CHAPTER 3
CENTRIFUGATION

3.1 INTRODUCTION

General Background: Centrifugal dewatering is widely used method for separating solid-liquid or liquid-liquid in several industries due to the higher gravitational forces affecting on the particles. In this method, if the applied centrifugal force created by the angular velocity of a rotating basket is larger than capillary force, liquid in the capillary tubes is spontaneously removed from the filter cake [1-10]. For this reason, the centrifugal filters are performed in high speed for the fine particles to obtain lower moisture content product [1,2,9].

When an aqueous suspension of particles is introduced to a centrifuge whose wall is made of a porous medium, the heavier and larger particles settle quickly on the medium while the lighter water (or any liquids) forms a layer over the cake. As centrifugation continues, water begins to flow through the cake. The initial dewatering process, in which water flows through the cake while the cake is covered with a layer of water, is referred to as *filtration*. In time, the layer of water disappears from the surface of the cake, and the capillaries in the cake become saturated with air. The dewatering process that still occurs at the end of filtration is referred to as *drainage*. Therefore, the drainage process is much slower than the filtration process [1,11-22]. In fact, the pressure drop becomes negative as cake thickness is increased in the basket. In this case, difficulty of the capillary water is arisen, and this causes high cake moistures [11-15].

In coal and mineral preparation plants, because the separation is usually carried out in an aqueous media, it is necessary to dewater the products before shipping to markets or ongoing processes. Basket and screen bowl centrifuges are mostly employed methods in those plants. The basket centrifuge is used to dewater the particles that are larger than approximately 1 mm, while finer particles are dewatered by means of the screen bowl centrifuge. The latter can be capable of providing considerably lower moisture contents than the traditional vacuum filters, partly due to the loss of finer particles as effluent during filtration. In general, the moisture content of dewatered products increases with decreasing the particle size due to the high surface area of the fine particles. Therefore, elimination of the finest particles as effluent should help lower the dewatered product, but it is not desired [11-14].

Process of the dewatering that relies solely on the centrifugal force entails high-energy consumption on the fine particles and requires high maintenance costs to obtain lower cake moistures. In this investigation, a method to overcome the associated problem will be introduced on the dewatering of fine particles. The new method includes a gas pressure inside the rotating centrifuge and/or a vacuum pressure outside. These provisions are designed to increase the pressure drop across the filter cake so that one can take advantage of the Darcy's law, which suggests that dewatering rate should increase with increasing pressure drop across a filter cake. The extraneous methods of increasing the pressure drop, as shown in the present studies, is particularly useful for increasing the rate of dewatering during the drainage period, which can be critical achieving lower cake moistures [1,12,18].

Theory: In centrifugal filtration, a perforated basket is installed inside a centrifuge machine, and connected to an external rotation supply. Changing the rotational speed or angular velocity ω of the vessel, which can be converted to G-force using the following relationship, varies the centrifugal force [1,12]:

$$G = \frac{r\omega^2}{g}, \tag{1}$$

in which r is the radius of the centrifugal dewatering vessel, and g is the gravitational acceleration.

Darcy's law can predict the rate of drainage through the filter cake [1,12]:

$$Q = \frac{K\Delta PA}{\mu L} \tag{2}$$

where Q is the flow rate, K is the permeability of the cake, ΔP is the pressure drop across the cake, A is the filtration area, μ is the dynamic viscosity of water, and L is the cake thickness. During the filtration period, the pressure drop across the cake is determined by the following relationship:

$$\Delta P = \frac{1}{2}\rho\omega^2\left(r_S^2 - r_0^2\right), \tag{3}$$

where ρ is the density of the liquid, and r_0 and r_S are the radial distances of the free water and the cake surface from the rotational axis of a centrifuge, respectively. From Equations [1] and [2], one can see that the rate of filtration should increase with ω and the thickness (r_S-r_0) of the water over a filter cake.

According to the Equation [3], ΔP becomes zero when the water over the cake disappears, i.e., r_0=r_S. As the water level in the cake decreases further, i.e., r_0>r_S, the pressure within the cake becomes lower than the ambient pressure [1]. This may be the fundamental reason that centrifuges cannot produce as low cake moistures as vacuum or pressure filters for the finer particles [1,12,23-28]. The model calculation reveals that the pressure in the cake becomes increasingly negative with increasing cake thickness, which may be due to the siphon effects in the capillary. In this model, which is based on the first principles, the pressure ($P_{(r)}$) through the radial distance, r, of a centrifuge can be predicted by the following equation:

$$P_{(r)} = \frac{\ln(r_b/r)}{\ln(r_b/r_s)} P_S + \frac{\rho\omega^2 r_b^2}{2}\left[\frac{\ln(r_b/r)}{\ln(r_b/r_s)}\left(1-\frac{r_s^2}{r_b^2}\right)-\left(1-\frac{r^2}{r_b^2}\right)\right] \qquad [4]$$

which is known as Zeitsch model. The sign r_b is the radial distance to the base of the filter cake. Thus, r_b-r_0 is the cake thickness. Figure1.11 in the Chapter 1 shows a plot of Equation [4], in which P is plotted vs. r. It is found that the larger the thickness of the layer of water over the cake surface, the higher the P_S (the pressure at the cake surface) becomes for higher dewatering rates.

Previous Work: There are presently several centrifugal filtration methods designed for the coal and mineral dewatering. Hultch et al. developed a method of creating a negative pressure on the outside wall of a centrifuge and thereby increasing the filtration rate. This is accomplished by creating a chamber outside the filter medium, in which filtrate water is collected. Since the water in this chamber is subjected to a larger centrifugal force, a negative (or vacuum) pressure is created due to a siphon effect. This technique is, therefore, referred to as the method of using *rotating siphon*. However, the effectiveness of this method breaks down as soon as air enters the filtrate chamber through the filter cake, and does not allow a sufficient drainage period, which is often necessary for producing low cake moistures [2-4, 29,30].

The same authors also showed that this method using rotating siphons in a pressure housing with superatmospheric pressure is controlled by a difference in filtrate liquid levels in the filtrate liquid chamber and the annular space following the filter. The liquid control prevents the penetration of filtrate liquid into the gas exhaust line [3,4].

It was found that a similar method of injecting a turbulent gas stream such as air or hot steam into the bed of particles during centrifugation could reduce the surface moisture of the particles. The turbulent flow created by the gas flow strips the water from the surface of the particles. This technique is useful if the particle sizes are in the range of 0.5 to 30 mm in basket centrifuges. In the invention, the stream of gas is injected into an open space without the pressure drop across the bed of particles. Moreover, it would be difficult to increase the pressure drop, when a scrawl, which is widely used to move the particles in the centrifuges, continually disturbs the cake [9,10,31]. Therefore, a blower rather than a compressor, which should make it difficult to create a high pressure drop across a filter cake, creates only the airflow.

From the literature results, it was also found that there were several centrifugal filtration methods applied on the fine coal, mineral, sludge and other tailing dewaterings. These centrifuges are used in the absence of air/vacuum pressure (or classical centrifuges) with the wide variety of models [20,21,32-37]. In the present work, G-force and air/vacuum pressure are considered together to further reduce the moisture contents of the fine particles.

Summary of Novel Centrifuge: Figure 3.1 shows the schematic illustration of the novel centrifuge in which three forces are acting on the cake surface. These are capillary pressure, centrifugal pressure and air/vacuum pressures. In this model, the centrifugal and air/vacuum pressures are against to the capillary pressure. The magnitudes of the pressures applied on a sample (0.5 mm x 0) are in the range of the capillary pressure, the centrifugal pressure at a 1500 G-force and air pressures (100 kPa). Thus, one can see that the major pressure on the cake is the air/vacuum pressure, which means that the fine particle dewatering could be higher in this model.

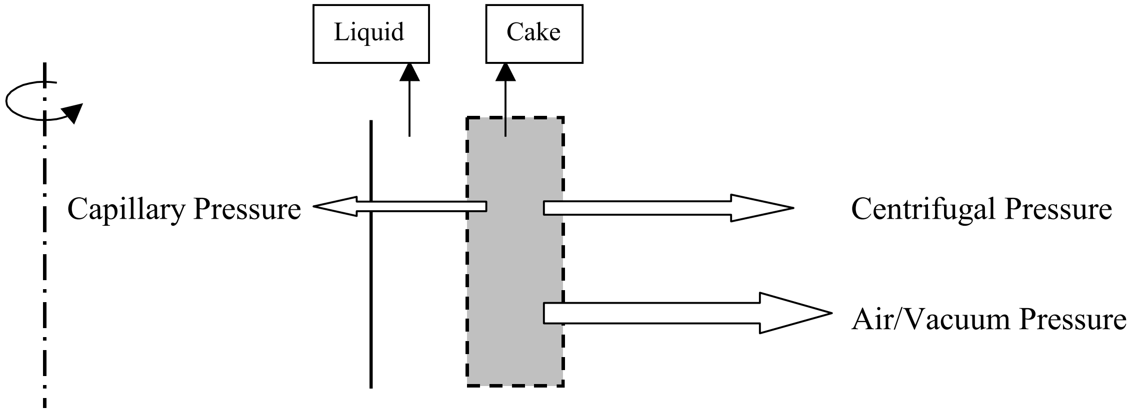

Figure 3.1 Schematic illustration of three acting pressures on the cake into the novel centrifuge

This centrifuge is operated as a batch unit. The particles in the slurry quickly form a cake over the porous medium by passing the liquid (water) through the cake. The rate of the water flowing through the cake is high when a layer of water covers the cake. As the water layer disappears from the cake surface, the pressure drop becomes zero, which will cause a decrease in drainage rate. The centrifugal force alone exceeds some of the capillary force that holds the water on the capillary wall and the hydrodynamic drag force, but not fine capillaries [1,7,8,12]. In the present model, water in the fine capillaries continues to flow through the cake under the applied pressures.

It was determined that water flow through the cake was dependent on the surface hydrophobicity. When a low HLB surfactant is used to increases the hydrophobicity of particulate materials, the rate of drainage during centrifugal dewatering can be faster. According to the Laplace equation, an increase in hydrophobicity should result in a decrease in capillary pressure, which should help increase the drainage rate. It was already stated that the use of the low HLB reagent increases the contact angle up to 90° at which the dewettability can spontaneously occur on the surface. This is particularly important for difficult-to-dewater materials, such as PCC, clay, silica, slug, etc [20,38-41].

The method of increasing the pressure drop across the cake described in the present models has several advantages as compared to the other dewatering methods. As mentioned, the classical centrifuges do not have a pressure drop across the filter cake and are not useful for the fine particles. The rotating siphon method stops working as soon as the air passes through the cake. It is generally known that water in larger capillaries is more readily removed than water in smaller capillaries. Therefore, air can pass through a cake very quickly (through the large capillaries) and nullify the pressure drop created by the rotating siphons. This will make it difficult to remove the water in smaller capillaries. The air blowing unit cannot be applicable since the size is lower than half mm. On the other hand, the method of applying air pressure or vacuum pressure in this method is effective during the entire period of drainage time. This will give opportunities for the water trapped in smaller capillaries to be removed, which will give lower cake moisture products.

3.2 EXPERIMENTAL

3.2.1 Samples

Coal and mineral samples used in this investigation were collected from different flotation and mineral preparation plants. The samples (lower than 2 mm in size) introduced to the centrifuge were all clean products. If the samples were run-of-mines or superficially oxidized, they were crushed, ground and floated (or refloated) using appropriate reagents. It was determined that ash content of the clean coal samples were less than 10%. Also, the mineral samples (chalcopyrite, sphalerite, galena, talc, phosphate, clay, silicate, and precipitate calcium carbonate (PCC)) were highly concentrated products. During the entire period of the tests, new samples were collected every four weeks to avoid the superficial oxidation of the sample surface that would affect the dewatering results. In addition, particle size distribution of the sample was measured by wet sieve screening before the tests.

In the present study, the samples obtained from operating plants were mostly in the form of slurry, so the clean samples were thickened to 40-70% solids by gravity filtration with a large filter funnel before use. The thickened sample was poured or pasted against the filter cloth, which was placed inside the centrifuge vessel before rotating at a desired r.p.m. The centrifugal dewatering tests were conducted by varying the G-force, air pressure, vacuum pressure, cake thickness, and spin (or centrifugation) time on the thickened samples.

3.2.2 Equipment Design and Setup

In centrifugal tests, a 3.5-inch diameter basket was installed inside a centrifuge machine, and connected to an external supply of compressed air or vacuum pressure. The air pressure was regulated so that the pressure could vary in the range of 25 to 600 kPa. The rotational speed of the vessel that is converted to G-force using Equation [1] are changed depending on the dewatering conditions. The cake thickness, which varied between 0.2 and 1.0 inch ranges, was measured after each test. The cake was then removed from the filter vessel, weighed, dried in a conventional oven overnight, and then weighed again to determine %moisture by weight of the filter cake.

Figure 3.2 shows the centrifuge vessel **1**, where compressed air was injected to create a pressure drop across the filter cake. The vessel was made of stainless steel with dimensions of 3.5 inches inside diameter and 3 inches in height. When in operation, it was placed vertically inside a centrifuge machine, which was capable of varying r.p.m. of the vessel. The sidewall was made of perforated stainless steel with 1/8-, 3/32- and 1/16-inch circular holes **2**. The filter vessel was tightened against the rotor **3** of the centrifuge by means of a screw **4**. A filter cloth **5,** which was designed to fit the contour of the centrifuge vessel **1**, was placed inside the vessel. A thickened slurry was then poured into the filter cloth **5** and the sidewall of the filter vessel to form a cake **6**. The filter vessel was then covered by a lid **7**, which was tightened against the filter vessel **1** by means of screws **8**. A compressed air inlet tubing **9** was connected at the center of the cover lid **7**. The tubing was terminated by a flat-polished surface **10**. A double ball-bearing connector **11** was used to couple the compressed air inlet tubing **9** with an external compressed air line **12**, which was equipped with an on/off valve **13**. The compressed air line carried an airflow meter and a pressure gauge.

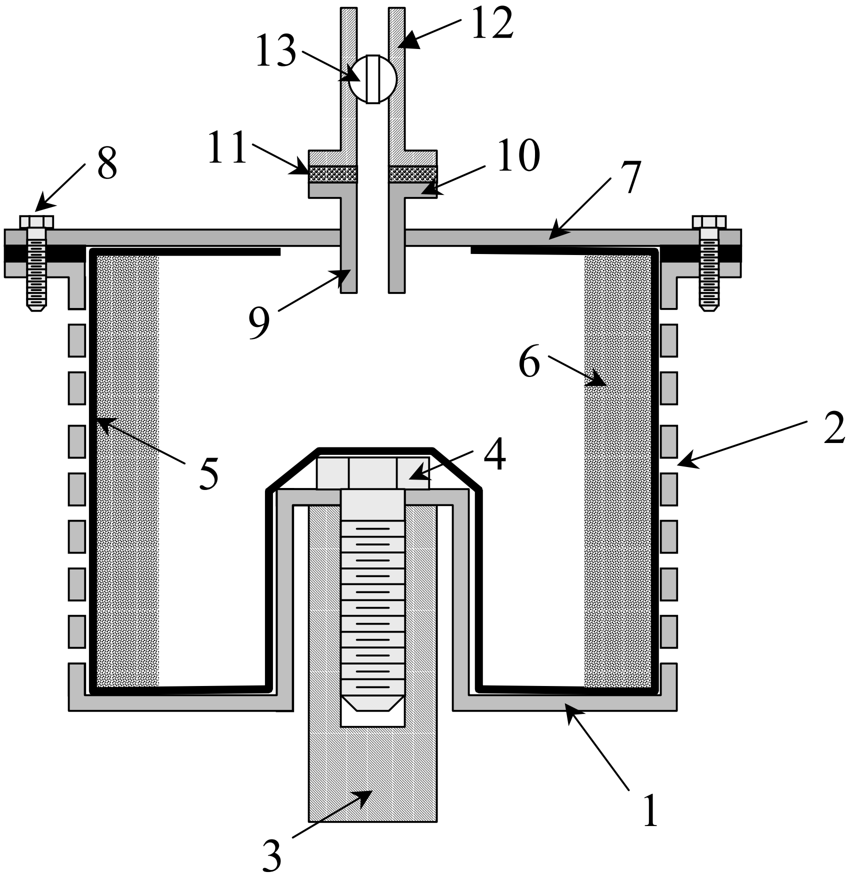

Figure 3.2 Schematic representation of the novel centrifuge with air pressure.

Figure 3.3 shows another model of the novel centrifuge, in which the pressure drop is created by combination of compressed air and/or vacuum pressure. The centrifuge vessel **1** was the same as shown and described above. After adding the thickened slurry into the filter medium in the manner described above, a vacuum chamber **14** was placed over the centrifugal filter vessel **1**. The vacuum chamber **14** was sealed from the atmosphere by means of a rubber gasket

15 and a bottom plate **16**, which was tightened against the vacuum chamber **14** using screws **17**. The vacuum chamber was connected to a vacuum pump through a tubing **18** and sealed against the rotor **3** by means of a ball-bearing seal **19**.

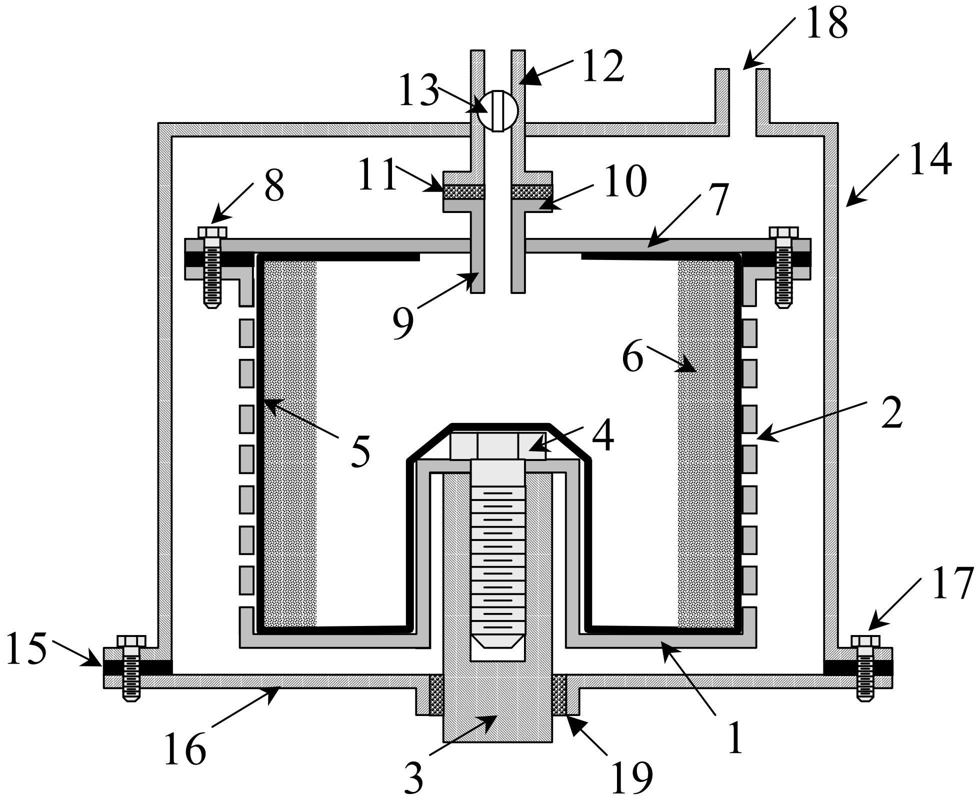

Figure 3.3 Scmematic representation of the novel centrifuge with air and vacuum pressures.

3.3 RESULTS AND DISCUSSIONS

3.3.1 Dewatering of Fine Coal Samples

a) Effects of Dewatering Aids

The benefits of using the novel and current methods during centrifugal filtration will be presented here in detail. In the first example, a series of centrifugal filtration tests were conducted on a sample using dewatering chemicals without compressed air and the test results are given in Table 3.1. The coal sample was obtained from the feed stream to the screen bowl centrifuges operating at the Goals Preparation Plant, Massey Energy – West Virginia. It was a combination of cyclone and flotation products with a nominal particle size of 1 mm x 0. The sample was deslimed at 38 μm using a 400-mesh screen. This step was taken to simulate screen bowl centrifuges, which loses most of the particles finer than 325 mesh (44 μm). The deslimed coal sample was conditioned for 5 minutes with 2 lb/ton of a dewatering aid, which was a 1:1 blend of TDDP and soybean oil. This reagent blend was used as a 33.3% solution in diesel oil. The sample is thickened in a laboratory funnel to 42.6% solid content. The tests were conducted at a 0.6-inch cake thickness, 15-120 second of spin times, and a 2000 G-force. Of the two reagents, soybean oil was substantially cheaper than TDDP; therefore, a blend of the two represents a more economic option as dewatering aids.

Table 3.1 Effects of Using a Blend of TDDP and Soybean Oil as a Dewatering Aid for the Centrifugal Filtration of a Deslimed Bituminous Coal Sample at 2000 G

Spin Time (seconds)	Moisture Content (% wt.)	
	No Reagent	2 lb/ton TDDP + Soy Bean Oil
0	42.6	42.6
15	26.1	19.1
30	24.3	17.7
60	24.2	16.4
120	24.0	15.7

In the absence of dewatering aid, cake moisture was reduced to 24.3% after 30 seconds of spin time. Further increases in spin time did not significantly improve the moisture reduction. In the presence of the novel dewatering aid, the moisture was reduced to 17.7% after a 30-second spin time, which represents a 27.2% reduction in moisture. Note that in the presence of the dewatering aid, the %moisture continued to decrease with increasing spin time. At 120-second spin time, the moisture was reduced to 15.7%, which represents a 34.6% moisture reduction as compared to the case of not using the dewatering aid. This finding agrees well with the general observations made with vacuum filters that the transport of the water ‘liberated’ by the use of the novel dewatering aids is a slow process, particularly when dewatering of the fine particles [36,43].

The moisture reductions observed with the Goals-West Virginia coal sample were less than those observed in the filtration experiments since air phase was not presented in the current centrifuge. One should note, however, that the tests were conducted on a deslimed coal sample. The % reductions in moisture would have been lower if the sample contained all of the fines.

Table 3.2 Centrifugal test results of West Virginia coal sample using TDDP, Air Pressures at 2000 G-force

Spin Time (sec)	Cake Moisture (%wt)			
	No air		Air at 200 kPa	
	No Reagent	TDDP (1 lb/ton)	No Reagent	TDDP (1 lb/ton)
0	36.5	36.8	35.6	35.8
15	25.2	21.5	12.3	9.1
30	23.1	18.4	10.2	7.6
60	22.5	17.6	9.6	6.3
120	22.3	16.9	9.3	6.1

Another coal sample from Massey Energy was used in a series of centrifugal filtration tests, in which effects of using the novel dewatering aids were compared with the methods of using compressed air. The coal sample was a feed to screen bowl centrifuges, and are finer than 1.7 mm. The results are given in Table 3.2. As is the case with the results shown in the first test, the moisture reduction without the dewatering aid or compressed air were over 20%. Also, the moisture reductions did not improve significantly beyond 30 seconds of spin time. In the presence of TDDP, a low HLB surfactant, the cake moisture was reduced to 16.9% after 120 seconds of spin time, which represents a 22.4% reduction in moisture. When using a 200 kPa of compressed air, much substantial moisture reductions were obtained. After 120 seconds of spin time, the moisture was reduced to 9.3%, which represents a 58% reduction in moisture from the base case of using no reagent. When 1 lb/ton TDDP was added as a dewatering aid, the moisture was reduced to 6.1%, representing an excellent 73% reduction in moisture. Thus, the combined use of the novel dewatering aid and compressed air in centrifugal filtration is a powerful means of achieving very high levels of moisture reductions. The results given in Table 3.2 were obtained with 5 minutes of conditioning time after the addition of the dewatering aid and at a 0.5-inch cake thickness.

For another set of centrifugal dewatering tests, -0.6 mm x 0 Pittsburgh coal sample was floated in a Denver laboratory flotation cell using 1 lb/ton kerosene and 100 g/ton MIBC. The froth product was thickened by simple gravity filtration and then used for a series of centrifugal filtration tests using the 3.5-inch diameter air centrifuge shown in Figure 3.2. The air pressure was varied in the range of 50-200 kPa, while the centrifugal force was kept constant at a 2000 G. The cake thickness was 0.45 inch in all tests. The tests were conducted with and without using a dewatering aid (2 lb/ton Span 80), which was used as a 25% solution in diesel oil. The results are given in Table 3.3. As shown, the use of the low HLB surfactant further reduced the cake moisture beyond what can be achieved using the centrifugal filter in the presence of air pressure. In general, cake moisture decreased with increasing spin time and air pressure. It should be noted here that the product moistures were very low even without using the dewatering aid, particularly at high air pressures. For this reason, the benefits of using the low-HLB surfactants were not as significant as observed with vacuum filters in Chapter 2.

Table 3.3 Effects of Using a Dewatering Aid on the Centrifugal Filtration of a Pittsburgh Coal at Different Air Pressures

Spin Time (seconds)	Moisture (%wt)					
	50 kPa		100 kPa		200 kPa	
	No Reagent	Span 80 2 lb/ton	No Reagent	Span 80 2 lb/ton	No Reagent	Span 80 2 lb/ton
0	36.5	36.5	36.5	36.5	36.5	36.5
30	18.3	14.9	14.2	11.1	13.2	10.1
60	16.3	13.6	12.9	10.5	10.6	8.2
120	15.1	12.8	10.6	8.6	9.1	7.3

To date, no comphrensive dewatering studies have been conducted on fine particle dewatering using centrifugal force and air pressure configuration. It is clearly seen that the method of using the air pressure across the cake gives opportunities for the water trapped in smaller capillaries to be removed, which result in low cake moistures. As mentioned in the early sections, the cake consists of the fine and large capillaries in its structure. The water in larger capillaries is easily removed by applying only G-forces, but not for the finer capillaries.

Therefore, during the centrifugation the air also passes through the fine capillaries and removes more water remained in the cake. In addition to that, when the particles are made hydrophobic by adding a low HLB surfactant, the moisture reduction is approximately 3-4% lower beyond the G-force and air pressure combination. As a result, this significant improvement of the fine cake dewatering offers tremendous benefits for the coal producers in the USA using thermal drying, which has environmental concerns, high operation costs and difficulty in maintenance.

b) Effects of Process Variables

The objective of these investigations was to study the effects of selected process variables on the performance of the novel centrifuge developed in the present work. The process variables studied in this section included air pressure, G-force, and spin time on the fine coal dewatering.

Air Pressure A -28 mesh x 0 Pittsburgh coal sample was subjected to a series of i) pressure filtration tests at a 100 kPa of air pressure, ii) centrifugal filtration tests at a 2000 G, iii) and the novel centrifugal filtration tests at 100 kPa of air pressure. All tests were conducted at a 0.5-inch cake thickness. The results obtained at different times for dewatering or centrifugation are given in Table 3.4. The results obtained with a combination of high-G force and air pressure gave significantly better results than with air pressure alone or centrifugal force alone. The improvements obtained using the combination are far superior to those obtained using either air pressure or G-force alone, demonstrating a synergistic effect. The synergism observed in the present investigation can be attributed to the creation of a pressure drop across filter cake so that one can take advantage of the Darcy's equation.

Table 3.4 Effect of Using Compressed Air for the Centrifugal Filtration of a Pittsburgh Coal[3]

Drying Cycle or Centrifugation Time (sec)	Cake Moisture (wt %)		
	Air Pressure[1] Alone	Centrifugal Force[2] Alone	Centrifugal Force[2]& Air Pressur[1]
0	82.2	38.7	38.7
30	27.5	24.4	14.2
60	25.8	22.6	12.9
120	23.8	21.0	10.6

[1]100 kPa of air pressure; [2] 2000 G; [3]0.5 inch cake thickness.

A flotation product obtained from the Microcel™ flotation columns at Middle Fork coal preparation plant, Virginia, was screened at 400 mesh (0.038 mm) to remove particles finer than 0.038 mm. The -0.3+0.038 mm fraction was subjected to the centrifugal filtration tests at a 2500 G force and a 0.5-inch cake thickness. The objective of the tests was to determine the particle size effects on the novel dewatering methods. The test results obtained by varying air pressure and spin time are given in Table 3.5. In control tests, the moisture was reduced from 41.1% of the thickened slurry to 25.0% after 150 seconds of spin time. The cake moisture obtained after 30 seconds of spin time was 27.5%. Thus, the centrifugal filtration without air pressure is not effective in reducing the residual cake moisture even after desliming. When using compressed air, however, the cake moistures were reduced to below 10%. At 150 seconds of spin time and a 250 kPa of air pressure, the moisture was reduced to as low as 3.9%. This is a big challenge of the novel method for lowering moisture content to desired levels in industrial applications.

Table 3.5 The Results Obtained with a Deslimed Microcel™ Flotation Product at 2,500 G and Varying Air Pressures

Spin Time (sec)	Cake Moisture (%wt)			
	None	Air Pressure (kPa)		
		50	150	250
0	41.1	41.1	41.1	41.1
30	27.5	12.2	10.0	9.1
60	26.2	10.9	8.0	7.1
90	25.9	8.9	7.1	6.1
120	25.4	8.0	6.3	4.6
150	25.0	7.6	6.0	3.9

As known, the capillary tube diameters are dependent on the particle size. When one removes the fine particles from the system, bundle of larger capillary tubes is increased in the cake structure. According to the test results, even a deslimed product gives higher moisture contents since overall size is still very fine for this sample. However, in the presence of the air pressure the moisture content of the cake is remarkably reduced to 3% levels due to the air displacement of the water remaining in the larger capillaries [1,5,10,12].

In another set of tests, the flotation product from the Bailey–Pittsburgh plant was screened at 200 mesh, and the screen underflow (-74 μm) was used for centrifugal filtration tests. Table 3.6 shows the results obtained by changing air pressure and spin time at a 2000 G and 0.5-inch cake thickness. In this test, it is objected to find out the fine capillary effects on the cake moisture. The moisture reductions achieved in control experiments were poor due to the fine particle size of the screen product. After 30 seconds of spin time, the moisture was reduced from 42.3 to 37.1%. The moisture reduction did not improve significantly even after longer spin times. When air pressure was applied, however, the cake moisture was further reduced. The extent of moisture reduction achieved by the application of compressed air increased with increasing the air pressure and spin time. At a 400 kPa of air pressure and 150 second spin time, the cake moisture was reduced to as low as 16%.

Table 3.6 Results Obtained with a Fine (-0.074 mm) Pittsburgh Coal Sample at 2,000 G and 0.5-inch Cake Thickness

Spin Time (sec)	Cake Moisture (% wt)				
	None	Air Pressure (kPa)			
		100	200	300	400
0	42.3	42.3	42.3	42.3	42.3
30	37.1	31.9	27.6	24.5	22.5
60	36.9	31.2	24.6	21.2	19.7
90	36.7	30.2	23.8	20.2	18.4
120	36.6	29.7	23.0	19.1	17.8
150	36.5	28.5	22.5	18.8	16.8

In accordant with the Laplace equation, it is very hard to remove water remained in the fine capillaries. It is known that the centrifuges are primarily designed for the coarser particles dewatering, and in lower sizes the efficiency of the unit is drastically decreased. If the particle size is reduced to below 100 μ, it is practically impossible to achieve significant coal dewatering [1,5-12]. However, even at very low particle size, the new method is capable of decreasing the total moisture content in the filter cake. Also, it was observed that at higher air pressures, there was no air leakage from the unit, which means that the applied air passes through the cake.

G-Force A series of centrifuge filtration tests were conducted by increasing G-forces up to 2,500 at 300 kPa of air pressure, and the results are given in Table 3.7. Also shown for comparison are the results obtained without using compressed air. The tests were conducted on the coal sample (1 mm x 0), collected from the feed stream to the vacuum disc filters at Bailey plant, Consol Energy. The spin time was varied from 30 to 60 seconds and the cake thickness was kept constant at 0.45-inch. The results showed that centrifugal dewatering was not effective without using compressed air. The effectiveness increased with increasing G-force; however, its effectiveness does not increase substantially above 1500 G. This may be attributed to the increased cake resistance at very high G-forces and decreased the air passing through the cake. The literature studies also showed that the cake resistance of the centrifuge could be varied based on the filtration conditions, so the water derange might be affected at the high G-forces. As known, such problems limit the use of the centrifuges at higher G-forces [1,7-14]. Thus, the use of compressed air should allow centrifuges to be used at low G-forces (or r.p.m.), which will reduce the equipment cost and reduce the wear and, hence, maintenance requirement.

Table 3.7 Effects of Centrifugal Forces on the Dewatering of a 1 mm x 0 Filter Feed from Consol Energy at 300 k Pa of Air Pressure

Spin Time (seconds)	Moisture (%wt)					
	1500 G-force		2000 G-force		2500 G-force	
	No Air Pres	300 kPa Air Pres.	No Air Pres	300 kPa Air Pres.	No Air Pres	300 kPa Air Pres.
0	42.3	42.3	42.3	42.3	42.3	42.3
30	24.3	12.1	23.0	11.4	22.2	11.2
60	23.9	10.3	22.1	9.8	21.1	10.0
120	23.2	8.4	21.1	8.2	20.9	8.1

Spin Time: The effect of spin time was investigated on several fine coal samples. Table 3.8 shows the results obtained with a -28 mesh Pittsburgh coal sample by varying spin time. The tests were conducted at a 100-300 kPa of air pressure and a 2000 G. The results show that there was a significant drop in moisture after 30 seconds of spin time but little further after 60 seconds. From the results, it is concluded that kinetics of the centrifuge is also very high, which can be beneficial for dewatering fine coal particles in processing plants.

Overall, it is seen that there is a clear difference between the novel and conventional centrifuges on the fine coal dewatering. This difference makes it an attractive method in lowering the total moisture contents of fine particles. As mentioned in the first Chapter, millions of tons of the fine coal have been rejected to the tailing ponds, and every year approximately 40 million tons are being lost through the ponds. This method may be a solution for the US coal producers to recover the fine coal from the tailing ponds.

Further examples of the effect of air pressure on the dewatering of coal samples are given in Appendix G.

Table 3.8 Effects of Spin Time for the Dewatering of a Pittsburgh Coal Sample at Different Air Pressures and at 2000 G

Spin Time (sec)	Cake Moisture (%wt)			
	None	Air Pressure (kPa)		
		100	200	300
0	35.9	35.9	35.9	35.9
30	22.5	15.3	14.2	13.5
60	21.3	13.9	12.5	11.3
90	21.1	13.2	11.5	10.4
120	21.0	12.4	10.6	9.5
150	20.6	12.1	9.9	9.3

3.3.2 Dewatering of Fine Mineral Samples

As shown, the novel centrifuge has given excellent dewatering performance on the dewatering of the fine coal particles. In other words, 40% to 80% moisture reductions were received depending on the dewatering conditions. In this section, it is objected that similar results can be also obtained on the dewatering of fine mineral particles (sphalerite, galena, chalcopyrite, clay, talc, phosphate, PCC and silica). For this purpose, the several mineral samples from different countries were subjected to the novel centrifugal dewatering tests varying spin time, G-Force, cake thickness and air pressures. The experimental producers and process variables were in the same manner described for the fine coal dewatering. Some of the selected minerals and their results are submitted in the following pages.

Sphalerite: A sphalerite concentrate (0.105 mm x 0) obtained from a flotation plant located in Boliden–Sweden was tested in the novel centrifugal filtration unit. The sample was thickened to 20.3% moisture prior to centrifugal filtration tests conducted at a 2000 G and a 0.62

inch cake thickness. The results, given in Table 3.9, show that the cake moisture was reduced to 3.3% at a 300 kPa air pressure and 120 sec spin time. At 30 seconds of spin time and 100 kPa air pressure, the moisture was reduced to 7.2% which may be sufficient for metallurgical purposes.

The size of the zinc sample was finer than that of coal samples (~0.5 mm). In the practical point of view, moisture levels of the fine particles should be higher than that of coarse particles according to the Laplace equation. However, if one looks at the test results, the moisture content of the zinc mineral is much lower than the coal sample. The reason is that the specific gravity of the sulfide minerals is higher than that of coal, and it causes a tighten cake and, hence, gives lower cake moisture. In addition, the sample was a flotation product and its surface was moderately hydrophobic, so this can be the other reason for high moisture reductions of the sulfide mineral [41-48].

Table 3.9 <u>The Results Obtained with a Sphalerite Concentrate at 2000 G and 0.62-inch Cake Thickness</u>

Spin Time (sec)	Cake Moisture (%wt)				
	None	Air Pressure (kPa)			
		50	100	200	300
0	20.3	20.3	20.3	20.3	20.3
30	13.2	8.4	7.2	5.8	5.0
60	13.1	8.1	6.5	4.7	4.2
90	12.8	7.2	6.1	4.5	3.5
120	12.4	7.1	5.9	4.2	3.3

<u>Chalcopyrite</u>: Table 3.10 shows the results of the centrifugal filtration tests conducted on a chalcopyrite concentrate (0.15 mm x 0) received from an operating plant located in Sweden. After the thickening, the samples were dewatered at a 2000 G and 0.7-inch cake thickness. The tests conducted without air pressure reduced the cake moisture from 22.9 to 14.1% after 90 seconds of centrifugation. Longer spin times did not significantly reduce the moisture further down. In the presence of applied air pressures, however, very low cake moistures were obtained. At a 100 kPa air pressure, the moisture was reduced to 6.9% after only 30 seconds of spin time. For industiral purposes, to obtain a 6% moisture content product, a 30second spine time is enough at a 300 kPa air pressure and a 2000 G-Force. According to these test results, it may be

concluded that this process can replace the thermal dryers prior to the next metallurgical processes for matte production [12,49-54].

Table 3.10 The Results Obtained with a Chalcopyrite Concentrate at 2000 G and 0.7-inches Cake Thickness

Spin Time (sec)	Cake Moisture (%wt)				
	None	Air Pressure (kPa)			
		50	100	200	300
0	22.9	22.9	22.9	22.9	22.9
30	15.1	9.5	6.9	6.1	6.0
60	14.5	9.0	5.8	5.1	4.9
90	14.1	8.4	5.7	4.6	4.1
120	14.0	8.0	5.5	4.0	3.1
150	13.9	7.8	5.1	3.6	2.5

Galena: The centrifugal filtration tests were also conducted on a clean galena concentrate (0.075 mm x 0) received from Boliden-Sewden. The samples were dewatered at a 1000 G and 0.7-inch cake thickness after the thickening. The tests conducted in the absence of air pressure decreased the cake moisture from 18.1 to 13.7% with 120 seconds centrifugation period (Table 3.11). Longer spin times did not improve the total moisture reduction. However, when a 300 kPa air pressure was applied to the sample, very low cake moistures (3 to 4%) were obtained. It was also determined that the galena sample always gave lower moisture content than the other samples used in these tests. This can be a reason of the high specific gravity (7.5 g/cm^3) of the sample [12,55-61].

Table 3.11 The Centrifugal Results Obtained with a Galena Concentrate at 1000 G and 0.6-inches Cake Thickness

Spin Time (sec)	Cake Moisture (%)				
	None Air	Air Pressure (kPa)			
		50	100	200	300
0	18.1	18.1	18.1	18.1	18.1
30	13.9	9.0	7.3	5.6	4.8
60	13.9	8.5	6.7	5.0	4.3
90	13.8	8.3	6.3	4.5	3.9
120	13.7	8.1	6.2	4.1	3.2

Clay: One of the most difficult materials to dewater is fine kaolin clay. The sample received from East Georgia (95% lower than 2 microns) was floated by adding 700 g/ton dodecylamine and 120 g/ton MIBC at pH 9.3 (lime) to make the surface more hydrophobic. The product was then thickened to 62% moisture by a funnel in the presence of a 300 g/ton of Super Floc 214, and then subjected to the novel centrifugal filtration at a 2000 G and 0.4-inch cake thickness. The test results are given in Table 3.12. In the absence of air pressure, the moisture was reduced to 47.9% after 210 seconds of spin time. At a 600 kPa air pressure and 210 seconds of spin time, the cake moisture was further reduced to 25.7%, which responds 59% moisture reduction. Such low moisture should obviate the energy need for spray drying, which is a costly method that has been used for dewatering aim in the clay industry.

Table 3.12 Results Obtained on an East Georgia Kaolin Clay at 2000 G and 0.4-inch Cake Thickness

Spin Time (sec)	Cake Moisture (%wt)				
	None	Air Pressure (kPa)			
		150	300	450	600
0	62.0	62.0	62.0	62.0	62.0
30	52.1	43.2	40.8	38.5	34.6
90	50.3	39.1	35.6	34.4	31.3
150	48.4	35.4	32.5	30.1	28.9
210	47.9	33.6	30.1	27.6	25.7

It is known that clay is a plate-like mineral that adsorbs water molecules in between the sheets. This makes the clay a hydrophilic mineral. Accordingly, the surface area of the mineral is also 20 to 300 times higher than that of the coal sample, so the capillary pressure in the cake can be higher for the clay particles. What it means is that removing the water from the clay minerals requires higher G-forces (or energies). As a result, the novel method can be a solution for the clay minerals dewatering in many plants that have been having dewatering problems with the current dewatering units [12,60,62].

<u>*Precipitated calcium carbonate (PCC)*</u>*:* PCC is another material that is very difficult to dewater in conventional dewatering methods. In this example, mostly nanosize PCC sample (-2 μm) received from Pittsburgh was used for the novel centrifugal filtration tests. According to the size of the PCC sample, the capillary diameter of the cake is the lowest among the other coal and mineral particles, so one can see that the moisture content can be higher in the final cake.

In order to treat the particle surface, the pH of the slurry was adjusted to 9.5 by adding lime before injecting a small amount (500 g/ton) of sodium oleate to float the particles. It renders the surface hydrophobic, which can help lower fine particle moisture [12,62-64]. The slurry was thickened to 70.3% moisture content before the filtration experiments were done on the samples (No:3). The tests were conducted at a 2000 G and 0.35-inch cake thickness. As shown in Table 3.13, the cake moisture was reduced to 57.8% after 3 minutes of spin time in the absence of the air pressure. At a 600 kPa air pressure, the moisture was further reduced to 34.2%, which represents approximately 52% reduction in moisture.

Table 3.13 <u>The Results Obtained on a PCC Sample at 2000 G and 0.35-inch Cake Thickness</u>

Spin Time (sec)	Cake Moisture (%wt)				
	None Air	Air Pressure (kPa)			
		150	300	450	600
0	70.3	70.3	70.3	70.3	70.3
30	62.1	51.2	46.7	41.6	37.9
60	60.6	49.3	43.6	38.5	36.3
120	58.3	47.3	41.1	36.9	35.1
180	57.8	46.7	40.0	35.5	34.2

Interestingly, it was observed that during the centrifugation cake breakage occurred on the cake surface at high air pressures. This obviously allows lower moisture reduction from the cake. The author assumes that it might be attributed to the removal of a large volume of water from the cake causing shrinkage on the cake surface. If a method could be found to prevent the breakage problem, the cake moisture of the product would be further reduced to be directly used in paper, ceramic or paint industries [12,24,36,43].

Phosphate: A phosphate ore (-0.42+0.038 mm) from Florida was floated using a tall oil fatty acid as collector and fuel oil as extender at a neutral pH, and then subjected to centrifugal filtration tests. A set of tests was conducted using compressed air with the apparatus shown in Figure 3.2, while another set of tests was conducted under vacuum pressure using the apparatus shown in Figure 3.3. The results are given in Table 3.14. In the control tests, the cake moisture was reduced from 40.4 to 17.2% after 2 minutes of spin time. At a -80 kPa of vacuum pressure and 80 kPa of air pressure, the moistures were reduced to 9.3 and 8.8%, respectively. The difference between the two sets of data are small, indicating that the performance of centrifugal filtration is dependent on the pressure drop (ΔP) across the cake.

Table 3.14 Comparison of Using Vacuum and Air Pressures on the Centrifugal Filtration of a Phosphate Sample at 2000 G

Spin Time (sec)	Cake Moisture (%wt)				
	None	Vacuum Pressure (kPa)		Air Pressure (kPa)	
		-40	-80	40	80
0	40.4	40.4	40.4	40.4	40.4
30	19.7	14.1	12.3	13.3	12.6
60	18.2	12.6	10.2	12.9	10.3
90	17.9	12.2	9.6	11.9	9.5
120	17.2	11.8	9.3	11.6	8.8

The centrifugal filtration tests were also conducted using both compressed air inside a filter vessel and vacuum on the outside at the same time (Figure 3.3). The tests were applied to the Florida phosphate concentrate (-0.42+0.038 mm) obtained by flotation using Tall oil and fuel oil at a neutral pH. In this test (Table 3.15), the positive pressures refer to air pressure, and the negative refer to vacuum pressures. It was shown that a combination of air and vacuum pressures gave excellent dewatering results. This also demonstrates that the pressure drop across the cake is needed to increase the dewatering performance of the phosphate (or any mineral). It does not seem to matter whether the increase is brought about by air pressure, vacuum pressure, or a combination of the two.

Table 3.15 Results Obtained on a Phosphate Concentrate Using Both Compress Air and Vacuum Pressure at 2000G[1]

Spin Time (sec)	Cake Moisture (%wt)		
	Air & Vacuum Pressures (kPa)		
	None	40 & -40	80 & -80
0	40.4	40.4	40.4
30	19.7	11.9	8.7
60	18.2	10.2	7.3
90	17.9	9.5	7.6
120	17.2	9.0	6.4

[1] 0.45 inches cake thickness

Talc: Several dewatering tests were conducted to find out the novel centrifuge effects on fine talc sample. A -100 mesh sample received from a talc company (Luzenac-America) was floated by adding 100 g/ton PPG type frother at neutral pH. The floated product was then thickened in a funnel before the centrifugation. The tests were carried out at a 0.46-inch cake thickness by varying drying cycle time or spin time at a 1500 G-force showed in Table 3.16. The test results indicated that the cake moisture was reduced from 35.6 to 24.9% with the current centrifuge after 2.5 minutes of spin time. At a 250 kPa of air pressure with the same conditions, the moisture was reduced from 35.6 to 10.2%.

Table 3.16 Novel Centrifugal Test Results Conducted on Luzenac-America Clean Talc Sample* at 1500 G-Force

Spin Time (sec)	Cake Moisture (wt %)					
	None Air	Air Pressure (kPa)				
		50	100	150	200	250
0	35.6	35.6	35.6	35.6	35.6	35.6
30	25.5	21.6	17.5	15.9	14.8	14.4
60	25.2	19.0	16.1	14.3	13.6	13.1
90	25.1	18.1	15.0	13.3	11.8	11.4
120	25.0	17.4	14.7	12.6	10.9	10.5
150	24.9	17.2	14.5	12.2	10.6	10.2

* Size –0.15 mm; cake thick 0.4 in; no reagent used; the sample floated using 100 g/ton MIBC

In order to determine a synergistic effect of using G-Force and air pressure, a series of tests were also conducted on the same sample and the results are given in Table 3.17. In these tests, cake moisture using air pressure filter was reduced from 25.7 to 21.9% at a 200 kPa air pressure after two minutes of drying cycle time. Under the same filtration conditions, applying a 2000 G-Force further decreased the moisture content from 15.2 to 11.6%, which is far from the individual units. As has been the case with the coal sample, use of the air pressure during centrifugal filtration also demonstrated synergistic effects for the dewatering fine talc particles. This can be also valid for the other mineral dewatering using the similar dewatering conditions. Consequently, the enhancements of dewatering obtained with high G and air pressure are better than the any other dewatering methods used in filtration industry.

Table 3.17 Synergistic Effects of Using Centrifugal Force and Compressed Air for the Dewatering of a Talc Sample[3]

Drying Cycle or Spin Time (sec)	Cake Moisture (wt %)					
	Air Pressure Alone (kPa)		Centrifugal Force Alone		Air Pressure and Centrifugal Force	
	100	200	1000G	2000G	100[1]&1000G[2]	200[1]&2000G[2]
30	30.2	25.7	26.0	25.1	19.1	15.4
60	27.2	22.3	25.8	24.8	16.8	13.2
120	25.8	21.9	25.5	24.6	15.2	11.6

[1]Air pressure in kPa;[2] G-Force; [3]0.46 inch cake thickness.

Silica: A series of centrifugal dewatering tests were conducted on a fine quartz powder obtained a plant located in Tennessee-USA. In order to increase the hydrophobicity of the particles (0.075 mm x0), flotation tests were conducted on the sample using 150 g/ton Dodecylamine and 100 g/ton MIBC at pH 9.5 (lime). The centrifuge test results conducted on the thickened sample are given in Table 3.18. In the base line tests, cake moisture was reduced to 25.4% at a 1500 G-force, 0.43 inch cake thickness and 2 minutes of spin time. At a 300 kPa of air pressure with the same conditions, the moisture content was decreased from 34.8 to 9.8%. The test results clearly confirm that G-force combined with air pressure gives very high moisture reductions; therefore, this product needs a very low energy input for the thermal dryers for the ongoing processes [12,24,43].

Table 3.18 Centrifugal Test Results Conducted on Tennessee Silica Sample Using Air Pressure at 1500 G-Force

Spin Time (sec)	Cake Moisture (%wt)				
	None Air	Air Pressure (kPa)			
		50	100	200	300
0	34.8	34.8	34.8	34.8	34.8
30	26.9	19.7	15.7	13.3	12.0
60	25.8	18.1	14.2	11.8	10.8
90	25.4	17.5	13.8	11.5	10.2
120	25.4	17.2	13.9	11.2	9.8

It is seen that the removal of water from the fine particles plays an important role in determining the plant recoveries, thermal drying and transportation costs. In order to understand the mechanisms of the novel centrifuge method, it can be possible to optimize different parameters of the unit by changing the filtration variables. For this reason, a microscopic population balance model (PBM) for the particle settlement has been developed on the novel centrifugal unit and given in Appendix I.

3.5 SUMMARY AND CONCLUSIONS

A novel centrifugal filtration was used to remove surface moisture of fine coal and mineral particles at different G-Force, air/vacuum pressure, spine time, cake thickness and chemical dosages. In this method, a 3.5-inch diameter basket was connected to an air/vacuum pressure supply and rotated at varying speeds to generate significant centrifugal forces on the surface of the filter cake.

A series of centrifugal filtration tests were conducted on deslimed coal samples in the absence of a compressed air. The deslimed sample (1 mm x 0.038) was used to simulate screen bowl centrifuges, which loses most of the particles finer than 44 µm [12,43]. The tests carried out at a 0.6-inch cake thickness, 15-120 seconds of spin times and a 2000 G-force showed that an approximately 8% moisture difference could be achieved by using a blend of TDDP and soybean oil dissolved 33.3% in diesel.

A West Virginia coal sample (-1.7 mm) was subjected to dewatering tests. The moisture reduction in the absence of a dewatering aid was only 20%. In the presence of TDDP reagent, the cake moisture was decreased to 16.9% after 120 seconds of spin time, which represents a 22.4% reduction in moisture. A More substantial moisture reduction was obtained using a 200 kPa of compressed air in the basket. After 120 seconds of spin time, the moisture was reduced to 9.3%, which corresponds a 58% reduction in moisture from the base case of using no reagent and compressed air. When 1 lb/ton TDDP was added as dewatering aid, the moisture was further reduced to 6.1%, representing a 72.6% total moisture reduction from the cake. Therefore, it can be concluded that such moisture content of the product may not need a thermal operation for the upstream processes.

In order to compare the filtration methods, Pittsburgh coal samples were subjected to a series of filtration tests using an air pressure filter at a 100 kPa, centrifugal filter at a 2000 G-force, and novel filtration tests at a 2000 G-force and 100 kPa air pressure together. A combination of high-G force and air pressure gave significantly better results than the individual units, which indicates that the combination of two units can give synergistic effects on the fine particle dewatering.

A flotation product obtained from Middle Fork - Virginia was screened at 400 mesh (0.038 mm) to remove particles finer than 0.038 mm, and the -0.3+0.038 mm fraction was performed for the centrifugal filtration tests at a 2500 G-force and 0.5-inch cake thickness. The cake moisture obtained after 30 seconds of spin time was 27.5% without air pressure. When the compressed air was applied to the basket, the cake moistures were reduced to below 4% based on the dewatering conditions. In other words, the dewatered product seemed to be a dried powder and could be used without any thermal operations.

Clean coal samples from Pittsburgh were screened at 74 micron and the screen underflow was performed for centrifugal filtration tests at a 2000 G-force and 0.5-inch cake thickness. The moisture reductions achieved in control experiments were not significantly enough due to the size of the particle. After 30 seconds of spin time, the moisture was reduced from 42.3% to 37.1%. It was observed that the moisture reduction did not improve significantly even after longer spin times. In contrast, the cake moisture was decreased to as low as 16% when a 400 kPa of air pressure was applied to the surface of the cake.

A set of centrifuge filtration test was also conducted on the coal sample (1 mm x 0) by increasing G-forces up to 2500 at a 300 kPa of air pressure. The spin time was varied from 30 to 60 seconds and the cake thickness was kept constant at a 0.45-inch. It was seen that the effectiveness of centrifuge increased with increasing G-force; however, its effectiveness did not increase substantially above 1,500 G. The compressed air, therefore, should allow centrifuges to be used at low G-forces, which will reduce the equipment cost and the wear on the machines.

Several fine mineral samples were also tested in the centrifugal dewatering method. In order to find out the novel centrifuge effects on the mineral samples, a clean sphalerite concentrate (0.15 mm x 0) was selected and used in the unit at a 2000 G-force and 0.62 inch cake thickness. The results showed that the cake moisture was reduced from 20.3 to 3.3% at a 300 kPa air pressure and 120 sec spin time.

One of the most difficult materials to dewater is fine kaolin clay (mostly nanosize). The thickened clay sample from East Georgia was dewatered at a 2000 G-force and 0.4-inch cake thickness. In the absence of air pressure, the moisture was reduced 62% to 47.9% after 210 seconds of spin time. However, when a 600 kPa air pressure was applied to the sample, the cake moisture was lowered to approximately 25% with the same conditions.

Phosphate samples were subjected to centrifugal filtration tests using compressed air as shown in Figure 3.2, and vacuum/air pressure together shown in Figure 3.3. Comparisons were made between vacuum and air pressure. In the first set of tests, cake moisture was reduced from 40.4% to 9% after 2 minutes of spin time. In the second set of tests, air and vacuum pressures were applied to the samples at the same time and a similar dewatering improvement was also achieved on the sample. In addition, a combination of air and vacuum pressures gave better moisture reductions from the samples.

A talc sample was dewatered in the novel centrifuge at a 0.46-inch cake thickness and a 1500 G-force. A synergistic effect of using G-Force and air pressure was seen in the present tests. The experimental results showed that, without air pressure, cake moisture was reduced from 35.6% to 24.9% after 2.5 minutes of spin time. At a 250 kPa of air pressure, the moisture content was decreased to 10%.

In the presence and absence of air pressure, centrifugal dewatering tests were also conducted on other selected minerals (chalcopyrite, galena, silica and PCC), and showed that the dewatering results were significantly better as the air was presented in the system. According to the test results, it can be concluded that in the presence of the novel filter the dewatering costs and environmental concerns created by the thermal dryers can be substantially decreased for the fine particle dewatering.

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