LOW TEMPERATURE DRYING OF ULTRAFINE COAL

by

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ABSTRACT

A new dewatering technology, called low temperature drying, has been developed to remove water from ultrafine (minus 325 mesh) coal particles. The process subjects partially dewatered solids to intense mechanical shearing in the presence of unsaturated air. Theoretical analysis of the thermodynamic properties of water indicates residual surface moisture should spontaneously evaporate under these conditions. This is contingent on the large surface area of these fine particles being adequately exposed to an unsaturated stream of air. To demonstrate this process, three dispersion methods were selected for bench-scale testing; the static breaker, air jet conveyor, and centrifugal fan. Each of these devices was chosen for its ability to fully disperse and pneumatically convey the feed cake. The moisture content of the feed cake, and the temperature and relative humidity of the process air were the key parameters that most significantly affected dryer performance. Of the three methods tested, the centrifugal fan produced the best results. The fan was capable of handling feeds as wet as 21.5% and consistently dried the coal fines below 2% moisture. The cost of the air and heat required to provide good drying performance was modeled to explore the practicality of the drying process. Modeling was accomplished by modifying equations developed for thermal dryers. The modeling results indicate, if good exposure of the fine particle surface area is achieved, dryers operating with either heated or unheated (ambient) air can be used for drying ultrafine coal

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1.0 INTRODUCTION

1.1 Preamble

According to the Energy Information Administration (EIA 2010), coal is used to generate nearly half of the electrical power consumed in the United States (Figure 1-1). However, in recent years, the environmental impact of coal mining, processing, and power generation has come under increasing scrutiny. There are even initiatives pushing for the burning of coal burning to be stopped entirely. Yet, coal remains America's most affordable source of electricity despite recent advancements in renewable energy and increasing interest in nuclear power, (Wald 2009). With 27% of the world's recoverable reserves, the United States has the largest coal reserves of any nation on earth (EIA 2009). Such a plentiful and cost effective resource is difficult to ignore and warrants great efforts to mitigate its environmental shortcomings.

One of the most prominent environmental issues facing the coal industry today is slurry impoundments and the water quality and flooding risks associated with them. Impoundments are

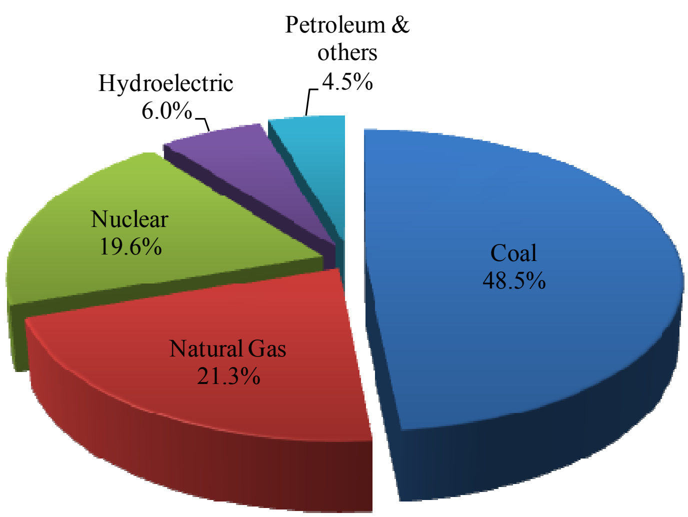

Figure 1-1. Electric power generation by energy source in the U.S. (EIA, 2010).

manmade ponds or lakes used to settle out the fine waste produced by coal preparation plants. It is possible for this waste to seep into the surrounding water table, potentially compromising the drinking water of local communities. There is also the more remote risk of this material escaping en masse in the form of a damn failure, like the one at Buffalo Creek WV in 1972, or a blowout through old works, as occurred in Martin County KY in 2000.

Ultrafine coal (minus 325 mesh) is one of the primary components of the fine waste found in impoundments. Ultrafine coal is discarded because the high moisture content such material makes this size category uneconomical to recover (DOE 2009). The loss of the minus 325 mesh material is especially tragic because coal particles that small are extremely well liberated. This allows lower ash values that would be impossible with larger particle sizes. If this material could be recovered and dewatered, impoundments could be made smaller and cleaner while simultaneously increasing coal production and lowering the ash content of processed coal.

In a conventional coal preparation plant all material under 100 mesh is typically recovered by froth flotation and sent on to screenbowl centrifuges for dewatering. This process produces a clean dewatered product, but as screenbowls remove water from the coal approximately half of the ultrafine feed solids are discarded (Luttrell et al., 2006). Some of the newest preparation plants pre-empt this loss by desliming the flotation feed with 6-inch diameter cyclones. This cuts out the minus 325 mesh material so that flotation capacity is not wasted on coal that will be discarded. This practice of desliming is even applied when fine coal is remined from closed impoundments. In effect, high-grading this supply of potentially marketable coal (Manlapig et al. 2001).

Processing plants that produce coal for the metallurgical market work somewhat differently. The amount of material lost from a screenbowl typically is not acceptable for this market, since coking coal commands a price that can be substantially higher than that of steam coal. Instead, vacuum filters may be employed to achieve higher recoveries of the ultrafine coal. This process gives near perfect recoveries, but also produces much higher moistures. Unfortunately, while coking coal contracts pay a premium, they also typically include strict moisture limits. Therefore, wherever possible, the wet filter cake is sent on to a thermal dryer where the water is forcibly boiled away via intense heating. Thermal drying can produce bone dry coal, but this process also presents a unique set of challenges. Exposing coal to high temperatures without combustion causes the coal to release volatile organic compounds (VOCs) which are an environmental concern. In the process of generating their heat, thermal dryers can also emit SOx and NOx. As potentially large sources of air pollution, new thermal dryers can be extremely difficult to permit.

1.2 Low Temperature Drying Process

In light of the problems associated with removing water from fine coal, a new process known as "low temperature drying" has been under development at Virginia Tech. Low temperature drying dewaters coal by taking advantage of liquid water's natural propensity to evaporate. A liquid's evaporation rate is directly related to its surface area and water exposed to air at less than 100% relative humidity is always evaporating, albeit slowly. Therefore, if a fixed mass of water is spread out over a large surface area and the air above that water is continually replaced to keep the air unsaturated, that water would evaporate very quickly.

Minus 325 mesh particles have an exceptionally large surface area per unit mass (e.g., 108.6 m^2/kg or 530 ft^2/lb). So, if the water that remains with the ultrafines after mechanical dewatering was to be spread evenly over that surface and the air around the water were continuously replaced, that water would swiftly evaporate. This is exactly how low temperature drying works. This process seeks to expose the entire surface of the ultrafines by using a shearing device to break up the filter cake into its constituent particles and prevents saturation of the air by pneumatically conveying the particles through the shearer.

1.3 Objectives

The goal of this project is to take slurry composed primarily of minus 325 mesh material and produce a clean product containing less than 10% moisture. The slurry may originate from a plant's deslime cyclones or an actual impoundment. Two cleaning paths and three drying devices were tested. The first path was cleaning by oil agglomeration followed by centrifugal dewatering. The second path was cleaning by froth flotation and dewatering by vacuum filtration. The three dryers tested were the static breaker, air jet conveyor and centrifugal fan. All three drying devices utilized the newly developed concept of low temperature drying where surface moisture is absorbed and carried away by ambient or slightly heated air. This project also explored the economic feasibility of low temperature drying via mathematical modeling of the process.

2.0 LITERATURE REVIEW

2.1 Fine Coal Cleaning

When attempting to dewatering fines, it is important to understand the preceding steps. Several factors determined by cleaning influence the final product moisture. These include, but are not limited to: percent solids, what sizes report to the clean product, and whether those sizes are ash or coal.

2.1.1 Froth Flotation

Froth flotation is the most widespread method to clean minus 100 mesh (minus 150 μm) coal particles and some sort of flotation circuit is present in all but the oldest of preparation plants (Aplan 1991). Flotation is a process where hydrophobic particles, like coal, are separated from hydrophilic particles such as those clays or silicas that constitute ash. This is accomplished by sparging air through dilute slurry in a mixing cell. The hydrophobic coal particles stick to the air bubbles and rise to the top forming a froth while the ash particles remain in solution with the water. The coal rich froth overflows the cell edges while the ash laden water is drained from the bottom of the cell and into the thickener.

Although conventional flotation sends the majority of the water to the thickener, there is still a significant volume of water that is required to form the froth that carries the clean coal particles away. This leads to an effect called hydraulic entrainment where the finer ash particles, especially clays, stay with the water wherever that water goes. Thus the ash split is almost identical to the water split. This problem can be rectified by desliming, multistage flotation or column flotation. Desliming is accomplished by sending the fine coal stream through 6-inch diameter cyclones, cutting out the minus 325 mesh (minus 44 μm) material. This is the size fraction that contains the most entrainable clays, has the highest feed ash, and is the hardest to dewater (Manlapig et al. 2001). Multistage flotation, the solution favored by the minerals industry, is to send the product froth through one or more "cleaner" flotation cells. This starts an infinite dilution loop where less and less waste reports to the product stream. Column flotation takes a different approach by introducing "wash water" into the froth section of the cell. The wash water flows down through the thin films of the foam displacing the original ash bearing water with clean water. The low unit value of coal makes multistage flotation cost prohibitive, leaving desliming or column flotation as the favored industry solutions (Davis et al. 1995).

2.1.2 Oil Agglomeration

Although oil agglomeration is far less commonly used than froth flotation, agglomeration does represent an alternative method of effectively cleaning fine coal while at the same time lowering its moisture content. As with flotation, oil agglomeration depends on the hydrophobicity of coal particles to differentiate them from the hydrophyllic ash particles. When oil is mixed with coal slurry, oil droplets stick to coal particles and oil coated coal particles stick to each other, eventually forming agglomerates of various shapes and sizes. Small amounts of water are trapped within these agglomerates so hydraulic entrainment still occurs. However, as moisture levels are much lower in the agglomerates than in flotation froth, so is the level of entrainment. Traditionally, the more oil used, the larger the agglomerates and the lower the moisture content.

Oil agglomeration made its debut during World War I as the Trent process where coal slurry and approximately 30% of the raw coal's weight in oil were mixed together for 15 minutes (Capes 1991). By the end of the mixing time, large nodules of clean coal had formed which could then be screened out from the ash bearing water. The Convertol process, developed by the West Germans in the 1950s, was able to reduce the amount of oil and mix time required. This was achieved through the use of high sheer mills that increased the collision rate between oil and coal. Another advantage Convertol had over Trent was the use of a screen centrifuge to separate the agglomerate from the bulk water instead of a static screen (Nicol and Swanson 1980). This lead to a scant difference in product moisture under normal operating conditions but when given exceptionally fine feed, Convertol vastly outperforms Trent (Table 2.1-1).

Many other techniques followed. Some of the more notable methods are the Spherical Agglomeration process developed by the National Research Council of Canada, the Shell Pelletizing Separator, the Olifloc process and the Selective Agglomeration process from BHP. Each of these processes had their own strengths but all possessed the same weakness; the high price of oil. In 1991, Capes noted that oil made up half to two thirds of the product cost for these methods. Between that year and 2008, the price for a barrel of oil had more than quadrupled (EIA 2008). When these processes were new, controlling oil costs was important. Now controlling oil costs is absolutely critical.

One potential solution was utilized in the Otisca process that used pentane, a light

Table 2.1-1. Comparison of Trent and Convertol processes (Nicol and Swanson 1980). Used under fair use guidelines, 2010

Property	Trent	Convertol
Oil (% wt of raw coal)	30	10-15
Mix Time (Min)	15	0.25-0.5
Typical Moisture (% wt)	8-12	10-15
Fine Moisture (% wt)	40	20-25

paraffin, as an agglomerating agent. The advantage of using pentane over other hydrocarbons is pentane has the exceptionally low boiling point of 36.1ºC (96.7ºF). This allows comparatively large amounts be used because pentane can be recovered later through mild heating and condensation. Unfortunately, this process was targeted at producing ultraclean (<1% ash) coal water mixtures called "CWM" (Keller 1995). As the name would suggest, a CWM is coal slurry containing 50-80% solids, which could be pumped and burned in the same manner as fuel oil (Yoon et al., 1991). When the CWM market soured in 1989, Otisca Ltd. ceased production, never to resume (Keller 1995).

2.2 Fine Coal Dewatering

Most coal cleaning operations are wet operations and thus their products are water laden. The water left on coal after processing is known as "free" or "surface" moisture but there are also coals that contain "inherent" or "chemically bound" moisture that is inside the coal or part of the coal structure. Either of these is undesirable as the vaporization of water steals heat energy during combustion, raises transportation costs, and creates handling problems when wet coal freezes in a stockpile or railcar. Only thermal drying can remove inherent moisture, but there are a number of steps that can be taken to remove surface water. For the larger size fractions, dewatering is accomplished with relative ease by high speed vibrators, basket centrifuges, and screenbowl centrifuges, as show in . But below 44 μm (325 mesh) it becomes extremely challenging to keep moisture to a reasonable level. These ultrafines are so difficult and by extension expensive to dewater, that it is a popular practice to simply discard them without processing (Manlapig et al. 2001).

There are a number of different ways to overcome this problem. In the United States, the most popular way to dewater fines is the screenbowl centrifuge. This method strikes a balance

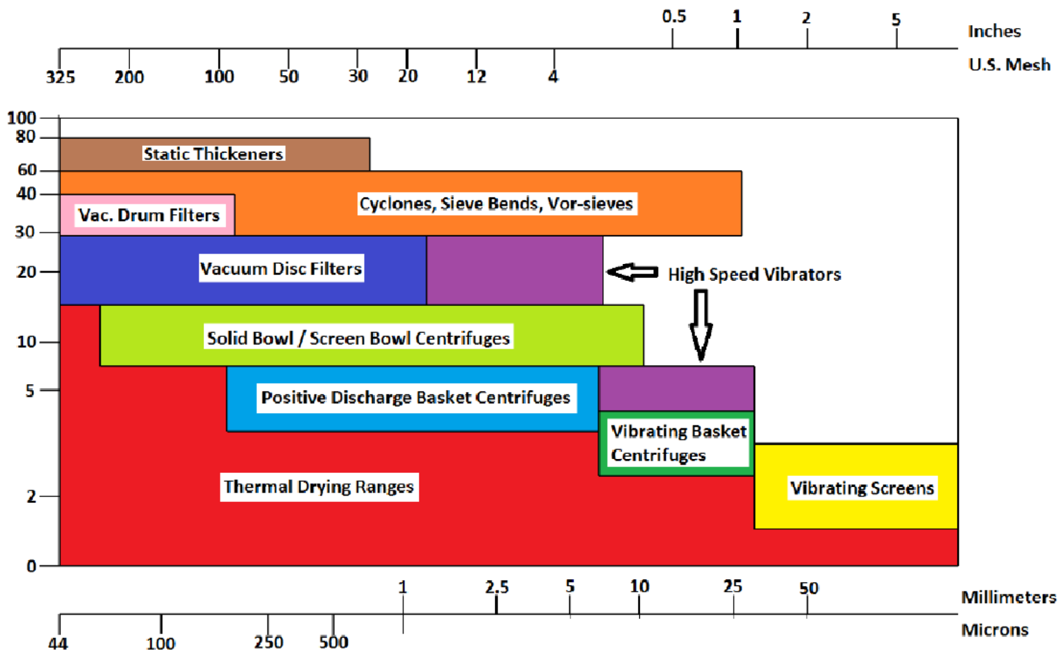

Figure 2-1 Common dewatering equipment (Parenkh et al. 1991)
Used under fair use guidelines, 2010

between moisture and recovery, maintaining reasonable moistures by discarding a fraction of the ultrafines (Luttrell et al., 2006). Vacuum filters achieve high recoveries but suffer from correspondingly higher moistures. Hyperbaric filters try to use higher than atmospheric pressures to attain low moistures while maintaining the same recovery as vacuum filters. Thermal dryers can achieve both near perfect recovery and a bone dry product but can also be a significant source of air pollution and are extremely difficult to permit.

2.2.1 Centrifugation

Screenbowl centrifuges were introduced to the coal industry in 1969 and, as the name implies, they are a hybrid of screen and bowl centrifuges. The feed end of the device is a solid bowl where the enhanced gravity of the centrifuge pulls any solids in the slurry to the wall. Concurrently, the clarified water escapes over a weir in the rear of the unit. A screw conveyor running the length of centrifuge turns slightly faster than the bowl pulling solids along the wall

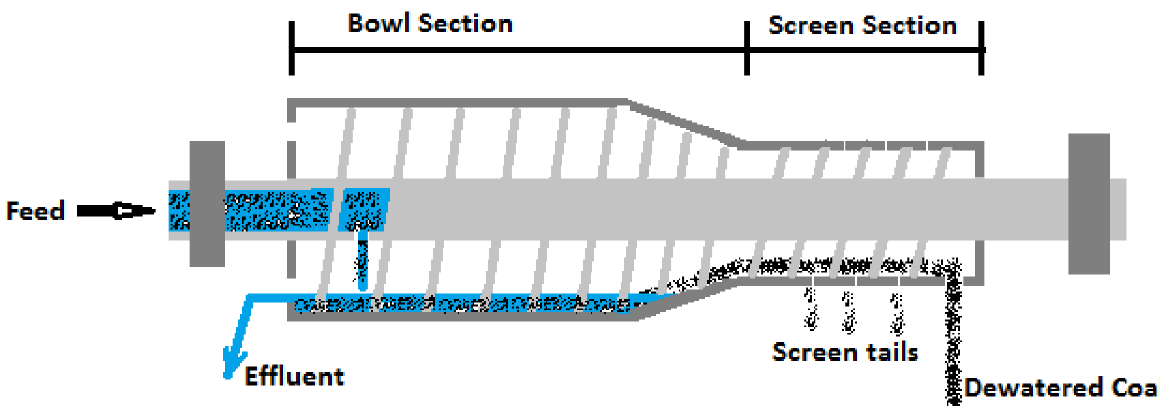

Figure 2-2. Cutaway view of a screenbowl centrifuge.

and towards the discharge. The walls of the centrifuge slope to the center as they approach the discharge, thus the screw drags material up and out of the bulk water. In a solid bowl centrifuge dewatering would be complete at this point but a screenbowl incorporates a screen section just prior to the discharge. The screen permits further dewatering of the cake and allows screenbowls to achieve approximately 12% moisture on a typical fine feed (Luttrell et al., 2006). Any solids lost through the screen section are recycled back into the original feed. A diagram of a screenbowl is shown in Figure 2-2.

Unfortunately, this performance comes at the expense of recovery, as a screenbowl can only achieve 80-90% recovery on most fine feeds with approximately 50% of the minus 44 µm (325 mesh) material lost with the main effluent (Luttrell et al, 2006). When fed straight ultrafines with an approximate mean size of 25 µm, as might be found in a pond reclaim operation, recovery can drop to 65% while cake moisture climbs to 30% (Parekh et al., 1999). That is both a poor recovery and a high moisture making screenbowl centrifuges an inappropriate choice for dewatering feeds containing any substantial amount of ultrafine material.

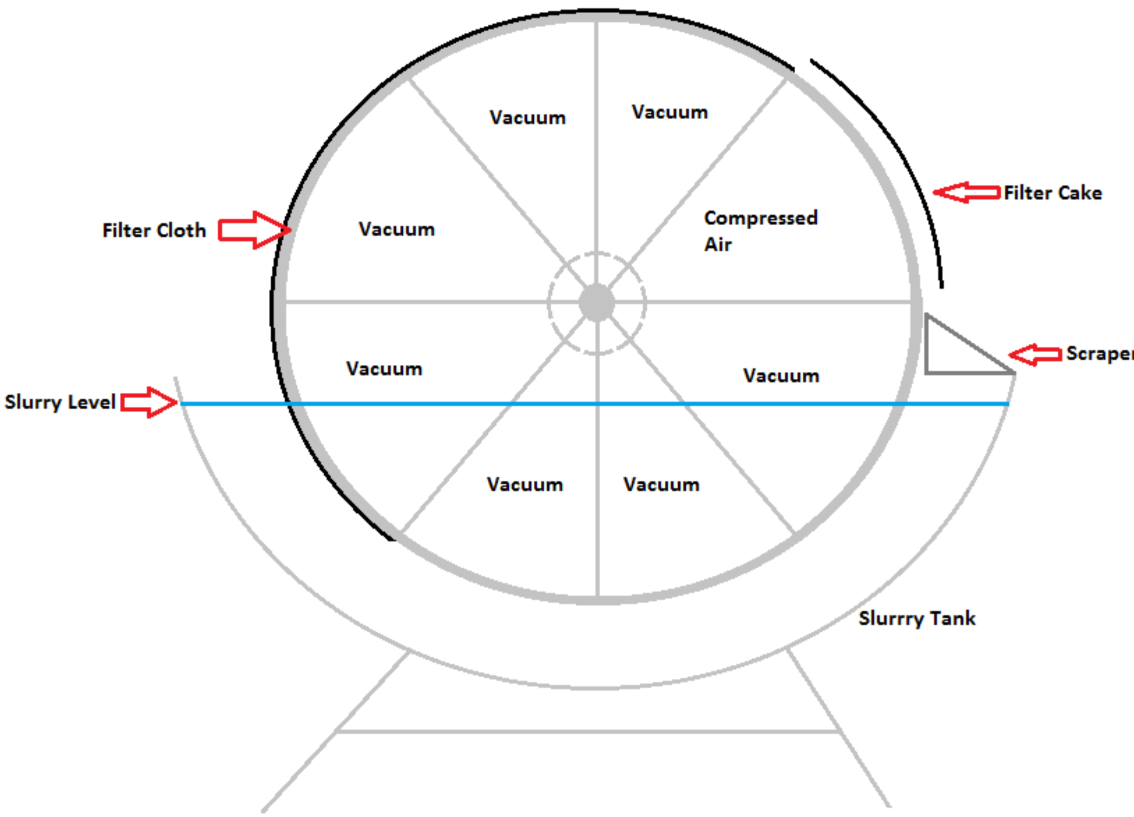

Figure 2-3. Cutaway view of a drum filter.

2.2.2 Vacuum Filtration

The vacuum filter is the only other common commercial method of dewatering coal fines. Available in drum or disc configurations vacuum, filters work by passing slurry over one side of a filter cloth while applying negative pressure to the opposite side. A cutaway of a drum filter is shown in Figure 2-3.

The drum rotates while partially submerged in a tank of slurry and vacuum is applied to the entire circumference of the drum with the exception of the discharge point. The cake forms on the section of the drum that is submerged and dewaters while the cake rotates around to the discharge point. At the discharge, the vacuum is replaced by compressed air that blows the cake off the filter. The more popular disc filter operates in the same manner, but instead of a drum with the filter cloth covering its perimeter, the disc filter is made up of a series of vertical discs with the filter cloth on their sides.

Vacuum filters enjoy near perfect recoveries (99%), but by capturing all the minus 44 μm (325 mesh) particles, they also capture a substantial amount of excess water. Depending on the size distribution of the slurry, vacuum filters can produce moistures anywhere between 15 and 30% (Aplan 1991). With a feed of straight ultrafines (approximate mean size of 25 μm), the cake moisture approaches 30%. This is still a very high moisture and no improvement over the screenbowl. Fortunately, vacuum filters respond well to dewatering aids, and with the addition of surfactants, the same material can be dewatered to as low as 24% moisture (Parekh et al., 1999).

2.2.3 Hyperbaric Filtration

Hyperbaric filters resemble vacuum filters that have been enclosed within pressure vessels. This is done so that they can achieve pressure differences across the cake that exceeds 1 atmosphere. Due to their high costs these units are quite rare in the coal industry, but they also achieve the best dewatering results. When fed straight ultrafines (approximate mean size of 25 μm), hyperbaric filters have achieved moistures below 24%. With the addition of cationic surfactants, product moistures can approach 19%. These moistures are attained while still maintaining the 99% recovery of a vacuum filter (Parekh et al., 1999).

2.3 Thermal Drying

Thermal drying was once the process engineer's trump card against moisture. After mechanical dewatering had brought moistures as low as possible and the coal was still too wet, a thermal dryer could always finish the job. Thermal drying is the only dewatering method that can reduce moisture content to 1% regardless of feed size. This is accompanied with high costs and a troubling amount of potential air pollution, but in many cases thermal drying is the only way to bring moisture within customer specifications. Thermal dryers are exceptionally popular with metallurgical coal processors as these operations produce a higher value product and larger amounts of fines (Fonseca 1995).

Most thermal dryers forcibly evaporate moisture by exposing the coal to hot gases. There are several different ways to arrange this interaction including, but not limited to; the fluidized bed, flash, multilouvre, rotary, and screen type dryers. The most popular by far is the fluidized bed design, which is shown in Figure 2-4. In this system, wet coal flows over a grate while hot air flows upwards through the grate putting most of the coal into suspension a few inches above the grate. Finer coal will follow the air flow and must be captured prior to the exhaust. This is

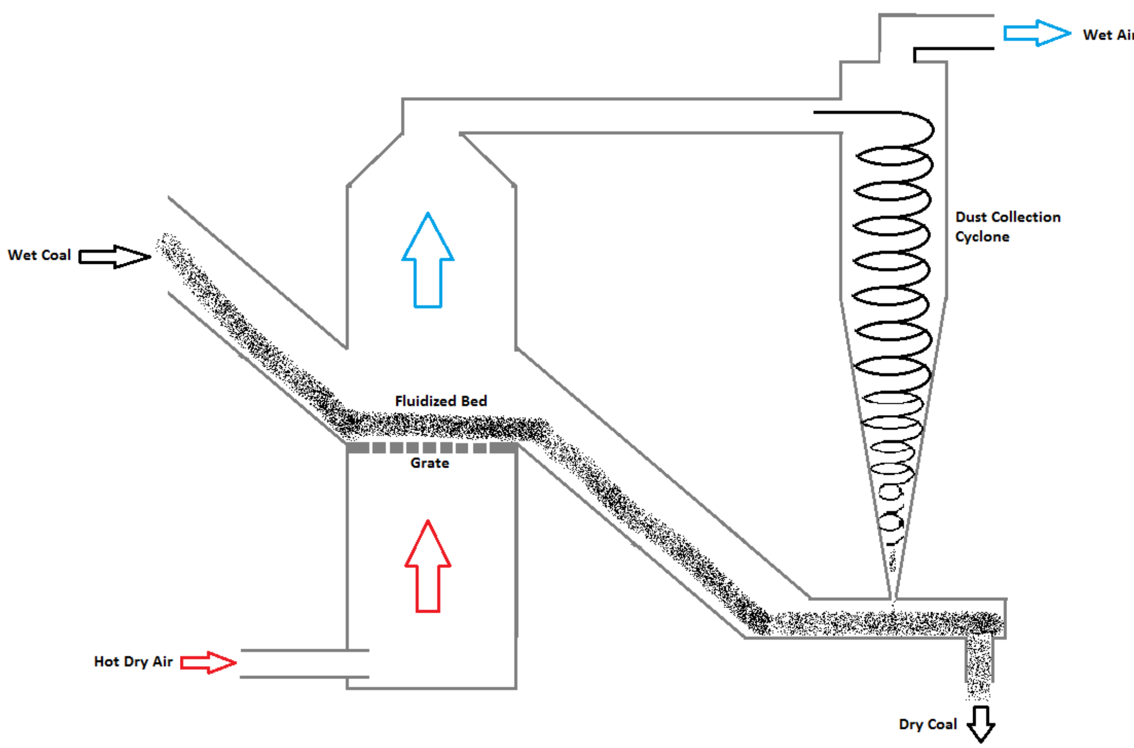

Figure 2-4. Cutaway view of a thermal dryer

normally accomplished with wide diameter cyclones.

Screen and flash dryers operate in a similar manner. A screen dryer uses less airflow than the fluidized bed dryer and coal slides across the grate without fluidization. In contrast a flash dryer uses enough air to carry all the coal with the airflow, allowing the coal to dry during its trip to the cyclone.

One of the hazards associated with thermal dryers is filter cake sticking together and forming lumps inside the drying chamber which will subsequently catch fire. To avoid this, it is a popular practice to mix 6.35mm x 0.595mm (1/4 inch x 30 mesh) coarse coal in with the cake in ratios from 2:1 to 4:1 (Luckie 1991). This practice prevents lumps from sticking inside the dryer, but also results in most of the coal going to the dryer being coarse coal that doesn’t need to be thermally dried in the first place.

An even worse problem with thermal dryers is their environmental impact. Exposing coal to high temperatures without burning the coal leads to the release of volatile organic compounds (VOCs), several of which are categorized as carcinogens by the EPA (EPA 2009). The temperatures that cause these unwanted emissions are summarized in Figure 2-5, which shows

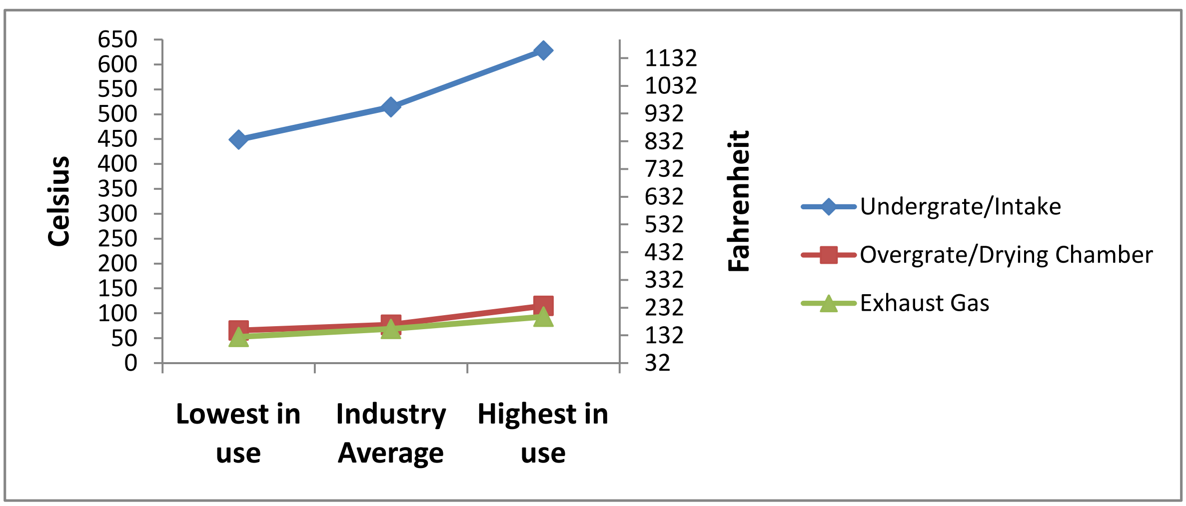

Figure 2-5. Operating temperatures of thermal dryers (Luckie 1991)
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the normal operating range of a fluidized bed dryer. Even the combustion to create the heat in the first place generates SOx and NOx. Thermal dryers have the potential to release such large amounts of these air pollutants that it can be exceedingly difficult to obtain operating permits.

3.0 EXPERIMENTAL

3.1 General Procedures

The end goal of the project is to produce clean marketable product from ultrafine coal slurry with a special emphasis on achieving low moistures (<10%). These moistures were to be achieved through the use of the low temperature drying process. The path to this goal can be broken into three sequential steps; cleaning, dewatering and drying.

3.2 Cleaning

Two methods of removing ash particles from the coal slurry were employed: oil agglomeration and froth flotation. In this work, cleaning was not performed so much to create a low ash product but to prepare the coal for dewatering by removing the clays present in the slurry. Clays are hydrophilic, clinging tenaciously to water, and keeping that water with them even after dewatering. Clays also fill the void space in filter cakes, thus lowering permeability and reducing the effectiveness of centrifugation or filtration. Filtration in particular suffers due to clays blinding the filter cloth.

3.2.1 Froth Flotation

Due to difficulty in obtaining a small-scale column flotation machine, a Dorr Oliver laboratory batch unit was employed instead. Since the cell was conventional, a rougher and two recleaning steps were necessary to remove all the free clays from the slurry. Prior to the rougher stage 0.75 kg/tonne (1.5 lb/ton) of hydrocarbon collector was added. MIBC (Methylisobutyl Carbinol) frother was added to the rougher and cleaner stages as was necessary to maintain a solid layer of froth. Approximately 1 liter of slurry was floated at a time and the froth was manually paddled off until the floatable solids were depleted.

3.2.2 Oil Agglomeration

Oil agglomeration was performed using 99% pure HPLC grade pentane from the Alfa Aesar Company. The agglomeration was performed in a 1 liter Nalgene separatory funnel (Figure 3-1). A nalgene funnel prevented accidental breakage and allowed for easier sample removal as wet coal sticks more strongly to glass. A dose of 20% of the clean coal's weight in

Figure 3-1. Separatory funnel used for laboratory testing.

pentane was utilized as an agglomerating agent. As many of the feed slurries had ash contents near 50%, this dosage was nearly equivalent to using 10% of the solid feed weight in pentane. Depending on the desired weight of product, anywhere from 400 to 800 ml of feed slurry was placed in the funnel followed by the appropriate amount of pentane. Due to pentane's fast evaporation rate, the funnel had to be sealed quickly and tightly to avoid pentane losses. Once sealed the funnel was shaken vigorously by hand for two minutes. Subsequently, the funnel was placed in a ring stand over an empty beaker. Finally, the stopcock at the bottom of the funnel was opened allowing the ash laden water to drain into the beaker. The pentane agglomerates were both buoyant and moderately stable, thus they floated in one large mass atop of the water while the water was draining. The agglomerants also bridged over the open valve once the water was gone. In this way, draining effectively separated product from tails just as screening or centrifugation had in older agglomeration processes.

3.3 Dewatering

Two different dewatering methods were employed to accommodate the unique products of the two cleaning processes. Oil agglomerates, although still high in moisture (>40%), could be handled as a solid and therefore put into a basket centrifuge. The flotation froth, on the other hand, was dilute and would run through the centrifuge basket before the solids could form a cake. Unlike the centrifuge, the vacuum filter was able to hold thin slurries in place while they formed a cake, making the filter a better choice for dewatering the float product. Furthermore, in order to compare the limitations of the different dewatering processes, they had to be tested on the same coal over a wide variety of size ranges. To this end, 2.38 mm (8 mesh) clean coal samples from the Moss No. 3 preparation plant were ground to different sizes in a laboratory ball mill. Once the samples were prepared, they were dewatered and dried by the following methods.

3.3.1 Centrifugation

A custom built 7.417 cm (2.92 in) diameter basket centrifuge was utilized for centrifugation. The basket had 0.02 in slots and was formed of bars taken from a full sized screenbowl. This centrifuge had a top speed of 4360 RPM and was capable of generating 788 Gs. The test unit is shown in Figure 3-2.

After the waste water had been drained from the separatory funnel, the funnel was

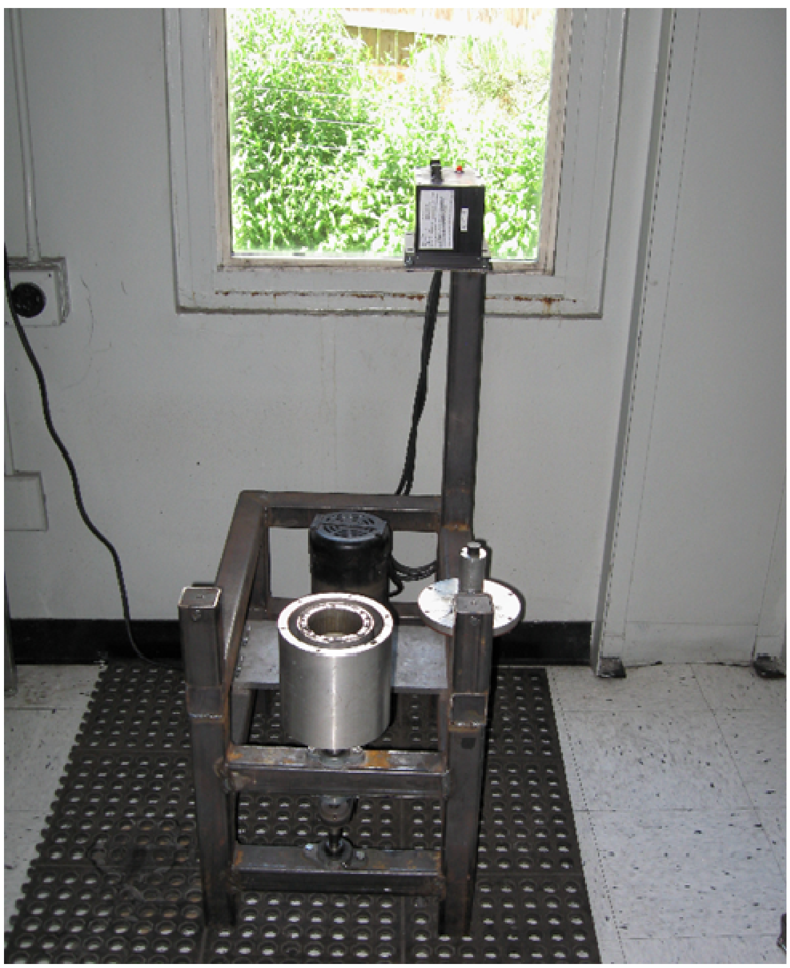

Figure 3-2. Screen centrifuge used for laboratory testing.

brought to the centrifuge and the agglomerates were poured into the basket. The agglomerates would then be spread evenly around the basket to ensure a uniform cake thickness and the centrifuge sealed. Once closed, the centrifuge was spun for 1 minute at top speed. The centrifugal force exerted on the agglomerates simultaneously compacted them and pulled out any free water.

Some samples were degassed after draining the funnel in order to test whether or not pentane could be recovered prior to centrifugation. This was accomplished by attaching a vacuum to the stopcock of the funnel. The pressure in the funnel was reduced below 508mm Hg (20 in Hg) and left that way for 1 minute. Opening the funnel revealed that the agglomerates had transformed into a thick paste. Centrifuging this paste for the same time and at the same speed as the agglomerates resulted in a cake with a moisture of just over 29%. This same paste occurred when the fragile agglomerates were compacted prior to centrifugation.

Moisture determination was normally performed by weighing samples, placing them in an oven at 80 ºC (176 ºF) for an hour or more and then weighing them again. In order to prevent unevaporated pentane from interfering with moisture determination the time for the pentane to completely evaporate had to be found. This was accomplished by placing a freshly agglomerated sample on a scale and recording its percent change in mass over time. The quickly evaporating pentane produced a high rate of mass loss and when the rate slowed all the pentane was assumed to be gone. The evaporation rate of a sample at 26 ºC (78 ºF) is shown in Figure 3-3. Based on this plot, an evaporation time of 6 minutes was established, i.e., all centrifuged samples were set aside in open air for at least 6 minutes before being subjected to moisture determination.

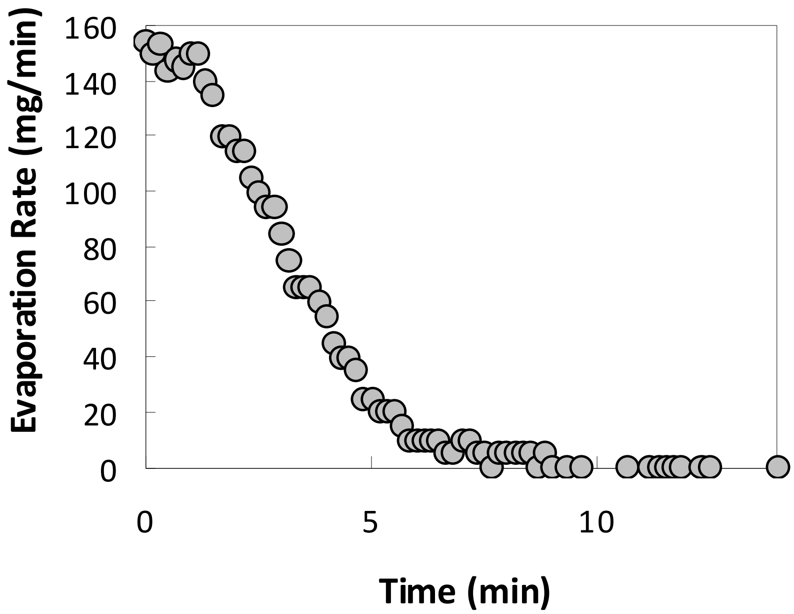

Figure 3-3. Evaporation time for pentane.

3.3.2 Filtration

Filtration was performed using a 6.35 cm (2.5 inch) diameter Peterson laboratory filter. This filter was attached to a vacuum pump capable of maintaining 508 mm Hg (20 in Hg) of vacuum while the filter was in use. Between the pump and filter there was a valve to control the flow of vacuum. Once the clean froth had been collected from the float cell and poured into the vacuum filter, the valve would be opened. This allowed the filter to go straight from atmospheric pressure to full vacuum without waiting for the pump to come up to speed. The slurry was left in the filter until all visible surface water was gone and the filter cake had cracked. Cake thickness was typically 0.635 cm (¼ inch) and the pump was left on until the cake was removed from the filter.

In cases where lower moistures were desired, a dewatering aid was added after flotation but prior to filtration. Reagent RU, developed at Virginia Tech, was used as the dewatering aide in all experiments. To be used effectively, Reagent RU had to be dissolved in 2 parts diesel fuel before the reagent was added to the slurry. In order to properly disperse RU, the slurry was churned in a high shear mixer for 5 minutes before the sample was poured into the vacuum filter.

3.4 Drying

All three drying methods operated by pneumatically conveying the filter cake through a shearing device that breaks the cake up into its constituent particles. Breaking up the cake exposes sufficient surface area for the water to evaporate and pneumatic conveyance refreshes the saturated air quickly enough to allow evaporation to continue unhindered. Unless otherwise noted, all drying tests were performed on samples taken from the overflow of the 6-inch diameter deslime cyclones at Arch Coal's Cardinal plant near Sharples, West Virginia. Once cleaned, this coal contained 79% ultrafine (minus 325 mesh) material.

3.4.1 Static Breaker

The static breaker shown in Figure 3-4 was designed to break up filter cake by slamming the cake into a pipe wall at high velocity. The primary component of this device was a 5.08 cm (2 in) diameter Plexiglas pipe which had an injection port bored into its side. To capture the dried coal, the pipe lead to an 18.93 L (5 gal) bucket lined with a plastic bag. To retrieve any undried material, an airlock was fitted to the base of the pipe. The injection assembly shown to the right of the pipe was a venturi tube made out of a pipe "tee" and a funnel. The injector was powered entirely by compressed air.

3.4.2 Air Jet Conveyer

Air jet conveyors are most typically used to transport small parts or foodstuffs (Exair 2011). The air jet conveyor was selected as a drying device in an attempt to intrinsically prevent the problem of cake sticking inside the dryer by breaking up the cake without that cake

Figure 3-4. Static breaker device used for low temperature drying.

contacting any solid surface. The device, which is made up of a ring of nozzles, was supposed to shear the filter cake apart with opposing streams of compressed air. The unit selected for testing was a 1.905 cm (¾ inch) line vac model built by the Exair Corporation. A diagram and picture of the line vac are shown in Figure 3-5.

To capture the dried fines, the line vac was screwed into the hose of a 30.28 L (8 gallon 3.5 HP ShopVac brand) wet/dry vacuum. The ShopVac was equipped with OEM medium filter bags. Combined in series, the two devices moved 3.693 m^3/min (130.4 CFM) of air with 60% of

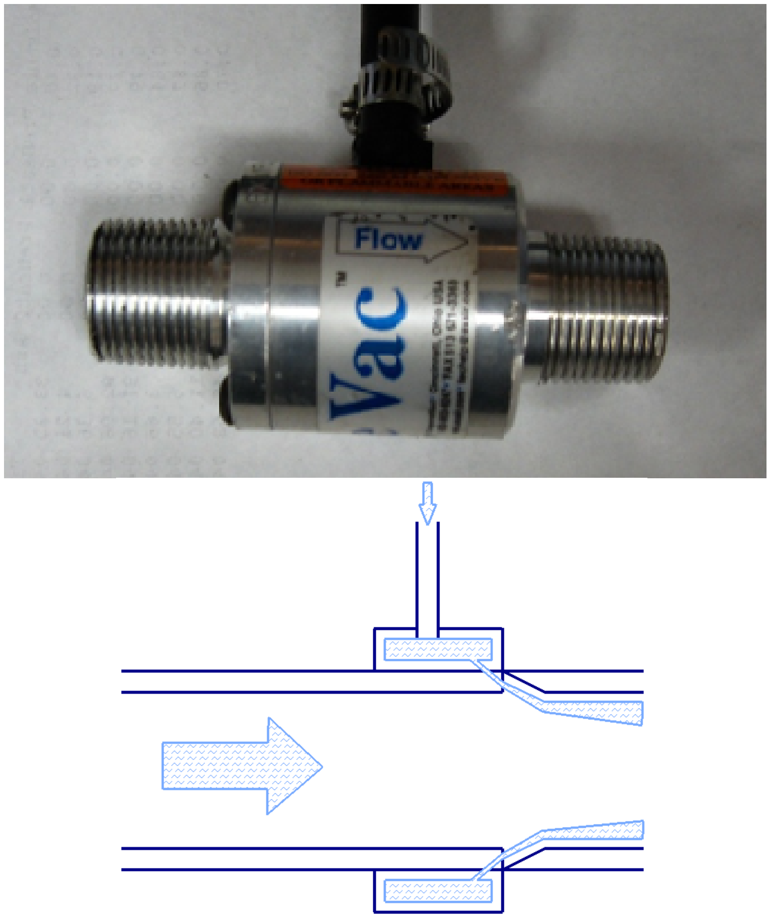

Figure 3-5. Air jet conveyor used for low temperature drying.

that volumetric flow originating as compressed air. Together, the two machines produced suction so strong that the coal didn't need to be poured into the line vac. Instead, the coal was spread out in a line and the device slowly moved down that line sucking up coal. Temperature and humidity readings were taken from inside the ShopVac prior to starting each test. This was necessary since the compressed air the line vac adds to the flow was both drier and cooler than the ambient air.

3.4.3 Centrifugal Fan

Centrifugal fans are popularly used as blowers for furnaces or as exhaust fans for pollution control. They consist of many small blades mounted on a hub. As the hub spins, air is drawn into its center and then forced radially outwards. The fan housing then guides the air in whatever direction the manufacturer desired. The centrifugal fan was selected as a potential drying device because it's small blades spinning a high speeds appeared to be an excellent way of breaking up and dispersing filter cake. An exploded view of a centrifugal fan with backward curved blades is shown in Figure 3-6. The blower selected for the experiment was a 43.86 W (1/17 hp) unit equipped with two 10.16 cm (4 in) forward curved fan wheels, only one of which was used for drying coal. This fan is shown in Figure 3-7 set up to receive filter cake. The fan was feed from a vibratory feeder and the same ShopVac used to collect dried fines from the air jet conveyor was attached to the fan exhaust. Together in series, the fan and ShopVac pulled 2.277 m^3/min (80.4 CFM) of air.

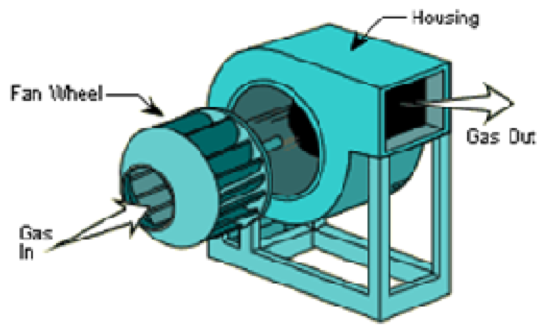

Figure 3-6. Centrifugal fan exploded view. (EPA 2010)

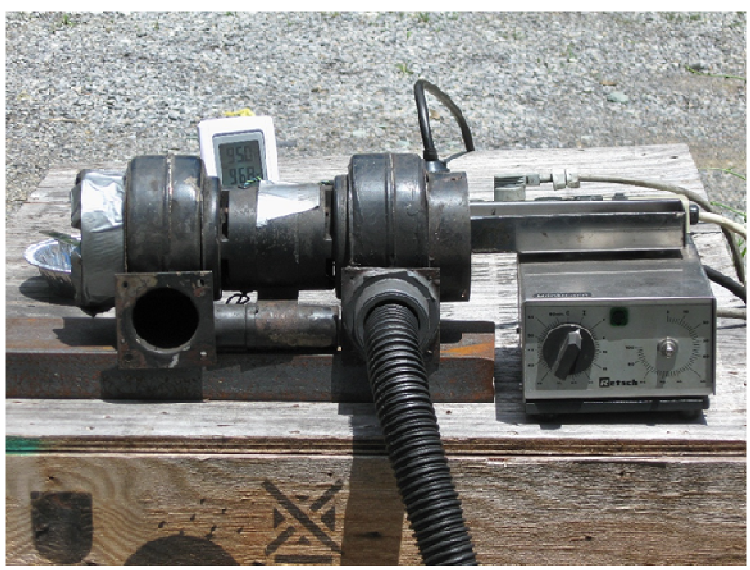

Figure 3-7. Centrifugal fan setup used for low temperature drying.

4.0 RESULTS AND DISCUSSION

4.1 Cleaning

Cleaning results are hard to quantify because the goal of cleaning was to remove liberated clay particles, and an ash analysis does not differentiate between free clays and noncombustibles bound within the coal particles. Yet, the importance of effective cleaning was still apparent in the dewatering results. When triple floated, a sample from the Clarksburg impoundment could be filtered down to 17.3% moisture. When the Clarksburg sample was only floated twice, the filter cake contained a higher moisture content of 23.6%.

4.2 Dewatering

Figure 4-1 shows how each of the three dewatering methods performed based on the fraction of ultrafine (minus 325 mesh) particles in their feed. The dashed line at 22% moisture represents the maximum moisture that can be effectively fed to a low temperature dryer without creating operational problems such as sticking and plugging. Inspection of the data reveals agglomeration followed by centrifugation can dewater even the finest of feeds to the level where they can be put through a dryer. This makes that process appropriate for pond reclamation projects where the size distribution of the feed can vary wildly. Vacuum filters utilizing dewatering aids can stay below 22% moisture all the way up to 60% ultrafines. Therefore, this approach may work well on flotation product from preparation plants where they do not deslime the flotation feed. Material that is coarse enough to be dewatered below 22% with just vacuum filters is unlikely to be in need of drying as the more advanced dewatering methods could be used to lower its moisture instead.

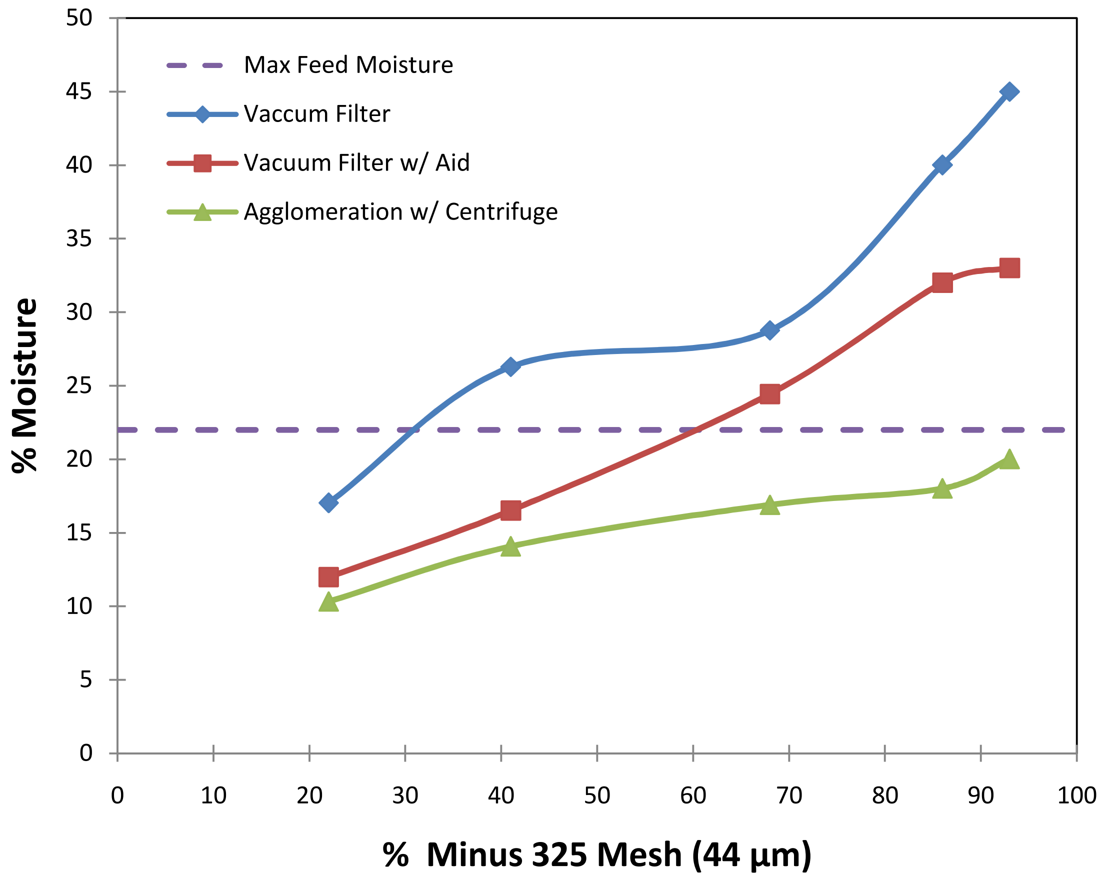

Figure 4-1. Comparison of dewatering methods.

4.2.1 Static Breaker

The static breaker could successfully produce coal with less than 1% moisture but suffered from recovery problems. Figure 4-2 provides an overview of the moistures and recoveries achieved under different operating conditions. In this case, all the coal samples were cleaned by oil agglomeration. The tests marked as intermittent feed were spooned into the injector by hand whereas the constant feed tests utilized a vibratory feeder. Both of these data sets used coal that was minimally dewatered with some samples containing moistures as high as 40%. The coal used in the final data set was dewatered in the centrifuge for a full minute before

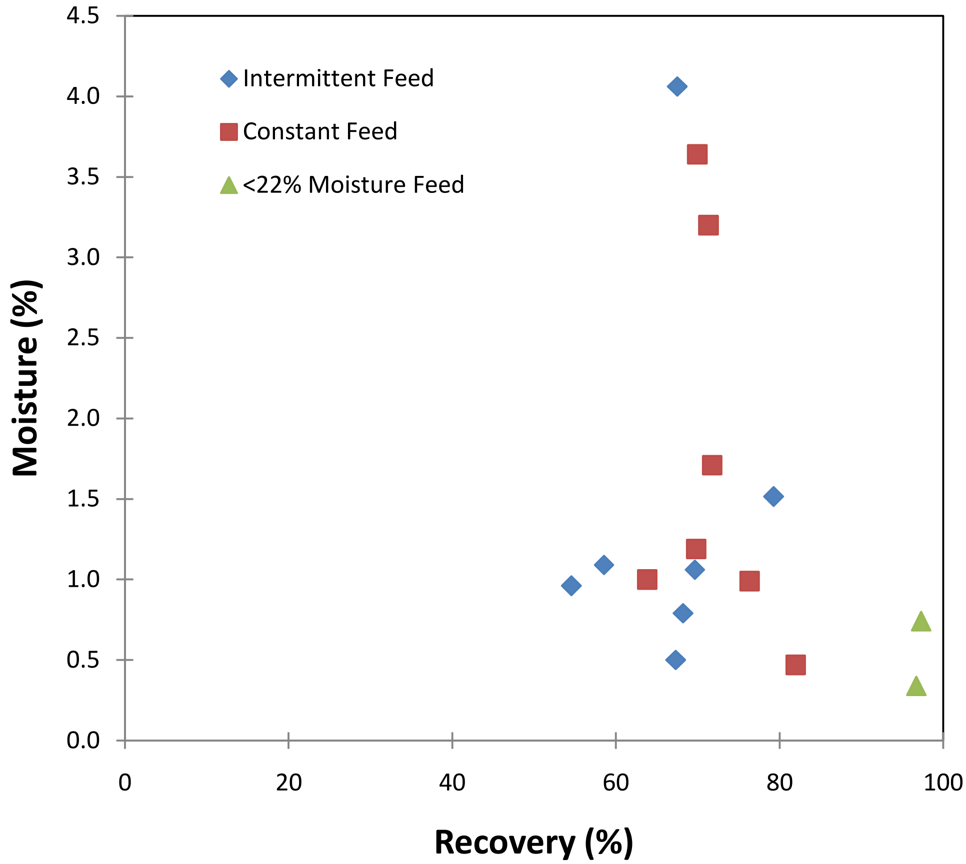

Figure 4-2. Overview of static breaker test results.

being put through the dryer. These fully dewatered samples were also fed to the injector using a vibratory feeder.

Recovery and moisture both increased when using the static breaker with a constant feed rate instead of an intermittent one. On average, the recovery increased from 65% to 72% and the product moisture increased from 1.4% to 1.7%. Using the centrifuge to dewater the feed below 22% moisture provided even larger improvements, with average recoveries and moistures to 97% and dropping 0.5% respectively.

The failing of the static breaker lies in how the rejects manifest themselves. Pieces of filter cake that fail to break apart do not simply bounce off the wall and fall to the bottom of the pipe; instead they stick to the wall upon impact. As more and more pieces stick to the wall a finger of rejects grows across the pipe to block the injection port. The rejects had the consistency of packed clay and striking the pipe wall was ineffective in dislodging the blockage. This plugging phenomenon occurred in all tests and not just those using high moisture feed. In any case where recovery was less than 100% the device would eventually become clogged. The only effective method of removing the blockage was to install a bolt opposite the injector which could push the rejects off the wall. Unfortunately this solution was deemed impractical for large scale use.

4.2.2 Air jet conveyor

Table 4.2-1 shows the test results for the air jet conveyor. Required sweep air refers to the

Table 4.2-1. Air jet conveyor results.

Temperature (°F)	**74**	**74**	**76**	**74**
Relative Humidity (%)	55	48	50	48
Dry Time (min)	0.5	1.5	2.5	2.0
Feed Moisture (%)	22.2	27.4	27.7	20.7
Product Moisture (%)	3.4	10.7	11.6	5.4
Rejects Moisture (%)	22.6	27.2	21.7	14.8
Combined Moisture (%)	9.3	21.2	11.8	5.9
Recovery (%)	80.0	44.0	98.2	95.5
Sweep Air Required (ft^3)	59.2	34.0	36.5	29.3
Sweep Air Actual (ft^3)	65.2	195.6	326.0	260.8
Actual/Required Air	1.1	5.8	8.9	8.9

amount of air that should have been necessary, as calculated by the low temperature drying model, for the moisture reduction achieved by the dryer. Inspection of data reveals that the conveyor never reaches moistures as low as those from the static breaker, 3.4 instead of 0.5%. Moreover, the conveyor can only attain higher recoveries when given copious amounts of extra air. A 98.2% recovery was achieved using the air jet as opposed to the static breaker's 97% and this required almost 9 times as much air as should have been necessary. The higher product moistures are likely the result of incomplete breakup of the filter cake as small pieces of intact cake could be found in the filter bag.

The relatively similar temperatures and humidities of the four tests are a result of the large volumes of sweep air that originated as compressed air to run the air jet conveyor. The drying times varied between 0.5 and 2.5 minutes, first in order to try to match the calculated amount of required air and later to see if a slower feed rate could improve product moistures. More air did help with the feeds containing greater than 27% moisture. The high moisture test that used only 5.8 times the required airflow had a 10.7% product moisture and a poor recovery of 44%. When the amount of air was increased to 8.9 times the required airflow, the product moisture did climb up to 11.6%, but recovery leapt up to 98.2%. The effect of extra air was also apparent with the feeds closer to 22% moisture. Increasing flow from 1.1 times to 8.9 times the required rate brought product moisture up to 5.4% from 3.4%, but increased airflow also raised recovery from 80% to 95.5%.

What the air jet conveyor could do that was impossible for the static breaker was to accept high moisture feeds without plugging. The device appeared to be self cleaning since the compressed air jets blasted free any buildup inside the conveyor tube. This also led to a notable difference in the location of the rejects. The static breaker's rejects where located at their first point of impact, while those produced by the air jet conveyor where found throughout the hose that connected the conveyor to the Shop Vac. The buildup seemed especially concentrated on the ribs of the hose. It is possible that given a smooth passage all the rejects would have passed into the filter bag without sticking.

The row marked “combined moisture” in Table 4.2-1 represents what the moisture would be if the rejects and product were blended together. This blending does little for the samples with high feed moistures, since the 11.8% and 21.1% combined moistures do not meet the project goal of less than 10% moisture. However, if the feed moisture is kept below 22%, blending can provide a 100% recovery while providing single digit moistures.

4.2.3 Centrifugal Fan

Table 4.2-2 shows fan performance when operating under a variety of weather conditions. Although the centrifugal fan produced moistures slightly higher than the static

Table 4.2-2. Centrifugal fan dryer results.

		Moisture (%)				Sweep Air		
Temp. (ºF)	RH (%)	Feed	Product	Rejects	Recovery (%)	Required (ft^3)	Actual (ft^3)	Actual/ Required
61	79	19.1	1.0	16.0	72.3	163	80.4	0.49
58	92	21.7	2.1	16.0	75.9	523.6	321.6	0.61
60	42	20.1	1.1	4.1	92.4	61.1	80.4	1.32
63	94	21.4	1.1	4.0	94.9	415.5	937.5	2.26
70	84	21.5	0.9	3.2	95.2	238.2	522.6	2.19
79	29	19.4	1.3	2.7	96.3	34.3	32.2	0.94
65	42	19.5	1.6	0	100	42.5	80.4	1.89

breaker, this device suffered from few of the same blockage problems. As long as the feed moisture did not significantly exceed 22%, the fan would not plug. The buildup which formed under normal operating conditions was low in moisture (below 4.1%). This indicates the material had dried and was similar to buildup which could be found on any fan with a large amount of particulate in the air flow. However, if the fan was fed unevenly, given feed moistures exceeding 22% or used with significantly less than the required amount of air, then stable deposits of high moisture (>16%) material would build up on the blades and the fan would plug. Choke feeding was distinctly unsuccessful as there was little to no increase in product moisture (2.1% and 1.0%) and recovery dropped significantly (75.9% and 72.3%). In contrast, the two samples with feed moistures under 20% produced the highest recoveries (96.3% and 100%) and in one case no detectable amount of coal remained on the blades. The fan also made very efficient use of its air. The highest successful ratio of actual-to-required air was 2.26 and the lowest was 0.94. For these ranges, and all the conditions in between, recoveries above 92% and product moistures below 1.6% were readily attainable. The process was even successful when tested in 94% humidity air with results of a 1.1% product moisture and a quite respectable 94.9% recovery.

The centrifugal fan was promising enough to be tested on more than the samples from the Cardinal cyclone overflow. Additional samples tested included material from three impoundments that were under consideration for pond reclaim operations. These samples were from Trans Alta WA, Alden KY, and Clarksburg WV. The fan's cutoff feed moisture was 22% and these samples were significantly coarser than the Cardinal overflow, making them excellent candidates to test whether feeds prepared without an oil agglomeration step could be dried effectively using low temperature drying. To investigate this possibility, all three of the pond samples were prepared both by agglomeration-centrifugation and by flotation-filtration. The test

Table 4.2-3. Pond sample fan dryer results.

	Agglomerated & Centrifuged			Floated & Filtered		
Pond	Trans Alta	Alden	Clarks-burg	Trans Alta	Alden	Clarks-burg
% Ultrafine (Minus325 mesh)	69	27	28	69	27	28
Cake Moisture (%)	21.4	21.6	22.3	23.0	14.4	17.3
Product Moisture (%)	0.9	1.6	1.2	0.5	1.5	1.0

results are shown in Table 4.2-3. The Trans Alta sample was treated with 2.5 kg/tonne (5 lb/ton) of Reagent RU dewatering aid, Alden was treated with 1.5 kg/tonne (3 lb/ton) and Clarksburg received none at all.

Both sets of samples were effectively dried and none of them caused buildup on the fan blades with the exception of the filtered Trans Alta. A minor amount of that sample stuck to the fan blades. Unfortunately the actual weight of those rejects is unknown due to the small quantity of buildup and difficulties associated with retrieving rejects from the device without turning the fan on. This buildup was likely due to the filtered Trans Alta containing feed moisture just beyond acceptable limits. Interestingly, the filtered samples all dried to a lower moisture than their centrifuged equivalents. This could be a result of filter cake being more fragile than centrifuge cake and thereby being much more thoroughly broken up in the dryer. Oddly enough, filtration also outperformed agglomeration and centrifugation in dewatering by more than 5% in both coarse pond samples. This unexpected result may be because agglomeration does a relatively poor job of recovering coarse particles. If agglomeration only recovered the minus 149 μm (100 mesh) solids, then centrifugation would not receive the same dewatering benefits that coarser particles provided to filtration.

4.3 Conclusions

While the static breaker produces the lowest moistures, that device also plugs itself on a regular basis and is therefore inappropriate for use on a commercial scale. The air jet conveyor excels at remaining unplugged, but does so at the expense of moisture and air consumption. That60% of final airflow from the air jet conveyor came into the system as compressed air may also prove an obstacle for scaling-up as an industrial dryer. Low temperature drying requires large amounts of airflow and compressing air is an expensive way to achieve that flow. However, the centrifugal fan is efficient in its use of air and produces low moistures without clogging as long as its feed contains less than 22% moisture. That moisture level can be readily achieved with oil agglomeration and centrifugation or, in many cases, with flotation and vacuum filtration (possibly with the addition of dewatering aids).

4.4 Recommendations

The static breaker may be worthy of further experimentation. Its plugging problem may be overcome by changing the shape of the breaker or by injecting coal at an angle against the pipe wall instead of straight at the wall. The air conveyor fails to thoroughly break up the cake and consumes too much air. Therefore, future work with the conveyor should focus on finding an air jet arrangement that can better shred the cake while leaving the generation of sweep air up to an exhaust fan.

The centrifugal fan used in this paper was equipped with forward curved fan wheels. That type of wheel is the most sensitive to particulate buildup, so much so that forward curved fans are rarely used in pollution control systems. There is another type wheel; the radial type where the blades extend straight from the hub. This radial wheel is less energy efficient but it is also less susceptible to particulate buildup (EPA 2010). Future work and scale-up efforts should employ the radial wheel and determine if a change in wheel shape can raise the feed moisture cutoff. If the cutoff can be brought high enough (>24%) then low temperature drying of even the finest coals could occur with common existing dewatering practices instead of pentane agglomeration.

5.0 MODELING AND SIMULATION

5.1 Low Temperature Drying

The new process of low temperature drying dries coal by creating optimum conditions to maximize the rate of natural evaporation of surface water. At terrestrial temperatures and pressures, liquid water is always, however slowly, evaporating. The rate of this evaporation is governed by Langmuir's expression of vapor pressure (Zemansky 1968), which is given by:

$$P = \frac{\dot{M}}{A}\sqrt{2\pi RT/M} \qquad [5.1]$$

where P is the difference between partial and saturated vapor pressures, $\dot{M}$ is the rate of mass loss, A is surface area, R is the gas constant, T is the absolute temperature and M is the molecular weight. The expression is more useful for determining evaporation rate when it is rewritten in the following form:

$$\dot{M} = AP\sqrt{M/(2\pi RT)} \qquad [5.2]$$

Table 5.1-1. Calculated surface area of coal fines.

U.S. Sieve Size	30	50	100	200	325	500
Surface Area (ft^2/lb)	38	77	153	310	530	914
Diameter (μm)	595	297	149	74	44	25
Surface Area (m^2/kg)	7.9	15.8	31.4	63.3	106.4	187.3

Hence, this expression shows that water with a higher exposed surface area will evaporate faster.

Ultrafine coal particles have an exceptionally large surface area per unit weight. This fact is illustrated in Table 5.1-1 where the surface area per unit weight of fines has been calculated for several common sieve sizes. The calculations assume the particles are perfect spheres as this shape provides the minimum possible surface area for a given volume. The table reveals that the minus 0.044 mm (325 mesh) particles have at least 14 times the surface area of the maximum floatable particle size of 0.595 mm (30 mesh) and 3.5 times as much surface area as the normal floatable top size of 149 µm (100 mesh). When spread over such large surface areas, water can

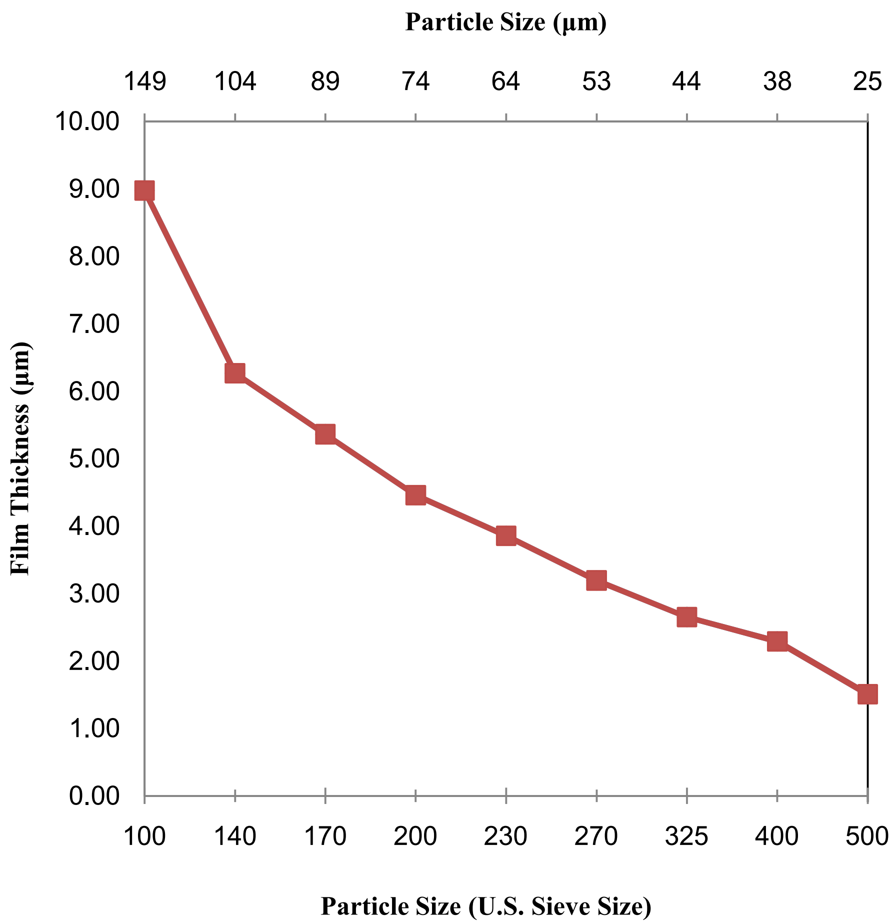

Figure 5-1. Water film thickness on fine coal particles.

be reduced to thin films or small droplets. How thin depends on the moisture content. Figure 5-1 shows equivalent water film thickness based on a moisture content of 22% by weight. Even on the largest particles of 100 mesh, an evenly spread film of water never exceeds a thickness of 9 µm. This thickness drops to 2.7 µm when water is evenly spread over the surfaces of 325 mesh particles.

It is worth noting that the film consistently adds more than 12% to the original particle diameters and 25% to their surface areas. If the new expanded surface area generated by this film

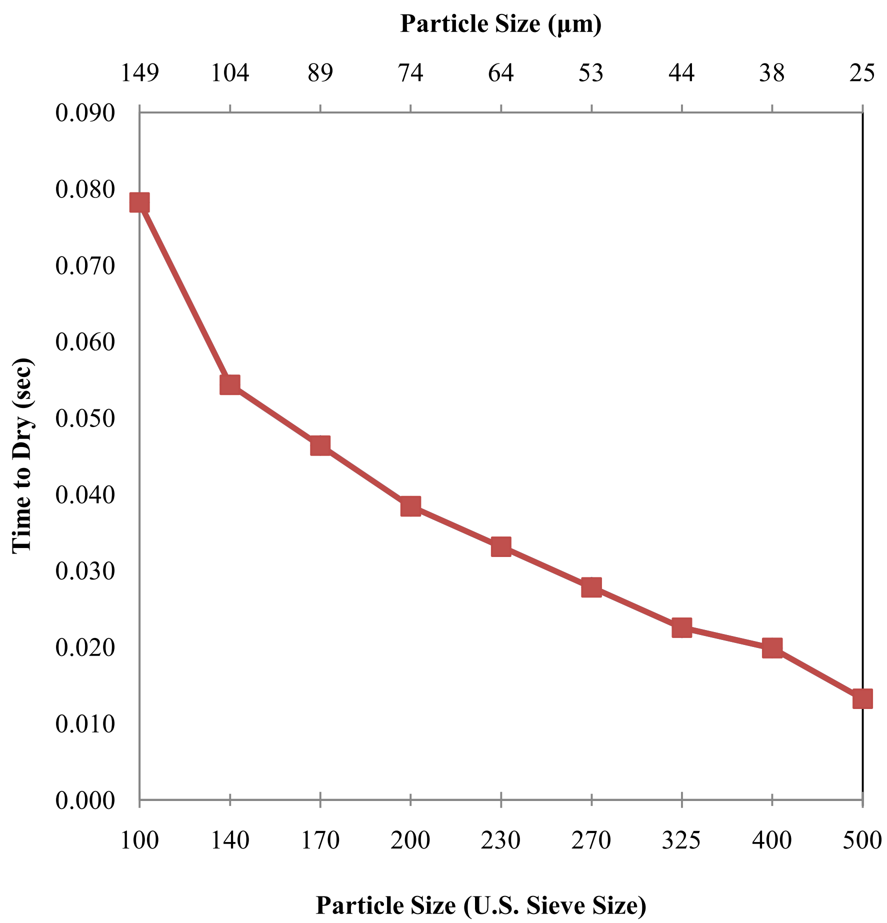

Figure 5-2. Evaporation time for water film on fine coal particles.

is entered into Langmuir's expression, the time it takes for all the water to evaporate can be mathematically estimated. Figure 5-2 shows the time taken for the water films in Figure 5-1 to evaporate completely at 4.44 ºC (40 ºF) and 90% relative humidity. As shown, none of the particles requires even a tenth of a second to dry and on the extreme fine end of the particle size spectrum, the 500 mesh particles dry in almost 1/100th of a second. The 44 μm (325 mesh) particles come in at the low end with a respectable 0.023 seconds. Any of these times, or even an order of magnitude slower, would be more than acceptable rate at which to dry coal.

The evaporation times in Figure 5-2 although impressively short, are almost never achieved for two reasons. First, Langmuir's expression calls for exposed surface area. The full surface area of fine coals is rarely exposed because they are normally packed together, limiting exposure to the outermost layer of particles. Second, the expression assumes that the difference in partial and saturated vapor pressures (P) remains constant as the liquid evaporates. In reality, as the water evaporates, the air immediately around the water's surface is quickly saturated, thereby drastically lowering the vapor pressure. The vapor pressure does rise again due to water vapor diffusing into the bulk air, but this is a slow process (Junk 2010). Therefore, in order to dry coal at rates approaching those in Figure 5-2, all the coal particles must be separated from each other and the air surrounding them replaced with unsaturated air as fast as the water can evaporate. The low temperature drying process attempts to overcome these limitations by fully dispersing the particles via mechanical dispersion and by replacing the saturated air at the surface by pneumatically conveying the particles.

For reference, the relevant calculations for the data presented in Table 5.1-1, Figure 5-1 and Figure 5-2 are provided in Appendix A.

5.2 Model Development

Low temperature drying uses natural evaporation instead of forced boiling like thermal drying. As a result, the process depends heavily on the water carrying capacity of the available air. Once the air is saturated, no further water can be removed. This in turn means that the process is highly sensitive to local weather conditions like temperature and relative humidity. These factors together determine how much water can be carried per unit of air. If conditions are unfavorable, more air can be used to carry away the same amount of water. However, at some critical point, conditions are so poor that the air has no appreciable carrying capacity for moisture.

In order to determine the cutoff weather conditions where low temperature drying becomes impractical, a mathematical model needed to be developed. One that would reveal how much air is necessary to remove a fixed amount of water under different temperature and humidity conditions. The foundation for such a model has already been developed by Luckie for thermal drying. (Luckie 1991) However, some modifications are necessary in order for this model to accurately describe the conditions relevant to the low temperature drying process.

The first modification was to calculate the entering humidity of the air based on weather conditions instead of using a constant 0.01 kg water per kg air (0.01 lb H_2O/lb air) that Luckie assumed. Entering humidity is only of minor concern when designing thermal dryers because the carrying capacity generated by heating the air dwarfs any naturally occurring humidity. However, in low temperature drying, the entering humidity makes up a large fraction of the total carrying capacity of the air; therefore, accounting for the impact of this factor cannot be left to an estimate. The actual entering humidity can be found using relative humidity (%RH) and maximum humidity. Maximum humidity can be calculated from air temperature.

The second modification required a change to the heating calculations so that they no longer include raising the water temperature to 100ºC (212ºF) or lowering the hot water vapor temperature down to the exhaust temperature. In low temperature drying, the water is only heated to the exhaust temperature.

The third and most significant modification only applies in cases when no heat at all is added to the air. The water gets its enthalpy of vaporization from the air whether the air is heated or not. Therefore, if the air is not heated, the air temperature drops when the water evaporates. Colder air carries less water, so that new cooler temperature must be used as inlet temperature for the dryer calculations. A number of correction factors that applied solely to heat loss were also replaced. For reference, both the original thermal dryer model by Luckie and all the modifications required to utilize the model for low temperature drying are summarized in Appendix B.

5.2.1 Unheated Model

A dryer's capacity or cost per ton of product depends heavily on its feed and product moistures. During normal dryer operation the non water part of the feed consumes some portion of the dryer's heating capacity. Thus, a dryer that is performing a large moisture reduction will have a high cost per ton of product, but low product throughput and cost per ton of water removed. In contrast, a dryer performing a small moisture reduction will have a low cost per ton of product, but high product throughput and cost per ton of water removed. 22% moisture was determined in this study to be the maximum allowable feed moisture for effective breakup of filter cake without sticking problems. Consequently, all the tables and figures in this chapter assume 22% moisture feed that is dried down to 1% surface moisture. These values were also used for the unheated dryer model so that the results could be fairly compared to the drying processes that do use heat.

Figure 5-3 shows the calculated million cubic feet per minute (MCFM) of sweep air that a low temperature dryer must maintain to produce one dried ton of coal per hour using unheated

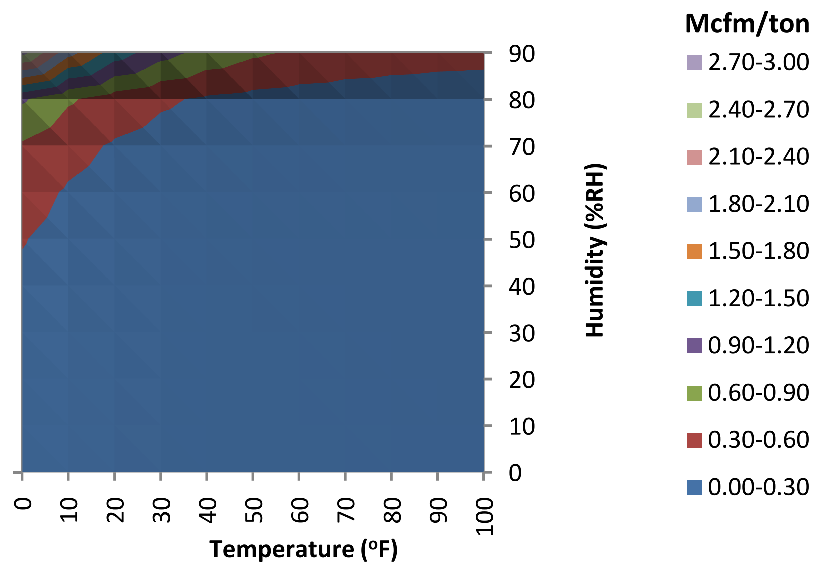

Figure 5-3. Sweep air requirements for unheated air.

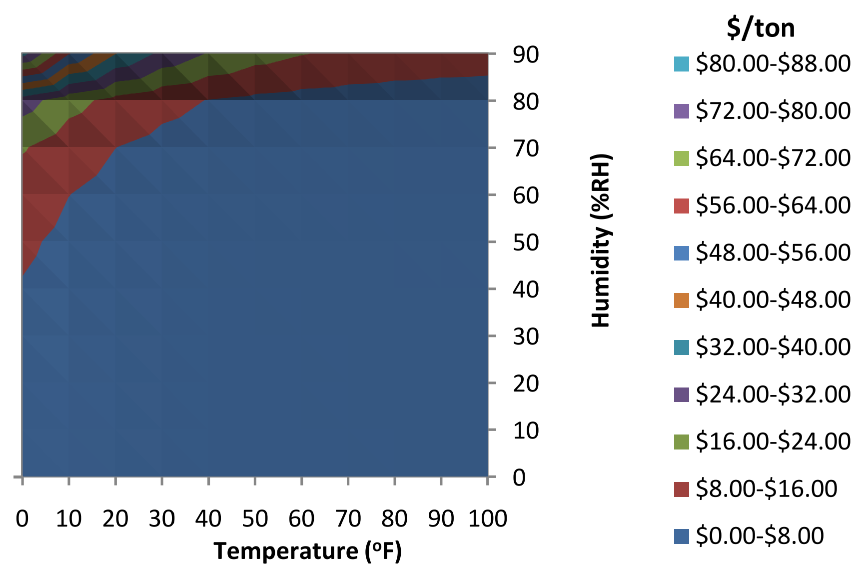

Figure 5-4. Energy cost per ton for unheated air.

ambient air. Inspection of plot reveals that there is a steep increase in the required amount of sweep air when there is a confluence of high humidity and extreme cold. This makes sense in that cool wet air has the smallest water carrying capacity. The range above 80% humidity and below -6.67 ºC (20ºF) is especially bad as the air requirements leaps from less than 14158 m^3/min (0.5 MCFM) to almost 84,950 m^3/min (3.0 MCFM). Moreover, no data is shown for a relative humidity greater than 90% due to the fact that the amount of sweep air required quickly approaches infinity as the moisture in the air nears maximum humidity.

In an effort to compare the low temperature drying method to those that employ heat, the cost of electricity to generate the sweep air, is shown in Figure 5-4. Under most weather conditions, unheated drying uses less than $8/ton worth of energy to dewater the coal. Sweep air costs actually drop below $1/ton of dried product under the ideal conditions of less than 30% humidity and temperatures higher than 21.11 ºC (70 ºF). Considering that without drying, the ultrafine coal is a waste product with zero dollar value. This operating cost would be quite tolerable for most coal operations. However, at a higher humidity and a lower temperature, the cost spirals out of control passing $19/ton at 80% humidity and -12.22 ºC (10 ºF) and culminating in an energy bill of $84/ton at 90% humidity and -17.77 ºC (0ºF). The former cost is likely to be expensive enough to start making the process unfeasible for steam contracts and the later price could only be supported on the most lucrative of metallurgical contracts. Consequently, a dryer using ambient air would not operate dependably during the cold winter months or in extremely humid climates. In most of the U.S. coal fields, this would limit the use of unheated air to specific seasons or periods of fair weather.

5.2.2 Low Heat Model

The results presented in the previous section indicate that drying with ambient air is not possible under all weather conditions and, therefore, the low temperature drying process may not be suitable for year round industrial use. A high relative humidity renders the dryer inoperable because air that is already saturated cannot carry away moisture. The only way to make low temperature drying an all-weather process is to increase the carrying capacity of the air. The least costly way to increase the moisture carrying capacity of air is to heat it. Heating does not actually remove any of the moisture from the air, but simply increases the air's ability to hold more moisture. The maximum humidity of air is exponentially related to its temperature. Each degree the temperature of air is raised adds more water carrying capacity than the last degree the air was raised. This approach is still different from thermal drying in that mild heating is only increasing the amount of water the sweep air can carry and is not raising the water to its boiling point.

Figure 5-5 shows the amount of sweep air necessary if the overgrate/drying chamber is operating at 48.89 ºC (120ºF). The addition of heat reduces the average sweep air required by two orders of magnitude and shifts the high air requirements away from the cold humid to the hot humid intake air. The latter is a result of the hot air undergoing a small temperature rise compared to the cold air and thus has a correspondingly low rise in carrying capacity. While the air requirements do rise sharply in the range above 80% humidity and 32.22 ºC (90 ºF) the increase is not that much more air in absolute terms. To operate at 100% humidity and 37.78 ºC (100ºF) the low heat dryer takes 424.8 m^3/min (15,000 CFM) more air than the dryer does on average. This is compared to an increase of 79,290 m^3/min (2.8 MCFM) for the unheated dryer to run under equivalently poor conditions. But this reduction in air flow is achieved at the expense of heat to raise the air temperature.

To demonstrate the tradeoff between heat and airflow are worthwhile the combined cost of the power to generate the sweep air and cost of the Btus to heat the air are shown in Figure 5-6. Not only can the low heat dryer now operate under all weather conditions the device does so at a third of the average energy cost of the unheated dryer, $1.80 instead of $6.16.

It also provides a normalizing effect on prices as its maximum and minimum energy costs are $2.56 and $1.45 respectively. If the other costs associated with the process come in as reasonably, any coal that is worth cleaning in a processing plant can be profitably put through a low heat dryer.

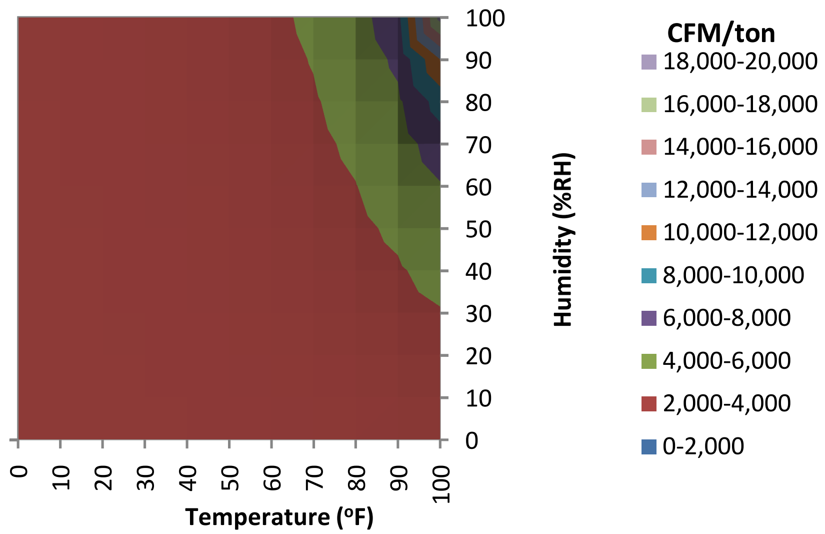

Figure 5-5. Sweep air requirements for low heated air.

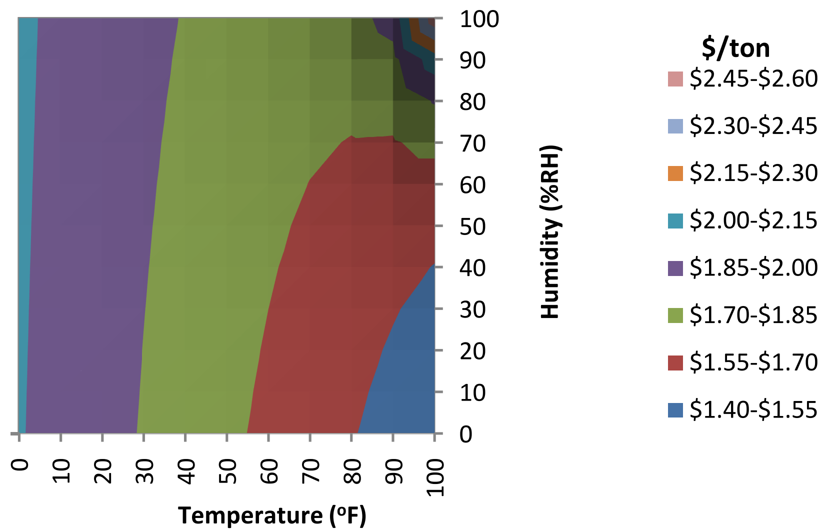

Figure 5-6. Energy cost per ton for low heated air.

Figure 5-6 demonstrates that with mild heating low temperature drying can be an all-weather process and operate far cheaper than a dryer using ambient air. This is while maintaining an overgrate temperature of 48.89 ºC (120ºF) and a undergrate temperature that never exceeds 241.67 ºC (467ºF). That is a 30% and 51% drop in the respective temperatures compare to the average fluidized bed dryer. Enough to significantly reduce if not eliminate the pollution normally associated with thermal drying. For further comparison with existing thermal processes, Figure 5-7 shows the sweep air required to operate a thermal dryer with an overgrate temperature of 61.11 ºC (151ºF). 61.11 ºC is the lowest temperature at which any known fluidized bed dryer operates. Overall the thermal dryer uses less than 40% of the air of the low heat dryer, albeit at a much higher temperature.

The energy costs to operate the low heat dryer are shown in Figure 5-8. With an average cost of $1.62/ton, it is easy to see why these units were so popular while they were permissible. The thermal dryer normalizes the cost of drying even more than the low heat dryer with only $0.22 cents difference in energy consumption over the whole range of weather conditions. On average the thermal dryer takes $0.18/ton less energy than the low heat dryer. Ironically, this is largely due to the low heat dryer consuming more Btus than the thermal one. Although operating at a much high temperature the thermal dryer has to heat only a fraction of the air that the low heat dryer does.

For reference, the data presented in Figure 5-3 through Figure 5-8, as well as other outputs of the dryer models, has been summarized in Appendix C.

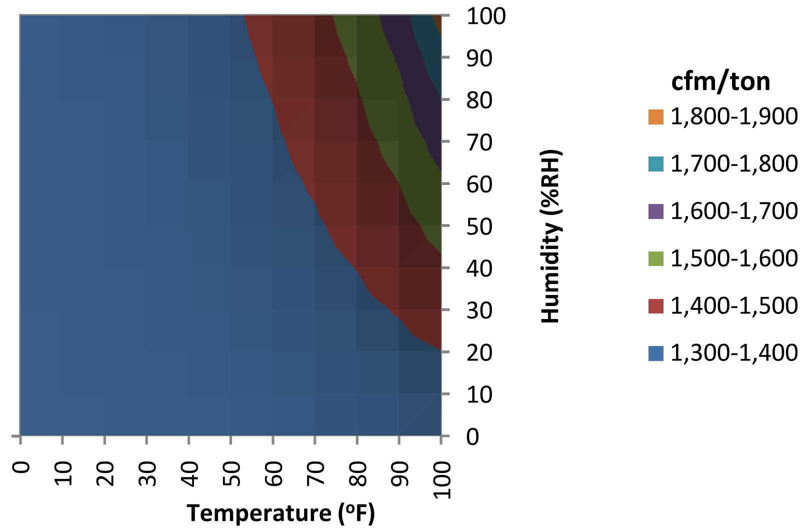

Figure 5-7. Sweep air requirements for high heated air.

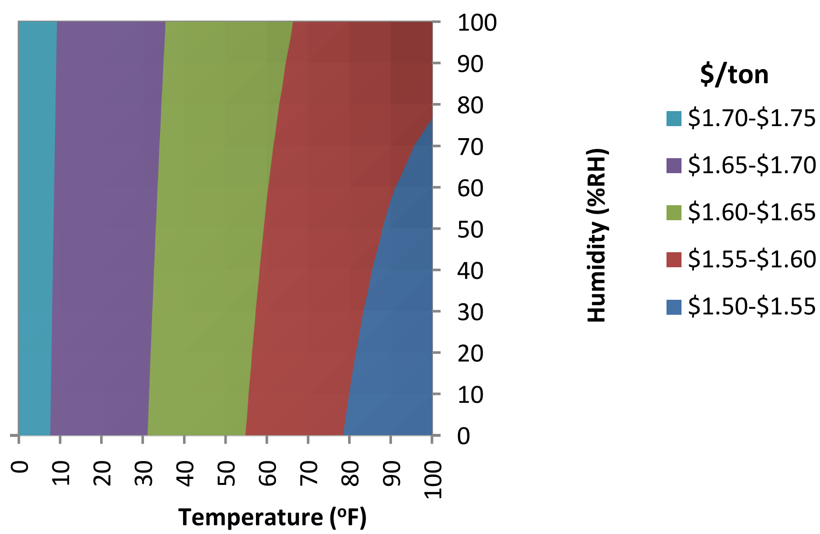

Figure 5-8. Energy cost per ton for high heated air.

5.3 Model Validation

To demonstrate that an expanded surface area is necessary to facilitate effective drying an experiment was performed between broken and unbroken wet coal samples. The first sample was put through the centrifugal fan in 1 minute thus shredding the filter cake and exposing coal particles to 2.28 m^3 (80.4 ft^3) of ambient air at 15.56 ºC (60ºF) and 42% relative humidity. The second sample was held in a pan and placed under a 2.209 $m^{3/}$min (78 CFM) flow of dry air for 10 min. This second flow of air was both generated and dehumidified by passing that air through a compressor. Because the sample sizes and feed moistures did not match exactly, the total weights of water removed were compared. The first test where the filter cake was thoroughly comminuted lost 9.35g (0.33 oz) of its original 9.64g (0.34 oz) of water content. As a rate of loss this would be 9.35 g/min (0.33 oz/min) or 4.10 g/$m^3$of air (0.00410 oz/ft^3). The second intact sample lost 3.4 g (0.12 oz) of its original 5.95g (0.21 oz) of water and its rate of loss would be 0.34 g/min (0.012 oz/min) or 0.15 g/m^3 of air (0.00015 oz/ft^3). Ergo the increase in surface area that results from the comminution of the filter cake allows water to be removed at almost threefold the rate of an intact sample, while using just over a tenth of the air. This is the case even if the broken filter cake is dried with wet air and the intact sample with dry air.

Other than increased surface area another possible driving force behind the swift evaporation of water from the fines' surface is the Gibbs Thomson effect in which small droplets of liquid exhibit vapor pressures higher than they would as flat films. When a droplet is sufficiently small, the surface tension of the liquid squeezes the whole droplet, effectively raising its vapor pressure. Artificially higher vapor pressures result in higher rates of evaporation or evaporation at humidites where evaporation would otherwise be impossible. How small a droplet needs to be to take advantage of this effect can be calculated using the equation:

$$P = P_o exp\left[\left(\frac{\bar{V}}{RT}\right) \times \left(\frac{2\gamma}{R_{curvature}}\right)\right] \qquad [5.3]$$

Where P is the new vapor pressure, P_o the original vapor pressure, $\bar{V}$ the specific volume of the liquid, R the gas constant, T the absolute temperature, γ the surface tension and R the radius of the droplet. The effect of changing R under a constant temperature of 298.15ºK can be seen in Figure 5-9. Through inspection it can be seen that droplets larger than 0.1 µm are not going to experience an increase in vapor pressure larger than 10 Pa. Under most terrestrial conditions the vapor pressure of water is measured in the hundreds or thousands of Pascals so any droplet over 0.1 µm isn't going to evaporate in a manner appreciably different from how a flat film would. Therefore, extremely few of the coal particles entirely enclosed in water could benefit from this effect. There is also little chance of droplets that small forming on the surface of the particles. Even the largest ultrafine coal particle (44 µm) does not have enough surface

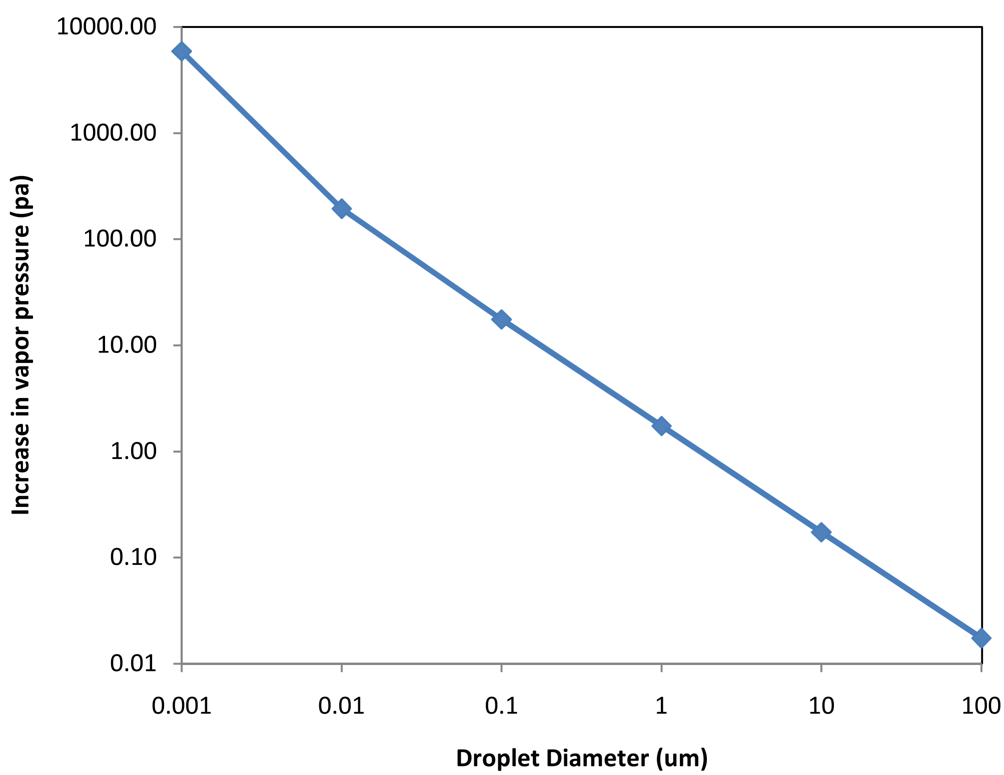

Figure 5-9. Example of the Gibbs Thomson Effect.

area to accommodate 22% of its weight in moisture in the form of 0.1 μm droplets without them coalescing into an encompassing film. If water droplets are being shorn from the coal's surface during the drying process they may be small enough to benefit from the Gibbs Thomson effect but no experiments were performed to detect such droplets.

The effect may explain why, even under the most ideal conditions there are minute amounts of surface water remaining after low temperature drying. When Gibbs Thomson is applied to a convex surface, like that of a droplet, the effect increases vapor pressure. Yet when applied to a concave surface, like that which forms inside a capillary, the effect decreases vapor pressure. So, if two coal particles failed to separate during the during the shearing step as the water evaporated, the water would recede farther and farther in to the space between particles and a concave surface with a smaller and smaller radius would be exposed to the air until the vapor pressure was so low evaporation stopped. In the same way water could become trapped in sub micron fissures in the surface of the coal particles. An illustration of how concave water surfaces could occur between particles or in fissures is shown in Figure 5-10.

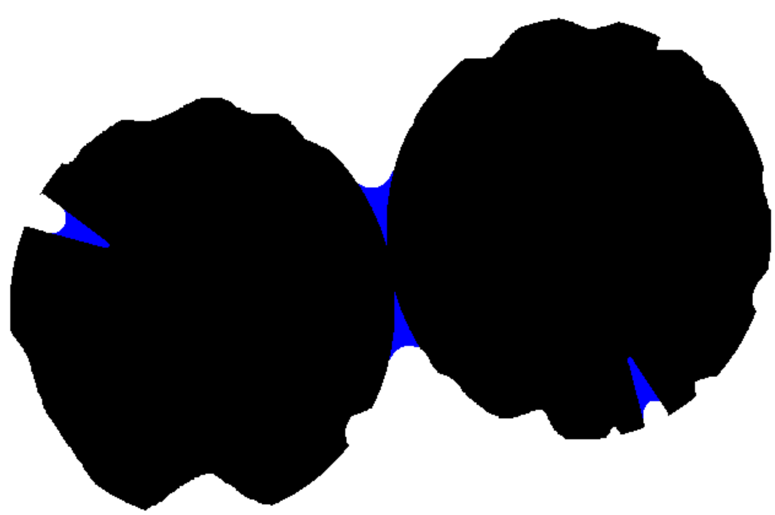

Figure 5-10. Concave Water Surfaces

5.4 Conclusions

Based on the energy consumption predicted by these models low temperature drying with unheated air is only economical in warm dry climates due to the process' vulnerability to changing weather conditions. Yet when accompanied with mild heating, low temperature drying becomes an economical method of dewatering fine coal under all weather conditions. Thermal dryers are a significant source of air pollution because they expose coal to high temperatures without combusting it. The average overgrate temperature of a thermal dryer is 171ºF and they commonly operate with intake temperatures in excess of 900ºF. However, a low temperature dryer can achieve a low moisture product without exceeding an overgrate of 120ºF or an undergrate of 467ºF. These drastically lower temperatures should allow the low temperature dryer to function with few of the environmental problems associated with thermal dryers.

5.5 Recommendations

The higher the overgrate temperature, the lower the operating costs for the dryer but at some temperature volatile organic compounds (VOCs) will start to be released from the coal. The modeled temperature of 48.89 ºC (120 ºF) was selected in an attempt to run as cold as possible while maintaining all-weather capabilities. If that temperature is raised to 61.67 ºC (143ºF) the low temperature dryer has the same energy costs as the thermal dryer operating at 61.11 ºC (151ºF) but then the dryer is no longer operating at a "low" temperature. Furthermore, it is not readily apparent whether it is the extended exposure to the high temperatures in the drying chamber or the brief exposure to the extremely high temperatures at the intake that cause the coal to release pollutants. Future work will have to determine what conditions lead to the creation

VOCs and tailor the operating parameters of the dryer to minimize cost while preventing air pollution.

6.0 SUMMARY AND CONCLUSIONS

The project goal was to dewater ultrafine coal particles below 10% moisture. This was successfully achieved through a new process called low temperature drying. Low temperature drying evaporates water from coal fines by exposing the entire surface area of those fines to air that is constantly replaced as that air becomes saturated with water vapor. A number of relevant discoveries were made about low temperature drying. Revelations about how the air carries away the moisture include:

- Pneumatically conveying the fines is an effective method of continually refreshing the saturated air around the water's surface.
- The volume of air required can be accurately predicted using the modified thermal dryer equations.
- The process works poorly with cold, humid air.
- Warming the air can make the process work well under any reasonable weather conditions. Drying chamber temperatures as low as 48.89 ºC (120 ºF) should be effective.
- Warming the air also drastically reduces the required volume of sweep air and lowers overall energy costs.

Discoveries about how to fully expose the surface of the fines include:

- The static breaker design produces moistures below 1% but this design is also prone to plugging.
- The air jet conveyor excels at remaining unplugged but produces moistures greater than 3%. Moreover, to achieve high recoveries the air jet must consume almost ninefold the volume of air that should be required to dry the fines.

- The centrifugal fan regularly dries fines below 2% moisture and does not plug when it's feed contains less than 22% moisture.
- Feeds containing less than 93% minus 44μm (325 mesh) material can be dewatered below 22% moisture through agglomeration with pentane and centrifugation.
- Feeds containing less than 60% minus 44μm (325 mesh) material can be dewatered to below 22% moisture through flotation and aided vacuum filtration.

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APPENDICES

A. Evaporation Appendix

This appendix contains the calculations that were performed to determine the evaporation rates of water from fine coal particles. These calculations demonstrate how the evaporation rates of surface water were calculated for different size fractions of coal. The gas constant R was valued at 8.314 J/(K*Mol) and a molecular weight of 0.018kg/mol was used for water.

$$\frac{\dot{M}}{A} = P\sqrt{M/(2\pi RT)}$$

Relative humidity is the ratio of the partial vapor pressure to the saturated vapor pressure. The later was found on a chart in Compressed Air and Gas Data by Ingersoll-Rand.(Gibbs 1971) Thus relative humidity can be used to find the difference between partial pressure and saturated pressure.

$$RH = P_{par}/P_{sat} \times 100$$

$$P = P_{sat} - P_{par}$$

To calculate the surface area A the total number of particles was found. This was done by taking the volume and then weight of the individual coal particles and dividing the total amount of coal by the individual particle weight. Particles were assumed to be perfect spheres with a density of 80 lb/ft3 (1281 kg/m3)

$$V = \pi d^3/6$$

$$W_{total} = \rho V_{part} n_{part}$$

Subsequently the total number of particles was multiplied by their individual surface area to obtain the total surface area of the coal.

$$A_{part} = \pi d^2$$

With fine particles the thickness of the surface water significantly contributes to the final diameter of the combined particle and therefore the surface area. To correct this, the volume of water was calculated from 22% of the coal's weight and a density of 62.4 lb/ft3 (1000 kg/m3). The thickness of the water film was then found by dividing the water volume by the surface area of the coal. Twice this thickness was added to the original coal particle's diameter to find the diameter for the combined particle.

$$L_{water} = V_{water}/A_{coal}$$

This combined diameter was then used to calculate the surface area an the combined particle and that area was multiplied by the original number of original coal particles to find the total exposed surface area of the water.

$$A_{total} = A_{cpart}n_{part}$$

The evaporation rate can then be found by reentering the total area into Langmuir's evaporation expression. Finally the dry time can be solved for by dividing the mass of water (22% mass of coal) by the evaporation rate. The surface area does change as water evaporates but this change had little impact on evaporation time in absolute terms.

B. Drying Appendix

This appendix contains the calculations for determining sweep air, operating temperatures and costs. The original formulae came from the 5th edition of Coal Preparation's Thermal Dewatering Chapter written by P.T. Luckie and J.W. Leonard III.

INPUT VALUES

Five inputs are required to begin.

A. TPH wet FEED

B. % H_2O in FEED (wet basis)

C. ºF ambient FEED temperature

D. % H_2O in Product (wet basis)

E. ºF PRODUCT temperature

All the calculations in this paper used A=1.27 B=22 C=60 D=1 and E is also called the overgrate temperature.

MASS BALANCE

Using these inputs a mass balance can be performed.

F. TPH dry FEED $= A \times (100 - B)/100$

G. TPH PRODUCT $= F \times 100/(100 - D)$

H. TPH of H2O to be removed $= A - G$

I. TPH of H2O in PRODUCT $= G - F$

To determine how much air will be necessary to carry away the water the maximum humidity of the air must be know. Maximum humidity is measured in lbs H2O per lbs of dry air. Temperature is in ºF and atm is atmospheric pressure in psi.

$$maximum\ humidity = \frac{18}{29}/(atm^{\left[\frac{6914.15186}{Temp+378.4}-14.39851)\right]}-1)$$

The carrying capacity of the water is the difference between this maximum humidity and whatever water the sweep air entered the dryer with. Luckie assumes that the sweep air enters with a humidity of 0.01 lbs H_2O per lb of dry air. This is a safe assumption because thermal dryers elevate the air temperature enough that variations in this entering humidity are dwarfed by the raise in the max humidity created by heating the air. Low temperature dryers by definition don't elevate the temperature nearly as high and so are much more vulnerable to the entering humidity of the sweep air. To get the actual entering humidity the max humidity is multiplied by the relative humidity of the ambient air that the dryer is operating in.

$$hum_{ent} = hum_{rel} \times hum_{max}$$

Now in reality a dryer cannot fully saturate its sweep air but near complete saturation is possible. According to Luckie thermal dryer designers like to achieve 90-95% relative humidity (RH) in their exhaust air. In this paper the relative humidity of the exhaust air was taken to be 95%. So the difference in humidities of the entering and exiting air is:

$$[hum_{max} \times RH/100] - hum_{ent}$$

And the tph of sweep air equals

$$H/[hum_{max} \times RH/100] - hum_{ent}$$

ENTHALPY BALANCE

Water's enthalpy of vaporization was taken to be 970Btu/lb and the following specific heats where used for the materials being heated or cooled during the drying process.

	Cp, Btu/lb/ ºF
Water	1
Water Vapor	0.46
Coal	0.3
Dry Air	0.46

Using these constants and the outputs from the mass balance an enthalpy balance can be performed.

The heat lost through water evaporation

J. Btus to raise 1 lb H_2O to 212 ºF $= 212 - C$

K. Btus to vaporize and cool 1 lb H2O to product temperature

$= 970 + 0.46(E\text{-}212)$

L. Btus to evaporate 1 lb H_2O $= J + K$

M. Btu/hr required to remove H_2O $= H \times L \times 2000$

The heat lost to the PRODUCT through temperature elevation

N. Btu/lb of PRODUCT moisture $= E\text{-}C$

O. Btu/hr in dry FEED $= 0.30 \times N$

P. Btu/hr lost in PRODUCT $[N \times F + O \times I]$

Q. Inlet temperature of air: does not have to equal C

The Enthalpy balance is where most of the modifications to the standard equations had to be made in. In all cases:

N_a. Btu/lb of Product moisture $= [O \times F + N \times I]$

This is what Luckie meant just not what he wrote. This is confirmed in his examples. In the lower temperature processes water isn't being heated to boiling so:

J_a. Btus to raise 1 lb H_2O to 212 ºF $= E\text{-}C$

K_a. Btus to vaporize 1 lb H_2O $= 970$

FINAL VALUES

R. MAX HUM: use the maximum humidity formula but with:

$temperature = E - 15$

This ensures that the water vapor will not condense in the ductwork as the vapor loses heat on its way out of the dryer.

S. lb dry air/hr need to dry FEED $= (H \times 2000)/(R\text{-}hum_{ent})$

T. Btus released per lb of dry air $= [1.02 \times (M + P)]/S$

1.02 corrects for radiative losses of hear

U. ºF UNDERGRATE temperature $= [E + 4 \times T]$

V. % INEFFICIENCY in generation and transfer of heat

5% was used for all cases in this paper

W. Btu/hr required $\left[S \times 0.25(U\text{-}Q)\right] \times \left[\frac{100}{100\text{-}V}\right]$

X. Fan Capacity SCFM = $H \times 2000 \times \left[\frac{0.2235}{R\text{-}hum_{ent}} + 0.0351\right]$

The 0.0351 accounts for the volume of water vapor being created inside the dryer and SCFM assume that the air is at standard temperature and pressure(60 ºF 14.696psi). But the gases are not at STP so Luckie employed two correction factors to turn SCFM into an actual flow rate.

$$C_1 = e^{\left[altitude\ in\ feet \times 3.872 \times 10^{-5}\right]}$$

$$C_2 = \left[temperature\ in\ {}^{o}\mathrm{F} + 460\right]/520$$

$$acfm = C_1 \times C_2 \times scfm$$

The calculations in this paper used an altitude of 1000ft. Luckie also included a minor correction factor for static fan pressure.

$$1/(1 + 2.458 \times 10^{-3} \times P_s)$$

But without knowing details of the fan being utilized this correction can't be used.

There are no modifications to the final value calculations for either of the dryers models that use heat but some changes are required for the dryer that uses no heat at all.

R_a. MAX HUM is the max humidity of the air based on the exhaust/product temperature E. If the water vapor isn't heated the vapor can't cool and condensate rendering the -15 ºF unnecessary.

T_a. Btus released per lb of dry air = $[(M + P]/S$

There is no heat so no radiative loss.

E_a. ºF PRODUCT temperature = $[C - (M + P)/(0.25 \times 2000 \times TPH\ of\ sweep\ air)]$

This final modification is due to the fact that the evaporating water is going to take its enthalpy of vaporization away from the air regardless of whether or not the air is heated.

This is however a circular reference, so the TPH of sweep air must be solved for iteratively.

COSTING

A price of $29.57 per million CFM was multiplied by ACFM to obtain the fan costs. This price was based on the cost of electricity to operate 47,000 CFM auxiliary fans found in Mine and Mill Equipment Costs (InfoMine 2008). A price of $1.96 per million Btus was multiplied by Btu/hr (W) to obtain the fuel costs. Mine and Mill Equipment Costs contained no heat prices for coal so this price was taken from the EIA (EIA 2010). All costs are for energy consumption only; no other costs of any kind were included.

C. Modeling Results Appendix

This appendix contains the outputs from the unheated, low heat and thermal dryer models.

Table C-1 Unheated Dryer Simulation Results Part 1

Atmospheric Temp (^{0}F)	Intake Relative Humidity (%)	Overgrate Temp (^{0}F)	Carrying Capacity (lb H_2O/lb air)	Sweep Air (tph)	Product Heat (Btu)	Water Heat (Btu)	ACFM (cfm)	$/Ton product
0	0	-2.5	0.00074	363.9	-38384	488962	148085	4.38
0	10	-2.2	0.00066	407.0	-38224	489103	165700	4.90
0	20	-2.0	0.00058	461.6	-38064	489243	188013	5.56
0	30	-1.7	0.00051	533.0	-37904	489384	217193	6.42
0	40	-1.4	0.00043	630.4	-37744	489524	256987	7.59
0	50	-1.2	0.00035	771.1	-37583	489665	314470	9.29
0	60	-0.9	0.00027	992.2	-37423	489805	404808	11.96
0	70	-0.7	0.00019	1390.1	-37263	489945	567434	16.77
0	80	-0.4	0.00012	2318.9	-37103	490086	946971	27.98
0	90	-0.1	0.00004	6966.5	-36943	490226	2846169	84.11
10	0	6.2	0.00112	240.5	-33072	493621	99774	2.95
10	10	6.6	0.00100	269.2	-32823	493839	111756	3.30
10	20	7.0	0.00088	305.6	-32575	494057	126935	3.75
10	30	7.4	0.00076	353.1	-32326	494275	146786	4.34
10	40	7.8	0.00064	417.9	-32078	494492	173859	5.14
10	50	8.2	0.00053	511.6	-31830	494710	212969	6.29
10	60	8.6	0.00041	658.8	-31583	494927	274430	8.11
10	70	9.0	0.00029	923.8	-31336	495144	385068	11.38
10	80	9.4	0.00017	1542.1	-31089	495360	643235	19.01
10	90	9.8	0.00006	4634.0	-30842	495577	1934159	57.16
20	0	14.3	0.00163	165.5	-28064	498012	69899	2.07
20	10	14.9	0.00145	185.5	-27693	498339	78429	2.32
20	20	15.5	0.00128	210.8	-27322	498664	89236	2.64
20	30	16.1	0.00110	244.0	-26952	498988	103373	3.05
20	40	16.7	0.00093	289.2	-26583	499312	122654	3.62
20	50	17.3	0.00076	354.5	-26215	499634	150510	4.45
20	60	17.9	0.00059	457.2	-25849	499956	194289	5.74
20	70	18.5	0.00042	642.0	-25483	500276	273097	8.07
20	80	19.1	0.00025	1073.2	-25119	500596	456974	13.50
20	90	19.7	0.00008	3228.2	-24756	500914	1375883	40.66
30	0	21.9	0.00228	118.4	-23400	502103	50854	1.50
30	10	22.8	0.00203	133.0	-22863	502574	57216	1.69
30	20	23.7	0.00178	151.5	-22329	503042	65280	1.93
30	30	24.5	0.00153	175.8	-21799	503508	75831	2.24
30	40	25.4	0.00129	208.8	-21271	503970	90226	2.67
30	50	26.2	0.00105	256.6	-20747	504430	111028	3.28
30	60	27.1	0.00081	331.7	-20226	504887	143728	4.25
30	70	27.9	0.00058	467.0	-19709	505340	202603	5.99
30	80	28.8	0.00034	782.6	-19195	505791	340000	10.05
30	90	29.6	0.00011	2360.9	-18685	506238	1027021	30.35

Table C-2 Unheated Dryer Simulation Results Part 2

Atmospheric Temp (^{0}F)	Intake Relative Humidity (%)	Overgrate Temp (^{0}F)	Carrying Capacity (lb H_2O/lb air)	Sweep Air (tph)	Product Heat (Btu)	Water Heat (Btu)	ACFM (cfm)	$/Ton product
40	0	28.9	0.00307	87.8	-19097	505876	38333	1.13
40	10	30.1	0.00272	99.0	-18345	506536	43304	1.28
40	20	31.4	0.00238	113.2	-17601	507189	49608	1.47
40	30	32.5	0.00204	131.8	-16865	507834	57860	1.71
40	40	33.7	0.00171	157.2	-16137	508473	69124	2.04
40	50	34.9	0.00139	193.8	-15417	509104	85406	2.52
40	60	36.1	0.00107	251.5	-14707	509727	111009	3.28
40	70	37.2	0.00076	355.3	-14004	510343	157116	4.64
40	80	38.3	0.00045	597.6	-13311	510951	264744	7.82
40	90	39.4	0.00015	1809.9	-12627	511551	803209	23.74
50	0	35.3	0.00400	67.4	-15154	509334	29842	0.88
50	10	37.0	0.00353	76.4	-14127	510235	33903	1.00
50	20	38.6	0.00307	87.7	-13118	511120	39056	1.15
50	30	40.3	0.00262	102.6	-12128	511988	45805	1.35
50	40	41.8	0.00219	123.0	-11156	512841	55022	1.63
50	50	43.4	0.00177	152.4	-10203	513677	68349	2.02
50	60	44.9	0.00136	198.7	-9268	514496	89309	2.64
50	70	46.4	0.00096	282.0	-8352	515300	127058	3.75
50	80	47.9	0.00057	476.5	-7455	516086	215164	6.36
50	90	49.3	0.00019	1448.7	-6576	516857	655618	19.37
60	0	41.2	0.00506	53.3	-11555	512491	23908	0.71
60	10	43.4	0.00443	60.8	-10182	513695	27365	0.81
60	20	45.6	0.00383	70.3	-8847	514866	31756	0.94
60	30	47.7	0.00326	82.7	-7550	516003	37511	1.11
60	40	49.8	0.00270	99.8	-6291	517108	45374	1.34
60	50	51.8	0.00217	124.4	-5068	518180	56748	1.68
60	60	53.7	0.00165	163.1	-3881	519220	74641	2.21
60	70	55.6	0.00116	232.9	-2730	520230	106873	3.16
60	80	57.4	0.00068	395.8	-1613	521209	182121	5.38
60	90	59.1	0.00022	1210.7	-530	522160	558534	16.51
70	0	46.5	0.00623	43.2	-8273	515369	19639	0.58
70	10	49.5	0.00542	49.7	-6471	516950	22697	0.67
70	20	52.3	0.00465	58.0	-4742	518466	26583	0.79
70	30	55.0	0.00391	68.8	-3084	519920	31680	0.94
70	40	57.6	0.00322	83.6	-1495	521313	38644	1.14
70	50	60.0	0.00257	105.0	28	522649	48715	1.44
70	60	62.4	0.00194	138.7	1488	523929	64554	1.91
70	70	64.7	0.00135	199.3	2888	525157	93080	2.75
70	80	66.9	0.00079	340.7	4230	526334	159676	4.72
70	90	69.0	0.00026	1048.5	5519	527464	492903	14.57

Table C-3 Unheated Dryer Simulation Results Part 3

Atmospheric Temp (^{0}F)	Intake Relative Humidity (%)	Overgrate Temp (^{0}F)	Carrying Capacity (lb H_2O/lb air)	Sweep Air (tph)	Product Heat (Btu)	Water Heat (Btu)	ACFM (cfm)	$/Ton product
80	0	51.4	0.00751	35.9	-5279	517994	16486	0.49
80	10	55.2	0.00646	41.7	-2947	520040	19283	0.57
80	20	58.8	0.00548	49.1	-748	521969	22840	0.67
80	30	62.2	0.00458	58.9	1326	523788	27503	0.81
80	40	65.3	0.00373	72.2	3283	525503	33871	1.00
80	50	68.3	0.00295	91.4	5129	527122	43082	1.27
80	60	71.2	0.00222	121.6	6874	528652	57562	1.70
80	70	73.9	0.00153	175.9	8525	530100	83618	2.47
80	80	76.4	0.00089	302.7	10089	531472	144431	4.27
80	90	78.8	0.00029	937.2	11573	532774	448798	13.26
90	0	55.9	0.00888	30.3	-2543	520394	14098	0.42
90	10	60.7	0.00754	35.8	441	523011	16735	0.49
90	20	65.2	0.00632	42.6	3193	525425	20086	0.59
90	30	69.3	0.00522	51.6	5736	527654	24477	0.72
90	40	73.2	0.00422	63.9	8089	529718	30466	0.90
90	50	76.7	0.00330	81.6	10273	531633	39118	1.16
90	60	80.0	0.00246	109.4	12304	533415	52710	1.56
90	70	83.1	0.00169	159.5	14200	535077	77155	2.28
90	80	86.0	0.00098	276.2	15973	536632	134190	3.97
90	90	88.7	0.00031	858.9	17637	538091	418877	12.38
100	0	59.9	0.01032	26.1	-34	522595	12249	0.36
100	10	66.1	0.00862	31.2	3746	525909	14802	0.44
100	20	71.6	0.00713	37.8	7140	528886	18042	0.53
100	30	76.6	0.00582	46.3	10199	531569	22277	0.66
100	40	81.1	0.00465	57.9	12971	533999	28044	0.83
100	50	85.2	0.00361	74.7	15494	536212	36364	1.07
100	60	89.0	0.00267	100.9	17803	538237	49414	1.46
100	70	92.4	0.00182	148.0	19928	540100	72863	2.15
100	80	95.6	0.00104	258.0	21890	541821	127546	3.77
100	90	98.6	0.00033	806.8	23712	543419	400554	11.84

Table C-4 Unheated Dryer Simulation Results Part 4

Atmospheric Temp (⁰F)	Intake Relative Hum (%)	Carrying Capacity (lb H_2O/lb air)	Required Air (tph)	Sweep Air Heat (Btu)	Undergrate Temp (⁰F)	ACFM (cfm)	Btu/hr required	$/Ton Product
0	0	0.05022	5.36	321861	467	2983	980998	2.01
0	10	0.05013	5.37	322426	467	2988	981604	2.01
0	20	0.05004	5.38	322992	467	2993	982212	2.01
0	30	0.04996	5.39	323560	466	2998	982823	2.01
0	40	0.04987	5.40	324131	466	3003	983435	2.02
0	50	0.04978	5.41	324703	465	3008	984050	2.02
0	60	0.04969	5.42	325277	465	3013	984666	2.02
0	70	0.04960	5.43	325854	465	3018	985285	2.02
0	80	0.04952	5.44	326432	464	3022	985906	2.02
0	90	0.04943	5.45	327013	464	3027	986530	2.02
0	100	0.04934	5.46	327596	464	3032	987155	2.02
10	0	0.05022	5.36	295039	457	2983	952200	1.95
10	10	0.05008	5.38	295869	457	2991	953091	1.96
10	20	0.04994	5.39	296703	456	2999	953987	1.96
10	30	0.04980	5.41	297543	455	3007	954888	1.96
10	40	0.04966	5.43	298387	455	3015	955794	1.96
10	50	0.04952	5.44	299235	454	3023	956705	1.96
10	60	0.04937	5.46	300089	453	3031	957622	1.97
10	70	0.04923	5.47	300947	453	3039	958543	1.97
10	80	0.04909	5.49	301810	452	3047	959470	1.97
10	90	0.04895	5.50	302679	452	3055	960403	1.97
10	100	0.04881	5.52	303552	451	3063	961340	1.97
20	0	0.05022	5.36	268218	447	2983	923402	1.90
20	10	0.05000	5.39	269400	446	2995	924672	1.90
20	20	0.04978	5.41	270593	445	3008	925953	1.90
20	30	0.04956	5.44	271797	444	3020	927245	1.91
20	40	0.04934	5.46	273011	443	3033	928549	1.91
20	50	0.04912	5.48	274237	442	3045	929865	1.91
20	60	0.04890	5.51	275473	441	3058	931192	1.91
20	70	0.04868	5.53	276721	440	3071	932532	1.92
20	80	0.04846	5.56	277980	439	3084	933884	1.92
20	90	0.04824	5.59	279250	438	3097	935248	1.92
20	100	0.04801	5.61	280532	437	3110	936624	1.93
30	0	0.05022	5.36	241396	437	2983	894604	1.84
30	10	0.04988	5.40	243031	435	3002	896359	1.84
30	20	0.04954	5.44	244688	434	3021	898139	1.85
30	30	0.04921	5.47	246368	432	3040	899942	1.85
30	40	0.04887	5.51	248071	431	3060	901771	1.86
30	50	0.04853	5.55	249798	429	3079	903625	1.86
30	60	0.04819	5.59	251549	428	3099	905505	1.87
30	70	0.04785	5.63	253324	426	3120	907412	1.87
30	80	0.04752	5.67	255125	425	3140	909345	1.87
30	90	0.04718	5.71	256952	423	3161	911307	1.88
30	100	0.04684	5.75	258805	422	3183	913296	1.88

Table C-5 Unheated Dryer Simulation Results Part 5

Atmospheric Temp (^{0}F)	Intake Relative Hum (%)	Carrying Capacity (lb H_2O/lb air)	Required Air (tph)	Sweep Air Heat (Btu)	Undergrate Temp (^{0}F)	ACFM (cfm)	Btu/hr required	$/Ton Product
40	0	0.05022	5.36	214574	427	2983	865806	1.78
40	10	0.04971	5.42	216765	424	3011	868159	1.79
40	20	0.04920	5.48	219002	422	3040	870560	1.80
40	30	0.04870	5.53	221285	420	3070	873012	1.80
40	40	0.04819	5.59	223617	418	3100	875515	1.81
40	50	0.04768	5.65	225998	415	3130	878071	1.81
40	60	0.04717	5.71	228430	413	3162	880683	1.82
40	70	0.04667	5.77	230915	411	3194	883351	1.82
40	80	0.04616	5.84	233455	408	3226	886078	1.83
40	90	0.04565	5.90	236051	406	3260	888865	1.84
40	100	0.04514	5.97	238706	404	3294	891716	1.84
50	0	0.05022	5.36	187752	416	2983	837008	1.73
50	10	0.04947	5.45	190597	413	3025	840062	1.73
50	20	0.04872	5.53	193529	410	3068	843211	1.74
50	30	0.04797	5.62	196553	406	3113	846457	1.75
50	40	0.04722	5.70	199673	403	3159	849807	1.76
50	50	0.04647	5.80	202894	400	3206	853265	1.77
50	60	0.04572	5.89	206220	396	3255	856836	1.77
50	70	0.04497	5.99	209657	393	3306	860526	1.78
50	80	0.04422	6.09	213210	390	3358	864342	1.79
50	90	0.04347	6.20	216886	386	3412	868289	1.80
50	100	0.04272	6.31	220691	383	3468	872374	1.81
60	0	0.05022	5.36	160931	406	2983	808210	1.67
60	10	0.04913	5.48	164498	401	3044	812040	1.68
60	20	0.04804	5.61	168226	396	3109	816043	1.69
60	30	0.04695	5.74	172128	392	3176	820232	1.70
60	40	0.04586	5.87	176215	387	3246	824621	1.71
60	50	0.04477	6.02	180501	382	3319	829222	1.72
60	60	0.04369	6.17	185000	377	3397	834053	1.73
60	70	0.04260	6.32	189730	372	3478	839131	1.75
60	80	0.04151	6.49	194708	367	3563	844476	1.76
60	90	0.04042	6.67	199954	362	3653	850108	1.77
60	100	0.03933	6.85	205490	357	3749	856053	1.79
70	0	0.05022	5.36	134109	396	2983	779412	1.61
70	10	0.04866	5.54	138407	389	3072	784027	1.63
70	20	0.04710	5.72	142990	382	3166	788947	1.64
70	30	0.04554	5.92	147886	375	3267	794205	1.65
70	40	0.04398	6.13	153130	368	3375	799835	1.67
70	50	0.04242	6.35	158760	361	3491	805879	1.68
70	60	0.04086	6.59	164819	354	3616	812385	1.70
70	70	0.03930	6.85	171359	347	3751	819407	1.72
70	80	0.03774	7.14	178440	340	3897	827009	1.74
70	90	0.03618	7.45	186131	333	4055	835267	1.76
70	100	0.03462	7.78	194514	326	4228	844268	1.78

Table C-6 Unheated Dryer Simulation Results Part 6

Atmospheric Temp (^{0}F)	Intake Relative Hum (%)	Carrying Capacity (lb H_2O/lb air)	Required Air (tph)	Sweep Air Heat (Btu)	Undergrate Temp (^{0}F)	ACFM (cfm)	Btu/hr required	$/Ton Product
80	0	0.05022	5.36	107287	386	2983	750614	1.56
80	10	0.04801	5.61	112215	376	3110	755904	1.57
80	20	0.04581	5.88	117617	366	3249	761705	1.59
80	30	0.04360	6.18	123566	356	3403	768092	1.61
80	40	0.04140	6.51	130148	346	3572	775159	1.62
80	50	0.03919	6.87	137471	336	3761	783022	1.64
80	60	0.03699	7.28	145668	327	3972	791822	1.67
80	70	0.03478	7.75	154904	317	4210	801739	1.69
80	80	0.03258	8.27	165390	307	4480	812998	1.72
80	90	0.03037	8.87	177399	297	4789	825892	1.76
80	100	0.02817	9.56	191289	287	5147	840805	1.80
90	0	0.05022	5.36	80465	376	2983	721815	1.50
90	10	0.04713	5.72	85731	362	3164	727470	1.52
90	20	0.04405	6.12	91735	348	3370	733916	1.54
90	30	0.04097	6.58	98643	334	3608	741333	1.56
90	40	0.03788	7.11	106676	320	3884	749957	1.58
90	50	0.03480	7.74	116133	307	4208	760111	1.61
90	60	0.03171	8.50	127430	293	4596	772241	1.65
90	70	0.02863	9.41	141162	279	5068	786985	1.69
90	80	0.02554	10.55	158211	265	5654	805290	1.74
90	90	0.02246	12.00	179944	251	6400	828624	1.81
90	100	0.01937	13.91	208598	237	7385	859390	1.90
100	0	0.05022	5.36	53644	365	2983	693017	1.45
100	10	0.04594	5.86	58637	346	3241	698379	1.46
100	20	0.04167	6.47	64655	327	3551	704841	1.49
100	30	0.03739	7.21	72051	308	3932	712781	1.51
100	40	0.03311	8.14	81356	289	4411	722772	1.55
100	50	0.02884	9.34	93421	270	5033	735726	1.59
100	60	0.02456	10.97	109689	250	5871	753192	1.65
100	70	0.02028	13.28	132816	231	7063	778024	1.73
100	80	0.01601	16.83	168301	212	8891	816123	1.86
100	90	0.01173	22.97	229660	193	12052	882004	2.08
100	100	0.00745	36.14	361431	174	18842	1023484	2.56

Table C-7 Unheated Dryer Simulation Results Part 7

Atmospheric Temp (^{0}F)	Intake Relative Hum (%)	Carrying Capacity (lb H_2O/lb air)	Required Air (tph)	Sweep Air Heat (Btu)	Undergrate Temp (^{0}F)	ACFM (cfm)	Btu/hr required	$/Ton Product
0	0	0.13371	2.01	152117	958	1325	856184	1.72
0	10	0.13362	2.02	152217	958	1325	856292	1.72
0	20	0.13353	2.02	152317	958	1326	856399	1.72
0	30	0.13344	2.02	152418	957	1327	856507	1.72
0	40	0.13336	2.02	152518	957	1327	856615	1.72
0	50	0.13327	2.02	152619	956	1328	856723	1.72
0	60	0.13318	2.02	152720	956	1329	856831	1.72
0	70	0.13309	2.02	152820	955	1330	856939	1.72
0	80	0.13300	2.03	152921	955	1330	857048	1.72
0	90	0.13292	2.03	153023	955	1331	857156	1.72
0	100	0.13283	2.03	153124	954	1332	857265	1.72
10	0	0.13371	2.01	142043	948	1325	845368	1.70
10	10	0.13357	2.02	142193	948	1326	845529	1.70
10	20	0.13343	2.02	142343	947	1327	845690	1.70
10	30	0.13329	2.02	142493	946	1328	845851	1.70
10	40	0.13314	2.02	142644	945	1329	846013	1.70
10	50	0.13300	2.03	142795	945	1330	846175	1.70
10	60	0.13286	2.03	142947	944	1332	846338	1.70
10	70	0.13272	2.03	143098	943	1333	846501	1.70
10	80	0.13258	2.03	143250	943	1334	846664	1.70
10	90	0.13244	2.03	143403	942	1335	846828	1.70
10	100	0.13230	2.04	143555	941	1336	846992	1.70
20	0	0.13371	2.01	131969	938	1325	834552	1.67
20	10	0.13349	2.02	132187	937	1326	834786	1.67
20	20	0.13327	2.02	132406	936	1328	835021	1.67
20	30	0.13305	2.02	132625	935	1330	835256	1.68
20	40	0.13283	2.03	132845	934	1332	835492	1.68
20	50	0.13261	2.03	133066	933	1334	835730	1.68
20	60	0.13239	2.03	133288	932	1336	835967	1.68
20	70	0.13216	2.04	133510	930	1337	836206	1.68
20	80	0.13194	2.04	133733	929	1339	836446	1.68
20	90	0.13172	2.05	133957	928	1341	836686	1.68
20	100	0.13150	2.05	134181	927	1343	836927	1.68
30	0	0.13371	2.01	121895	928	1325	823736	1.65
30	10	0.13337	2.02	122204	926	1327	824067	1.65
30	20	0.13303	2.03	122514	925	1330	824400	1.65
30	30	0.13269	2.03	122826	923	1333	824735	1.65
30	40	0.13236	2.04	123140	921	1336	825072	1.66
30	50	0.13202	2.04	123455	920	1339	825410	1.66
30	60	0.13168	2.05	123771	918	1341	825750	1.66
30	70	0.13134	2.05	124090	916	1344	826092	1.66
30	80	0.13101	2.06	124410	915	1347	826435	1.66
30	90	0.13067	2.06	124731	913	1350	826781	1.66
30	100	0.13033	2.07	125055	911	1353	827128	1.66

Table C-8 Unheated Dryer Simulation Results Part 8

Atmospheric Temp (^{0}F)	Intake Relative Hum (%)	Carrying Capacity (lb H_2O/lb air)	Required Air (tph)	Sweep Air Heat (Btu)	Undergrate Temp (^{0}F)	ACFM (cfm)	Btu/hr required	$/Ton Product
40	0	0.13371	2.01	111821	918	1325	812919	1.63
40	10	0.13320	2.02	112247	915	1329	813377	1.63
40	20	0.13269	2.03	112677	913	1333	813838	1.63
40	30	0.13218	2.04	113110	910	1337	814303	1.63
40	40	0.13168	2.05	113546	908	1341	814771	1.64
40	50	0.13117	2.05	113985	905	1346	815243	1.64
40	60	0.13066	2.06	114428	903	1350	815718	1.64
40	70	0.13015	2.07	114874	900	1354	816197	1.64
40	80	0.12965	2.08	115324	898	1359	816680	1.64
40	90	0.12914	2.09	115778	895	1363	817167	1.64
40	100	0.12863	2.09	116235	893	1368	817658	1.64
50	0	0.13371	2.01	101747	907	1325	802103	1.61
50	10	0.13296	2.03	102321	904	1331	802719	1.61
50	20	0.13221	2.04	102901	900	1337	803342	1.61
50	30	0.13146	2.05	103488	896	1343	803972	1.61
50	40	0.13071	2.06	104081	893	1350	804609	1.62
50	50	0.12996	2.07	104681	889	1356	805253	1.62
50	60	0.12921	2.08	105289	885	1363	805905	1.62
50	70	0.12846	2.10	105903	882	1369	806565	1.62
50	80	0.12771	2.11	106524	878	1376	807232	1.62
50	90	0.12696	2.12	107153	874	1383	807907	1.62
50	100	0.12621	2.13	107790	871	1390	808591	1.62
60	0	0.13371	2.01	91673	897	1325	791287	1.59
60	10	0.13262	2.03	92426	892	1334	792095	1.59
60	20	0.13153	2.05	93191	887	1343	792917	1.59
60	30	0.13044	2.07	93969	881	1352	793752	1.59
60	40	0.12935	2.08	94760	876	1361	794601	1.60
60	50	0.12826	2.10	95565	871	1371	795465	1.60
60	60	0.12717	2.12	96383	865	1381	796344	1.60
60	70	0.12608	2.14	97216	860	1391	797237	1.60
60	80	0.12500	2.16	98063	855	1401	798147	1.60
60	90	0.12391	2.17	98924	849	1411	799072	1.61
60	100	0.12282	2.19	99802	844	1422	800014	1.61
70	0	0.13371	2.01	81599	887	1325	780470	1.57
70	10	0.13215	2.04	82562	879	1337	781504	1.57
70	20	0.13059	2.06	83548	872	1351	782563	1.57
70	30	0.12903	2.09	84558	864	1364	783647	1.58
70	40	0.12747	2.11	85593	857	1378	784758	1.58
70	50	0.12591	2.14	86653	849	1392	785896	1.58
70	60	0.12435	2.17	87739	841	1407	787063	1.58
70	70	0.12279	2.19	88854	834	1422	788260	1.59
70	80	0.12123	2.22	89997	826	1437	789487	1.59
70	90	0.11967	2.25	91170	818	1453	790746	1.59
70	100	0.11811	2.28	92373	811	1469	792039	1.59

Table C-9 Unheated Dryer Simulation Results Part 9

Atmospheric Temp (^{0}F)	Intake Relative Hum (%)	Carrying Capacity (lb H_2O/lb air)	Required Air (tph)	Sweep Air Heat (Btu)	Undergrate Temp (^{0}F)	ACFM (cfm)	Btu/hr required	$/Ton Product
80	0	0.13371	2.01	71525	877	1325	769654	1.55
80	10	0.13150	2.05	72725	866	1343	770942	1.55
80	20	0.12930	2.08	73965	855	1362	772274	1.55
80	30	0.12709	2.12	75249	844	1382	773652	1.56
80	40	0.12489	2.16	76577	834	1402	775079	1.56
80	50	0.12268	2.20	77954	823	1423	776556	1.56
80	60	0.12048	2.24	79381	812	1445	778089	1.57
80	70	0.11827	2.28	80861	801	1467	779678	1.57
80	80	0.11607	2.32	82397	791	1491	781327	1.57
80	90	0.11386	2.37	83993	780	1515	783041	1.58
80	100	0.11165	2.41	85652	769	1541	784822	1.58
90	0	0.13371	2.01	61451	867	1325	758838	1.53
90	10	0.13062	2.06	62902	852	1350	760396	1.53
90	20	0.12754	2.11	64424	836	1377	762030	1.53
90	30	0.12445	2.16	66021	821	1406	763744	1.54
90	40	0.12137	2.22	67699	806	1436	765546	1.54
90	50	0.11828	2.28	69464	791	1467	767441	1.55
90	60	0.11520	2.34	71324	776	1500	769438	1.55
90	70	0.11211	2.40	73287	761	1535	771545	1.56
90	80	0.10903	2.47	75360	746	1572	773772	1.56
90	90	0.10595	2.54	77555	731	1611	776128	1.57
90	100	0.10286	2.62	79880	716	1653	778625	1.57
100	0	0.13371	2.01	51377	856	1325	748022	1.50
100	10	0.12943	2.08	53075	836	1361	749844	1.51
100	20	0.12515	2.15	54888	815	1399	751791	1.51
100	30	0.12088	2.23	56830	794	1441	753876	1.52
100	40	0.11660	2.31	58915	773	1485	756114	1.52
100	50	0.11232	2.40	61158	752	1533	758523	1.53
100	60	0.10805	2.49	63578	731	1584	761122	1.54
100	70	0.10377	2.60	66199	710	1640	763935	1.54
100	80	0.09950	2.71	69044	689	1701	766990	1.55
100	90	0.09522	2.83	72145	668	1767	770320	1.56
100	100	0.09094	2.96	75538	647	1839	773962	1.57