University of Alberta

Dry Cleaning of Coal by a Laboratory Continuous Air Dense Medium Fluidised Bed Separator

by

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Dedicated to my beloved "Ma" only…….

ABSTRACT

The laboratory continuous air dense medium fluidised bed separator was tested on the high ash coal of Genesee Mine and has proven to be an effective method for coal dry cleaning. The results show that we can get a yield of 80% with an ash content of 10%, which is a good achievement from the feed coal that generally has an ash content of 26%. The effect of air velocity, bed height, and time of fluidisation and comparison of different media were studied. The design of the continuous batch mode apparatus requires modification, so that better flow at the bottom end can be achieved. This will allow the higher specific gravity coal particles to move towards the discharge side.

ACKNOWLEDGEMENTS

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g	Gravitational acceleration force in m/sec^2
Ar	Archimedes number, dimensionless
A	Cross Section Area in m^2
L	Depth of the Bed in meter
ΔP	Pressure drop in N/m^2
P1	Pressure at point 1 in N/m^2
P2	Pressure at point 2 in N/m^2
SCFM	Standard Cubic Feet per Minute
S.G.	Specific Gravity
Vom	Minimum Fluidisation Velocity in m/sec
Vo	Approach Velocity in m/sec
W	Total weight of the medium solids in Kg
ε	bed voidage
ρ	bed density
ρ_s	density of solid in kg/m^3
ρ_f	density of fluid in kg/m^3
ρ_g	Gas density, kg/m^3
u_{mf}	Superficial gas velocity at minimum fluidisation conditions, cm/s
d_p	Geometric diameter based on screen analysis, μm
g	Acceleration of gravity, 9.81 m/s^2
ε_{mf}	Void fraction at minimum fluidizing conditions, dimensionless

ϕ_s	Sphericity of a particle, dimensionless
μ	Viscosity of gas, kg/m·s
μ_{mb}	Minimum Bubbling Velocity in m/sec
$Re_{p,mf}$	Reynolds number of particles at minimum fluidizing conditions, dimensionless

CHAPTER 1 INTRODUCTION

Coal is a solid fossil fuel and is known as a non-renewable energy source. It is second only to oil in meeting the world's total energy demands today. Coal is originally a carbon rich mineral deposit which has varied quality depending on its occurrences and composition. Coal was formed when organic plants decayed under prolonged geological compression and environmental conditions (Dave et al, 2010). It was the source of the Industrial Revolution in the 1800s and now, as shown in Figure 1, it is meeting more than 25% of the world's total energy requirements. It is not only the source of electricity generation, but also provides energy for cement and steel production around the world.

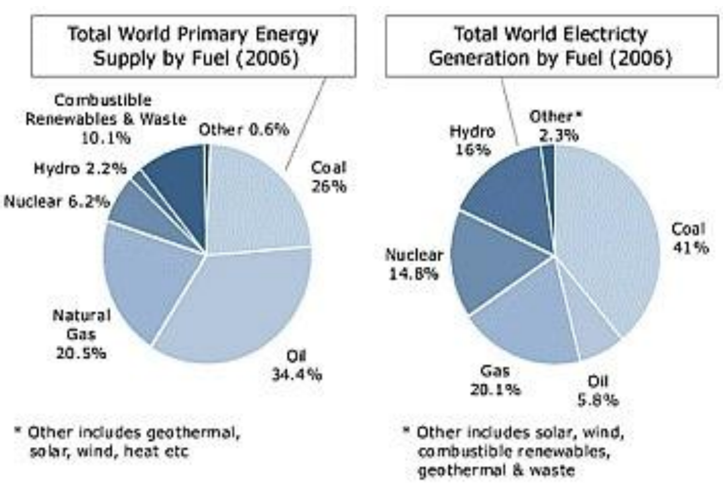


Figure 1. World fuel consumption outlook and electricity generation
(Coal Stat.-World coal Inst. www.worldcoal.org/resources/coal-statistics)

Being such an important source of energy, coal was also criticized by the scientists as a major source of greenhouse gases and toxic metal pollution of the environment. In the process of generating electricity, coal-fired power plants emit greenhouse gases such as Carbon Dioxide (CO_2), Methane (CH_4) and Carbon Monoxide (CO) into the environment. At the same time, power plants also release process water contaminated with non-biodegradable toxic metals, such as mercury, arsenic and selenium (Choung, J et al, 2006). Negligence and lack of strict laws resulted in coal combustion becoming the major source of pollution.

Major environmental impacts caused by the industrial use of coal are listed below.

- Acid drainage
- Greenhouse gases
- Nuisance dust generation
- Release of heavy metals into water etc.

Due to its environmental effects and implementation of new stringent rules, industries started looking for alternate sources of energy, including solar, nuclear, wind and/or biomass. Such alternate energies have shown promises, but heavy installation and maintenance costs have prevented many industries from implementing the technologies, thus necessitating the need to produce environmentally-friendly coal. This is also known as “the clean coal”.

Clean coal technology (or as it is sometimes called, green coal) is the term used to describe the technologies used to generate energy without influencing the environment. The present-day clean coal technologies focus on reduced emissions of CO_2 and other harmful greenhouse gases while burning the coal, as well as removing harmful heavy minerals before the coal is used in the power plant. The wet coal cleaning methods have been practiced since last century by using techniques like floatation and dense media separation. However the paucity of freshwater in recent years and environmental impacts of the effluent treatment from these wet processes have led to more research in dry coal cleaning.

Dry coal cleaning has been practiced in two ways: one is to remove the high mineral matter content bearing low rank coal before it is fed into the power plant and the other method is carbon capture and gasification technology. The first technique uses various physical parameters like shape, size, gravity, color, and magnetic properties etc. to identify various heavy mineral-bearing coal and remove them before the coal is fed to a fuel source in the power plant, while the second method uses chemicals to remove harmful gases like CO, CO_2 and SO_2 before they are emitted into the environment.

1.1 *Coal Cleaning and Importance of Dry Cleaning:*

The objective of coal cleaning is to separate its ash-forming mineral matter from solid hydrocarbons, which then improves the coal's combustion efficiency. In addition to this, coal cleaning also reduces materials handling and boiler maintenance and associated downtime production loss. The emission of harmful gases and traces of heavy metals increases the importance of coal cleaning. The impurities in coal have been widely divided into two main groups: sulphur-containing minerals and other ash-forming mineral matters (Sahan and Kozanoglu, 1997). The organic sulphur is part of the solid hydrocarbons and cannot be removed by physical methods. The inorganic sulphur, however, can be reduced by coal cleaning (Sahan and Kozanoglu, 1997).

The industries, since the 1920s, have used both dry and wet coal cleaning methods for removal of the ash-forming mineral matter, thus increasing the quality of coal to the boilers. The wet cleaning methods are more popular as they can achieve higher levels of mineral matter rejection, if properly liberated at relatively small particle sizes. Methods such as heavy media cyclone, jigs and floatation have been in use at commercial scales. However, some challenges do exist with wet cleaning. The notable challenges are the source of water as the separation medium for certain regions, water pollution and dewatering of the clean coal products before transportation, which incurs thermal energy needs and leads to the release of more greenhouse gases (GHG) (Sahan and Kozanoglu,1997). The density-based dry separation processes, on the other hand, lead to less transportation, handling and storage cost, and are feasible in areas where water is scarce. The dry separation also eliminates the need for dewatering and drying, saving energy costs and reducing greenhouse gases (GHG) emissions. For certain types of low rank coals, sliming of waste rocks/silts makes wet processing impossible. The sliming of rocks in Alberta sub-bituminous coal is clearly seen in the photo shown in Figure 2. This kind of low rank coal has shown a quick reaction with water and which makes them difficult to process with wet washing. In this case, dry cleaning of coal proved more advantageous.

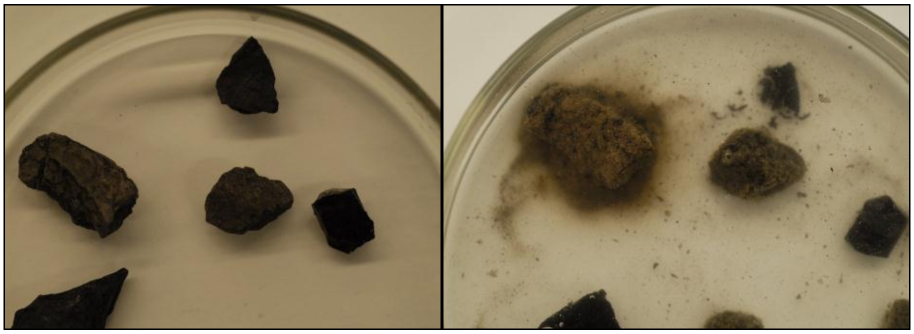


Figure 2. Sliming of Alberta sub-bituminous coal (Dave et al, 2010)

There has been a lot of discussion around the pros and cons of dry vs. wet processing. The following major advantages and disadvantages of density-based dry coal cleaning have been summarized by Jim Donnelly (Donnelly, 1999) and Houwelingen et al (Houwelingen et al, 2004).

Advantages:

- No harmful environmental impact on water as well as economically feasible, as it does not require expensive effluent water treatment plant and reagents
- Does not require expensive dewatering and drying processes and easy for storage and transportation
- Lower overall cost and higher yield
- Very much advantageous in dry areas or areas where there are harsh winters

Disadvantages:

- Less efficient for finer sizes
- Dust generation is a problem
- Feed moisture reduces the separation performance

In this research, the continuous mode air dense medium fluidised bed separator (ADMFB) was compared with the batch mode separator used by Mak (Mak, 2007) to clean the sub-bituminous Alberta coal. The work done by Mak was assumed as our base for this research and some of those proven parameters (e.g. bed height, air velocity, medium size distribution) was evaluated to run the continuous separator (ADMFB). Initially the continuous mode ADMFB separator was evaluated with sand as a medium, and feeding coal and sand mixture into one end and discharging from the other end. The discharge end has three separate openings, which can be controlled by increasing or decreasing their individual screw threads. Mak (Mak, 2007) achieved successful separation at different levels for her batch separator, using magnetite as the medium. The scope of this thesis is to evaluate the continuous mode ADMFB separator by using the same kind of separation principles, but with sand as a medium.

The initial evaluation for the continuous mode ADMFB separator has been done by allowing running it continuously but due to design constraints and lack of a proper mechanism for heavy coal removal, it was decided to use the continuous mode separator as a batch separator by utilizing only one cell. The continuous ADMFB separator when used as a batch separator with sand as a medium has shown successful separation for the EPCOR, E35 coal with 1.0-5.66 mm size fraction, which has been the best accomplishment of this research. Both the separators (batch and continuous mode with single cell) were evaluated on various parameters like fluidisation velocity, coal size, coal percentage loading and time of fluidisation and determined that the continuous mode ADMFB separator is more efficient in coal cleaning than the batch separator when operated as a single cell. The author recommended design modification to run the continuous mode air dense medium fluidised bed separator effectively.

CHAPTER 2 LITERATURE REVIEW

Fluidisation is a process in which solid particles are transformed into a liquid-like state through suspension in a gas or liquid. There are many various forms of this liquid-like state, from minimum fluidisation to lean phase fluidisation with pneumatic transport (Kunii & Levenspiel, 1991). In today's world, fluidisation principles are applied in various industries such as coal gasification, solids drying, material transportation, coal de-volatilisation, coating metal objects with plastic, catalytic synthesis and fluidised combustion of coal (Mak, 2007).

2.1 *The Fluidisation behaviour*

Fluidisation can be explained as a phenomenon in which a solid gets suspended and achieves a fluid-like state by passing gas or liquid in an upward motion. The various fluidisation conditions are explained in the following Figure 3 (Kunii & Levenspiel, 1991).

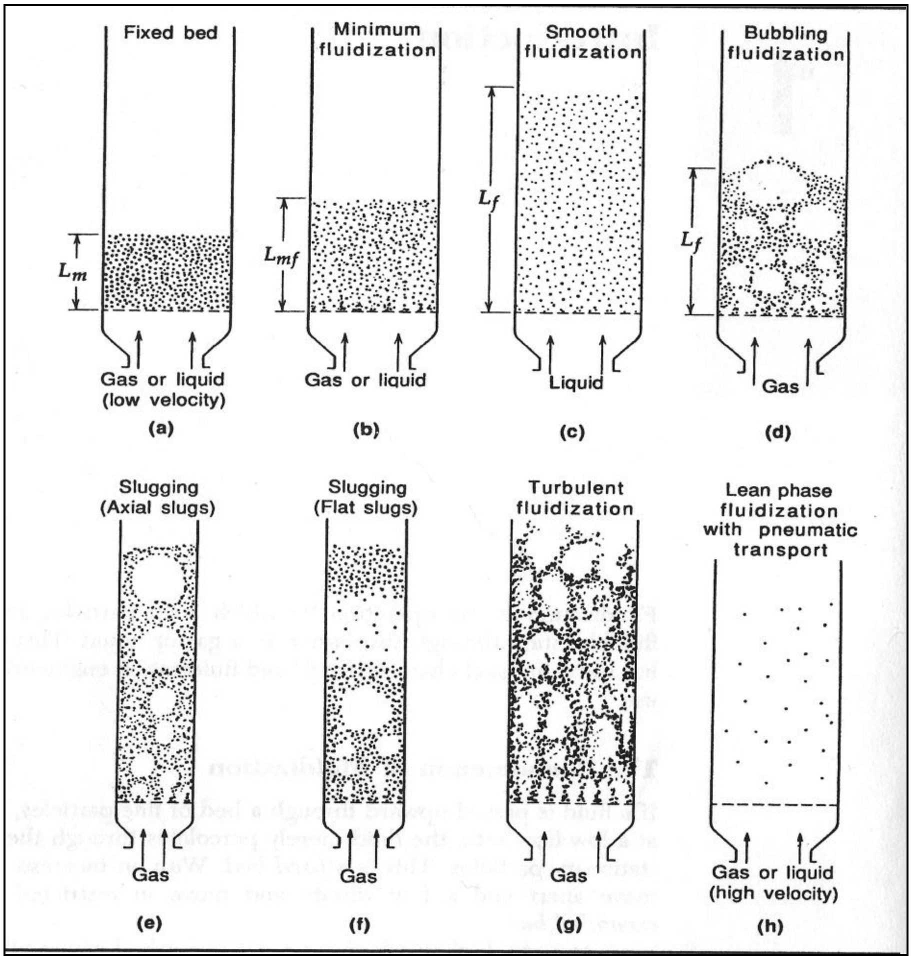


Figure 3. Various form of Fluidisation (Kunii & Levenspiel, 1991)

As shown in Figure 3, when fluid (gas or liquid) was initially introduced in an upward direction, the particles resisted the flow and barely allowed the fluid to pass through, which is called “Fixed bed”. When the velocity is very low, the particles just allow the fluid to pass through or create vibration in their restricted region, which is called expanded bed. As the increase in velocity occur, a point is reached where all the particles are suspended in the air by the upward flow of gas and the gravitational force of particles are counterbalanced by the drag force of the velocity of the fluid. This situation or state of solid bed is called the bed at minimum fluidisation. As further increase made in the gas velocity, the behaviour varies for the liquid-solid bed and gas-solid bed. In this context, a gas-solid bed has been considered and the bed behaves differently here. Channelling and agitation is observed through the bed. The higher flow-rate increases the bubbling inside the bed; this type of bed is called a bubbling bed. The increase in flow-rate changes the state of the solid bed to a sluggish bed and the worst condition is turbulent fluidisation where one can observe violent momentum in the solid particles.

The fluidisation characteristics of most fine particle systems are summarized in a standard pattern as shown in Figure 4.

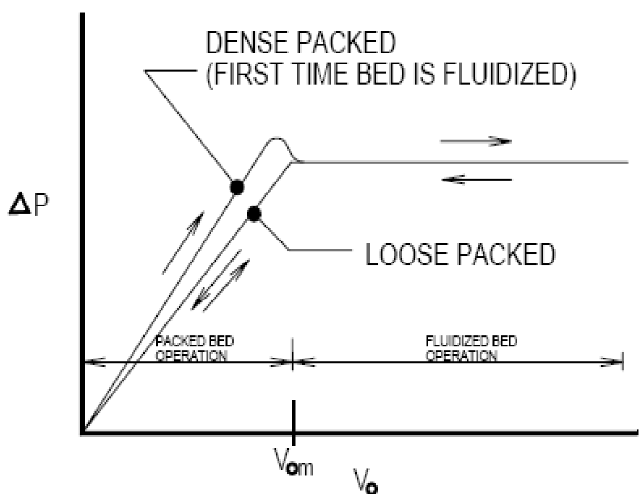


Figure 4. Standard patterns of solids fluidisation (Chase, 2004)

As shown above in Figure 4, pressure drop versus velocity diagram describes the standard pattern of fluidisation behaviour of the packed bed and pressure drop across the cylinder. For the initial low velocity rate (less than V_{om}), the pressure drop is approximately proportional to the gas velocity. The first time, when the bed is packed, the pressure drop is slightly higher than the actual static pressure drop due to interparticle cohesion, as shown in the above Figure, at the junction point of the packed and fluidised bed. After this point, as the bed expands and voidage increases, the pressure drop remains insensitive to the increase in velocity (V_o). When the velocity of the gas decreases, the fluidised particles settle down into a loosely packed state with some voidage in between them.

Coal beneficiation using an air-dense medium fluidised bed (ADMFB) relies on the pseudo-fluid character of the medium to develop a stable gas-solid suspension of a particular bulk density. The fluidisation starts at the point V_{om}, as shown in Figure 4. The mean density of suspended solids (fluidised bed) can be calculated using Equations 1 & 2 (Honaker, 2007).

$$\rho = (1-\varepsilon) \times \rho_s + \varepsilon \times \rho_f = W/ (L \times A \times g) \tag{1}$$

and as $\rho_s >>> \rho_f$, Equation 1 can be simplified as

$$\rho = (1- \varepsilon) \times \rho_s = W/ (L \times A \times g) \tag{2}$$

Where:

A= Cross Section Area in m^2
g= Gravitational acceleration force in m/s^2
L= Depth of the bed in m
W=Total weight of the medium solids in kg
ε = bed voidage
ρ = bed density in kg/m^3
ρ_s = density of solid in kg/m^3
ρ_f = density of fluid in kg/m^3

Hence, it could be determined from the above equations that the medium solid density and void fraction are playing important roles in defining the bed density. In addition, the bed void fraction depends on the size distribution, shape and gas velocity (Luo et al, 2007). The choice of medium, particles size distribution of medium and optimum gas velocity plays an important role in creating a stable and uniform bed density. This is very important, as the bed will otherwise behave erratically. In addition, having more than one density than the stratification is not ideal and separation may not perform very well.

As it shown in Figure 5(a), the fluidised bed behaves similarly to a liquid after the fluidisation; it looks like a boiling liquid and exhibits liquid-like behaviour. The pseudo-fluid characteristic of the gas-solid bed after the fluidisation is illustrated by the fact that even if the container is at an angle, the surface of the bed is horizontal, as shown in Figure 5(b).

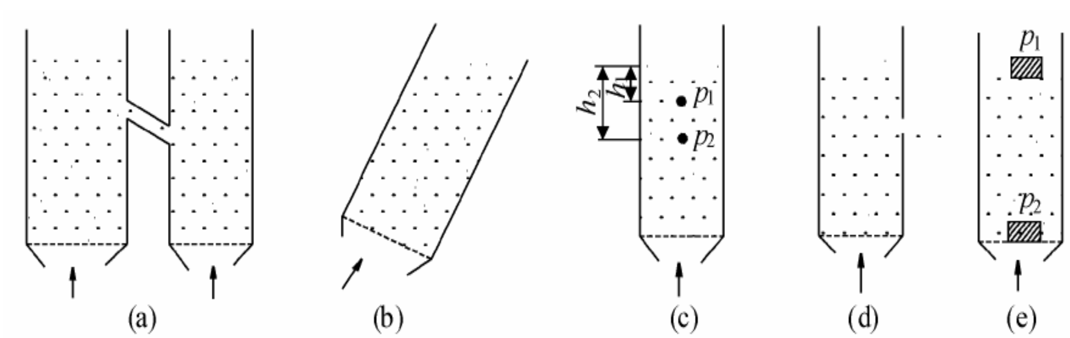


Figure 5. Liquid-like behavior of gas-solid bed after fluidisation (Zhen-fu et al, 2007)

As shown above in Figure 5(c), the pressure drop at any two points in a fluidised bed is the difference between their hydrostatic heads and is given by the Equation 3 (Dwari, 2007 and Zhen-fu et al. 2007)

$$\Delta P = P_1 - P_2 = (h_1 - h_2) \times \rho \qquad (3)$$

Where:
ΔP = Pressure drop in N/m^2
P1 = Pressure at point 1 in N/m^2
P2 = Pressure at point 2 in N/m^2

h_1 = Height of point 1 in m
h_2 = Height of point 2 in m
ρ = Density in Kg/m^3

As shown in Figure 5(d), the material will spray out in the way as the water, which also indicates the fluid-like behaviour of the gas-solid fluidised bed (Zhen-fu et al, 2007). The fluidised gas solid bed also observes Archimedes' law by allowing the heavier particles, whose relative density is higher than the bed, to sink, and at the same time, float the lighter particles with relative density lower than the bed density. This is shown above in the Figure 5(e) (Zhen-fu et al, 2007).

The fluidisation state occurs when all the particles are suspended by the means of upward flowing gas and the drag force from the upward moving gas is counterbalanced by the weight of the particles. This is called the minimum fluidisation velocity (u_{mf}) and Kunii and Levenspiel (1991) provided a formula for estimating the minimum fluidisation velocity (u_{mf}), shown in Equation 4 (Kunii & Levenspiel, 1991).

$$u_{mf} = \frac{d_p^2(\rho_s - \rho_g)g}{150\mu} \frac{\varepsilon_{mf}^3 \phi_s^2}{1-\varepsilon_{mf}}, \quad \mathrm{Re}_{p,mf} < 20 \tag{4}$$

Where $R_{e\ p,mf}$ is given by the following equation

$$\mathrm{Re}_{p,mf} = [(33.7)^2 + 0.0408Ar]^{1/2} - 33.7 \tag{5}$$

$$Ar = [d_p^3 \times \rho_g \times (\rho_s - \rho_g)g]/\mu^2 \tag{6}$$

Where:

Ar	Archimedes number, dimensionless
u_{mf}	Superficial gas velocity at minimum fluidisation conditions, cm/s
d_p	Geometric diameter based on screen analysis, m
ρ_s	Solid density, kg/m^3
ρ_g	Gas density, kg/m^3

g	Acceleration of gravity, 9.81 m/s^2
ε_{mf}	Void fraction at minimum fluidizing conditions, dimensionless
ϕ_s	Sphericity of a particle, dimensionless
μ	Viscosity of gas, kg/m·s
$Re_{p,mf}$	Reynolds number of particles at minimum fluidizing conditions, dimensionless

The minimum fluidisation velocity calculated using the above equation should be the minimum velocity at which a good density-based separation of the material could be observed. This minimum fluidisation velocity is lower than the minimum bubbling velocity where bubbles start to flow in the solid bed.

The following advantages and disadvantages of the fluidised bed are given by George Chase (Chase, 2004).

Advantages:

- Better control and automation due to its liquid nature
- Quick mixing and better uniform temperature control
- Can control rapid thermal expansion or contraction
- Better heat and mass transfer capability

Disadvantages:

- Fine particle back-mixing
- Erosion by solid particles impact
- Bubbling beds are very difficult to predict

In 1973, Geldart studied the characteristics of the different types of medium and, based on their densities and sizes, classified the medium into four different categories and developed the Geldart fluidisation chart, as shown in Figure 6.

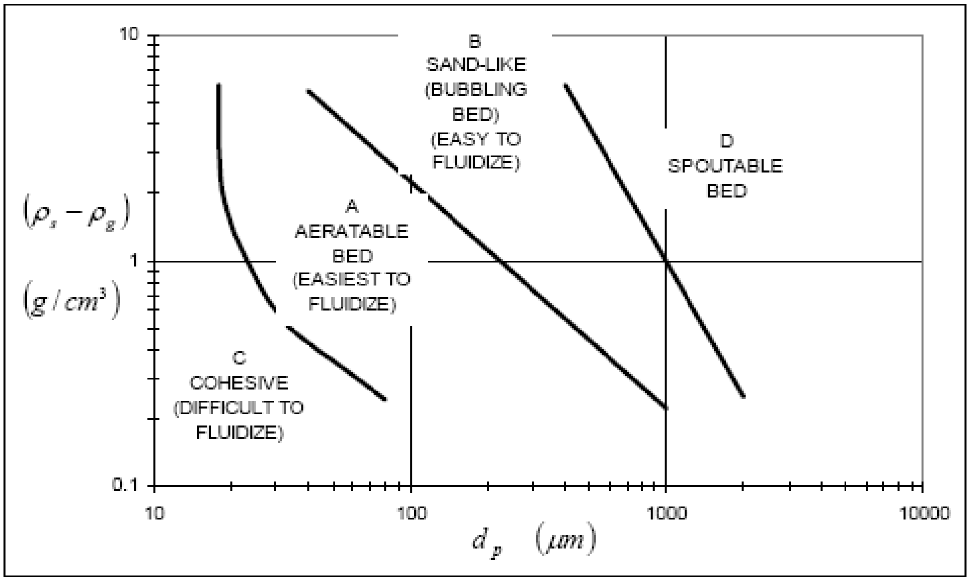


Figure 6. **Types of Gas Fluidisation (Geldart, 1973)**

Geldart has characterised different medium particles into four groups based on their behaviour (Kunii and Levenspiel, 1991). These groups are:

1. Group C: These types of particles are very cohesive and very fine in size. Due to greater inter-particle forces, fluidisation of this group of particles is extremely difficult. The cosmetic powder, flour and starch are typical example of this kind of solid.
2. Group A: The particles in this group have very low mean particle diameters and low densities (<~1.4 g/cm^3). They are easily fluidised and create aeratable beds. The examples of this type of solid are face centred cubic catalyst particles.
3. Group B: This group represents sand type of particles and the main characteristic of this group is that most particles are of size 40 μm<d_p<

500 μm and density $1.4<\rho_s< 4$ g/cm^3. They are easily fluidised and show controlled bubbling action for stratification with growing bubbles.

4. Group D: This group contains large and/or dense particles, as can be seen in Figure 6. In this group of particles, fluidisation is difficult and channelling is frequent. In food industries like vegetable drying, bean roasting and coal gasification are typical examples of this group.

The evolution of the density based dry separator was compiled by Jong and it is shown in the Figure 7.

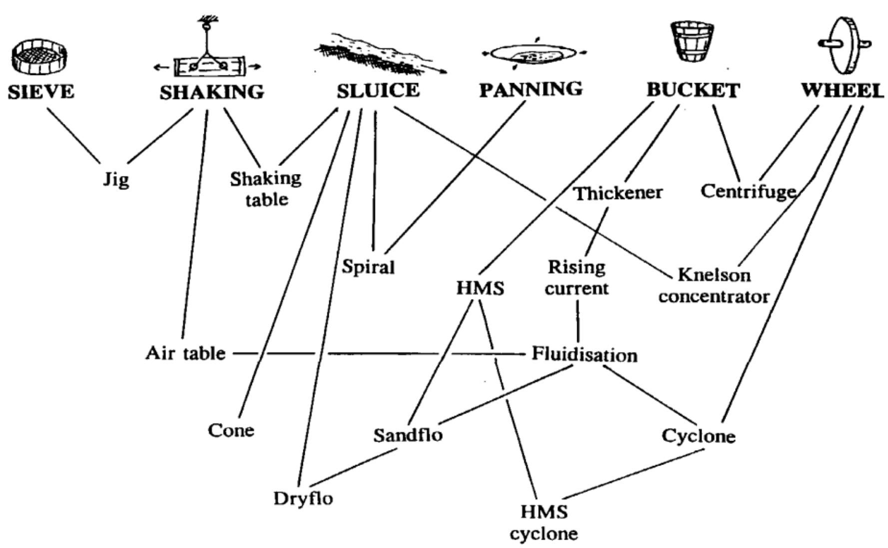


Figure 7. Development of Density Separators (Jong, 1999)

In 1926, Fraser and Yancy (Fraser, 1926) invented a separator to part the coal in float and sink sections with river sand of bulk density 1.45 gm/cm^3 as a medium. Since then, various attempts have been made to beneficiate the coal including the successful commercial unit for processing 50 tph of coal in China in

1994 to process 50 to 6 mm size coal (Chen, 2003). Some of the main problems associated with separation of fine particle by fluidisation were particle-particle and particle-wall cohesive forces, segregation in medium particle, size and density difference, as well as back-mixing and packing ratio (Mak, 2007). The cohesive forces between wall and particles can be reduced by applying different linings while an intra-particles force creates friction and grinding due to attrition that lead to segregation in size and density difference. In addition to that, various types of bubble properties, and correct amount of bubbling velocity are also having significant effect on the fluidisation separation efficiency (Mak, 2007).

The gas passes upwards through the porous plate and then through the layer of medium particle where it creates a fluidised bed. The drag force of the upward flow is counterbalanced by the gravitational force of the particle and the whole bed becomes a fluidised bed with a certain specific gravity. The fresh feed from the top passing downward interact with the air bubbles and due to pseudo-fluid structure of the bed, the particles heavier than the density of the bed settle down to the bottom and the particles which are lighter than the bed density float to the top from where they can be removed by different means.

2.2 *ADMFB and its use for coal cleaning*

Dry separation of coal has been known since the 16th Century (Houwelingen, 2004). Various types of dry separation methods are summarized in Table 1. The most commonly-used dry separation methods are based on the properties like buoyancy, density, fluidisation, film flow and oscillation. The density and magnetic properties of the medium have been considered the main parameters of dense medium-based dry separation in the present industry (Dave et al. 2010).

Characteristics	Process
Appearance/Color	Sorting
Coefficient of Friction	None direct
Size and/or Shape	Screening
Friability/Elasticity	Rotary breaker and differential crushing
Density	Pneumatic separation and fluidised bed separation
Magnetic susceptibility	Magnetic separation
Electrical resistivity	Electrostatic separation
Radioactivity	Sorting

Table 1 Dry Separation techniques (Dwari & Rao, 2007)

The dry beneficiation process needs to be efficient and economical to compete with wet cleaning methods. Dry coal cleaning with an Air dense medium fluidised bed has been proven an efficient and economical coal beneficiation method. This method, based on density differences between solid hydrocarbons and mineral matters with the density of fluidizing medium falling in-between, was first employed by Fraser and Yancey in 1926 (Houwelingen, 2004). They used sand with a bulk density of 1.45 gm/cm^3 as a medium and separated the good coal (light) as float and coal with mineral matters (heavy) as sink rejects. The researchers at Warren Spring Lab had developed an inclined bed separator that consists of an inclined vibrating trough with a porous base which can stratify clean coal with excess sand at the weir side while sinking particles can be transported to the opposite end by vibration (Houwelingen, 2004). In this process, the ADMFB separator utilises air and specialised medium particle to create a bed of specific density which allows the heavier coal to sink while lighter coal to float in the overflow. The air creates a pseudo-fluid bed where the solid particles behave as a liquid and separate the heavy and light coal based on their density.

The main objective of this study is to utilise principle of fluidisation and evaluate the performance of a laboratory continuous ADMFB separator in separating the Alberta sub-bituminous coal.

CHAPTER 3 EXPERIMENTAL SETUP AND MATERIAL SELECTION

3.1 *Materials selection*

3.1.1 Media particles selection

Sand: Glass sand is used in this study as one of the media which was brought from SIL Industrial minerals, Canada. The sand is having the median particle size of 262 micron and a bulk density of 2.65 g/cm^3.

Magnetic Media: The magnetic particles used for the initial testing (to compare with batch model) were brought from Ward's Natural Science Establishment in Utah, USA. It was available in the lab. The magnetite is having the median particle size of 208 micron and a bulk density of 3.3 g/cm^3.

3.1.2 Test Material (Coal)

The coal samples were collected from the EPCOR mines near Genesee, Alberta, Canada. The Sub-bituminous coal samples were marked as Seam 1, 2 and 3.Seam 2 coal was mainly used including E35 coal samples for this study. The coal samples were crushed and dried in ambient temperature and then stored at ambient temperature. A lab scale Jaw crusher was used to reduce the coal samples to less than 22 mm. These coal samples were then classified into three fractions using Ro-Tap sieve shaker and a stack of different sieves ranging from 1 mm to 22 mm: 22.6x5.66 mm, 5.66x3.36 mm and 3.36x1.00 mm. The same procedure was followed for the E35 coal, but we classified it into 1mm to 5.66 mm size. The following table shows the main characteristics of the E35 coal.

Moisture	Volatile Matter	Ash	Fixed carbon
7.2	34.8	25.7	32.4

Table 2 Proximate analysis of coal used in this study, all in weight percent (Dave et al, 2010)

3.2 *Experimental setup:*

3.2.1 Operational Setup:

This study was designed to compare two different setups. They are: Batch mode and Continuous mode. The air dense medium fluidised bed (ADMFB) system used in this research study is shown schematically in Figures 8 and 9.

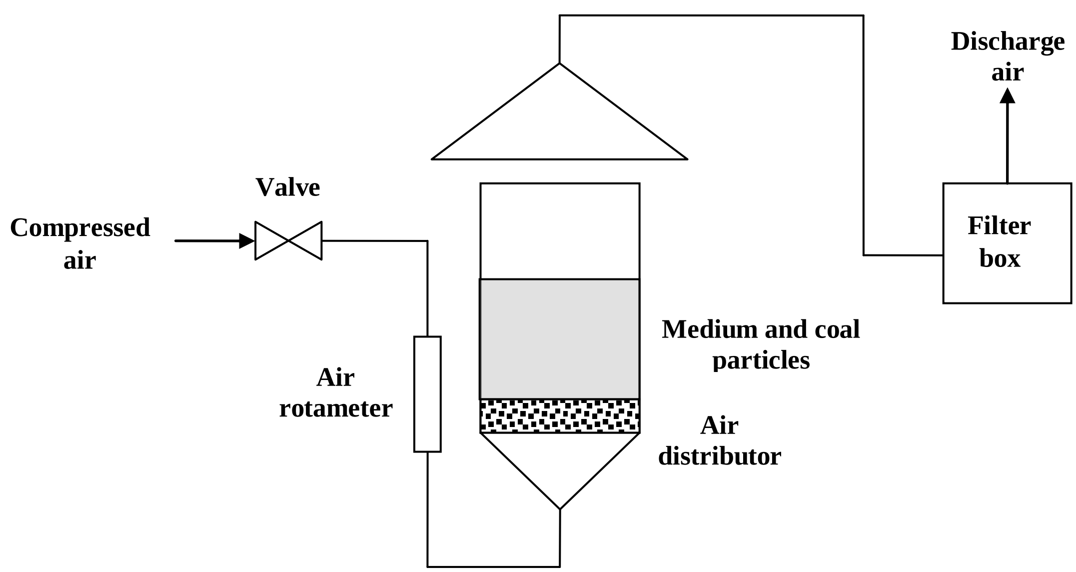


Figure 8. Schematics for the Batch mode Air Dense Medium Fluidised Separator (Zheng et al, 2007)

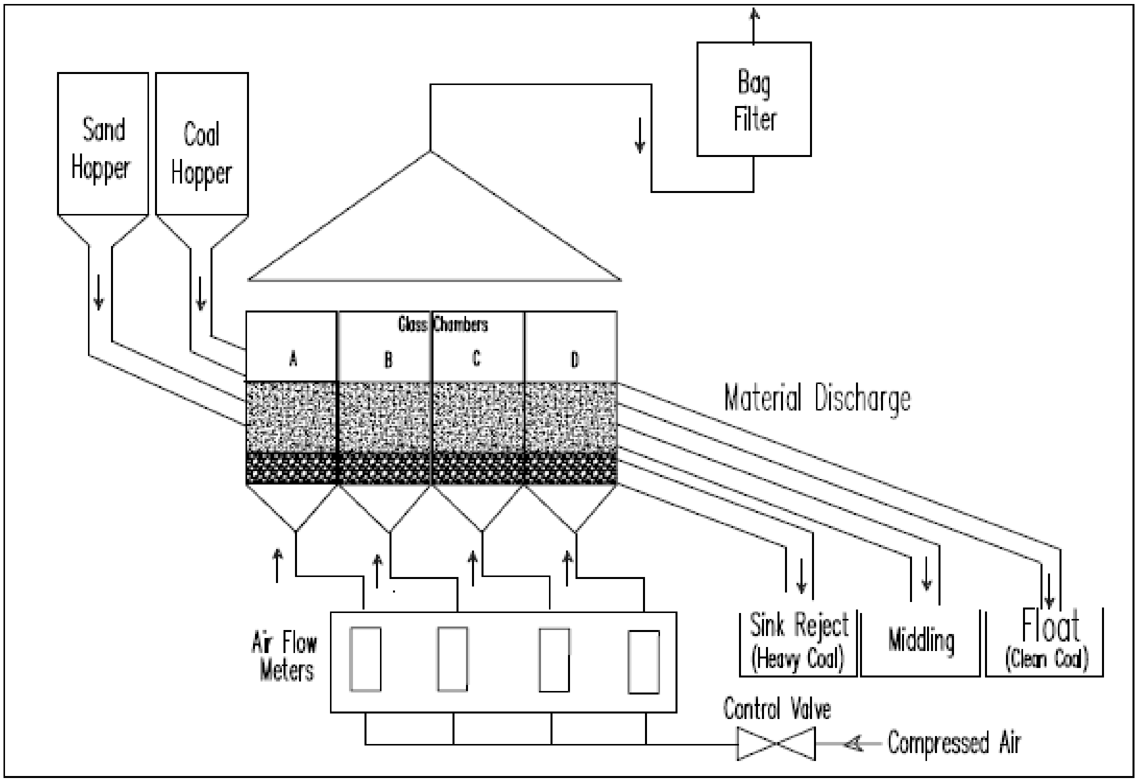


Figure 9. **Schematics of the Continuous mode Air Dense Medium Fluidised Bed Separator (Dave et al, 2010)**

For the initial batch mode ADMFB experiments, a 20 cm diameter Plexiglas separator with an air distributor at the bottom was used, as shown in Figure 8. The height of the cylinder is 40 cm tall and the air distributor is a 0.3 cm thick metallic porous plate with an overall average pore size of 40 µm. The medium bed height in the separator is measured by the metric ruler at a precision of 0.1 cm. The bottom of the separator is connected with the air pipe and the airflow is measured through the Blue-White air rotameter and controlled by the valve as shown in Figure 8. A Nederman's Filter Box (Helsingborg, Sweden) was used to collect the trapped particles and the filtered air is discharged into the atmosphere.

For the continuous mode ADMFB separation experiments, a rectangular Plexiglas cell with four equal cells inside (98 mm×240 mm), as shown in Figure 9 was used. The nearest separator cell from the discharge point which is called “A” and the subsequent cells are called “B", “C" and “D". They have a common porous plate attached to them at the bottom and are of the same size as the separator with 0.3 cm thickness and 40 micron average diameter pores. The air pipe is connected to each separator cell separately and measured by rotameter and controlled by a valve. The discharge end has one sliding gate and two discharge chutes for float material and one bottom chute for sink materials. The sink and float materials are collected in separate buckets. The trapped particles are collected through the Nederman’s Filter box and the filtered air is discharged into the atmosphere. Each separator can be isolated and operated individually by placing it in a barrier.

3.2.2 Experiment procedure

***Batch mode and continuous mode with one cell*:**

Batch mode refers to the apparatus used in Mak’s (Mak,2007) experiments while continuous mode with one cell refers to the continuous mode separator with only one cell working and separated from the rest of the cells with a plate (no horizontal movement).

In this experiment, the medium particles were placed in the separator at a certain height (15.6 cm) after turning the dust collector “ON”. The air flow was measured by the rotameter and controlled by the valve as needed. The air was controlled at a level suitable to fluidise the medium bed at their minimum fluidisation level and set at that level. The uplifting air fluidised the medium particle and made it behave like a pseudo-liquid. The weighed dry coal sample was then added from the top of the separator into the fluidised bed and allowed them to separate for one minute.

The air was shut off immediately after one minute of fluidisation, which allowed the total bed to settle down in a packed state. The height of the bed was then divided into two portions of float (top to 1cm above the porous plate) and sink (<1 cm to bottom). The mixed material was then taken out separately by a scoop and screened through a 1 mm sieve to separate the sand (medium) particles from the coal particles. The remaining coal in both the sections (i.e. float and sink) was then weighed and recorded and the ash analysis was performed on it.

***Continuous mode*:**

In this experiment, the sand was first fed from the hopper at feed end with the gates closed and allows it to reach the bed height of 15.6 cms. Once the bed reaches at the required height the air was introduced at their minimum fluidisation level and the gates at discharge end opened. The air velocity was controlled from the bottom by rotameter in each cell separately. The height of the bed was maintained at the 15.6 cms. The coal sample was then added immediately from the top at cell “A” and sand plus coal samples were allowed to discharge from the three sections at the discharge side and collected in three separate bucket. After 1 minute of fluidisation, the air was shut off and the discharge gates closed at the same time. The coal and sand mixture was then collected with the scoop above 3cms, 2-3 cms and less than 2 cms bed height from each cells and named separately. The greater than 3 cms are considered as float samples. While the material from 2-3 cms section is considered as middling and less than 2 cm bed height was considered as Sink and collected separately. The mixture was then screened to separate coal from sand and then coal samples were analysed for ashing.

3.3 *Procedure for Analyses*

3.3.1 Particle size distribution determination

The particle size distribution was performed by stacking the U. S. standard brass sieves purchased from Fisher Scientific Canada. The crushed coal sample was first put in the weigh scale and the measured coal was then placed in the sieve stack. The W. S. Tyler’s Ro-Tap sieve shaker was used in the sieve analysis and sieving time was fixed at 15 minutes. The sieve sizes depended on the top and bottom sizes of the sample as well as the experiments to be performed. The retained coal particles on each sieve was then calculated and documented as cumulative weights.

3.3.2 Density determination

The density of the medium particle used for the fluidisation experiment was determined by the Gay-Lussac specific gravity bottles (50 ml) purchased from Fisher Scientific Canada. The bottle was dried and weighed (with cap) before each experiment and the weights were documented. After this, a measured amount of medium particles was poured into the bottle and mixed with water of a known density (with respect to water temperature). Air was then sucked up by the vacuum pump connected to the bottle to remove entrained air in the sample/water mixture. The bottle cap was then inserted onto the bottle and the outer surface was dried and the weight was taken. The specific gravity of the medium particles was calculated using the above weights and volume.

3.3.3 Ash Analysis

The ASTM Method D 3174: Standard Practice for Proximate Analysis of Coal and Coke was followed to perform the ash analysis of the sample. The coal sample from the float and sink section of each experiment was pulverized by a Brinkmann-Retsch pulverizer to the size required for ash analysis. The porcelain crucibles (17 ml in size) bought from Fischer Scientific was dried in the oven before each analysis. The crucibles were weighed before and after placing the coal sample, using a Denver Instrument analytical balance with 0.1 mg precision. The coal samples with the crucibles were dried for 4 hours in desiccators before being placed in the Barstead-Thermolyne furnace at 750°C for 3 hours. The coal samples were then placed in the desiccators again after removing them from the furnace. The coal samples with crucibles were weighed before and after placing them into the desiccators. The ASTM standard was used to calculate the ash content.

3.3.4 Float-sink test

The ASTM Method D 4371-91 for determining the Washability Characteristics of Coal was followed to perform the float-sink test. Toluene, dibromomethane and/or tetrachloroethylene were used to prepare various liquid media, ranging from a specific gravity of 1.3 to 1.9. A hydrometer was used to test the specific gravity of the prepared liquid. Initially, a coal sample of the preferred size (i.e. 5.66 mm × 22.6 mm) was placed into the liquid medium and allowed to settle down for 3 minutes. The coal which floated to the top was removed using a strainer with an opening of 1.00 mm. The fine size coal (< 3.36 mm), the floating particles were filtered to remove the liquid form the material. The rest of the settled particles were then filtered and placed into the next higher specific gravity liquid. This process was continued until the majority of the coal particles floated. The weight of each sample particle was then measured after each pass and documented.

CHAPTER 4 EXPERIMENTS WITH ADMFB SEPARATOR CONTINUOUS MODE AND PARAMETER EVALUATION

In this research, separation characteristics of the continuous mode air dense medium fluidised bed (ADMFB) apparatus was studied with air and sand as a medium to separate coal from its heavy mineral matter. The study confirms the results obtained by the batch mode ADMFB apparatus and effects of various operating parameters were discussed. The study was also done to evaluate the optimal level of the operating parameters and find out the best method to separate a run of mine coal from clean coal.

In this study, a batch and continuous mode separator was used to evaluate the best method to beneficiate coal processing. Like the previous study done by Mak (Mak, 2007), coal sample from the Genesis Mine run by EPCOR was used. The samples were crushed and screened to the following sizes:

1) 1.00 - 3.36 mm
2) 3.36 - 5.66 mm
3) 5.66 - 22.60 mm

The continuous mode separator was evaluated with various fluidisation velocities, different feed locations and volume loading. The separation efficiency of the separator was calculated based on the proximate distance of the ash analysis curve to the float sink curve for every test performed. Figure 10 shows the float sink curve for seam 2 coal of various feed size.

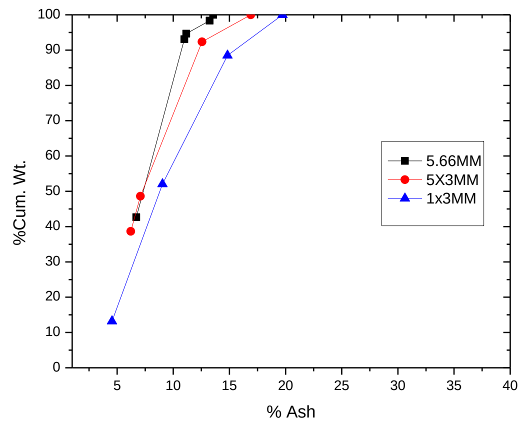


Figure 10. Float sink analysis for various size of Seam 2 coal

The float sink curve represents the true washability characteristic of the consecutive fractions. As seen in the Figure 10, the float sink curve proves that the clean coal (lower ash content) lies in the lower density range from 1.2 to 1.5, while the coal with heavy minerals (higher ash content) lies in the higher density range from 1.7-1.9. This makes it very easy to separate them based on the gravity compared to other methods of coal cleaning. In this study, air was used to fluidise the sand and the sand behave like a pseudo-liquid with a particular specific gravity and allow the feed coal particles to separate into the float or sink area based on their gravity. Sand makes a consistent 1.56 specific gravity bed when fluidised and allowed the feed coal to separate efficiently based on their specific gravity at a finer cut. In addition to that, Geldart's chart of fluidisation classification proved that the coal is lying in the range of well fluidised to difficult to fluidise region (B and D) while sand lies in the region of easily fluidised (B) so sand can be an excellent medium.

4.1 *Experiments with Continuous mode apparatus and the problem associated with it:*

The continuous mode apparatus was set up for the continuous mode ADMFB experiments, as shown in Figure 9, Chapter 3.

As shown in Figure 9, the setup included a feed hopper, fluidisation apparatus and dust collector. The medium is being fed from the sand hopper and is collected from the discharge end after the four vertical cells. The discharge of the apparatus has three outputs at three different levels for the purpose of collecting the product at three different levels. The continuous mode setup was designed to continuously feed the sand and coal from the hopper and collect the separated material from the discharge end at three separate levels while keeping the bed fluidised constantly. The following analysis and discussion were based on the experiments we ran with our continuous mode separator and the unsuccessful attempt to separate the coal on a continuous basis.

Sand was chosen for its characteristics to separate finer coal, flowability properties and easy availability. The experiment was initiated with EPCOR seam 2 coal and the following three fractions were collected from the discharge end.

- Plus 3 cm (float)
- Minus 3 to plus 2 cm (middling)
- Minus 2 cm (sink)

Initially the experiment was started with 5.66×3.36 mm size fraction, as that coal fraction was very difficult to separate. Sand hopper was used to feed the sand into the apparatus and allowed it to fluidise for one minute by keeping the discharge gates closed. Once the sand was fluidised and bubbling was observed, the measured coal particles were introduced from the top of the first cell "A" from the feed end. At the same time, we also opened the discharge gate and fed the sand from the hopper at a rate to maintain the bed height. Once the sample got added to the bed, the sand was allowed to run continuously until the sand hopper gets empty.

Flow rate & Bed height: As mentioned in Mak's thesis, the experiments were started with flow rate from 5.88 SCFM and bed height of 15.6 cm.

4.1.1 Initial continuous mode experiments and their failure:

EPCOR seam 2 coal was used for the initial experiments. The characterisation is shown above for three different sizes. The initial experiments have shown the problems in the design of the apparatus that is getting the material constantly flowing with the sand at the discharge gates. When the discharge gate was sliding to open position, the sand was flowing very quickly and the bed height was very difficult to maintain due to hopper size. In addition, the heavier coal got stuck in the opening of the discharge gates as well as sank to the bottom of the cells without moving towards the discharge end. The continuous mode became the batch mode as collection of samples was done manually by using the scoop at the same height at the discharge gate opening and consider them as they were actually at that height during the continuous mode. The following effect of different parameters was studied under the above conditions.

4.1.1.1 Effect of output flow/ discharge:

As can be seen in the following diagram, the size separation characteristics of the apparatus with flow (Experiment A) and no flow (Experiment B) at the discharge end was compared. The separation characteristic is almost equal for both the conditions except the % yield in the top fraction (plus 3 cm) for Experiment A condition. The % ash reduction from the top fraction is almost insignificant for the Experiment A and middle fraction in Experiment B. The other difference is that in Experiment A (no flow), better % yield was observed compared to Experiment B. (i. e. 55% compared to 65%). The main problem observed was the flow of the heavy coal at the minus 2 fraction. The heavy coal particles were not able to get enough momentum and settled above the plate in the cells. The big chunks of 5.66×3.36 mm coal particles got stuck in the discharge opening and obstructed the flow of the sand.

The size analysis graphs obtained from the above experiment is shown below in Figure 11. The comparison of the experiment's size separation curve with float sink curve indicates that for Exp. A, there has been no collection from plus 3 cm fraction and very less amount of material from middle section (i.e. 2-3 cm section).

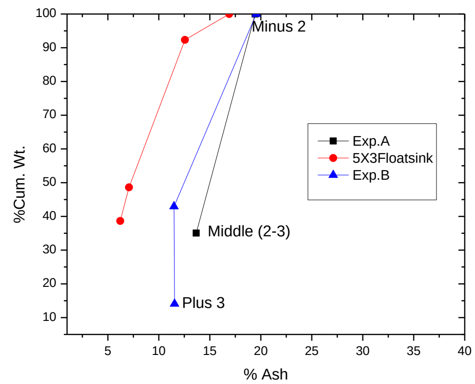


Figure 11. Effect of Discharge flow on Continuous Mode ADMFB Separator

It can be easily determined that the coal beneficiation was not observed in either experiment A or B. The proximity of their analysis curves are far away from the float sink curve for the related size. However, we have seen some stratification in both the experiments. This has indicated the effectiveness of the separator and the flaw in design in the continuous mode ADMFB separator for running it for a long time.

4.1.1.2 Effect of Size:

After the failure of the initial experiments, it was decided to test smaller sized coal (1×3.36 mm), as the larger-sized coal was getting stuck into the opening during the fluidisation and obstructing the flow out of the discharge gate. The problem observed during the experiment with smaller particles was that they were grounded into smaller fractions. It was found that almost approx. 8% of the feed sample was being lost during the experiment. The following is the separation analysis graph for the 1×3.36 mm size.

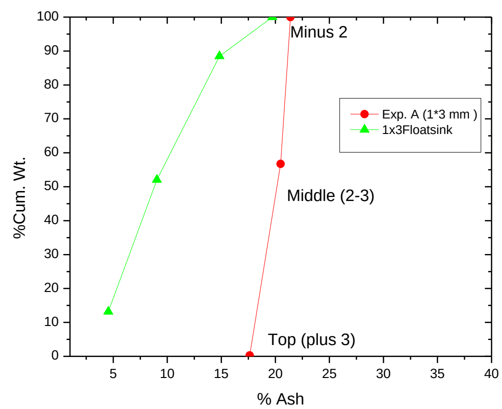


Figure 12. Effect of size on Continuous mode ADMFB Separator

It could be concluded from the above graph that, the size separation efficiency for the smaller 1×3.36 mm size is much less due to backflow and misplacement of the particles. This could be determined easily by comparing it with the 5.66×3.36 mm size separation curve in Figure 11, which shows very close proximity to their respective float sink curves.

After the unsuccessful attempts of the above experiments, several other experiments were attempted by changing the feed point to the second cell and changing the flow rate with this 1×3.36 mm coal, but for all of these experiments, the separation was not observed and it was following the same trending as shown in Figure 12. Due to change in feed location to the second cell and so on to the consecutive cells, the important observation made was the separation in the same cell as where the feed was introduced. The individual cell behaviour was found to be equal and the same separation was observed.

4.1.1.3 Effect of Feed location:

After the unsuccessful attempts to separate smaller-sized coal on the continuous mode ADMFB separator, it was decided to use plus 5.66 mm coal from the same EPCOR mine seam 2. For this experiment, the continuous mode ADMFB separator was divided in four individual cells and parted each cells into two equal height called A1, A2, B1, B2, C1, C2, D1 and D2 accordingly from the feed end, as shown in Figure 13. These 2 sections were only for the total bed height (i.e. 15.6 cm) and not the total height of the cell. The retention was also increased by decreasing the gap at the discharge end for the coal and sand particles.

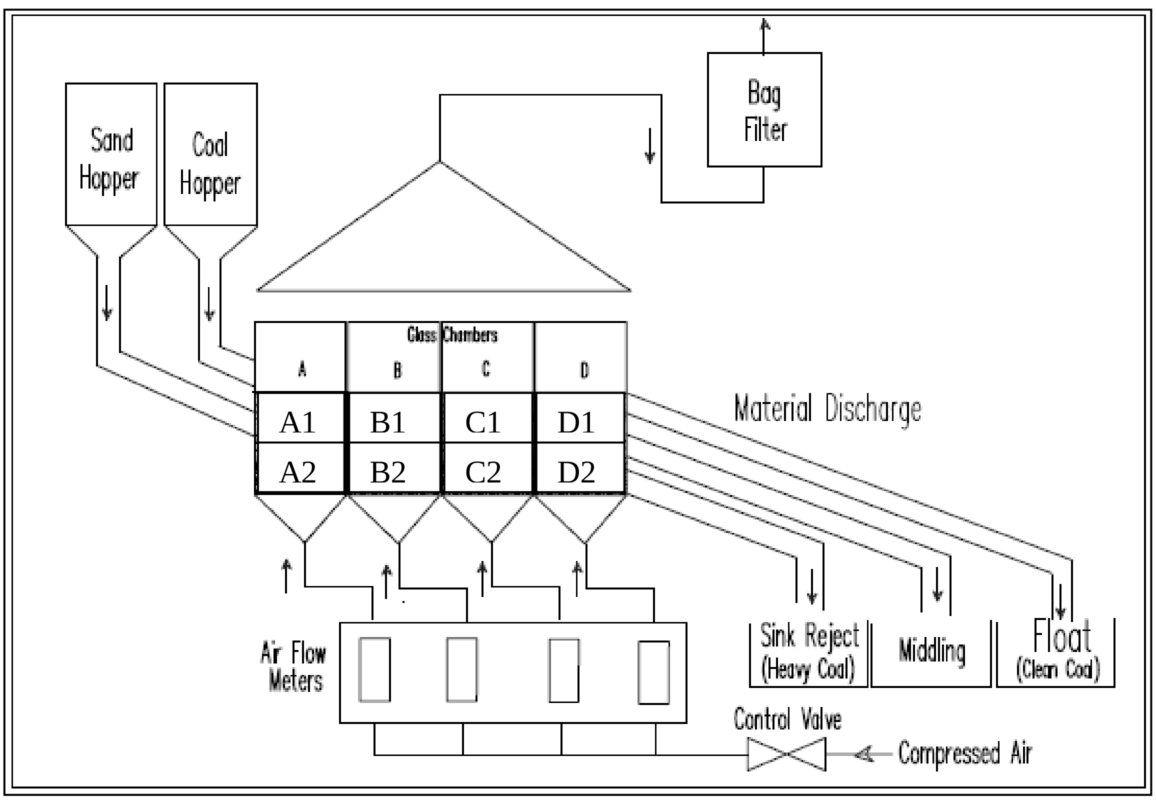
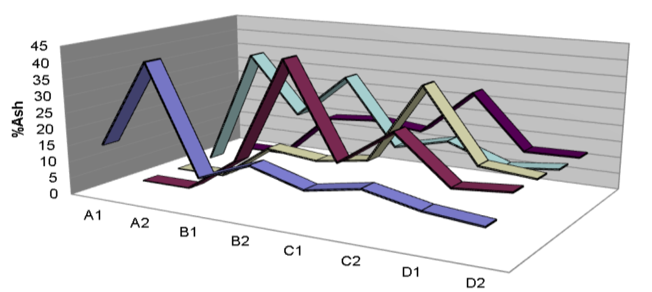


Figure 13. Separating individual cell of Continuous mode separator in two parts.

- <u>Feed at various locations</u>:

  As mentioned above, the discharge opening was reduced to 8 mm only to increase the retention time for sand and coal particles for this experiment. The Epcor seam 2 coal of 5×22 mm size is being fed to different cells to introduce the coal particles. The fluidisation flow rate for the cell 1 to 4 is 5.9-5.9-6.5-7.1 SCFM from the feed end to the discharge end, respectively, to allow more fluidisation at the last two cells and increase recovery. The following graph explains the separation performance of continuous mode ADMFB separator when the coal was being fed at various locations.



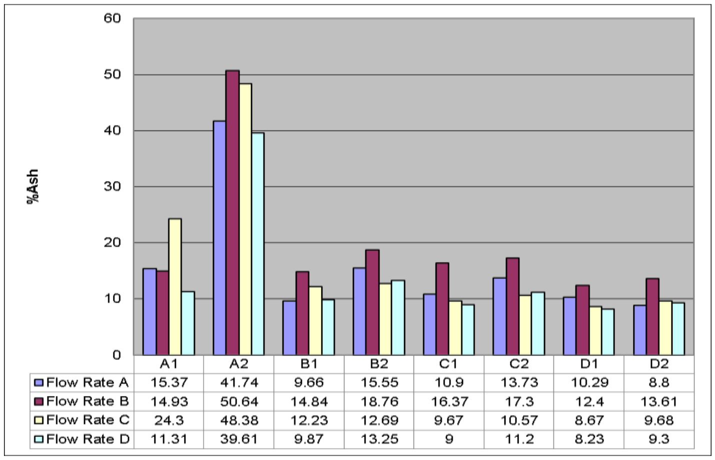
	A1	A2	B1	B2	C1	C2	D1	D2
FEED AT CELL1	15.37	41.74	9.66	15.55	10.9	13.73	10.29	8.8
FEED AT CELL 2	0	0	10.74	42.98	14.79	25.72	12.18	13.51
FEED AT CELL 3	0	0	11.03	9.31	11.64	35.82	14.45	12.98
FEED BETWEEN CELL 1 & 2	0	36.52	18.77	32.27	12.14	15.96	10.02	11.79
FEED BETWEEN CELL 2 & 3	0	0	14.1	15.41	13.69	27.87	11.2	11.49

Figure 14. Effect of Feed Location on Continuous mode Separator

As it shown in the above Figure 14 that the heavy coal particles with heavy mineral matter tends to separate from their lighter good coal in the bottom section of the same cell (A2, B2, and C2 respectively) where they were introduced. The higher % ash shown in any section indicates the separation of heavier coal in that section. The experiment only lasted for only 1 minute, as the feed particles were getting stuck in the discharge opening in Cell 4 and didn't allow the sand to flow through, due to the small opening (8 mm). When the feed was being introduced at Cell C, the experiment has to be shut down in 30 seconds, as the light good coal particles travelled through Cell D and got stuck in the discharge end. It was concluded by means of separation in same cell that a good separation could be achieved in the same cell itself where the feed gets introduced. In addition to this, it was also observed that the fluidisation is ineffective in moving the heavy particles towards the discharge end and the lighter coal was found in the subsequent cell's bottom section. It was determined from the above experiments that the apparatus needs some kind of horizontal movement for the heavy particles to continuously separate and a better transport mechanism is required to remove the fluidised coal particles from the discharge end.

4.1.1.4 Changing flow rate:

After the above experiment of feeding at various locations, it was decided to test the effect of flow rate on the fluidisation of coal particle and separation of heavy coal. In the previous set of experiments, the flow rate used was A (5.9-5.9-6.5-7.1 SCFM from the feed end to the discharge end for Cells 1 to 4 respectively) as shown in Figure 14 , but for this experiment the flow rate was varied to B (7.1-6.5-5.9-5.9 SCFM from the feed end), Flow rate C (8.2-6.5-5.9-5.9 SCFM from the feed end) and flow rate D (9.4-6.5-5.9-5.9 SCFM from the feed end) to have a better effect of fluidisation in the first two cells, as it was observed that the separation was taking place in the early stages only. The effect of the increased flow rate can be seen in the following Figure 15.



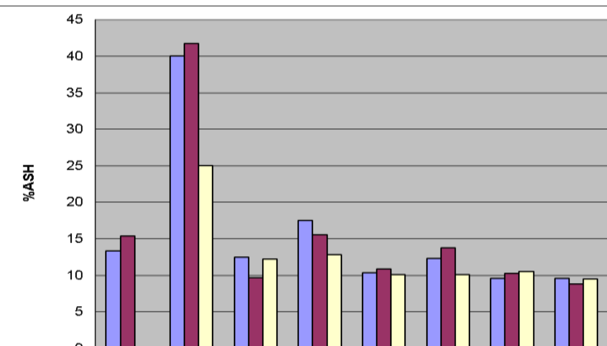
	A1	A2	B1	B2	C1	C2	D1	D2
Flow Rate A	15.37	41.74	9.66	15.55	10.9	13.73	10.29	8.8
Flow Rate B	14.93	50.64	14.84	18.76	16.37	17.3	12.4	13.61
Flow Rate C	24.3	48.38	12.23	12.69	9.67	10.57	8.67	9.68
Flow Rate D	11.31	39.61	9.87	13.25	9	11.2	8.23	9.3

Figure 15. Effect of Flow rate on Continuous mode Separator

As it can be seen from the above Figure, the flow rate B (7.1-6.5-5.9-5.9 SCFM from the feed end) has the best capability of separating coal particles from its heavier coal in the first cell. This set of experiments again proved that the maximum separation is being performed in the first cell only and the rest of the cells are the additional resources to perform fine separation. The experiment B shows a better separation than the other experiments. The coal in the section A2 has 51% ash content from the feed which contains 17% ash content. It was also noted that the section D almost shows same separation for all four trials due to the flows of lighter coal in section D. As most of the heavier coal sink into the bottom portion of section A and no movement of heavier coal observed in the experiment, the final section D contains most of the lighter coal for all the trial and thus shows no change.

4.1.1.5 Effect of Change in volume loading:

After optimising the air velocity and best location to feed the coal particles, it was decided to test the optimal volume loading for the feed sample to get the best separation performance. As in the earlier experiments, 500 gms of coal feed particles was used as based on Mak's experiments (Mak, 2007).



	A1	A2	B1	B2	C1	C2	D1	D2
FEED=1KG	13.32	40.05	12.48	17.5	10.36	12.32	9.61	9.57
FEED=500 GMS	15.37	41.74	9.66	15.55	10.9	13.73	10.29	8.8
FEED=100 GMS	0	25.06	12.21	12.86	10.11	10.09	10.5	9.47

Figure 16. Effect of Volume Loading on Continuous mode Separator

It can be easily conclude from the above graph that the optimal loading for the feed particles should be in the range of 500 gms to 1000 gms, as that will provide enough material to segregate in the bed, as opposed to segregation of none. It was evident from the above figure that the lower volume of the coal particles in the bed also increases the chances of the back mixing and decreases the separation efficiency while higher volume loading at the same air flow breaks the fluidisation and increases the chances of bed collapse. When only 100 gms of coal being fed, it was observed that there were a few particles in section A1 and most of them got segregated in the first two cells only. The difference between higher and lower loading is significant and it was observed that the 500 gms of feed sample gained better separation than any other sample.

4.2 *Continuous mode ADMFB on inclined surface:*

The coal with the heavier mineral matter sank to the bottom within the first 60 seconds of the fluidisation while the lighter coal particle floated in the top layers. It was observed during the above experiments that the lighter coal particles were easily flowing with the medium particles while the heavier coal particles remained at the bottom section of the separator and after some time they blocked the air flow from the bottom. Thus the movement of the heavier coal particles remained as a bottleneck to the continuous operation of the separator. To improve the flow of the heavier particles and provide them some momentum, the grading angle increased up to 5 degree from the feed end side. This is shown in the following Figure 17.

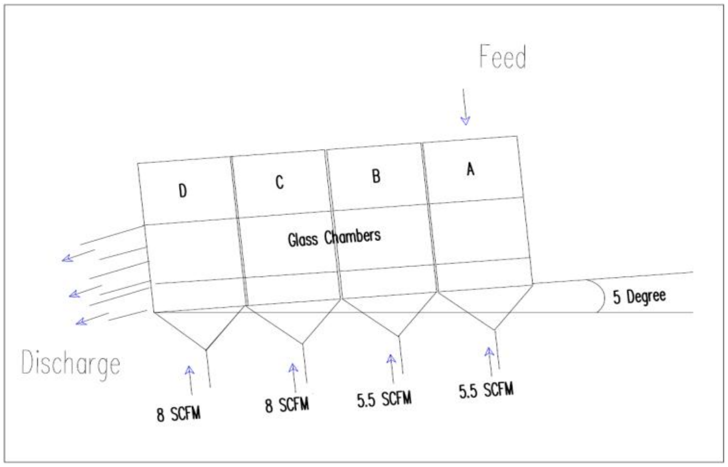


Figure 17. Effect of adding gradient to add momentum.

The experiment was tested with 300 gms of feed coal of 1mm-5.66 mm size and the air flow was as shown in the above Figure 17. The experiment was only ran for only 1 min while having the higher airflow in Cells C and D compared to Cells A and B so as to give additional time to the coal particles to stay in Cells A and B, as well as improve the chances of heavier coal particles moving. The opening at the discharge end was kept at 10mm to provide better retention time. It was observed that while increasing the grading angle to 5 degree from the feed end side, as shown in the above Figure, helped the heavier material move a little bit but at the same time this also allowed the medium particles to flow rapidly with the lighter coal towards the discharge end and disturb the segregation and choke the discharge opening area with lighter coal particles.

This proves that we need to modify our design to allow the continuous removal of the heavier coal particles to make this separator a successful model. It was not recommended to increase the grading that reduces the segregation and increases the medium flow, but it would be better if a mechanical device could be added, which could continuously remove the heavier coal from the bottom without disturbing the air flow.

<u>Summary</u>:

The continuous mode ADMFB separator was tested against the various parameters and conditions to achieve the optimised separation of the feed coal. After all of the above set of experiments was completed, it was determined that the location, flow rate, volume loading and height of the bed are some of the important parameters on which separation of coal particles depends. It was observed that horizontal transportation and length of the transportation (i.e. no. of cells) are the most valued parameters and are the main reason for the failure of the continuous mode ADMFB separator. The ADMFB separator was failed as a continuous mode separator when a mixture of feed coal and sand is being fed from one end and discharge on the other end due to various issues related to movement of heavier coal, discharge opening and design flow. The author has tried to increase the airflow or incline the separator to increase the momentum on heavier coal but that was not enough to remove the heavier coal from the bottom portion of the separator. Even the increased airflow disturbed the bed to the level of causing turbulence in it.

This proves that to the design required several modifications to allow the continuous removal of the heavier coal particles to make this separator a successful model. It was also determined that single cell is enough to segregate the coal particles based on their gravity and design modification should consider single cell only as batch mode. The successful operation of single cell where the feed is introduced is enough to make the required cut and one minute of fluidisation gives proper stratification with sand as a medium.

CHAPTER 5 UTILISING A CONTINUOUS MODE AIR DENSE MEDIUM SEPARATOR AS A SINGLE CELL (BATCH MODE)

The continuous mode separator was tested with various parameters to gain optimised fluidisation benchmarks for the best separation of heavier coal particles from their lighter counterparts, but was unsuccessful due to its design. The seam 2 coal from EPCOR's Genesee mine was replaced with a low rank slimed coal (please refer Figure 2) from the same mine, which is more likely to react rapidly with the water and for which the dry coal cleaning is of utmost necessity. The E35 coal was received from the EPCOR mine and due to its low ranking, it was decided to evaluate its cleaning on continuous mode and batch mode (Mak’s apparatus) ADMFB separators to clean the coal and compare their performance. The coal was crushed and screened into 1-5.66 mm sizes and the float sink analysis was performed to check the ability of a gravity-based separator to clean that coal. The float sink process is performed based truly on gravity and so it is called the ideal separation for any gravity-based separation. It is also evident that the float-sink process does not depend on the size or shape of coal, so it was concluded that the float-sink curve is an ideal target for any gravity based separation process to achieve and the closest proximity to the float-sink curve determine the efficiency of separation (Mak, 2007).

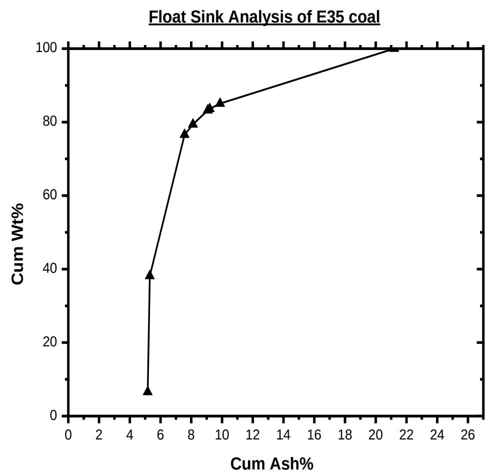


Figure 18. Float-Sink analysis of 1.0-5.66 mm E35 coal from Epcor

As it is determined from the Figure 18, gravity-based density separation is the best available dry coal cleaning method for this type of coal. There is an increasing trend of ash contents from 1.3 to 1.9 sp. gr. and the lighter coal has a specific gravity of less than 1.6. The total ash contents of the E35 coal was 21.20% while 85% of the coal has less than 10% of ash content. This makes it a very good feed for the ADMFB separator.

- In the previous study with the continuous ADMFB separator, it was determined that 1 min of fluidisation is sufficient to separate the heavier coal on the basis of gravity. It was also observed that sand was an excellent medium to separate the coal and it required only one cell to separate the coal, rather than the whole bank of cells as it was in the existing continuous mode ADMFB separator. The selection behind the single cell is based on the finding of the previous experiments as described in Chapter 4 and the successful stratification found in the first cell where the feed gets introduced. In continuous mode separator, if the horizontal movement between cells gets blocked by means of aluminium plate, then the single cell operation is acting as a batch mode.

- The experiment was conducted for one minute and airflow was stopped. We have also determined from the calculation that (see Appendix 1) the minimum fluidisation velocity is 5.5 SCFM, which is a little higher than the μ_{mb}.

5.1 *Comparison between batch mode and Continuous separator in batch mode (single cell)*

For this set of experiments, a comparison was made between the apparatus used in the batch mode and the continuous mode separator in batch mode (single cell). Based on the previous study and the work done by Mak (Mak, 2007), it was decided to check the repetitiveness of the same result achieved by Mak with this E35 coal for 1mm to 5.66 mm size fraction. The same practise of cutting the bed in layer after the fluidisation was followed, as was used in the batch mode by Mak for her experiment and medium B (magnetite) and medium C (sand) was compared for the better medium for E35 coal cleaning. Based on the previous study with the continuous mode, several changes were made to Mak's method of cutting the layer. The layers were cut into four segments, which are greater than 12 cm, 5cm to 12 cm, 1 cm to 5 cm and less than 1cm from top height of 15 cm. The separation performance was determined by their proximity to the float-sink curve for E35 (Figure 18). The closer the proximity of the curve to the float-sink curve, the better the separation performance.

5.1.1 Effect of fluidising medium:

The fluidising medium is one very important variable in obtaining optimised separation, as every medium particle behaves as per Geldart's chart and Medium B (Magnetite) and Medium C(Sand) used in every experiments are under Group B, while the coal particles falls into Group D of Geldart's classification chart (refer Figure 6). Basically with the fluidising air velocity, the medium behaves as a pseudo-liquid and forms the bed with a uniform specific gravity, which is then used to separate the coal. Depending on the bed's specific gravity, the coal particles can either float or sink based on their specific gravities. Thus, the medium is a very important part of the success of the fluidising bed separation. The following Figure shows the particle size distribution of the medium particles used in the study (Mak, 2007).

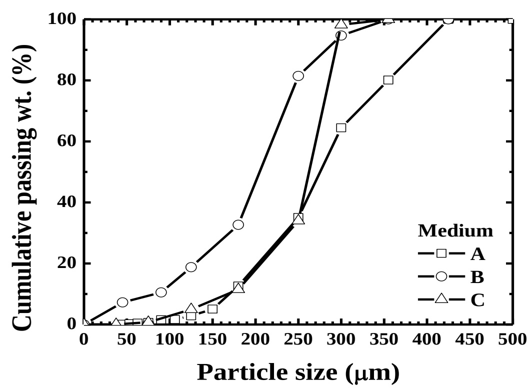


Figure 19. Size distribution for different mediums (Mak, 2007)

Our objective with this experiment was to compare the effects of fluidising medium on the separation performance of batch and continuous mode separator acting in a batch mode.

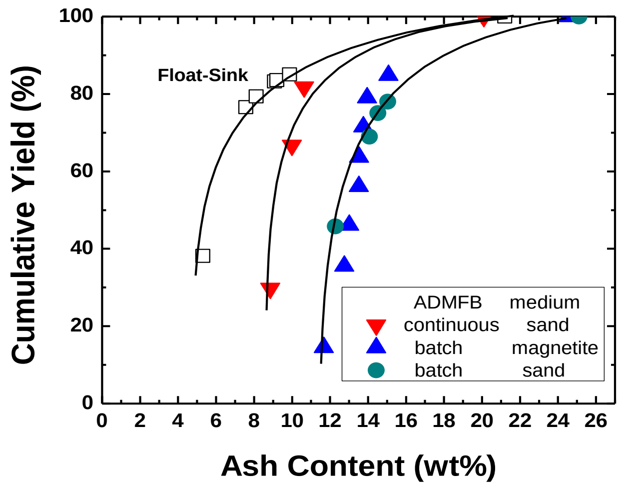


Figure 20. Effect of types of medium on ADMFB separators operated at batch mode on Separation performance (1 minute Fluidisation stratification). (Dave et al, 2010)

As determined from the above Figure that the continuous mode separator when acted as a batch mode perform better coal cleaning than batch mode separator with sand as a medium. The batch mode ADMFB separator showed almost the same performance with sand and magnetite as a medium. The above analysis confirms that the continuous mode air separator, when operated on a batch mode (single cell) operation, shows better separation performance than the batch mode separator as, illustrated by the data points that are shifted towards the closer proximity of the float-sink curve. It was evident from the Figure 20 that the product ash reduced from 25% to 10% at 80% yield, which is an excellent performance. As observed in the graph for both types of separators, all the separation took place above 1 cm height and the heavier coal particles sank in the final layer of less than 1 cm, as they were very difficult to fluidise due to their size. The same separation was observed for both the medium in batch mode and continuous mode when operated in batch mode.

5.1.2 Effect of Fluidisation time:

The duration of fluidisation is another important factor affecting the efficiency of separation of fluidisation process. As mentioned above, the success of the fluidisation separator depends mainly on the specific gravity developed by the bed with the fluidisation air and it separates the material based on gravity. In this section, the continuous mode separator was decided to utilise in batch mode and evaluates the effect of fluidisation time on the separation of heavier coal. In previous chapter with the continuous mode when using all four cells in the separator, the separator was not able to run the experiment continuously for more than one minute and it was also observed that the one minute fluidisation time period was enough to separate the heavier coal from its lighter counterparts. For this set of experiment, sand was used as a medium and 300 gms of E35 coal as the feed sample of 1-5.66 mm size. Based on the calculation and experiment (discussed later in this chapter in Section 5.1.3), air velocity of 5.5 SCFM was used as fluidisation velocity for this experiment. Figure 21 indicates the evaluation of various fluidisation time periods (i.e. 30 sec, 1min and 5 min) for their effects on the separation.

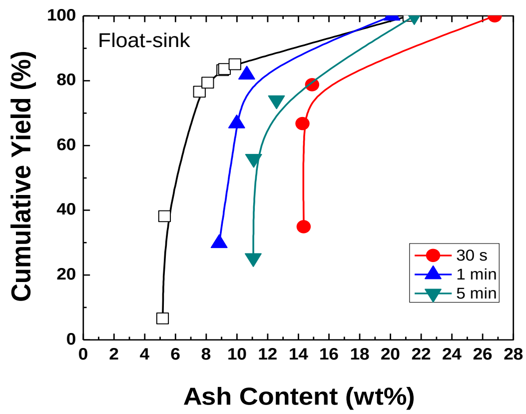


Figure 21. Effect of Fluidisation time on Laboratory continuous ADMFB separator operated at Batch mode (Dave et al, 2010)

It could be determined from Figure 21 above; the duration of the fluidisation is a very important factor for the efficiency of separation. As one can see from the above graph, the 1 minute of fluidisation duration was found to be the optimised fluidisation time. The washability curve in Figure 21 has shown that at the 1 minute fluidisation period, the ash contents reduced from 25% to 10% at 80% yield and the data point has the closest proximity to the float-sink curve. As the same trend of faster settling for heavy particles was observed and generated a proper stratification for coal cleaning in 1 minute of fluidisation duration. The increase in fluidisation period generates the pores between the medium particles and allows the lighter coal particles to perforate through the gap. This trend was observed by looking at the separation curve for 5 minutes in Figure 21; during this time, the curve was shifting away from the float-sink curve and the ash content increased from 9% to 13% at the same 80% yield. This was the result of the migration of lighter particles due to increased bed expansion by the longer fluidisation period. The effect of a shorter fluidisation time was observed, which shows the poorest separation of all three fluidisation times studied. It was concluded from the above experiment that the 30 seconds fluidisation time is not enough to expand the bed and does not create a proper bed density to allow the coal particles to segregate by means of gravity. This was the repetition of Mak's experiments for batch mode when she compared the bed for 30 seconds and 15 minutes (Mak, 2007). As mentioned in Mak's batch experiment, the 30 seconds has shown better separation when the bed height was reduced to 8 cms for magnetite (medium A) as a medium. This was not studied for the scope of this study. This can be done as a future research study.

5.1.3 Effect of Fluidisation velocity:

The fluidisation velocity is the most important factor in achieving optimised performance from the ADMFB separator. The minimum fluidisation velocity is the one which is necessary to fluidise all the particles in the medium while the velocity higher than the min. fluidisation velocity increases the channeling and leads to deterioration of the separation performance. The flow rate was calculated for the minimum fluidisation velocity and multiplied by the area of the single cell of the continuous mode separator. The feed sample is 300 gms and the bed height is 15 cms, while the medium used was sand. Figure 22 shows the evaluation of various fluidisation flow rates around the minimum fluidisation flow rate in SCFM.

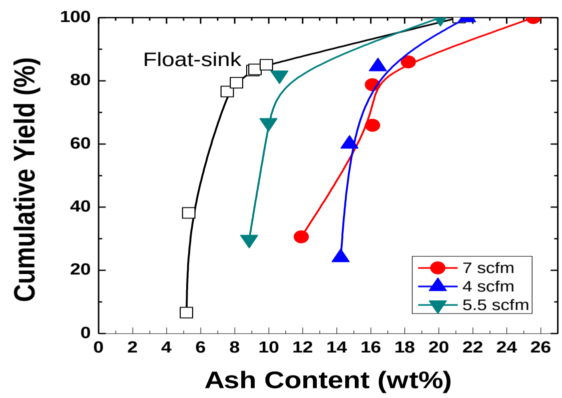


Figure 22. **Effect of different air velocity on separation for continuous ADMFB separators operated at batch mode for single cell (Dave et al, 2010)**

It is very clear from the above Figure that the effect of the fluidisation air velocity has the most profound effect on the separation of the coal particles. As discussed in the previous chapter, the continuous mode separator operated in batch mode operation showed the same trending when it was operated in continuous mode around the same velocity. The minimum fluidisation velocity calculated by the Kunii and Levenspiel equation was determined at 5.5 SCFM. We evaluated 4.0 SCFM and 7.0 SCFM for this study. It was evident from the above graph that the optimum velocity for the best coal cleaning performance was 5.5 SCFM which is the minimum fluidisation velocity for this separator. It could be determined from the above graph that at 5.5 SCFM, the ash content is reduced to 10% at an 80% yield. The separation curve for the 5.5 SCFM velocity is the nearest to the float-sink curve, while the curve for the other velocity was shifted away from the float-sink curve and was almost equal in performance. The higher fluidisation velocity increases the pores and channeling inside the fluidising bed and, hence, an increase in the ash content to almost 26% in the last 1 cm of the bed was observed. The higher velocity increases the turbulence and back-mixing of the coal particle rather than helping them stratify. The decrease in fluidisation velocity lower than the minimum fluidisation velocity did not allow enough energy to lift the medium particles and create a proper pseudo-fluid bed and that is shown as an almost vertical separation curve for that velocity.

Summary:

The continuous air dense medium fluidised bed separator when operated in the batch mode illustrates a highly efficient separation compared to its batch mode separator. We have considered some of the parameters like bed height, coal size, wall effect etc. as a fixed parameter and future experiments can be planned to study them, as well as more detailed studies of the current parameters. The separation of the heavier coal was easily achieved by using the continuous mode ADMFB separator and the effect of air velocity, bed height and time of fluidisation has been evaluated to achieve the optimal achievable separation for this setup. The calculated and experimental fluidisation velocity was found to be correlated with each other for the continuous mode separator.

CHAPTER 6 CONCLUSION

The laboratory-based continuous air dense medium fluidised bed separator was evaluated on the high ash coal of Genesee Mine and it has shown promising results. It was found to be a very effective method for dry coal cleaning when operated in a single cell. The laboratory-based ADMFB reduced the feed coal to 10% from 26% at 80% yield for the coal with a size fraction of 1-5.35 mm, which was very difficult with the earlier continuous mode separators. A comparison between the batch mode and the continuous mode was performed and the continuous mode separator acting as a batch mode exhibited better performance for dry coal cleaning. The existing laboratory-based continuous model evaluation indicated that the separator design needs to be revamped to reduce the residence time and allow continuous removal of the heavier coal from the bottom to run the separator in a continuous mode. We have evaluated various parameters like the coal fluidisation velocity, medium, bed height, volume loading and fluidising time and found that all of them have a significant impact on coal cleaning.

CHAPTER 7 FUTURE WORK

The laboratory-based continuous mode air dense medium fluidised bed separator needs some design modifications to allow the continuous removal of coal in less residence time. The recommendation should be to use some kind of external energy in terms of vibration or horizontal movement to the heavy sink particle so we can use this laboratory-based continuous Air Dense Medium Fluidised Bed separator in continuous operation.

The wall effect and effect of different type of media, as well as better control of the fluidisation velocity should be studied. The correlation of high ash removal with mercury and sulphur also needs to be part of future studies for this type of separator with new design modification.

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APPENDICES

Appendix I

The calculation for the volume of the individual cell and minimum fluidisation is calculated as below;

Length= Length of single cell in cm= 24 cms
Width= Width of single cell in cm= 9.8 cms
Height= Height of Bed in cm= 15.6 cms

Volume of single cell= Length×Width×Height
= 24×9.8×15.6
= 3669.12 cm^3 (7)

d_p = 0.0262 cm
(from Mak, 2007)
ρ_s = 2.7 gms/cm^3
W = Weight of medium= 5359 gms

ε_{mf} is calculated from the following equation:

$$\varepsilon_{mf} = 1 - \frac{volume\ of\ medium}{volume\ of\ fluidized\ bed\ at\ minimum\ fluidization}$$

(Mak, 2007)

ε_{mf} = 1- [(W/ ρ_s)/3669.12]

ε_{mf} = 0.456 (8)

From the value of $\varepsilon_{mf,}$ we can calculate u_{mf} from the equation 4, 5 and 6

$$u_{mf} = \frac{d_p^2(\rho_s - \rho_g)g}{150\mu} \frac{\varepsilon_{mf}^3 \phi_s^2}{1-\varepsilon_{mf}}, \quad \mathrm{Re}_{p,mf} < 20$$

u_{mf} = [((0.0262)^2× (2.7-0.0012) ×981)/ (150×0.00018)] [((.0456)^3× (0.86)^2)]

u_{mf} = 8.67 m/sec or 5.6 SCFM

Where;

$Ar = [d_p^3 \rho_{g\,(}\rho_{s-}\,\rho_{g)}\ g]/\mu^2 = 1761.72$

And,

$Re_{\,p,mf} = [\ (33.7)^2 + 0.0408\ Ar]^{1/2} - 33.7 = 1.05$ which is < 20 (valid number)