COAL CLEANING BY GAS AGGLOMERATION

Final Technical Progress Report

October 1, 1997 – December 31, 1998

T. D. Wheelock
Principal Investigator

Meiyu Shen
Graduate Assistant

Royce Abbott
Research Assistant

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Chemical Engineering Department
Center for Coal and the Environment
2114 Sweeney Hall
Iowa State University
Ames, Iowa 50011-2230

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ABSTRACT

The technical feasibility of a gas agglomeration method for cleaning coal was demonstrated by means of bench-scale tests conducted with a mixing system which enabled the treatment of ultra-fine coal particles with a colloidal suspension of microscopic gas bubbles in water. A suitable suspension of microbubbles was prepared by first saturating water with air or carbon dioxide under pressure then reducing the pressure to release the dissolved gas. The formation of microbubbles was facilitated by agitation and a small amount of i-octane. When the suspension of microbubbles and coal particles was mixed, agglomeration was rapid and small spherical agglomerates were produced. Since the agglomerates floated, they were separated from the nonfloating tailings in a settling chamber.

By employing this process in numerous agglomeration tests of moderately hydrophobic coals with 26 wt.% ash, it was shown that the ash content would be reduced to 6 – 7 wt.% while achieving a coal recovery of 75 to 85% on a dry, ash-free basis. This was accomplished by employing a solids concentration of 3 to 5 w/w%, an air saturation pressure of 136 to 205 kPa (5 to 15 psig), and an i-octane concentration of 1.0 v/w% based on the weight of coal.

It was also shown that the process of agglomeration can be reversed by subjecting an aqueous suspension of agglomerates to a pressure sufficient to redissolve the microbubbles. This technique was used for recleaning agglomerated coal in a second stage. By starting with coal with an ash content of 33.0 wt.%, it was shown that the ash content could be reduced to 10.4 wt.% in a single stage or to 6.3 wt.% in a second stage. However, the overall recovery of clean coal decreased from 88.7% for one stage to 82.0% for two stages.

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EXECUTIVE SUMMARY

This investigation showed that ultra-fine size coal particles in an aqueous suspension can be agglomerated selectively by mixing with a colloidal suspension of microscopic gas bubbles in water. A suitable suspension of gas bubbles was prepared by first saturating water at ambient temperature with either air or carbon dioxide under pressure in the range of 136 to 205 kPa (5 to 15 psig). After adding a small quantity of i-octane to the gas-saturated water, the pressure was released as the mixture was agitated, and a colloidal dispersion was produced with a fog-like appearance. The dispersion appeared to consist of microscopic gas bubbles encapsulated in a hydrocarbon film which increased the stability of the suspension. Without the i-octane, the microbubbles tended to coalesce into larger bubbles. When the microbubbles and coal particles were mixed vigorously, agglomeration was rapid, and spherical agglomerates were produced which floated because of the gas incorporated in the agglomerates. Therefore, it was possible to recover the agglomerates by allowing the unagglomerated mineral particles to sink and the agglomerated coal to float under quiescent conditions.

This method of agglomeration and separation was demonstrated in a series of agglomeration tests involving Pittsburgh No. 8 coal and Upper Freeport coal which had been ground to ultra-fine size. In the case of dilute suspensions with 1.0 w/w% solids, the progress of agglomeration was monitored by observing changes in the turbidity of the suspension, whereas in the case of more concentrated suspensions with 3.0 to 9.0 w/w% solids the results were determined by recovering and analyzing the agglomerated product and tailings. The tests made with dilute suspensions showed that while the rate of agglomeration was proportional to gas concentration, it was hardly affected by i-octane concentration. The tests

made with more concentrated suspensions showed that moderately hydrophobic coals with an ash content of 26 wt.% can be cleaned to produce a product with 6-7 wt.% ash while providing a coal recovery of 75 to 85% on a dry, ash-free basis.

Tests made with both dilute and more concentrated suspensions showed that the process of agglomeration can be reversed by increasing the system pressure and thereby redissolving the gas bubbles holding agglomerates together. This discovery made it possible to demonstrate a two-stage agglomeration process in which the agglomerates produced in the first stage were recleaned in a second stage by deagglomerating the material to release trapped mineral particles and then reagglomerating the coal particles. A comparison of the results of single stage and two stage agglomeration tests with Upper Freeport coal having an initial ash content of 33.0 wt.% showed that while the ash content could be reduced to 10.4 wt.% in a single stage with a coal recovery of 88.7%, the ash content could be reduced to 6.3 wt.% in two stages with an overall coal recovery of 82.0%. These results were achieved by employing an initial solids concentration of 3.0 w/w%, an initial air saturation pressure of 205 kPa (15 psig), and an i-octane concentration of 1.4 v/w% based on the initial weight of coal.

INTRODUCTION

One of the more promising methods for cleaning ultra-fine size coal has been the oil agglomeration method. However, its use has been largely inhibited by the relatively large amounts of oil required, typically from 10 to 30% based on the weight of coal. While investigating this method, it was discovered that gas plays a very important role in the process (1, 2). Aqueous coal suspensions which had been degassed could not be

agglomerated with heptane until a small amount of air was introduced to trigger the process (2, 3). The evidence suggested that small gas bubbles are involved in the agglomeration mechanism. Such a mechanism was suggested long ago by Taggart (4). Upon realizing that gas must be present for agglomeration of an aqueous suspension, it was shown that various hydrophobic materials such as sulfur, gilsonite, graphite and Teflon can be agglomerated by gas alone (5). To take full advantage of this discovery, the present work was undertaken.

The overall purpose of the present project was to show that gas agglomeration is a technically feasible method of cleaning ultra-fine size coal. At the outset it was realized that small amounts of oil or a liquid hydrocarbon such as i-octane would probably be needed to make the surface of the coal particles more hydrophobic but not to serve as a binder. Subsequently it was discovered that i-octane facilitated the formation and stabilization of microscopic gas bubbles produced by first saturating water with gas under pressure, and then as the water was agitated, releasing the pressure. This technique produced a cloud of microscopic gas bubbles which were probably coated with a film of i-octane. When the dispersion of microbubbles was mixed with an aqueous suspension of coal particles, agglomeration was rapid and small spherical agglomerates were produced which were held together by the microbubbles.

A large number of agglomeration tests were conducted to investigate the relative importance of various parameters such as the concentration of suspended solids, the concentration of i-octane, and the gas pressure employed for saturating the water used for generating microbubbles. In the case of dilute suspensions, the results were evaluated by observing the rate of change of turbidity of a suspension being agglomerated. For more

concentrated suspensions, the results were measured by determining the recovery and ash content of the cleaned coal.

Additional experiments were conducted to demonstrate the reversibility of the gas agglomeration process and to demonstrate the feasibility of a two-stage agglomeration process.

EXPERIMENTAL METHOD

Agglomeration Systems

Two different laboratory mixing systems were used for conducting gas agglomeration tests. Although both systems were enclosed to control the amount of gas present, the first system could not be sealed and had to be operated at atmospheric pressure, whereas the second system could be sealed and pressurized. The first system consisted largely of an enclosed, flat-bottom, cylindrical tank fitted with four vertical baffles attached to the inner surface of the tank. The vertical tank had an inside diameter of 15.24 cm and an inside height of 15.70 cm. The width of each baffle was 1.27 cm. The measured net volume of the tank was 2870 cm³ when it was fitted with baffles and an agitator. The walls of the tank and baffles were made of clear Plexiglas, whereas the top and bottom were made of stainless steel. The top of the tank was slightly concave to facilitate venting gas from the system. Agitation was provided by a single Rushton-type turbine impeller mounted on a vertical drive shaft so that the impeller disk was 2.54 cm above the bottom of the tank. The impeller had six vertical flat blades mounted on a horizontal disk; the overall diameter of the impeller was 5.08 cm. The impeller shaft was driven by a variable speed, 93 watt (1/8 hp) motor which was operated by a calibrated control unit which indicated both shaft speed and torque.

A collar attached to the top of the tank surrounded the agitator drive shaft and made it possible to completely fill the tank with a suspension of coal particles even though there was a small gap between the collar and the shaft.

Since the first system could not be pressurized, a second mixing system was constructed for conducting agglomeration tests under pressure. A schematic diagram of the system appears in Figure 1. The system included a flat-bottom cylindrical mixing tank similar in design to the one described above but smaller, and it was fitted with a shaft seal so that it could be pressurized. The new tank had an inside diameter of 11.43 cm and inside height of 11.43 cm. It was fitted with four vertical baffles with each baffle projecting inward a distance of 0.95 cm. The net volume of the tank fitted with baffles and agitator was

Figure 1. Experimental agglomeration system used for investigating the influence of gas pressure.

1190 cm³. The walls of the tank and baffles were made of clear Plexiglas, whereas the top and bottom were made of aluminum. A cooling coil was attached to the bottom of the tank. The top of the tank was slightly concave to facilitate venting gas from the system. The central opening in the top of the tank was fitted with an oil-impregnated bronze bushing which served as a bearing for the agitator shaft. This bushing also served as a retainer for a spring-loaded, graphite reinforced Teflon shaft seal. A Rushton type turbine impeller was attached to the lower end of the agitator shaft. The impeller was similar in design to the one used in the larger system except that it was 3.65 cm in diameter. The impeller disk was located 2.54 cm above the tank bottom. The impeller shaft was driven by the same variable speed motor used with the larger system. The second system also included special equipment for pressurizing the system with compressed gas, for saturating water with gas, and for introducing coal particles into the water-filled, pressurized system. Before conducting an agglomeration test, water was placed in the elevated surge tank for saturation with a compressed gas, and the slurried feed material was placed in a coal storage tank located next to the mixing tank. A peristaltic circulation pump was used for introducing the feed into the mixing tank.

When either one of the systems described above was used for agglomerating dilute particle suspensions, the progress of agglomeration could be monitored by observing the changing turbidity of the particle suspension. This was accomplished by continuously passing a stream of material from the mixing tank through the measuring cell of a photometric dispersion analyzer (PDA) and back to the mixing tank. As the stream passed through the measuring cell, the light transmittance of the suspension was determined. The measurement was made with a PDA 2000 instrument manufactured by Rank Brothers Ltd.

The action of the impeller in the new, smaller mixing tank created enough difference in pressure to cause material to circulate through the external loop encompassing the PDA. However, when the larger mixing tank was employed, circulation was maintained with a peristaltic pump placed between the PDA and the mixing tank.

Agglomeration Materials and Methods

Coal for the agglomeration tests was obtained from two sources. One source was the Pittsburgh No. 8 coal seam in Belmont County, Ohio, and the other source was the Upper Freeport coal seam in Indiana County, Pennsylvania. The first coal is regarded as a high volatile A bituminous coal, while the second coal is probably a medium volatile bituminous coal. Normally the second coal was more hydrophobic than the first coal, which was moderately hydrophobic. Both coals had a large ash content, ranging from 25 to 35 wt.%, depending on the sample. Each coal was first crushed with a jaw crusher and then ground by passing it successively through a roll mill and a high-speed impact mill. The material was ground further with a stirred ball mill to produce particles having projected area mean diameter of about 4 μm for Pittsburgh coal and 5 μm for Upper Freeport coal. For this step the ball mill was charged with 250 g coal, 300 ml water, and 1200 g stainless steel balls having a diameter of 3 mm. A stirring speed of 540 rpm was employed for 20 min. The product was washed through a 270 mesh screen and any oversize particles were discarded. The screened slurry was partially dewatered with a Büchner filter funnel, and the recovered paste containing approximately 54% solids was stored in a refrigerator set at 5°C.

For an agglomeration test, coal particles were suspended in deionized water having a resistivity of 17 – 18 megohm•cm. A small amount of pesticide grade i-octane with an

indicated purity of 99.5% was used to promote gas agglomeration. This material was obtained from Fisher Scientific.

Two general procedures were used for generating the microscopic gas bubbles needed for gas agglomeration of coal particles. The first general procedure was employed with the larger mixing tank which could only be operated under atmospheric pressure. At the start of an agglomeration test the coal particles were suspended in cold water (7-10°C) which had first been saturated with gas. As the suspension was agitated and its temperature rose, gas came out of solution in the form of very small bubbles which then served to agglomerate the coal. The second general procedure was employed with the smaller mixing tank which could be pressurized. To prepare for an agglomeration test, coal was suspended in water which had first been saturated with gas under pressure (usually about 2 atm.) at room temperature. Then when the system pressure was reduced at the start of an agglomeration test, the gas came out of solution in the form of very small bubbles which served to agglomerate the coal. The temperature of the system was kept constant by circulating cooling water through the coil attached to the bottom of the mixing tank. These procedures are described below in greater detail.

The first procedure was initiated by cooling 4 liters of deionized water to 2 - 4°C and saturating it with gas at atmospheric pressure. The gas was bubbled through the water for about 1 hr. by using a fitted glass dispersion tube to generate small bubbles. A portion of this water was poured into the larger mixing tank so that the tank was approximately 75% filled. At the same time a predetermined amount of previously prepared coal paste was weighed out and mixed with 200 – 300 ml of the cold, gas-saturated water. The resulting slurry was added to the mixing tank together with enough gas-saturated water to completely fill the

mixing tank. The agitator was turned on, and the desired agitator speed was established. A small amount of oil (usually i-octane) was injected with a syringe. As agitation continued the temperature of the system was observed to rise gradually, and the turbidity of the system was observed to change. After the turbidity of the suspension appeared to reach a steady state, the run was discontinued.

The second general procedure was employed with the equipment shown in Figure 1. The surge tank was first filled with deionized water at room temperature and saturated with gas at a predetermined pressure. For agglomeration tests conducted with dilute suspensions (i.e., 1 w/w% solids), agglomeration was monitored by observing changes in the turbidity of the suspension. For these tests the tubing connecting the mixing tank to the PDA and to the coal storage tank was filled with water. In addition, the small amount of oil required for the test was introduced into the tubing connecting the mixing tank to the PDA. Also a predetermined quantity of coal paste was mixed with 50 ml of deionized water and placed in the coal storage tank. Sufficient water was added to completely fill the coal storage tank and the tubing connecting the tank to the mixing tank. Valves V_2 and V_3 were opened gradually to pressurize the mixing tank. After the tank was fully pressurized, gas was bubbled through the water in the surge tank for another 5 min. to insure complete saturation. Valves V_4 and V_5 were then opened to allow the gas-saturated water to completely fill the mixing tank. The agitator was turned on and the proper speed (generally, 2000 rpm) established. Valve V_1 and the gas cylinder regulator were adjusted to reduce the system pressure a predetermined amount which caused some of the gas to come out of solution and form a colloidal suspension that was fog-like in appearance. In most cases the pressure was reduced to atmospheric pressure. Since the colloidal suspension only appeared when both gas and oil

were present, the suspension seemed to consist of oil-coated, microscopic gas bubbles. After the fog appeared, the peristaltic pump was started in order to introduce the coal into the mixing tank. After about 1 min. of operation, the pump was stopped. Particles started to agglomerate immediately, and the process of agglomeration was monitored by observing the changing turbidity. As agglomeration proceeded the agitator speed was held at 2000 rpm and the temperature of the suspension was kept close to room temperature by circulating water through a cooling coil attached to the bottom of the mixing tank. A run was continued until the turbidity approached a constant value. At the end of a run, a sample of the suspension was examined with an optical microscope to determine the size range of the agglomerates.

The results of the agglomeration tests are reported below in terms of the relative turbidity change which took place during a given test. The relative turbidity change ($\Delta\tau_r$) in percent is defined by the following expression:

$$\Delta\tau_r = [(\tau_o - \tau) / \tau_o] 100 \quad (1)$$

where τ_o represents the initial turbidity of the unagglomerated suspension and τ represents the turbidity after agglomeration has taken place. It is apparent that as agglomeration takes place the relative turbidity change will increase while the absolute turbidity decreases.

For agglomeration tests involving suspensions with particle concentrations greater than 1 w/w%, the procedure was altered because the measurement of turbidity was not reliable and could not be counted on to provide a measure of the extent of particle agglomeration. For these tests the mixing tank was first filled completely with deionized water which had been saturated with gas under a selected pressure in the range of 136 to 205 kPa (5 to 15 psig) at room temperature (22 – 24°C). An agitator speed of 2000 rpm was usually selected and a measured amount of pure i-octane was introduced. The mixture was

conditioned for 1 - 2 min. at the selected stirring rate, and then the pressure was reduced to 101 kPA (0 psig) which allowed the dissolved gas to come out of solution in the form of microscopic bubbles. A concentrated coal slurry was then introduced quickly from the coal storage tank so as to provide a preselected solids concentration in the range of 3.0 to 9.0 w/w%. Particles started to agglomerate immediately, and as agglomeration proceeded the agitator speed was held constant, and the temperature of the suspension was kept close to room temperature by circulating water through a cooling coil attached to the bottom of the mixing tank. Agitation was continued for either 10 or 30 min. At the end of this time, agitation was stopped, and the suspension was transferred to the special settling chamber shown in Figure 2 where the agglomerates were allowed to rise to the surface and the mineral particles were allowed to sink to the bottom over a period of several hours. The settling chamber was then partitioned by raising a plug which blocked the opening between the upper

Figure 2. Settling chamber used for separating agglomerated product and tailings.

and lower parts of the chamber. By this means it was possible to remove the layer of agglomerates without disturbing the remaining suspended particles or settled material. The agglomerates were dewatered by vacuum filtration, and the remaining suspension was also filtered to recover unagglomerated mineral matter. The filter cakes were subsequently dried, weighed, and analyzed for ash content.

RESULTS AND DISCUSSION OF AGGLOMERATION TESTS

Preliminary Agglomeration Tests with Dilute Suspensions

A number of preliminary agglomeration tests were carried out with the larger, unpressurized mixing system to establish an experimental procedure which gave consistent results and to explore the effects of several independent variables including oil concentration, agitator speed, and type of gas. In all of these tests a solids concentration of 1.0 w/w% was employed so that a measurable change in turbidity would occur as agglomeration took place. Pittsburgh coal was used for these tests together with a small amount of i-octane to promote agglomeration with a gas which was usually air.

The results of several runs made with different i-octane concentrations are shown in Figure 3. The large increase in the relative turbidity change over time with as little as 1.0 v/w% i-octane meant that extensive particle agglomeration took place even though only a small amount of i-octane was present. The quantity of i-octane is much lower than the 10 to 30 v/w% required for a conventional oil agglomeration process. It should be noted that the hydrocarbon liquid concentration or oil concentration is based on the weight of coal so that a concentration of 1.0 v/w% corresponds to 1.0 ml oil/100 g coal.

Figure 3. Evidence of agglomeration produced by a series of runs made with different i-octane concentrations in the unpressurized system with a stirring speed of 2000 rpm.

The results presented in Figure 3 also show that an increase in i-octane concentration from 1.0 to 2.5 v/w% produced an increase in the relative turbidity change. The results of other tests which are not shown indicated that a further increase in i-octane concentration to 5.0 v/w% or even 7.5 v/w% had very little additional effect as long as an agitator speed of 2000 rpm was employed. All of the runs conducted with an agitator speed of 2000 rpm exhibited a temperature rise of about 10°C over a period of 45 min.

The effect of agitator speed on the test results is indicated by Figure 4. A decrease in agitator speed from 2000 to 1700 rpm reduced the rate of particle agglomeration markedly. Some decrease in rate of agglomeration was to be expected since the classical theory of

Figure 4. Effect of agitator speed on the relative turbidity change for tests conducted with 2.5 v/w% i-octane in the unpressurized system.

particle flocculation suggests that the rate should be proportional to the shear rate (6).

However, the rate of agglomeration could also have been affected by the rate of gas bubble generation which depended on both the rate of temperature increase of the suspension and cavitation. At 2000 rpm the average rate of increase in the temperature of the suspension was $0.2^{\circ}\text{C}/\text{min.}$, whereas at 1700 rpm the rate of increase was $0.17^{\circ}\text{C}/\text{min.}$ This difference seemed too small to have a significant effect. On the other hand, cavitation around the impeller could have been affected significantly by the change in speed.

Another factor which had a major effect on the rate of agglomeration was gas concentration. When the water used for an agglomeration test was first saturated with carbon dioxide instead of air, the ensuing rate of agglomeration was much faster (see Figure 5). This

Figure 5. Effect of gas type on the relative turbidity change for tests conducted with 2.5 v/w% i-octane in the unpressurized system with a stirring speed of 2000 rpm.

difference was due to the fact that a solution saturated with carbon dioxide will contain much more gas than if it were saturated with air. Consequently, a small rise in the temperature of the solution will release more gas if it is saturated with carbon dioxide instead of air. Also cavitation is more likely to take place with a higher dissolved gas concentration and thereby provide another source of bubbles.

Further Agglomeration Tests with Dilute Suspensions

The pressurized mixing system (Figure 1) was used for conducting further agglomeration tests with dilute suspensions. Both Pittsburgh coal and Upper Freeport coal were used for these tests. The particular samples of coal selected contained 27 wt.% ash in

the case of the Pittsburgh coal and 25.5 wt.% ash in the case of the Upper Freeport coal. A solids concentration of 1.0 w/w% was employed in each test as well as an agitator speed of 2000 rpm.

Several agglomeration tests were carried out to determine the reproducibility of the results and to see how the results would be affected by the type of coal. Therefore, two tests were conducted with Pittsburgh coal and two tests with Upper Freeport coal. For each test enough water was first saturated with air under an absolute pressure of 205 kPa (15 psi gauge pressure) at room temperature (24°C) to fill the stirred tank completely. Sufficient i-octane was then introduced to provide a concentration of 2.5% v/w% based on the weight of coal (i.e., 0.025 ml/g coal). As the mixture was agitated at 2000 rpm, the system pressure was reduced to atmospheric pressure over a period of 30 to 60 s which created a fog-like colloidal dispersion. Soon thereafter a concentrated slurry of coal particles was transferred from the coal storage tank to the mixing tank, which created a suspension with 1.0 w/w% solids. While the initial turbidity of the suspension was very large, the turbidity decreased rapidly as the particles were agglomerated. Consequently, the relative turbidity change ($\Delta\tau_r$) increased rapidly as indicated by Figure 6. Within 10 to 15 min, $\Delta\tau_r$ approached a final level which indicated completion of the process of agglomeration.

Figure 6 indicates that the test results were highly reproducible for each type of coal. It also suggests that the apparent rate of agglomeration was higher for Pittsburgh coal than for Upper Freeport coal, which was unexpected since the hydrophobicity of Pittsburgh coal is normally less than that of Upper Freeport coal. However, since the coals had been stored for

Figure 6. Agglomeration test results with Pittsburgh No. 8 coal and Upper Freeport (UPF) coal.

a long time, albeit under argon, their surface properties might have changed. Also the particle size distributions of the coals were not exactly the same which could have influenced the results.

Additional tests were conducted with both types of coal to study the effect of gas bubble concentration on the apparent rate of agglomeration. The gas bubble concentration was varied among runs by saturating the water with air at different pressures, since the dissolved gas concentration would have been directly proportional to pressure according to Henry's Law. In each case the gas-saturated water was treated with enough i-octane to provide a concentration of 2.5 v/w% based on the weight of coal. After the pressure was

reduced to atmospheric, coal was introduced and agglomeration proceeded at a rate which appeared to reflect the initial gas concentrations (Figures 7 and 8). It can be seen that the $\Delta\tau_r$ reached during the first 5 min. rose with increasing gas saturation pressure. Also it is apparent that increasing the saturation pressure from 136 kPa to 170 kPa (5 to 10 psig) had a greater effect than increasing the saturation pressure from 170 kPa to 205 kPa (10 to 15 psig).

The effect of gas concentration on the apparent rate of agglomeration was also observed by comparing the results of tests made under similar conditions except for the type of gas. In one case the water was first saturated with air at 136 kPa (5 psig) while in another case the water was first saturated with carbon dioxide under similar conditions. Since carbon dioxide is much more soluble than air in water, the dissolved gas concentration was much higher when carbon dioxide was employed. For these tests an i-octane concentration of 2.5 v/w% was employed. The results achieved with Pittsburgh coal are shown in Figure 9 and those achieved with Upper Freeport coal in Figure 10. In both cases, the apparent rate of agglomeration was greater with carbon dioxide than with air because of the greater concentration of carbon dioxide.

To see whether the concentration of i-octane had an effect on the apparent rate of agglomeration, the concentration was varied between tests made under similar conditions.

Figure 7. Effect of air saturation pressure on the agglomeration of Pittsburgh No. 8 coal.

Figure 8. Effect of air saturation pressure on the agglomeration of Upper Freeport coal.

Figure 9. Effect of gas type on the agglomeration of Pittsburgh No. 8 coal.

Figure 10. Effect of gas type on the agglomeration of Upper Freeport coal.

For these tests the water was first saturated with air at 205 kPa (15 psig). The results obtained with the different types of coal are indicated by Figures 11 and 12, respectively. The results suggest that the rate was affected only slightly by i-octane concentration, since the change in $\Delta\tau_r$ during the first 10 min. was only slightly greater with 2.5 v/w% i-octane than with 1 v/w%.

Another agglomeration test was conducted to learn more about the fundamental characteristics of the process and to see if the process is reversible. For this experiment the water used to fill the mixing tank was first saturated at room temperature (24°C) with air under a pressure of 205 kPa (15 psig). Enough of the air-saturated water was added to the mixing tank to completely fill it. Next 0.28 ml i-octane was dispersed in the water by agitation at 2000 rpm, and the pressure in the mixing tank was reduced from 205 kPa (15 psig) to 101 kPa (0 psig) over a period of 30 – 60 s which created a fog-like colloidal dispersion of microscopic gas bubbles encapsulated in i-octane. Soon thereafter a concentrated slurry of Pittsburgh coal particles was pumped from the coal storage tank into the mixing tank as agitation was continued at 2000 rpm. The amount of coal introduced was 11 g on a dry basis which provided a solids concentration of 1 w/w% for agglomeration. The amount of i-octane introduced initially corresponded to a concentration of 2.5 v/w% based on the weight of coal present.

Particle agglomeration commenced almost as soon as the coal slurry entered the mixing tank. This result was indicated by a rapid increase in the relative turbidity change as shown in Figure 13. Within a period of about 10 min. the relative turbidity change reached a value of 42% and became constant indicating completion of agglomeration. Shortly thereafter the system pressure was raised to 274 kPa (25 psig) which caused the air bubbles

Figure 11. Effect of i-octane on the agglomeration of Pittsburgh No. 8 coal.

Figure 12. Effect of i-octane concentration on the agglomeration of Upper Freeport coal.

Figure 13. Effect of changes in system pressure on the relative turbidity change caused by agglomerating particles treated with 2.5 v/w% i-octane at 2000 rpm.

in the coal suspension to redissolve, and that in turn destroyed agglomerates as indicated by the decrease in relative turbidity change. The system pressure was then reduced again to 101 kPa (0 psig) which caused the particles to reaggregate with a corresponding increase in the relative turbidity change. These pressure changes and corresponding changes in the relative turbidity of the coal suspension are both indicated in Figure 13.

This experiment showed that the coal particle agglomerates were held together by microscopic gas bubbles, and, therefore, microscopic gas bubbles had to be provided to produce agglomerates. The experiment also showed that the process was reversible since coal could be deagglomerated by subjecting the agglomerated particle suspension to a pressure that was high enough to redissolve the microscopic gas bubbles. Therefore, it was possible to control agglomeration and deagglomeration by manipulating the system pressure.

Samples of the agglomerated material were collected after a number of tests and examined, as well as photographed, with a light microscope. Figure 14 is a photomicrograph of some of the material produced in run 98 with Upper Freeport coal using the following conditions: 1.0 w/w% solids, 2.8 v/w% i-octane, and 205 kPa (15 psig) air saturation pressure. A large number of approximately spherical agglomerates can be seen which ranged from 20 to 100 μm in diameter. In addition, there are a large number of smaller, flakes or flocs. When another run (No. 62) was made under similar conditions except for the air saturation pressure which was reduced to 136 kPa (5 psig), the results shown in Figure 15 were observed. It appears that the spherical agglomerates tended to be smaller, and that the proportion of agglomerates to flocs also was smaller for the lower air saturation pressure. However, when carbon dioxide was substituted for air and run 65 was conducted with a gas saturation pressure of 136 kPa (5 psig), the results presented in Figure 16 indicate that the

Figure 14. Photomicrograph of agglomerated Upper Freeport coal resulting from the use of an air saturation pressure of 205 kPa (15 psig).

Figure 15. Photomicrograph of agglomerated Upper Freeport coal resulting from the use of an air saturation pressure of 136 kPa (5 psig).

Figure 16. Photomicrograph of agglomerated Upper Freeport coal resulting from the use of a CO₂ saturation pressure of 136 kPa (5 psig).

proportion of large spherical agglomerates to flocs was much larger than for the other two cases.

The preceding results provided additional evidence that the production of spherical agglomerates is favored by the concentration of gas dissolved initially in the water used for producing the colloidal suspension of gas bubbles that is employed for agglomerating coal particles, because the concentration would have been highest for water saturated with carbon dioxide at 136 kPa (5 psig) and lowest for water saturated with air at this pressure. Since individual agglomerates consist of a mixture of gas bubbles and coal particles, they float to the surface of a suspension when not constrained. Also since the unagglomerated particles tended to sink under quiescent conditions, the results indicated that the materials could be

separated in a settling tank. This separation method seemed more promising than screening because the agglomerates were very fragile.

Agglomeration Tests with More Concentrated Suspensions

A large number of agglomeration tests were conducted with coal suspensions containing from 3 to 9 w/w% solids. Since the particle concentration was too large for the accurate measurement of turbidity, the results were evaluated by determining the recovery and ash content of the agglomerated product together with the ash rejection in the tailings. This required separating the agglomerates from the tailings after each test by allowing the materials to settle.

The agglomeration tests were conducted with both Pittsburgh coal and Upper Freeport coal using the system shown in Figure 1, but dispensing with the photometric dispersion analyzer (PDA). The coals were finely ground as previously described. The Pittsburgh coal had an ash content of 26.0 wt.% and the Upper Freeport coal an ash content of 25.6 wt.%, both on a dry basis. An aqueous suspension of the Pittsburgh coal had a natural pH of 6.8, whereas a similar suspension of the Upper Freeport coal had a natural pH of 5.7. The lower pH of the Upper Freeport coal suspension suggests that the surface of some of the coal's constituents may have become oxidized. This possibility was reinforced by the further observation that a suspension of a more recent sample of Upper Freeport coal had a natural pH of 6.8. Preliminary agglomeration tests with the earlier sample, which will be labeled UPF(A), showed that much better results were achieved when the pH of the aqueous suspension was raised by 10 by adding a small amount of sodium carbonate to the suspension. Raising the pH increased the dispersion of the mineral particles so that fewer

were entrapped in the coal agglomerates, and therefore, the product had a lower ash content. The effect of raising the pH was much less pronounced for Pittsburgh coal since the natural pH of a suspension of this material was almost neutral to begin with.

The agglomeration tests were conducted as previously described for more concentrated suspensions. A concentrated coal slurry was mixed with an emulsion of microscopic gas bubbles which had been prepared by saturating water with air under pressure, adding a small amount of i-octane, and then releasing the pressure. After agitating the suspension for either 10 or 30 min., the material was transferred to the settling chamber depicted in Figure 2 and allowed to separate. The product and tailings were recovered subsequently and analyzed.

The results achieved with Upper Freeport coal are presented in Table 1 and those achieved with Pittsburgh coal in Table 2. The agitator speed N , solids concentration and pH of the suspension, and i-octane concentration based on the weight of coal are indicated for each test. Also shown are the agitation time and the air pressure used for saturating the water. Both the absolute air pressure in kPa and the gauge pressure in psig are indicated. The results are expressed in terms of the ash content of the agglomerated product, ash rejection to tailings, and coal recovery in agglomerates. The recovery represents the ratio of coal recovered to coal supplied, both expressed on a dry, ash-free basis.

A review of the tabulated data indicates that the results were not always consistent nor reproducible. However, it proved possible to classify many of the test results into self-consistent groups which are listed in Table 3. Within each group similar results were observed with respect to product ash content and coal recovery. All of the test results included in this table were obtained with an agitator speed of 2000 rpm and a suspension pH of 10. The results of the two tests within group A showed that the ash content of UPF(A)

Table 1. Experimental conditions and results of single stage, batch agglomeration tests with Upper Freeport coal, UPF(A), and i-octane.

Test No.	N, rpm	Solids, w/w%	i-Oct. v/w%	Air press.		pH	Time, min.	Ash, w/w%	Ash Rej., %	Recov., %
				kPa	psig					
112	2000	1	2.5	205	15	5.7	15	11.59	77.5	88.6
117	2000	3	2.7	205	15	10	30	9.86	72.6	85.2
118	2000	3	0.9	205	15	10	30	6.38	83.8	81.8
119	2000	3	0.4	205	15	10	30	7.00	84.9	66.3
120	2000	3	0.4	205	15	10	30	9.46	76.0	82.1
121	1500	3	0.9	205	15	5.7	30	19.00	57.3	61.5
122	2000	3	0.4	136	5	10	30	9.64	74.3	84.8
123	2000	3	0.2	115	2	10	30	9.40	80.4	65.0
124	2400	3	0.9	205	15	10	30	9.70	72.1	89.5
125	1500	3	0.9	205	15	10	30	9.08	73.9	88.8
126	2000	5	0.5	136	5	10	30	10.39	73.9	79.1
127	2000	5	1.0	205	15	10	30	11.06	67.5	90.1
128	2000	5	0.5	205	15	10	30	11.30	66.8	90.6
129	2000	5	0.5	205	15	10	30	8.50	79.8	75.5
131	2000	3	0.4	136	5	10	30	8.80	77.1	84.2
134	2000	3	0.9	205	15	10	30	6.92	88.2	86.9
135	2000	5	1.0	136	5	10	30	11.76	64.9	90.4
136	2000	3	0.9	136	5	10	30	8.65	77.1	84.8
137	2000	5	0.5	205	15	10	30	10.74	68.6	89.9
138	2000	3	0.4	205	15	10	30	8.90	76.4	83.6
182	2000	9	1.0	205	15	10	10	12.00	74.5	59.5
183	2000	9	2.0	205	15	10	10	15.48	60.4	79.7
184	2000	9	2.0	239	20	10	10	15.87	54.6	85.1

Table 2. Experimental conditions and results of single stage, batch agglomeration tests with Pittsburgh No. 8 coal and i-octane.

Run No.	N, rpm	Solids, w/w%	i-Oct. v/w%	Air press.		pH	Time, min.	Ash, w/w%	Ash Rej., %	Recov., %
				kPa	psig					
130	2000	5	1.0	136	5	10	30	5.94	86.5	77.3
132	2000	5	1.0	205	15	10	30	5.32	87.9	75.4
139	2000	3	0.9	205	15	10	10	7.95	---	---
140	2000	3	2.7	136	5	6.8	10	6.04	84.3	84.8
141	2000	3	0.4	136	5	10	10	5.76	92.5	42.6
141a	2000	3	0.4	136	5	6.8	10	6.08	85.8	71.9
142	2000	5	2.4	205	15	6.8	10	8.86	76.0	85.4
143	2000	3	2.7	136	5	6.8	10	7.62	84.1	65.5
144	2000	5	0.5	136	5	6.8	10	8.04	82.6	66.8
145	2000	3	0.4	205	15	6.8	10	6.72	84.4	71.6
146	2000	5	0.5	136	5	6.8	10	7.50	83.7	69.6
147	2000	3	0.4	205	15	6.8	10	6.97	86.8	60.1
148	2000	3	2.7	205	15	6.8	10	6.64	82.8	88.7
149	2000	5	0.5	205	15	6.8	10	7.77	87.0	55.8
150	2000	5	0.5	136	5	6.8	10	9.50	84.7	52.3
151	2000	3	2.7	136	5	6.8	10	9.25	80.9	68.2
152	2000	5	2.4	205	15	6.8	10	8.15	88.3	47.5

Table 3. A summary of consistent results of single stage batch agglomeration tests with different coals and i-octane.

Group I.D.	Test No.	Coal Type	Solids, w/w%	i-Oct., v/w%	Air press.		pH	Time, min.	Ash, wt. %	Ash Rej., %	Coal Rec., %
					kPa	psig					
A	118	UPF(A)	3	0.9	205	15	10	30	6.38	83.8	81.8
A	134	UPF(A)	3	0.9	205	15	10	30	6.92	88.2	86.9
B	131	UPF(A)	3	0.4	136	5	10	30	8.80	77.1	84.2
B	122	UPF(A)	3	0.4	136	5	10	30	9.64	74.3	84.8
B	120	UPF(A)	3	0.4	205	15	10	30	9.46	76.0	82.1
C	137	UPF(A)	5	0.5	205	15	10	30	10.74	68.6	89.9
C	128	UPF(A)	5	0.5	205	15	10	30	11.30	66.8	90.6
C	135	UPF(A)	5	1.0	136	5	10	30	11.76	64.9	90.4
C	127	UPF(A)	5	1.0	205	15	10	30	11.06	67.5	90.1
D-1	182	UPF(A)	9	1.0	205	15	10	10	12.00	74.5	59.5
D-2	183	UPF(A)	9	2.0	205	15	10	10	15.48	60.4	79.7
D-3	184	UPF(A)	9	2.0	239	20	10	10	15.87	54.6	85.1
E	130	Pitts.	5	1.0	136	5	10	30	5.94	86.5	77.3
E	132	Pitts.	5	1.0	205	15	10	30	5.32	87.9	75.4

coal was reduced from an initial value of 25.6 wt.% to a final value of 6.65 wt.% on average by using a solids concentration of 3 w/w% and an i-octane concentration of 0.9 v/w%. At the same time a coal recovery of 84.4% on average was achieved. For the same solids concentration, the results of three tests within group B showed that a reduction in i-octane concentration to 0.4 v/w% produced an increase in product ash content to 9.3 wt.% on average and an insignificant decrease in coal recovery to 83.7% on average. The results of the tests within group B did not seem to be affected significantly by a change in air saturation pressure within the range of 136 to 205 kPa (5 to 15 psig).

When UPF(A) coal was used in a higher solids concentration (5 w/w%) for the four tests included in group C, the product ash content increased to 11.2 wt.% on average and coal recovery increased to 90.3% on average. Consequently, less ash forming material was rejected in the tailings than was observed with the lower solids concentration. With the 5 w/w% solids concentration, the results were not affected by a variation in either the i-octane concentration over a range of 0.5 to 1.0 v/w% or the air saturation pressure over a range of 136 to 205 kPa (5 to 15 psig).

When UPF(A) coal was used in 9 w/w% solids concentration, the results of the three tests included in group D showed a further increase in product ash content over the previous results. The results of the different tests also suggest that coal recovery depended on both i-octane concentration and air saturation pressure. Consequently, an increase in i-octane concentration from 1.0 v/w% to 2.0 v/w% seemed to cause an increase in coal recovery from 59.5% to 79.7%. Moreover when 2.0 v/w% i-octane was used, an increase in air saturation pressure seemed to produce an increase in recovery from 79.7% to 85.1%. These trends

suggest that with 9 w/w% solids, the concentration of microbubbles became a limiting factor, whereas with 5 w/w% solids or less such was not the case.

The results of two tests with Pittsburgh coal included in group E showed that with a solids concentration of 5 w/w% the coal recovery and product ash content tended to be somewhat lower than for Upper Freeport coal. As in the case of Upper Freeport coal, the results did not seem to be affected by a change in air saturation pressure.

Comparison of One and Two Stage Agglomeration

To lay the foundation for a two stage gas agglomeration process, a preliminary experiment was conducted with the system shown in Figure 1. Upper Freeport coal with an ash content of 35 wt.% was used for this experiment. The mixing tank was first filled with water which had been saturated with air under a pressure of 205 kPa (15 psig). As the system was agitated at 2000 rpm, 0.5 ml of i-octane was introduced and dispersed. Then the system pressure was lowered gradually to 101 kPa (0 psig) which produced a colloidal dispersion of microscopic gas bubbles and created a fog-like appearance. A concentrated coal slurry which had been prepared previously and placed in the coal storage tank was pumped into the mixing tank, and the resulting suspension was stirred for 10 min. Agitation was stopped and virtually all of the coal particles floated to the top of the mixing tank while the lighter colored mineral particles remained suspended throughout the tank. Microscopic examination of the floating material produced in other tests under similar conditions showed that such material consisted largely of 0.05 to 0.10 mm diameter spherical agglomerates. Next the system pressure was raised to 287 kPa (27 psig) and the contents of the mixing tank was stirred at 2000 rpm for 5 min. After agitation stopped virtually all of the coal particles

settled to the bottom of the tank showing that the agglomerates had been destroyed.

Agitation was resumed, and the system pressure was released gradually. After 5 min. of additional stirring, agitation was stopped again, and most of the coal floated to the top of the tank as before.

The results showed that microscopic gas bubbles were an integral part of the agglomerated material since it floated. Furthermore, they showed that the agglomerates were destroyed when the bubbles were eliminated by increasing the system pressure and redissolving the gas. When agitation was stopped, the deagglomerated coal settled to the bottom of the tank. Again it was shown that agglomeration and deagglomeration could be controlled by varying the system pressure.

The quantity of coal used for this experiment was 35 g on a dry basis which provided a solids concentration of 3 w/w% during agglomeration. The quantity of i-octane corresponded to a concentration of 1 w/w% based on the weight of coal. The coal suspension was made slightly alkaline to improve the dispersion of mineral particles. This was accomplished by adding a small amount of sodium carbonate which raised the suspension pH to 10.

To demonstrate a two stage agglomeration process and compare its characteristics with those of a single stage process, a series of one and two stage batch agglomeration tests were conducted following the general scheme indicated by Figure 17. These tests were conducted with the system shown in Figure 1 using a more recent sample of Upper Freeport coal designated as UPF(B). This material had an ash content of 33.0 wt.% on a dry basis, and an aqueous suspension of the ground coal exhibited a pH of 6.8. Some of the tests were carried through the first stage of agglomeration and recovery, while other tests were carried through

Figure 17. Flowsheet for a two-stage agglomeration process.

two complete stages for comparison. An improved separator was used for separating and recovering the agglomerated coal from the other material. The separator was similar to that shown in Figure 2 except that it was fitted with a Teflon slide valve for isolating the upper chamber from the lower chamber after the materials had separated.

For conducting the first stage of agglomeration, the mixing tank was first filled completely with deionized water which had been saturated with gas under a pressure of 205 kPa (15 psig) at room temperature (22 - 24°C). After an agitator speed of 2000 rpm was established, a measured amount of pure i-octane was introduced. The mixture was conditioned for 1 – 2 min., and then the pressure was reduced to 101 kPa (0 psig) which allowed the dissolved gas to come out of solution in the form of microscopic bubbles. A concentrated coal slurry was then introduced quickly from the coal storage tank so as to provide an ultimate solids concentration of 3.0 w/w%. Particles started to agglomerate immediately, and as agglomeration proceeded the agitator speed was held at 2000 rpm and the temperature of the suspension was kept close to room temperature by circulating water through a cooling coil attached to the bottom of the mixing tank. Agitation was continued for 10 min. At the end of this time agitation was stopped, and the suspension was transferred to a special settling chamber where the agglomerates were allowed to rise to the surface and the mineral particles were allowed to sink to the bottom over a period of several hours. The layer of agglomerates was removed from the settled suspension and dewatered by vacuum filtration, and the remaining suspension was also filtered to recover the unagglomerated mineral matter. For a test involving only a single stage of agglomeration, the filter cakes were dried, weighed, and analyzed for ash content.

For a test involving a second agglomeration stage, the moist filter cake of agglomerated coal particles was not dried but instead was mixed with water to form a concentrated slurry which was returned to the coal storage tank. The mixing tank was refilled with water which had been saturated with gas at only 136 kPa (5 psig). The concentrated coal slurry was then pumped into the mixing tank, displacing an equal volume of water. The system pressure was increased subsequently to 274 kPa (25 psig) to redissolve the gas bubbles holding the agglomerates together. To aid the destruction of the agglomerates and release of trapped mineral particles, the suspension was stirred at 2000 rpm. After several minutes of agitation, 0.10 ml of i-octane was introduced and the pressure was reduced gradually over 1 to 2 min. to release the dissolved gas and to reform the coal agglomerates. The suspension was stirred at 2000 rpm for another 5 min. to complete agglomeration. The agglomerates were subsequently separated and recovered using the same method as described above for single stage agglomeration.

For conducting these tests a small amount of sodium carbonate was added to the coal slurry to provide a pH of 10 for the first stage of agglomeration. Since no more sodium carbonate was added before the second stage of agglomeration, the pH decreased to 7 for this stage. The total quantity of i-octane employed (0.50 ml) was the same for both the one stage and two stage batch tests. However, for a one stage test the entire amount was introduced in the first stage, whereas for a two stage test, 0.40 ml was introduced in the first stage and 0.10 ml in the second.

The results of one and two stage tests are indicated in Table 4. The first two tests were single stage, while the last two were two stage. For the single stage tests, the ash content is

Table 4. Results of one and two stage batch agglomeration tests with Upper Freeport coal

Test No.	Coal type	Stage I conditions				Stage II conditions				Stage I results				Stage II results			
		Solids, w/w%	Sol'n. pH	i-Oct., v/w%	Air P, psig	Solids, w/w%	Sol'n. pH	i-Oct., v/w%	Air P, psig	P ₁ ash, wt. %	T ₁ ash, wt. %	Ash Rej., T ₁ , %	Coal Rec., P ₁ , %	P ₂ ash, wt. %	T ₂ ash, wt. %	Ash Rej., T ₂ , %	Coal Rec., P ₂ , %
180	UPF(B)	3	10	1.4	15	--	--	--	--	10.60	76.1	78.3	88.2	--	--	--	--
181	UPF(B)	3	10	1.4	15	--	--	--	--	10.20	77.5	78.6	89.2	--	--	--	--
178	UPF(B)	3	10	1.1	15	2.1	7	0.4	5	--	77.5	78.1	--	6.50	40.6	10.5	81.2
179	UPF(B)	3	10	1.1	15	2.0	7	0.4	5	--	77.1	80.3	--	6.10	44.4	8.8	82.8

indicated for both the product P_1 and tailings T_1 , while for the two stage tests, the ash content is shown for the product of the second stage P_2 and for the tailings from both the first and second stages, T_1 and T_2 , respectively. It can be seen that the ash content of the coal was reduced from an initial value of 33.0 wt.% to a value of 10.4 wt.% on average by subjecting the coal to a single stage of agglomeration and separation, whereas by subjecting the coal to two stages of agglomeration and separation, the ash content was reduced to 6.3 wt.% on average. On the other hand, coal recovery on a dry, ash-free basis was 82.0% on average after two stages of agglomeration and separation compared to 88.7% on average after a single stage of agglomeration and separation. These values represent the percent of the coal supplied on a dry, ash-free basis which was recovered in the agglomerated product. To achieve a cleaner product by employing two stages, some additional coal was lost. This type of tradeoff is inherent in any type of coal cleaning process.

CONCLUSIONS

The technical feasibility of a new and innovative method of cleaning coal was demonstrated involving gas agglomeration of an aqueous suspension of ultra-fine particles. The investigation showed that mixing such particles with a colloidal suspension of microscopic gas bubbles produces small spherical agglomerates composed of both coal particles and microbubbles. The process is facilitated by the presence of a small amount of i-octane which appears to coat the gas bubbles and prevent coalescence. Since the agglomerates float, it was shown that they can be recovered by allowing a treated suspension to separate under quiescent conditions.

Numerous agglomeration tests with moderately hydrophobic bituminous coals having an ash content of 26 wt.% showed that the coals can be cleaned by single stage, gas agglomeration to produce a product with 6 -- 7 wt.% ash while achieving a recovery of 75 to 85%. This can be accomplished by saturating water with air under a pressure of 136 to 205 kPa (5 to 15 psig) and adding 1.0 v/w% i-octane based on the weight of coal. Higher coal recoveries can be achieved by accepting a higher product ash content.

Single stage agglomeration tests with Upper Freeport coal also showed that coal recovery and ash content are affected to some extent by the selected operating conditions. Product ash content increased steadily as the initial solids concentration was raised from 3 to 9 w/w%, whereas coal recovery was a maximum for a solids concentration of 5 w/w%. At the highest solids concentration the concentration of microbubbles may have been a limiting factor.

The results of agglomeration tests with dilute suspensions containing 1.0 w/w% solids showed that the rate of agglomeration is proportional to gas concentration and is not affected significantly by i-octane concentration in the range of 1.0 to 2.5 v/w% based on the weight of the coal. Other agglomeration tests with both dilute and more concentrated suspensions showed that the process is reversible and can be controlled by manipulating the system pressure. Therefore, it is possible to reclean agglomerates produced in one stage by subjecting the material to a process of deagglomeration, washing, and reagglomeration in a second stage. Such a process was demonstrated with Upper Freeport coal having an initial ash content of 33.0 wt.%. By employing two stages, the ash content was reduced to 6.3 wt.% while achieving an overall coal recovery of 82.0%. By comparison, in a single stage the ash content was reduced to 10.4 wt.% while achieving a recovery of 88.7%.

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PUBLICATIONS AND PRESENTATIONS

The publications and presentations which report the results of this research are listed below. Additional publications including a PhD thesis will be forthcoming in the near future.

Publications

M. Shen, R. Abbott, and T. D. Wheelock, "Gas Agglomeration of Coal Particles in Aqueous Suspension," Fifteenth Annual International Pittsburgh Coal Conference Proceedings, on CD-ROM, University of Pittsburgh, Pittsburgh, PA, September 14-18, 1998.

T. D. Wheelock and M. Shen, "Coal Beneficiation by Gas Agglomeration," provisional patent application filed with U.S. Patent Office on March 16, 1999.

M. Shen, "Development and scale-up of ultra-fine particle agglomeration systems for coal beneficiation," PhD thesis, Iowa State University, Ames, Iowa (in final preparation).

Presentations

M. Y. Shen and T. D. Wheelock, "Coal Cleaning by gas agglomeration of coal particles in an aqueous suspension," presented at the 110 Annual Meeting of the Iowa Academy of Science, Mason City, IA, April 24-25, 1998.

M. Shen, R. Abbott, and T. D. Wheelock, "Gas Agglomeration of Coal Particles in Aqueous Suspension," presented at the Fifteenth Annual International Pittsburgh Coal Conference, Pittsburgh, PA, September 14-18, 1998.