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**HANDLING, TRANSPORT AND DISPERSION OF SORBENT POWDER
FOR IN-FURNACE INJECTION**

Fifth year final report

by

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EXECUTIVE SUMMARY

The focus of this project is on sorbent injection technologies using dry, calcium-based sorbents for high-sulfur coal flue gas desulfurization. The goal is to provide research findings on handling, transport and dispersion of sorbent powder, aimed at improving SO_2 (to at least 90%) removal and increasing sorbent utilization in a cost-effective fashion. With this goal, the purpose of this project is to investigate the fundamental aspects of powder technology relevant to the fine sorbent powders, and to provide means of improving sorbent performance through superior dispersion and reduced dispersed particle size.

The fifth year's project contains three phases, Phase I "Characterization of Electrostatic Properties", Phase II "Cohesive Strength of Modified Sorbents", and Phase III "Modeling of Powder Dispersion". Work under Phase I involves characterization of the sorbents in terms of their electrostatic properties. Phase II investigates the flow properties of several calcium-based sorbents under different handling and transporting conditions. In Phase III, experimental studies are performed to measure the sorbent powder size distribution in different apparatuses and under different conditions. The population balance model proposed in previous studies can reasonably simulate these experimental results.

In phase I, the effects of antistatic agents on the electrostatic properties of $\text{Ca}(\text{OH})_2$ have been examined. Aluminum oxide (a free-flow agent) has been found to have little influence on the charge generation. The addition of carbon black to $\text{Ca}(\text{OH})_2$ seems to result in a less charge accumulation. It is found that the alumina and silicon oxide tend to be charged positively and negatively, respectively. The results on the bulk density show that the addition of alumina to $\text{Ca}(\text{OH})_2$ results in an increase in both loosely packed bulk density and the tapped density at small percentages of alumina followed by a decrease in both densities as more alumina is added. The effects of CTAB on the charging ability of $\text{Ca}(\text{OH})_2$ was determined. Aluminum oxide was found to improve the flowability of $\text{Ca}(\text{OH})_2$ better than silicon dioxide. The presence of CTAB did not seem to affect the size distribution of $\text{Ca}(\text{OH})_2$ during transport.

In Phase II, the effect of lignosulfonate concentration on the cohesive strength of the modified lignosulfonated hydrates have been examined. The results show that the modified hydrates become less cohesive as the concentration of the lignosulfonate surfactant increases in the sorbent. Also, in

coordination with project 1.1, a new sorbent has been prepared for mechanical testing to evaluate its flow properties. This sorbent, Forsby limestone, was observed to have a very high capability of sulfur capture. A particle size distribution analysis has been performed on three sorbents using the sedigraph to study the effect of the surfactant used. The tested sorbents are: modified sugar hydrate with a sugar weight concentration of 1.5 %, modified CMA hydrate with 1.5 % weight concentration of calcium-magnesium acetate added to the water of hydration, and an unmodified pure hydrate. The sedigraph analysis shows finer particles in the modified hydrates. Mechanical testing of the sorbents shows that the surfactant used have improved the flow properties of the modified hydrate.

In Phase III, the agglomerate size distributions have been measured using a cascade impactor at both the entrance and the exit of a powder flow system. The experimental results show that the agglomerate size at the entrance is larger than that at the exit of the system, which verifies the agglomerate breakup mechanism proposed in the powder dispersion model in the last year. Experiments are conducted to measure the agglomerate size distribution in the powder transport apparatus of Project 1.1 under high temperature conditions. The population balance model proposed last year can reasonably simulate the experimental results. Efforts are also taken to simulate the experimental results of the agglomerate size distribution in the powder dispersion nozzle which were reported in the previous final reports. It is found the value of the breakup parameter in the model almost remains constant at about 4.9×10^{-9} under all conditions.

Also, during the course of the research work performed during the fifth year of this project, Chapter outline and several versions of draft text were prepared and submitted to the program manager for the Chapter titled "Sorbent Transport Properties" (Chapter 4 in the Monograph).

I. Phase I: Characterization of Electrostatic Properties

I.1 Introduction

The major goal of this phase is to examine the role of the electrostatic attraction force in the formation of powder agglomerates. Electrostatic charging is a very complex surface phenomenon. Although numerous studies have demonstrated that some antistatic agents have better charge reducing ability on dielectric materials than others, it is still unclear about their superiority and the mechanisms behind their effectiveness. The first task under this phase involves testing the effect of antistatic agents, which include Al_2O_3 , carbon black and ammonium salts. The agglomerate size analysis are then carried out, once the proper antistats are identified. In the measurement of particle size, the powder is sampled in the Cascade impactor isokinetically. The effect of transport conditions, especially gas flow rate on the powder agglomeration, is investigated in conjunction with the results of charge build-up on the powder.

I.2 Work Performed

As shown in Figure 1.1, in the experiments of alumina, no significant decrease in charge pick-up ability was observed for $\text{Ca}(\text{OH})_2$. There might be two reasons for this. First, the size of alumina used is around 100 μm , which is larger than the size of $\text{Ca}(\text{OH})_2$. The reason for less charge accumulation on PVC powder (or mild electrostatic activity) when the alumina powder is mixed with the PVC powder (Cross, 1987) is that fine alumina acts to reduce the real contact area between larger PVC particles (200 μm) although alumina is non-conducting. Therefore, the larger alumina powder is not able to reduce the contact area among the smaller $\text{Ca}(\text{OH})_2$ particles. Secondly, in order to make sure $\text{Ca}(\text{OH})_2$ and alumina are well mixed, blending is necessary, which might induce charge generation and offset the advantage of using free-flow agents.

Antistatic agents reduce the accumulation of electrostatic charge by either reducing the generation of charge or increasing the conductivity of the substance to which they are added. The second mechanism, which is employed more often, involves adding a conducting materials such as metal, carbon, or by causing a surface to adsorb more water from the atmosphere. Figure 1.2 shows that the presence of carbon black decreases the charge build-up of $\text{Ca}(\text{OH})_2$ for the case not only with the transport tube, but also with both the feeder and the transport tube. The weight % of carbon

black in this case is 0.1%. We expect that the charge accumulation will decrease as an increase in carbon black concentration. This effect will be studied later.

Another way to characterize the effects of antistatic agents is measuring the resistivity of a powder/agent mixture. Steiger (1985) reported a linear relation between the logarithms of charge and resistivity. Therefore, the resistivity can serve as an indicator to the extent of charge accumulation. The measurement of resistivity of Ca(OH)_2 of different concentrations of antistatic agents is being carried out.

The experimental setup of the transport system with the Anderson cascade impactor is shown in Fig. 1.3. In this setup, the transport tube is connected to a large chamber for an isokinetic sampling so that an accurate particle size distribution can be obtained. The cascade impactor inserted into the bottom of the chamber is connected to a vacuum pump with a flowmeter in order to control the gas sampling rate. The results obtained before show no significant reduction in the charge accumulation on the powder with alumina powder. This is because the alumina powder used is comparable in size with the sorbent powder and consequently fails to play as spacers between powder particles. Tests on the charging polarities of larger alumina and silica particles showed that they have a strong affinity for positive and negative charges, respectively.

To understand the physical characteristics of sorbent powders mixed with antistatic agents, the LPBD and the TD of Ca(OH)_2 have been measured using the Hosokawa Powder Tester for three different weight percentages of submicron alumina: 0.1%, 0.5%, and 1%. As shown in Table 1.1, the LPBD increases with the addition of alumina to a certain level and then decreases slowly as the weight percentage of alumina keeps increasing. The same phenomenon is observed for the tapped density.

To study the effect of antistatic agents on the charging behavior of Ca(OH)_2 , we mixed cetyltrimethylammoniumbromide (CTAB) -- a cationic surfactant -- with Ca(OH)_2 and measured its specific surplus charge. Figure 1.4 shows the specific surplus charge of the powder mixture with 0.01 wt% of CTAB. For comparison, the charging curves of pure Ca(OH)_2 and lignosulfonated hydrate are also included. It was found that the CTAB-modified Ca(OH)_2 was charged the least and had opposite polarity to the other sorbents. In general, one would expect the addition of cationic

surfactants should lead to more positive charges; however, the results showed the opposite trend. It is unclear about the cause at this moment.

The antistatic agents can affect not only the charging characteristics of powder but also the bulk density of the powder. It was observed that the tapped density of $\text{Ca}(\text{OH})_2$ reduced by around 10% with 1.27 wt% of SiO_2 as shown in Fig 1.5(a). Figure 1.5(c) shows that the Hausner ratio reduces from 2.42 for pure $\text{Ca}(\text{OH})_2$ to 2.16 for the $\text{Ca}(\text{OH})_2$ with 1.27 wt% of Al_2O_3 . These results indicate that Al_2O_3 can more effectively reduce the cohesiveness of $\text{Ca}(\text{OH})_2$ than SiO_2 .

The size distribution of $\text{Ca}(\text{OH})_2$ during transport was determined using cascade impactor. Since the weight percentage of CTAB is very small (0.01 wt%), its contribution to the total powder mass flow rate can be neglected. Figure 1.6 shows the pre- and post-transport particle size distribution of $\text{Ca}(\text{OH})_2$ with and without CTAB at powder mass flow rate of about 0.01 g/s. It was found that there was no significant difference in the size distribution between the modified and pure $\text{Ca}(\text{OH})_2$. This may be because of low powder concentration, which leads to less contact between the $\text{Ca}(\text{OH})_2$ and the CTAB, and weak electrostatic forces among particles, which is insignificant compared with the van der Waals forces.

II. Phase II: Cohesive Strength of Modified Sorbents

II.1 Introduction

As was shown in past studies performed in project 1.2, the addition of lignosulfonate, which is an anionic surfactant, to the hydration water of CaO improves the dispersibility and reactivity of the modified sorbents. The lignosulfonate reduces the primary particle size of the modified hydrates and prevents agglomeration of the formed particles (Krichgessner and Lorrain, 1987). New modified calcium-based sorbents are introduced using several types of surfactants. The sedigraph particle size analyzer is used to examine the effect of the surfactants on the particle size distribution of the modified sorbent. The cohesive strength and other flow properties of the modified sorbents (e. g. bulk density, dispersibility, and Hausner ratio) are measured on the Ajax cohesion tester and the Hosokawa powder characterization tester. Also, the effect of moisture content on the flow properties of the sorbents has been studied using the Hosokawa powder characterization tester.

II.2 Work Performed

The effect of lignosulfonate concentration on the cohesive strength of the modified lignosulfonated hydrates has been examined using the Ajax cohesion tester. The standard procedure for the cohesive strength measurements using this tester is as follows. The sample container, fitted with a removable sleeve, is filled with the powder to well cover the joint. The loading bridge is then placed in position with the loading plate resting on the surface of the powder. Weights are carefully placed on the plunger top for 30 minutes to allow the density to stabilize and air to escape from the voids of the sample. After compaction, the load is removed and excess powder is scraped away from the sample container base and the sample is weighed in order to determine the bulk density of the powder. Then the sample is subjected to a torque introduced by the floating loading cell imbedded into the sample. The torque is increased gradually until failure occurs. The counter reading at failure gives the cohesive strength of the powder. Four lignosulfonated hydrates with 0.0%, 0.5%, 1.0%, and 1.3% lignosulfonate concentration have been tested under loose and packed conditions. In the loose condition, the sample container was filled with the powder by using the vibrating unit of the Hosokawa powder characterization tester which allows the powder to freely and uniformly fall into the container. Then, the sample was directly placed into the Ajax tester without applying any weights to the loose powder sample prior to the testing. In the packed condition, the powder sample was packed by placing a 45 lb weight for 30 minutes on the plunger top. Results of the tests show the tendency of the modified hydrates to be less cohesive with the increase of the lignosulfonate concentration in the product, as shown in Fig. 2.1.

Two modified hydrates were prepared by using Calcium Magnesium Acetate (CMA) and sugar as surfactants during the hydration of CaO. The preparation procedure of the modified sorbents is as follows. A pre-measured amount of chemical grade CaO powder (99.99%) is placed in a beaker. The necessary mass of the surfactant (Calcium Magnesium Acetate or sugar) to equal the final product mass percent is dissolved in the water of hydration. The surfactant solution is then added slowly to the beaker. Then, the formed slurry is dried for 24 hours in a vacuum oven operating in the range of 110°C-125°C and a vacuum of 25 inches of mercury. The dried cake is ground in a ball-mill for 24 hours. The weight percentage of the two surfactants was chosen to be 1.5 % for the modified hydrates.

A sedigraph 5100 V3.05 was used to measure the particle size distributions for the modified sugar hydrate and the Calcium-Magnesium acetate hydrate (CMA hydrate). Also, a pure unmodified calcium hydrazide powder was examined. Comparing the sedigraph results, shown in Fig. 2.2, for the three hydrates shows that both of the two modified hydrates are composed of finer particles compared to the pure hydrate. Also, the modified CMA hydrate has a wider particle size distribution than the other hydrates. These results indicate that the modified hydrates have larger surface areas and, accordingly, better flow properties should be expected for the modified sorbents.

The Hosokawa powder characteristics tester was used to measure some of the mechanical properties of the unmodified hydrate, the modified sugar hydrate, and the modified CMA hydrate. The measured properties are the aerated and packed bulk densities, compressibility, Hausner ratio dispersibility, cohesion number, angles of repose, spatula, fall and difference. The degrees of flowability and floodability of the sorbents were calculated (Carr, 1965) from the values of the measured flow properties. The experimental procedure and definitions of the flow properties are listed in details in the fourth year's final report of Project 1.2.

Results of the measured properties are listed in Figs. 2.3 to 2-5. Both of the two modified hydrates appear to have better flow properties compared to the unmodified hydrate properties. As can be seen in Fig. 2.3, the CMA hydrate has the best properties since both its compressibility and Hausner ratio are considerably lower than those for the other hydrates. This is confirmed in Fig. 2.5 where it is shown that both of the modified hydrates, the CMA and the sugar hydrates, has better degrees of flowability and floodability than the unmodified hydrate. However, the results show "bad" degree of flowability for the all tested sorbents and "fairly high" degree of floodability for the modified hydrates and "very high" degree of floodability for the unmodified hydrate. These results agree with the conclusion that the surfactant used enhance the flow behavior of the modified sorbents.

Tests were conducted on the unmodified hydrate, the modified sugar hydrate (1.5%), and the modified CMA hydrate (1.5%) to study the effect of moisture content on their flow properties. Moisture content is defined as the weight ratio of the water contained by a sample of the powder to the dry weight of the sample. Changes in the moisture content of powders affect most of their mechanical properties. The effect of moisture on the flow properties of sorbents was examined within the range of moisture content between 0% and 5%. The Hosokawa powder characteristics tester was

used to measure several mechanical properties of the three sorbents at different levels of moisture content. The measured properties were: dispersibility, angle of repose, and compressibility.

Samples of the sorbents were dried (moisture content $<0.5\%$) by placing them in an oven at a temperature of 140°C for 24 hours. In order to increase the moisture content, four to five different samples of each sorbent were exposed to a stream of water vapor for different periods of time to achieve reasonable distribution of moisture content values. During this operation, the samples were periodically stirred by a mixer in order to make sure the sorbent sample is homogeneous. Results of the effect of moisture content on the flow properties of the modified hydrates are shown in Figs. 2.6 to 2.8. It should be noted that the results shown in these Figures are average results taking over 4-6 measurements for each test. Increasing the moisture content in the tested sorbents appears to have bad effect on the flow properties of sorbents. This is because of the water bonds between the particles which increases the amount of cohesive forces in the sorbent and causes the particles to agglomerate. Figures 2.6 and 2.7 show increase of the values of the compressibility and the angle of repose of the sorbents with the increase of the moisture content. Figure 2.8 shows that dispersibility was among the properties that have been badly affected by the presence of moisture.

III. Phase III: Modelling on Powder Dispersion

III.1 Introduction

Several improvements on the existing model have been made. Experiments on agglomerate size distribution at different axial location are conducted by using a PIV system. The expression for $B_w(x)$ are improved. Temperature effects are also considered. Necessary experiments are conducted in collaboration with Project 1.1 and their high temperature apparatus are used. A generalized correlation for break-up parameter, C , is obtained and a complete model for this sorbent dispersion system is established.

III.2 Work Performed

To verify the sorbent powder dispersion mechanism proposed in the population balance model, a set of experiments is carried out in conjunction with Project 1.1. Agglomerate size distribution data are obtained in their experimental apparatus (Figure 3.1). The feeder gas (nitrogen)

is metered into the feeder and entrains powder particles (calcium hydroxide) into the transport line. Sufficient vibration is provided to loosen the particles in the feeder. At the entrance of the tubular flow system, the gas and particle stream from the feeder is mixed with the bulk gas (nitrogen) and flows into the tubular flow system. A cascade impactor (Andersen Mark III) is used to collect the agglomerates before the powder is mixed with the bulk gas and after it flows out of the tubular flow system as shown in the figure. The agglomerate size distribution can thus be obtained at both the inlet and the exit of the tubular flow system by analyzing the agglomerate samples in the cascade impactor. Figure 3.2 shows the experimental results at 300 K. It is seen that the agglomerate size at the exit is smaller than that at the entrance, which means the agglomerates are broken up into smaller ones while flowing. This set of experimental results is simulated by the same model as proposed in the last year and the simulation results can reasonably fit the experimental results. Therefore, the powder dispersion mechanism proposed is verified.

For a better understanding of the powder dispersion mechanism in a sorbent powder conveying system and verifying agglomerate breakup mechanism proposed in a population balance model of powder dispersion in the last year, the fine powder dispersion system designed in 1991 - 1992 is reconstructed and modified. The schematic diagram is shown in Figure 3.3. The system consists of a powder feeder, a transport column, a powder separation sub-system and a powder recirculation device. The transport column is a cylindrical column with viewing windows and is 6 inch in diameter. The entrance of the transport column is an expansion nozzle (2" in diameter and about 12" long) with two booster air jets, which showed an optimum powder dispersion and was simulated by the powder dispersion model proposed last year. The sorbent powders are fed into the transport column through the expansion nozzle by a powder feeder, of which the details were described in the third year report. The expansion nozzle has a viewing window made of PYREX glass which allows a direct visualization of powder motions inside the nozzle. The powder entrained by the stream is separated from the gas by a two-stage filter and then collected in a powder hopper. Figure 3.4 shows the schematic diagram of the imaging and recording system in the experiments of this quarter. The nozzle is illuminated by a 2 mm thick laser sheet generated by a 4 watt Argon ion laser. The pictures of the particles in the nozzle are recorded by a CCD (Charge Coupled Device) camera. Its exposure time can be controlled by an adjustable shutter. The laser sheet and the CCD camera are moved in

the axial direction of the nozzle. Thus, the axial variation of the agglomerate size distribution is obtained. High shutter speeds are employed and consistent results are obtained.

The experimental results are shown in Figure 3.5. It can be seen that the counts of the large agglomerates continuously decrease and that of the small agglomerates continuously increase along the axial direction, and, therefore, the mean size of agglomerates in the system decreases. It can also be seen that the variation rate of the size distribution decreases along the axial direction. The axial variation of the agglomerate size distribution is intimately related to the axial variation of the cross sectionally averaged turbulent energy dissipation rate (Fig. 3.6), which was calculated from $k-\epsilon$ turbulent model in last year. The turbulent energy dissipation rate reaches its maximum value at the entrance of the nozzle and decreases sharply along the axial direction. In the population balance model proposed last year, the dominant mechanism of the agglomerate breakup is by the shear stress induced by the high turbulence intensity. As the turbulent energy dissipation rate decreases sharply, so does the shear stress and, thus, the breakup rate of large agglomerates decreases when approaching the exit of the nozzle.

$B_{vv'}(x)$ the probability of the generation of agglomerates (volume v) by the break-up of larger agglomerates (volume v'), was assumed to be in a uniform distribution, as shown in Eq. 3.1.

$$B_{vv'}(x) = \frac{1}{v' - v_{\min}} \quad (3.1)$$

Although it is simple and gives reasonable simulation results, it has little physical meaning. According to the results of Kousaka (1979), it is more difficult for a agglomerate to be broken into two fragments of equal size than to be broken into pieces of different sizes. It is assumed here that $B_{vv'}(x)$ is in a log-normal distribution (based on counts)

$$B_{vv'} = \frac{1}{\sqrt{2\pi} v (v'/30)} \exp \left[-0.5 \frac{(\ln v - v'/20)^2}{(v'/30)^2} \right] \quad (3.2)$$

To test this new expression for $B_{vv'}(x)$, the model is reprogrammed with this expression. The simulation results of this new model is shown Fig. 3.7. Comparing the simulation results from the old model and the new model shows that the new expression is a better assumption.

To study the temperature effects on the sorbent powder dispersion, experiments are carried

out in conjunction with Project 1.1 at a temperature of 1173 K. Agglomerate size distribution data are obtained in their experimental apparatus (Figure 3.1). Figure 3.8 shows the experimental results at a temperature of 1173 K. The experimental results is simulated by the improved model described before. From the comparison of the simulation results and the experimental data, it is clear that this model can be used under high temperature conditions and that temperature affects powder dispersion mainly by changing the hydrodynamics inside the powder dispersion system.

To develop a generalized empirical correlation for the breakup parameter, the population balance model is applied to the same expansion nozzle with two booster air jets, under different air flow rates. The primary air velocity is 10.9 m/s and the booster air velocity is 34.8 m/s. Figure 3.9 shows the axial variation of the cross sectionally averaged turbulent energy dissipation rate. Figure 3.10 shows the simulation results for this case. It is seen that this model reasonably simulates the experimental results. However, certain deviations of the simulation from the experimental data can be observed, especially in the small size range. The reason for this deviation is probably the neglect of the coalescence. When the air flow rates are increased, the shear rate in the nozzle is higher and the breakup frequency of the agglomerates is increased. As a result, the number density of small agglomerates becomes higher and the coalescence begins to affect the powder dispersion.

The breakup parameters for different systems and under different operating conditions are listed in Table 3.1. From this table, the breakup parameter almost remains constant and the average value for this parameter is 4.9×10^{-9} .

Table 3.1 Values of C for different systems and under different conditions

System	Temperature	Gas flow rates	C
Expansion nozzle with two booster air jets	300 K	Primary $U_g=5.58$ m/s Booster $U_g=34.7$ m/s	6.8×10^{-9}
	300 K	Primary $U_g=5.58$ m/s Booster $U_g=34.7$ m/s	6×10^{-9}
Apparatus of Project 1.1	300 K	$U_g=0.23$ m/s	2.13×10^{-9}
	1173 K	$U_g=0.89$ m/s	4.3×10^{-9}

IV. Concluding Remarks

In phase I, Characterization of Electrostatic Properties, the effects of antistatic agents on the electrostatic properties of $\text{Ca}(\text{OH})_2$ have been examined. Aluminum oxide - a free-flow agent has been found to have little influence on the charge generation. On the other hand, the addition of carbon black to $\text{Ca}(\text{OH})_2$ seems to result in a less charge accumulation. It is found that the alumina and silicon oxide tend to be charged positively and negatively, respectively. The results on the bulk density show that the addition of alumina to $\text{Ca}(\text{OH})_2$ results in an increase in both loosely packed bulk density (LPBD) and the tapped density (TD) at small percentages of alumina followed by a decrease in both densities as more alumina is added. The effects of CTAB on the charging ability of $\text{Ca}(\text{OH})_2$ was determined. Aluminum oxide was found to improve the flowability of $\text{Ca}(\text{OH})_2$ better than silicon dioxide. The presence of CTAB didn't seem to affect the size distribution of $\text{Ca}(\text{OH})_2$ during transport.

In phase II, Cohesive Strength of Modified Sorbents, the effect of lignosulfonate concentration on the cohesive strength of the modified lignosulfonated hydrates have been examined. The results show that the modified hydrates become less cohesive as the concentration of the lignosulfonate surfactant increases in the sorbent. Also, new modified hydrates have been prepared by adding Calcium Magnesium acetate and sugar to the water of hydration. A particle size distribution analysis has been performed on three sorbents using the sedigraph to study the effect of the surfactants used. The tested sorbents are: modified sugar hydrate with a sugar weight concentration of 1.5 %, modified CMA hydrate with 1.5 % weight concentration of calcium-magnesium acetate added to the water of hydration, and an unmodified pure hydrate. The sedigraph analysis shows finer particles in the modified hydrates. Mechanical testing of the sorbents shows that the surfactants used have improved the flow properties of the modified hydrate. Several flow properties have been determined for three sorbents using the Hosokawa powder characterization tester. The results show "bad" flowability and "fairly" to "very" high floodability for the tested sorbents. The presence of moisture in the tested sorbents is shown to be badly affecting their flow properties.

In phase III, Modelling of Powder Dispersion, the agglomerate size distributions have been measured using a cascade impactor at both the entrance and the exit of a powder flow system. The experimental results show that the agglomerate size at the entrance is larger than that at the exit of the system, which verifies the agglomerate breakup mechanism proposed in the powder dispersion model in the last year. The agglomerate size distribution is measured with the PIV technique at 4 different axial locations in the powder dispersion nozzle. The experimental results show that the counts of the large agglomerates continuously decrease and that of the small agglomerates continuously increase along the axial direction, and, therefore, the mean size of agglomerates in the system decreases. The expression for the probability of the generation of agglomerates (volume v) by the break-up of larger agglomerates (volume v'), i.e., $B_{vv'(x)}$ in the model proposed last year, is improved from a uniform distribution to a parabolic one which is physically reasonable. Experiments are conducted to measure the agglomerate size distribution in the powder transport apparatus of Project 1.1 under high temperature conditions. The population balance model proposed last year can reasonably simulate the experimental results. Efforts are also taken to simulate the experimental results of the agglomerate size distribution in the powder dispersion nozzle which were reported in the previous final reports. It is found the value of the breakup parameter in the model almost remains constant at about 4.9×10^{-9} under all conditions.

V. Articles and Presentations

"The effects of entrance geometry on powder dispersion," Ind. Eng. Chem. Res., 1994, Jiang, P. J., K. C. Hofacre and L.-S. Fan (in review).

"Characterization of lignosulfonate-modified hydrated lime powders", AIChE J., 1994, Lee, Rhonda J., Hsia, Chungwei, and L.-S. Fan (in press).

"The Effect of Solid Interaction Forces on Pneumatic Handling of Sorbent Powders," presented at the 1991 Annual AIChE Meeting, Los Angeles, Nov 17-22, 1991; AIChE J., 39, 988-999 (1993) R. Lee and L.S. Fan.

"Nozzle Effects on Limestone Powder Dispersion During Pneumatic Transport," presented at the AIChE Annual Meeting, Miami Beach, Florida, Nov. 1-6, 1992, P. Jiang, K.C. Hofacre, and L.-S. Fan; AIChE J (in review).

"Dispersion and Transport of Fine Powders in Air," presented at the 1991 Pittsburgh Coal Conference, Pittsburgh, Oct. 14-18, 1991, R. Eubanks, K. Raghunathan, and L.-S. Fan. (paper in conference proceedings).

"Sorbent Powder Handling in Furnace Infection," presented at 6th Meeting of U.S. DOE Duct Injection Technology Working Group, Battelle Memorial Institute, Columbus, OH, April 28-29, 1992, L.-S. Fan.

"The Effect of Additives on the Reduction of Agglomeration in Calcium Based Powder Materials," presented at the AIChE Annual Meeting, Miami Beach, Florida, Nov. 1-6, 1992, Rhonda J. Lee, E. Abou-Zeida, C. Hsia, F. Bavarian, and L.-S. Fan.

"Powder Agglomeration Effects in the Dispersion and Transport of Calcium-Based Sorbents," presented at the American Filtration Society Annual Meeting, Chicago, May 10-14, 1992, (paper in conference proceedings), R. Eubanks and L.-S. Fan -- Received Best Paper Award.

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Fig. 1.1 Variation of specific surplus charge with mass flow rate for Ca(OH)_2 with/without alumina

Fig. 1.2 Variation of specific surplus charge with mass flow rate for $\text{Ca}(\text{OH})_2$ with/without carbon black

Figure 1.3 Schematic of the charge measurement apparatus.

Figure 1.4 Specific surplus charges of CTAB-modified Ca(OH)_2 compared with those of pure hydrate and lignosulfonated hydrate.

Figure 1.5(a) Tapped densities of $\text{Ca}(\text{OH})_2$ with various wt% of free-flow agents

Figure 1.5(b) LPBD of $\text{Ca}(\text{OH})_2$ with various wt% of free-flow agents.

Figure 1.5(c) Hausner ratios of $\text{Ca}(\text{OH})_2$ with Al_2O_3 and SiO_2 .

Figure 1.6 Effects of CTAB on the size distribution of Ca(OH)_2 during transport.

Table 1.1: LPBD and TD of $\text{Ca}(\text{OH})_2$ for different weight percentages of alumina

wt. % Alumina	LPBD (g/cm^3)	TD (g/cm^3)
0.0	0.280	0.56
0.1	0.330	0.65
0.5	0.350	0.70
1.0	0.30	0.62

Figure 2.1 Effect of lignosulfonate concentration on the cohesive strength of the modified hydrates.

Figure 2.2 Sedigraph results for particle size distribution of unmodified and modified hydrates.

Sorbent	Moisture Content (%)	Bulk Density (gm/cm ³)		Compressibility (%)	Hausner Ratio
		Aerated	Packed		
Unmodified Hydrate	0.75	0.376	0.721	47.9	1.92
Modified Sugar Hydrate (1.5 %)	0.66	0.339	0.638	46.9	1.88
Modified CMA Hydrate (1.5%)	0.51	0.48	0.796	39.7	1.66

Figure 2.3 Hausner ratio and compressibility of the modified and unmodified hydrates.

Sorbent	Angle of Repose (degree)	Angle of Spatula (degree)	Angle of Fall (degree)	Angle of Difference (degree)
Unmodified Hydrate	55	63	20	35
Modified Sugar Hydrate (1.5%)	53	66	26	27
Modified CMA Hydrate (1.5%)	50	65	20	30

Figure 2.4 Results for the angles of repose, spatula, fall and difference.

Sorbent	Dispersibility (%)	Flowability (%)	Floodability (%)
Unmodified Hydrate	38	34	80
Modified Sugar Hydrate (1.5%)	36	28	69
Modified CMA Hydrate (1.5%)	38	26	72

Figure 2.5 Results for dispersibility, flowability and floodability. -

Figure 2.6 Effect of moisture content on the compressibility.

Figure 2.7 Effect of moisture content on the angle of repose.

Figure 2.8 Effect of moisture content on the dispersibility.

Figure 3.1 Schematic of experimental set-up of Project 1.1.

Figure 3.2 Comparison between experimental results and simulation results

Figure 3.3 Schematic diagram of powder dispersion system.

Figure 3.4 Schematic diagram of imaging and recording system.

Figure 3.5 Axial variation of the agglomerate size distribution.

Figure 3.6 Axial variation of the cross sectionally averaged turbulent energy dissipation rate.

Fig. 3.7 Comparison between the simulation results from the improved model and from the original model.

Figure 3.8 Experimental data and simulated results at 1173 K.

Figure 3.9 Axial variation of the cross sectionally averaged turbulent energy dissipation rate.

Figure 3.10 Comparision of Simulated Results and Experiments