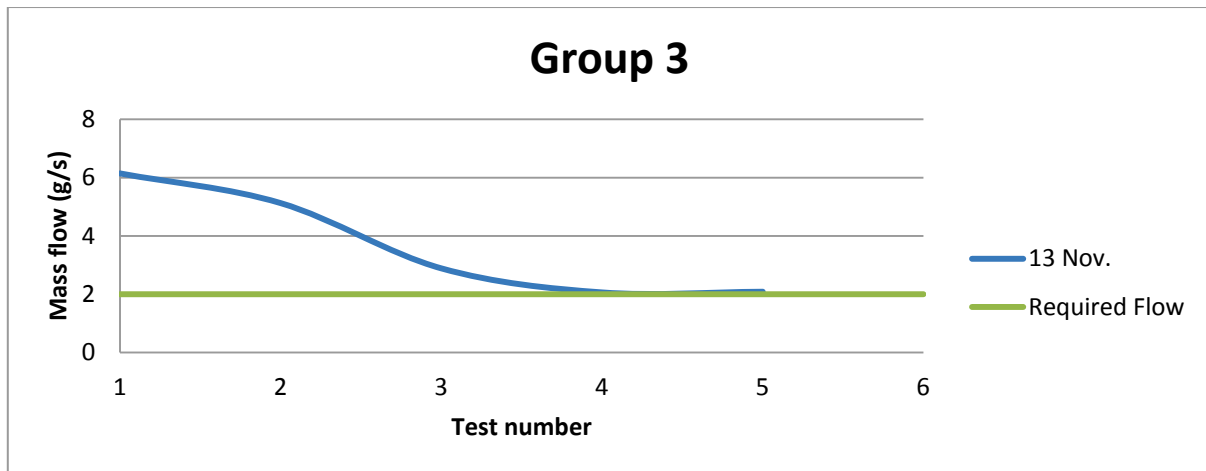


Figure 58 Comparison of flow behaviours between group 3 and auger design flow rate.

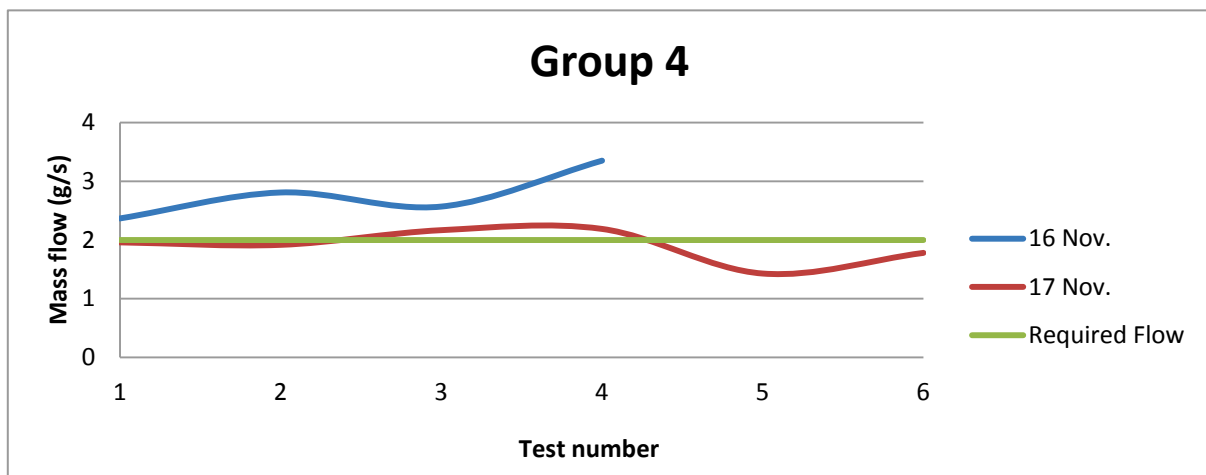


Figure 59 Comparison of flow behaviours between group 4 and auger design flow rate.

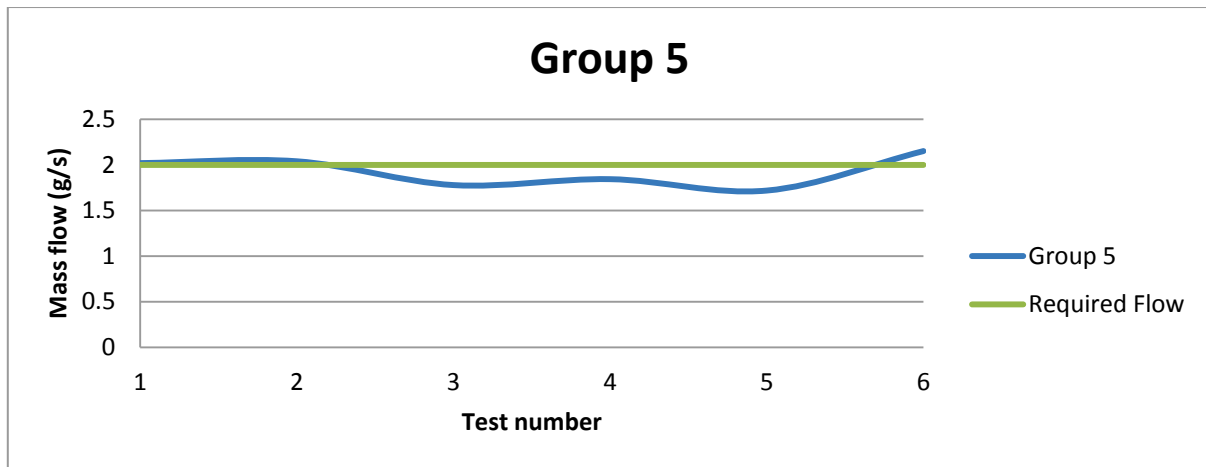


Figure 60 Comparison of flow behaviours between group 5 and auger design flow rate.

In Figure 61, the exact same “wet” and “dry” flow behaviour was seen as in the previous Figures. However, the different flow behaviours observed in Figure 61 is due to the effect daily humidity can have on the behaviour of the feeders flow rate.

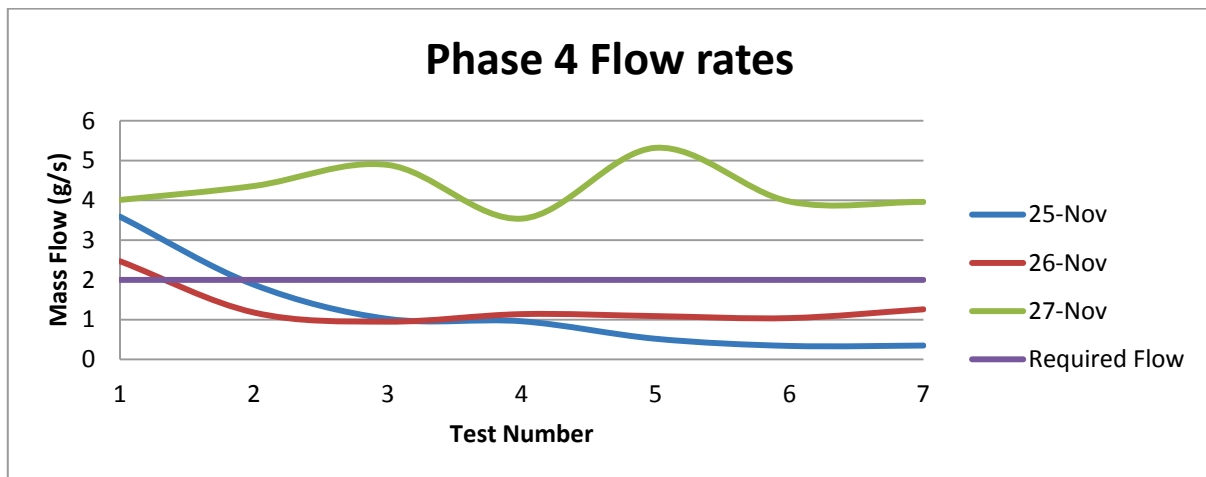


Figure 61 Comparison of flow behaviours between group 5 and auger design flow rate.

This clearly definable operational range of the “dry” flow behaviour makes it possible to predict the flow rate of the PF feeder. Nevertheless, pre-tests will still have to be done in order to establish the boundaries of the operational range for the specific day.

Chapter 7: Conclusions and recommendations

7.1. Introduction

The conclusions including a number of recommendations to the design of the prototype PF feeder is discussed that can help improve future feeder designs.

7.2. Conclusions

The current design of the prototype PF feeder is incapable of successfully delivering a specific constant flow rate and could only deliver an average flow rate close to it, provided that the desired flow rate was within the obtained operational range.

However, the prototype PF feeder is capable of delivering a flow rate within the required range, only if some requirements are met. These requirements were that the PF should not contain any moisture, the obtained operational range remains small and that a larger number of pre-test should be done to more accurately predict the size of operational range so that the gas input is adjusted accordingly.

Atmospheric conditions such as humidity could have an effect on the performance of the prototype PF feeder since the dried powder absorbs moisture from the surrounding atmosphere due to its hygroscopic nature. The total amount of moisture that the PF could absorb could be directly depended on the humidity of the particular day that explains the results of phase 4.

This absorbed moisture in the PF may strengthen the formed bridges at the bottle exit as shown in the resulting pressure graphs of phase 3 and phase 4. The pressure graphs of the test results shows how the formation of bridges can affect the ability of the PF to flow out of the feeder. They can have a great impact on the resulting flow rate. There are four types of bridge formations that can be classified into different classes, with each one having a different effect on the flow rate of the PF feeder and its controllability.

First, in some cases relatively weak bridges (Class 1) were formed that broke up easily and did so quite frequently, resulting in low bottle pressure with stable flow rates as a result. These weak bridge formations can be observed in the pressure graphs of Figure 43 (Test 19T9) and Figure 45 (Tests 10T6 and 10T9), which also shows that the flow rates of these can easily be controlled by controlling the gas flow into the bottle.

Secondly, bridges were at times a little stronger (Class 2) and broke up more difficulty and less frequently, leading to higher pressures in the bottle than compared to the weaker bridges. When the bridges did finally break, much pressure was released, resulting in larger PF flow rates being observed. The flow rates from these stronger bridges were still stable, but controlling them was a bit more difficult. It could still be done by controlling the gas flow to the bottle. These stronger bridges can be observed in the pressure graphs of both Figure 41 (Tests 17T7 and 17T8) and Figure 43 (Test 19T8).

Third, some bridges that seemed almost indestructible (Class 3) formed, resulting in even higher pressure build-up inside the bottle as the gas was unable to penetrate the powder bed and exit the feeder. This inability of the gas to exit the feeder resulted in a decreased flow with only a small amount of PF flow. These indestructible bridges can be observed in the pressure graphs of Figure 50 (test 25T8) and Figure 52 (26T3).

Lastly, the strength of the bridges at times seemed to change (Class 4) during a test. They alternated between weak and strong bridges that can be identified in the pressure graph from the frequency with which they broke. Alternating bridges result in unstable and uncontrollable flow rates that make these types of bridges very undesirable for the PF feeder. The alternating bridges can be observed from the pressure graphs of Figure 47 (Test 13T1) and Figure 54 (test 27T4).

7.3. Recommendations

Drying the PF powder improved the flow ability of the powder, making it easier to control the flow rate more reliably. However, it also increased the ability of the powder to absorb moisture from the atmosphere. Therefore, it is recommended that the exposure time between the PF and atmosphere must be limited as much as possible. This could be accomplished by drying the PF inside the feeder thereby ensuring it never comes into contact with any external sources of moisture. Additionally, if air from the compressor is used when the PF feeder is connected to the microburner, it is recommended that the air is first dried using an air dryer and that the compressors water trap is regularly cleaned.

The auger was successful in destroying most bridges that formed in the bottle and prevented the formation of rat holes entirely. However, as mentioned earlier, the current auger design is incapable of preventing the formation of bridges and at times had difficulty to destroy them, which ultimately had a negative effect on the controllability of the PF feeder. As a result, it is recommended that the auger should be redesigned to enable it to prevent the formation of bridges better and more easily destroy any bridges that may form directly, increasing the controllability of the PF feeder.

The windscreen motor performed well in the task of turning the auger in the powder bed for this prototype design. However, the motor was underpowered and the rotational speed of the motor had a tendency to fluctuate as shown in the results of phase 4. It is therefore recommended that the windscreen motor be replaced with a higher watt motor.

In order to further increase the flow ability of the PF powder and improve the controllability of the feeder, it is recommended that the size of the smallest PF particle be increased to a larger size, as these larger particles are less susceptible to both mechanical interlocking and agglomeration. This should help reduce the strength of the bridges.

Operating the PF feeder is labour intensive and time consuming as all inputs have to be done manually. This may also not result in the best accuracy, especially when the valves have to open correctly. Additionally, outputs of the feeder are typically received as raw data that first have to be converted and analysed before any alterations can be made to the flow.

Therefore, it is recommended that the entire process be automated with the gas flow to the feeder being controlled by a computer using electronic valves so that the necessary corrections can be made instantaneously to ensure that the required PF flow rate can be achieved.

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Appendices

Appendix A: Testing the materials resistance to elevated temperature.

To ensure that the ABS plastic material could resist the high temperatures it will encounter during operation, a simple test had to be conducted first.

Two simple bending tests were performed on a piece of ABS plastic, with one side fixed in a vice, leaving the other side clear for a force to act on it. These tests were conducted at different temperatures with one at room temperature, a cold test as the control, and another at an elevated temperature.

The goal of this experiment was to see if the plastic lost any of its resistance against bending when heated up and if it could return to its original shape after cooling down.

First, the ABS plastic piece was placed into a container of water that was heated up to a temperature of 80 °C as seen in Figure A1.



Figure A1: ABS plastic placed into the hot water.

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After about five minutes, one side was secured in a vice while the other end was bent backwards. There was no difference in the bending resistance when compared to the cold test. The piece was kept bent for about a minute to allow it to cool down. After releasing the piece it went straight back to its original shape without any problem.

Appendix B: Prototype Gearbox

This gearbox was a prototype to observe what effect the PF powder level in the bottle would have on the auger and its rotational speed in the powder bed. Furthermore, it was used to test if the motor would be powerful enough to turn the auger through the powder bed by using a simplistic gearbox configuration.

Figure B1 shows the completed prototype gearbox as it was used for the preliminary testing of the newly designed PF Feeder.

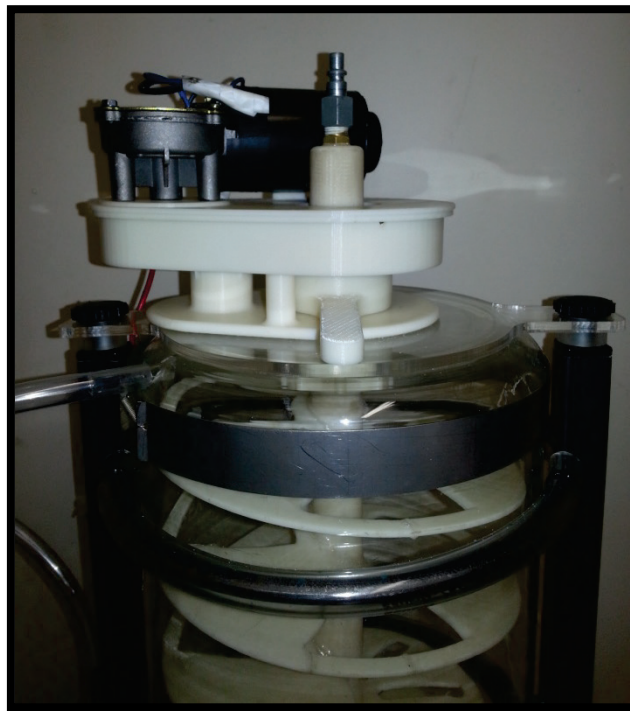


Figure B1: The prototype gearbox.

The gearbox was designed by using the first stage reduction gearbox design with the smaller gear, the pinion (P), receiving power directly from the motor. The power is transferred to the auger shaft by means of the main gear (G). As shown in Figure B2.

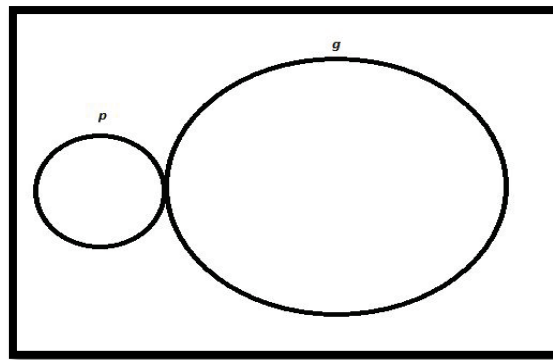


Figure B2: First stage reduction gearbox.

As the gearbox was to be placed on top of the bottle it had to be both compact and as light as possible to avoid making the PF feeder top-heavy. There is a limit to the size the gears can be in this configuration due to the limited space available for use above the bottle.

To increase the torque delivered by the motor, the size of the pinion should be significantly smaller than that of the main gear, while the opposite is true for the main gear. Therefore, the pinion gear diameter was made as small as practically possible, giving it a diameter of 30mm, which rotates at the same speed of 108 RPM. The size of the main gear, however, was made as close to maximum as possible, giving it a diameter of 100mm, which rotates at a speed of 32.4 RPM while delivering 14.74 Nm of torque.

Another gear was inserted in between the pinion and main gear to allow the auger to run in reverse by transporting the PF upwards, as mentioned in the auger design. This extra gear is the same size as the pinion and has no other function than reversing the augers' turning direction.

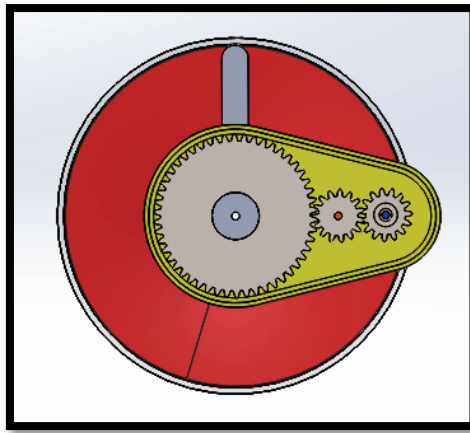


Figure B3: Additional middle gear.

The gearbox was designed to allow the main gear to move vertically upwards and downwards freely when the auger is lifted or lowered and still be in full contact with the extra gear. This was made possible by increasing the width of the main gear by the exact maximum distance the auger can lift, which is about 5mm.

The possibility of wear between moving surfaces in the gearbox is high as small amounts of PF powder could enter the gearbox and easily contaminate any type of liquid lubricant that is used.

In order to avoid PF contamination, it was decided to use a material that can act as a dry lubricant between the rotating surfaces to provide the necessary lubrication. Nylatron is the perfect material to use as a dry lubricant in the gearbox as it is a self-lubricating, highly wear resistant thermoplastic that is hard enough to be machined to any desired shape.

Additionally, because the Nylatron is so easily machine able and provides the necessary lubrication, it was decided that the middle gear support would also be made from Nylatron.

Both the middle and main gear were given a small foot underneath to help decrease the area of contact with the Nylatron to lower the friction and decrease the load on the motor, as seen in Figure B4below.

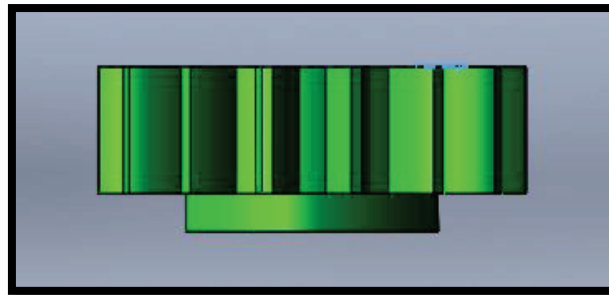


Figure B4: Middle gear with "foot".

Each separate part of the gearbox was manufactured using the 3D-printer as it proved to be both quick and efficient in making the complex auger.

Figure B5, shows the complete assembly of the prototype gearbox including how the main gear is fixed to the auger shaft by means of screws. Furthermore, it also shows how the Nylatron supports the middle gear and provides lubrication to both the middle and main gear.

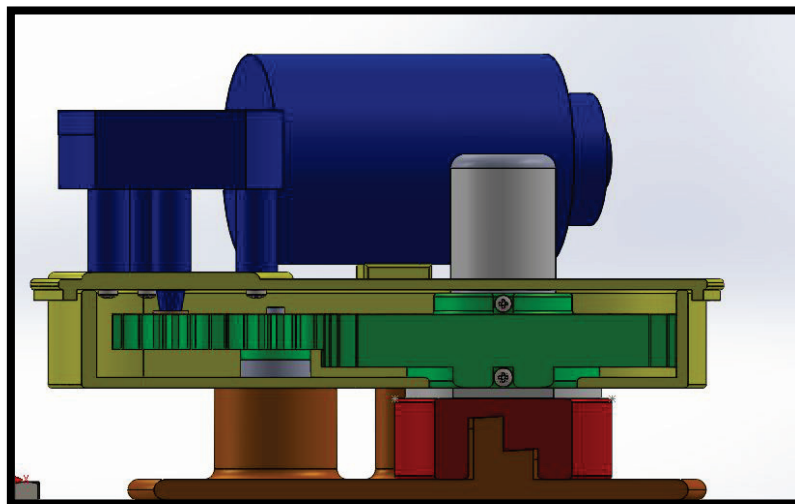


Figure B5: Assembly of the prototype gearbox.

Testing with the prototype gearbox showed that it was more than sufficient to allow the auger to turn in the powder bed. However, it was apparent that when the bottle was filled more than half way, the RPM of the auger would start to decrease and the motor would start to heat up rapidly, shortening the operational time.

When the tests were conducted, the bottle was filled between full and 3/4 filled. The motor started to suffer, making a strained noise until the middle gear finally failed under the stress. Therefore, the middle gear was replaced, but the replacement also failed, along with the pinion gear. The broken middle gear is shown in Figure B6.



Figure B6: Middle gear failure.

Appendix C. Auger Redesign Test Report.

After numerous observations of the PF feeder operation, it was noted that PF tended to build up on the surface of the auger blade after refilling the bottle and after the PF level had dropped during operation. This prevents complete emptying of the bottle. A new approach had to be examined to see whether this problem could be solved.

An attempted was made to solve this problem by changing the solid surface of the auger to that of a grid to allow the powder to fall freely through while still allowing for a strong and rigid structure, as it still has to move through the PF bed to agitate it.

For this experiment two separate grids with different hole sizes was 3D-printed to see which one of these would allow the PF through more effectively while keeping its strength. The first grid had 10x10mm holes, Figure C1, while the second one had 20x20mm holes, Figure C2.

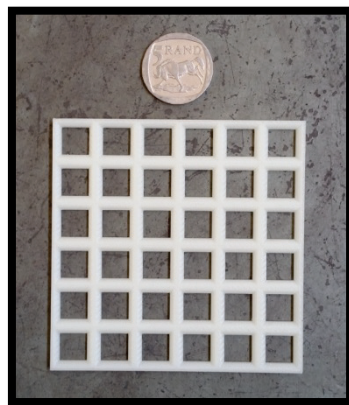


Figure C1: The 10x10mm grid square.

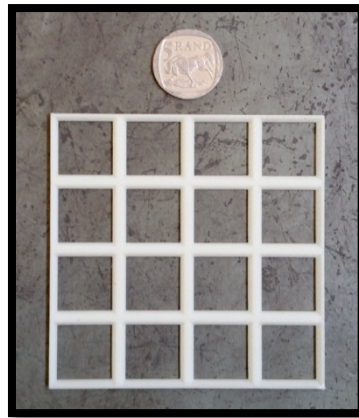


Figure C2: The 20x20mm grid square.

Test procedure

The test consists of two separate test methods with each trying to simulate the conditions found in the bottle during both filling and operation. The first test method is an attempt to simulate when new PF is added to the bottle and it lands on the surface of the auger blade, while the second test method tries to simulate when the PF level has lowered below that of the auger blade.

The first method

For this method, each grid was placed in a container, but lifted off the bottom by two plastic t-sections to allow the powder to go through and prevent powder build-up. PF was slowly sprinkled over the grid to see whether powder will build up on the surface of the grid.

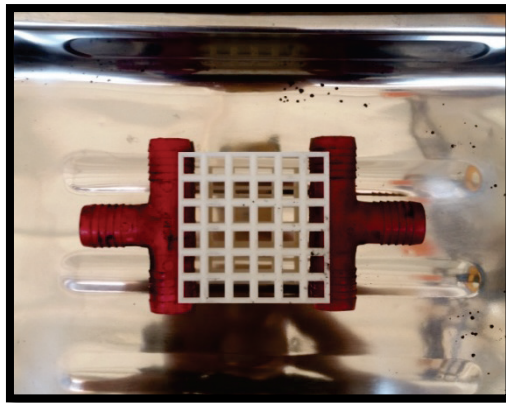


Figure C3: Placement of grid square for testing purposes.

The 10x10mm square grid in Figure C4 shows no problem when letting the powder through when it is sprinkled on top of it, although some build-up is observed on the structure of the grid. However, it is minimal and does not build up more than is what is shown in the figure. The same is observed in Figure C5, as both are fully capable of letting the PF through with minimal PF build-up on the grid structure. This build-up should disappear when the auger is in motion.

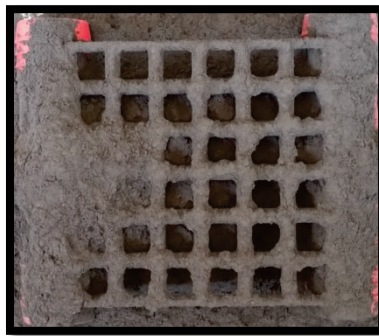


Figure C4: Test 1 result for 10x10mm square grid.

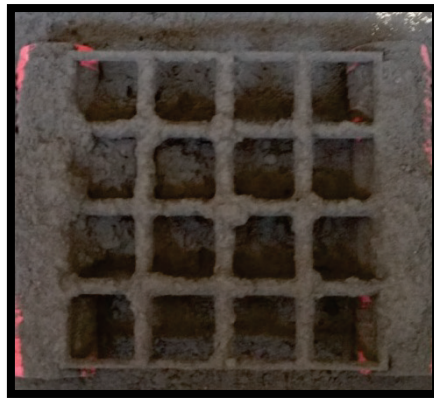


Figure C5: Test 1 result for 20x20mm square grid.

The second method

The grid was first placed on the bottom of the container and covered with PF to submerge it completely. The grid was then lifted and placed onto the t-section to see if the PF will automatically fall through the grid without any need for the application of an external force.

Figure C6 shows that some of the PF fell through the 10x10mm grid when lifted out of the PF pile, although the bridges formed at each hole was still strong enough to prevent the rest of the PF from going through the grid. Only after the side of the container was lightly tapped a couple of times did most of the bridges collapse and allow the PF to go through the grid as shown in Figure C7.

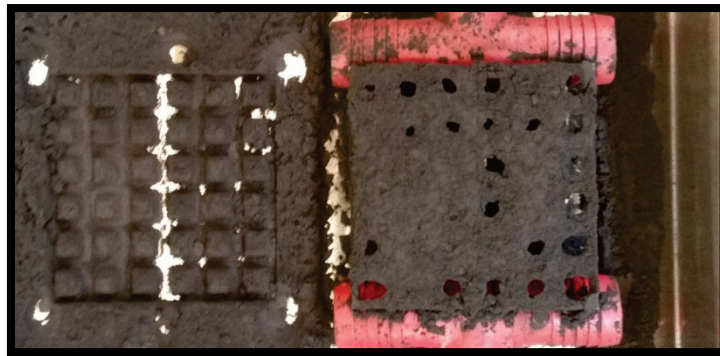


Figure C6: Test 2 result 10x10mm square grid.

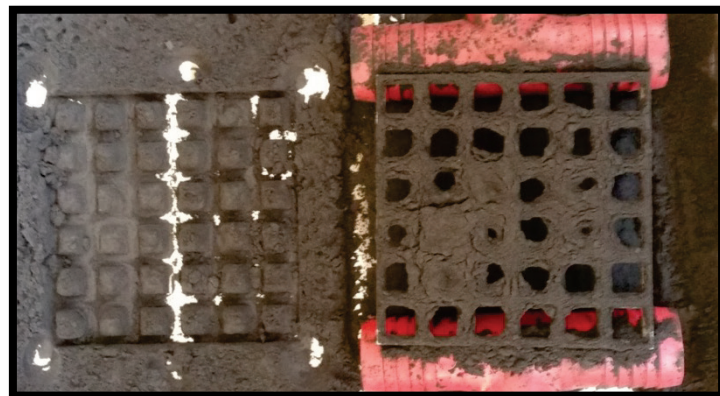


Figure C7: Test 2 result 10x10mm square grid after tapping.

Figure C9 shows that the 20x20mm square grid performs much better than the 10x10mm grid in allowing the PF to move through the grid, while also preventing some bridges to form over the holes. Similarly, the 20x20 performs even better when a small external force is applied to the container helping to dislodging the PF and stopping the build-up as seen in Figure C9.

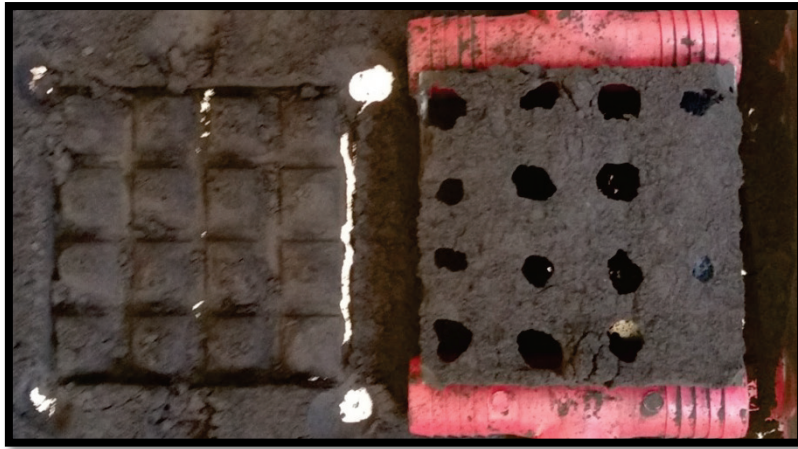


Figure C8: Test 2 result 20x20mm square grid.

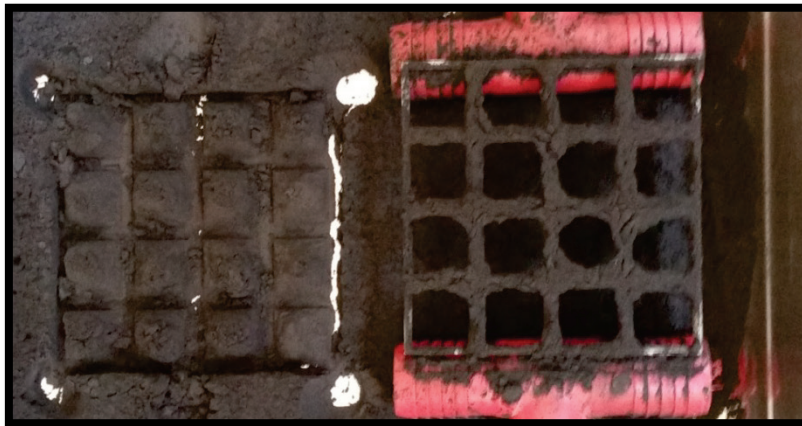


Figure C9: Test 2 result 20x20mm after tapping.

Test conclusion

Both grids perform excellent for the first method and allow the PF to move freely through each grid without any clear difference noticeable between them. However, for the second method it is clear that the 20x20mm grid is better than the 10x10mm grid, allowing for better movement of PF through the grid while preventing the formation of bridges near the holes.

Appendix D. NCV_p Analyser with input parameters

Table D1 was supplied by Professor Chris Storm, who is in charge of the NCV_p microburner project, and shows the required design parameters for the NCV_p microburner. The requirements that the prototype PF feeder needs to meet is highlighted in yellow as shown in table D1.

The flow rate which the feeder is expected to deliver to the microburner is shown in table D1. Hence, the PF FLOW min and PF FLOW max give the range where in the feeder has to be able to feed the microburner. Additionally, PF FLOW nominal gives a specific required flow rate inside of this range which the feeder has to try and deliver if possible.

T primary air is the maximum temperature of the air which will be supplied from the air heater that will be entering the glass bottle. However, it was not necessary to use this elevated temperature during testing as the air heater of the microburner was not yet operational. Nevertheless, it was still necessary to include this in to the design parameters of the prototype PF feeder as it would have to be able to operate at this temperature when the air heater does become operational eventually. Lastly, the PF bunker size shows that the 10 litre glass Pyrex bottle is to be used as the hopper for the prototype PF feeder.

Table D1: Microburner Input Parameters.

NCV _p ANALYSER DIMENSIONS AND FLOWS					
INPUT PARAMETERS					
PF FLOW _{MIN}	1,7	[g/s]	Q _{IN} GAS BURNER	15,0	[%]
PF FLOW _{NOMINAL}	1,9	[g/s]	NCV _p PROPANE	46,2	[MJ/kg]
PF FLOW _{MAX}	2,7	[g/s]	A:F _{STOICH. PROPANE}	15,6	[kg _{AIR} / kg _{PROP.}]
CV _{COAL MAX}	23,5	[MJ/kg]	A:F _{LEL PROPANE}	6,6	[kg _{AIR} / kg _{PROP.}]
CV _{COAL NOMINAL}	20,5	[MJ/kg]	A:F _{UEL PROPANE}	29,7	[kg _{AIR} / kg _{PROP.}]
CV _{COAL MIN}	14,3	[MJ/kg]	A:F _{PROPANE LEL USED}	2,8	[kg _{AIR} / kg _{PROP.}]
P _{ATM}	86,4	[kPa]	P _{PROPANE (GAUGE)}	56,1	[kPa]
T _{AMBIENT}	25,0	[°C]	P _{CORE AIR (GAUGE)}	13,7	[kPa]
R _{PROPANE AMBIENT T @ P}	0,2	[kJ/kg-K]	R _{PROPANE AMBIENT T @ GAUGE P}	0,2	[kJ/kg-K]
R _{AIR AMBIENT T & P}	0,3	[kJ/kg-K]	R _{AIR AMBIENT T & GAUGE P}	0,3	[kJ/kg-K]
ρ _{PROPANE AMBIENT T & P}	1,6	[kg/m ³]	ρ _{PROPANE AMBIENT T & GAUGE P}	2,6	[kg/m ³]
ρ _{AIR AMBIENT T & P}	1,0	[kg/m ³]	ρ _{AIR AMBIENT T & GAUGE P}	1,2	[kg/m ³]
T _{PRIMARY AIR}	70,0	[°C]	R _{PROP. PRIMARY T @ AMB P}	0,2	[kJ/kg-K]
T _{SECONDARY AIR}	275,0	[°C]	R _{AIR PRIMARY T @ AMB P}	0,3	[kJ/kg-K]
R _{PROP. PRIMARY T @ GAUGE P}	0,2	[kJ/kg-K]	ρ _{PROP. PRIMARY T @ AMB. P}	1,3	[kg/m ³]
R _{AIR PRIMARY T @ GAUGE P}	0,3	[kJ/kg-K]	ρ _{AIR PRIMARY T @ AMB. P}	0,9	[kg/m ³]
ρ _{PROP. PRIMARY T @ GAUGE P}	2,2	[kg/m ³]	R _{AIR SECONDARY T @ GAUGE P}	0,3	[kJ/kg-K]
ρ _{AIR PRIMARY T @ GAUGE P}	1,0	[kg/m ³]	R _{PROP. SECONDARY T @ GAUGE P}	0,2	[kJ/kg-K]
ρ _{AIR SECONDARY T @ GAUGE P}	0,6	[kg/m ³]	C _D PROPANE NOZZLE	0,6	[-]
ρ _{PROP. SECONDARY T @ GAUGE P}	1,4	[kg/m ³]	C _D PRIM. CORE NOZZLE	0,6	[-]
R _{AIR SECONDARY T @ AMB P}	0,3	[kJ/kg-K]	C _D SEC. CORE NOZZLE	0,7	[-]
R _{PROP. SECONDARY T @ AMB P}	0,2	[kJ/kg-K]	Ø ID _{PROPANE NOZZLE}	0,7	[mm]
ρ _{AIR SECONDARY T @ AMB. P}	0,5	[kg/m ³]	Ø ID _{PRIM. CORE AIR NOZZLE}	2,0	[mm]
ρ _{PROP. SECONDARY T @ AMB. P}	0,8	[kg/m ³]	Ø ID _{SEC. CORE AIR NOZZLE}	4,0	[mm]
C _D PF/PA NOZZLE	0,7	[-]	A:F _{STOICHIOMETRIC COAL MAX CV}	7,9	[kg _{AIR} / kg _{COAL}]
C _D SA NOZZLE	0,8	[-]	A:F _{STOICHIOMETRIC COAL NOMINAL CV}	6,9	[kg _{AIR} / kg _{COAL}]
C _D TA NOZZLE	0,8	[-]	A:F _{STOICHIOMETRIC COAL MIN CV}	5,0	[kg _{AIR} / kg _{COAL}]
Ø ID _{PF/PA NOZZLE}	6,0	[mm]	A:F @ 3.5 % O ₂ COAL MAX CV	9,5	[kg _{AIR} / kg _{COAL}]
Ø ID _{SA NOZZLE}	11,0	[mm]	A:F @ 3.5 % O ₂ COAL NOMINAL CV	8,2	[kg _{AIR} / kg _{COAL}]
Ø ID _{TA NOZZLE}	8,0	[mm]	A:F @ 3.5 % O ₂ COAL MIN CV	6,0	[kg _{AIR} / kg _{COAL}]
ρ _{BITUMINOUS COAL}	1346,0	[kg/m ³]	FLAME SPEED _{PROP. LAM. AMB, STOICH.}	0,4	[m/s]
ρ _{CARBON/GRAPHITE}	2250,0	[kg/m ³]	REL. BULK ρ _{PF DRY BASIS}	0,7	[-]
PF BUNKER SIZE	10,0	[l]	REL. BULK ρ _{PF AS RECEIVED}	0,8	[-]

Appendix E. Declaration of Language Editing



Director: CME Terblanche - BA (Pol Sc), BA Hons (Eng), MA (Eng), TEFL
22 Strydom Street Tel 082 821 3083
Baillie Park, 2531 cumlaudelanguage@gmail.com

DECLARATION OF LANGUAGE EDITING

I, Christina Maria Etrechia Terblanche, hereby declare that I edited the
research study titled:

**Development and manufacturing of a prototype pulverized fuel feeder
for a microburner**

for Jaco Botha for the purpose of submission as a postgraduate dissertation
for examination. Changes were suggested and implementation was left to
the discretion of the author.

Regards,

CME Terblanche

Cum Laude Language Practitioners (CC)

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