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

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by

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TABLE OF CONTENTS

Executive Summary	ii
I. Introduction	1
II. Powder Characterization	2
A. Electrostatic Characteristics of Powder	2
A.1 Introduction	2
A.2 Experimental	6
A.3 Results and Discussion	7
B. Modeling on Powder Dispersion	11
B.1 Introduction	11
B.2 Model for Flow Field	12
B.3 Population Balance Model	12
III. Powder Handling Properties	17
A. Introduction	17
B. Experimental	17
B.1 Tested Sorbents	17
B.2 Testing Equipment and Measured Properties	18
B.3 Definitions and Testing Procedures	18
B.4 Effect of Moisture	24
C. Results and Discussion	24
IV. Concluding Remarks	27
V. References	28

EXECUTIVE SUMMARY

In the fourth year, the overall charging tendency and the charge polarity of three sorbent powders have been examined. It was found that CaCO_3 and lignosulfonated hydrate are charged positively during transport and lignosulfonated hydrate exhibits the highest charge pick-up ability. All sorbent materials exhibit a decrease in specific surplus charge with increasing powder mass flow rate but an increase with increasing gas flow rate. An increase in humidity was found to result in less charge build-up on powder. A comparison of the charge pick-up ability of $\text{Ca}(\text{OH})_2$ for three tube materials shows that the powder acquires charges the lowest when transported through carbon steel tubes. Theoretical calculations of the attraction forces demonstrate that the electrostatic force dominates at larger separation distances. Also, mechanical testing equipments have been used to measure and analyze the flow properties of calcium carbonate, hydrate, and lignosulfonated hydrates under different handling and transport conditions. The tests performed showed that calcium carbonate has low flowability and dispersibility compared to the hydrates. Results proved also that increasing the lignosulfonate percentage improves the flow properties of the modified hydrates. Presence of moisture was shown to affect badly the flowability of the tested sorbents because of bonding between adjacent water layers which increases the cohesive strength of the sorbents.

One of the major accomplishments in the fourth year is the development of an integral model for powder dispersion. Previous studies on powder characterization and powder handling have been integrated to establish a mathematical model, in which both hydrodynamic forces and interparticle forces have been taken into account. The agglomerate size distribution is dependent on two simultaneous processes, i.e., coalescence and break-up of agglomerates. Both processes are controlled by hydrodynamic forces and interparticle forces in the system.

The turbulent flow in the sorbent conveying system is simulated by $k-\epsilon$ model. Simulation results show that turbulence intensity is very high in the nozzle and drops rapidly along the nozzle. It is found that under conditions in previous experimental studies, most agglomerates are smaller than energy dissipation eddies (Kolmogorov eddies) in the turbulent flow and therefore, viscous shear stress is dominant.

I. INTRODUCTION

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 SO₂ (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 fourth year's project contains two phases, Phase I "Powder Characterization" and Phase II "Powder Mechanical Properties". Work under Phase I involves characterization of the sorbents in terms of their electrostatic properties. The triboelectric charging of powders are studied in detail by measuring sorbent charging as a function of material properties as well as transport conditions. A variety of sorbents are tested, including laboratory-made lignohydrates, calcite, dolomite, dolomitic hydrate and hydrated lime. The effects of transport tube material and gas properties, specifically humidity and velocity on the extent of sorbent charging are also investigated. A population balance model is developed to account for the particle size distribution for powder dispersion through gas-solid injection nozzles. The model takes into consideration the transition probability of one class of particle size to the other. The variations of the transition probability with the booster air velocities is examined. Simulation of the particle size distributions under some operating conditions is conducted. Phase II investigates the flow properties of several calcium-based sorbents under different handling and transporting conditions. Effect of moisture content, as an important handling condition, on these properties is examined. The determined properties has been analyzed to study their effect on the transport and handling processes.

II. POWDER CHARACTERIZATION

A. Electrostatic Characteristics of Powder

A.1 Introduction

Handling and transport of fine powders such as calcium based sorbents used in the LIMB process involve extensive contact and friction between the powder and the surface of the handling and the transport apparatus. As a result, the powder becomes electrically charged. This charging mechanism is known as the triboelectric effect. The study of electrostatic characteristic of the powder is of both industrial and fundamental significance. As the charge on the powder builds up to a certain level, electrostatic hazard may occur. The presence of charges in gas-solid systems can have a significant influence on the dynamic behavior of the powder and the hydrodynamics of the system. In addition, electrostatic forces can give rise to powder agglomeration, which has unfavorable effects on reactivity. The study in this section is aimed at examining the effect of transport conditions and sorbent materials on the charge accumulation on calcium-based sorbent powder during transport. A comparison of the electrostatic force with the van der Waals forces is also conducted. A brief review on the charging mechanisms, tendency, the resulting attraction forces, and other affecting factors will be presented below.

Charging mechanisms and Charging tendency

Triboelectrification is a charging process which involves non-conducting materials. There are two major kinds of triboelectric charging: contact charging and friction charging (Harper, 1967). A typical example of contact charging is the charging of an insulator after immersion in mercury where there is no friction involved. Frictional charging occurs when rough surfaces slide against each other. The evidence for frictional charging comes from observations that two identical surfaces become oppositely charged when rubbed together. Experimental evidence has shown that both kinds of charging are significantly dependent on pressure, rubbing speed, and the roughness and the cleanness of surfaces.

The majority of the studies on the charging behavior of insulators has mainly been concerned with polymers due to their highly insulating characteristics (Cunningham and Hood,

1970; Akande and Lowell, 1985). There have been some contradictory findings regarding the dependence of the amount of charge transferred between polymers and the metal on the metal work function. The work function refers to the energy required to move the electron from the highest energy level out of the metal to infinity. Therefore, the metal with smaller work function tends to lose electrons to that with greater work function. Davies (1967) measure the charge density of polymers brought into contact with a metal and found that for each polymer, the charge density is approximately proportional to the metal work function. This allows a value of work function to be assigned to each polymer. However, Akande and Lowell (1985) found that the magnitude of charge transferred to PTFE was independent of the metal work function but the charge transferred to nylon increased with the work function. Therefore, they concluded that charge transfer cannot be solely determined by the work function.

It has been observed that insulators can acquire more charges by repeated contact with metals (Harper, 1967; Lowell, 1976). The charge on the insulator significantly increases after the second contact with the metal and continues to accumulate as the number of contact increases. Two mechanisms for the charge accumulation have been proposed based on these observations: (1) the insulator being conducting is responsible for the charge accumulation; (2) the charge accumulation is consequence of an increase in the contact area due to either the viscoelastic properties or the relocation of the contact. However, some contradictory findings have been reported regarding the mechanisms leading to charge accumulation. Lowell (1984) deposited charge on the surface of a polymer film and found that the charge spreads very slowly. He discharged a sample and repeated contacts at the same location, and found the charging behavior and magnitude are similar to that of the first time. Furthermore, he reported that a deliberate relocation of the contact area doesn't show a significant increase in the charge. Therefore, he concluded these mechanisms does not seem to be responsible for the increase in charge in highly insulating materials such as polyethylene and polytetrafluoroethylene.

Electrostatic forces

One significance about charged particles is that the electrostatic forces can have a considerable contribution to the adhesion forces among particles, resulting in powder agglomeration. The attraction force between the point charge, q , and its image charge, $-q$, in

a dielectric medium such as the air can be obtained by Coulomb's law:

$$F = \frac{qq'}{16\pi\epsilon_0 d^2} \quad (1.1)$$

where q and q' are the amount of charges on particles, ϵ_0 , ϵ_r represent the dielectric constants of vacuum and the medium, respectively, and d is the separation distance (Cross, 1987). If a sphere is in contact with a plane surface, d is two times larger than the sphere diameter. In the absence of external fields, the attraction force in a vacuum between a charged particle and an adjacent uncharged particle with fully developed image charge is given by:

$$F = \frac{q^2}{16\pi\epsilon_0 d^2} \quad (1.2)$$

Since the above equation is only valid under the assumption of point charge on the particle and a plane metal surface of infinite extent, the image charge on a particle of radius r is smaller than q and the attraction force is reduced to (Bailey, 1984)

$$F' = \frac{q^2 \left(1 - \frac{d}{\sqrt{r^2 + d^2}} \right)}{16\pi\epsilon_0 r^2} \quad (1.3)$$

Comparison between the van der Waals and the electrostatic forces

It is significant to compare the van der Waals and the electrostatic forces. Due to the complex nature of the electrostatic attraction, the attraction forces can only be obtained for ideal contact models such as plate/plate, sphere/plate, and sphere/sphere. Krupp calculated both attraction forces for the system of conducting sphere and conducting half-space and reported that the range of electrostatic forces is large than that of van der Waals forces by a few orders of magnitude. Schubert (1981) theoretically estimated the attraction forces for the sphere/plate system. As shown in figures 1.1 and 1.2, for separation distances larger than $1 \mu\text{m}$, the electrostatic attraction force becomes larger than the van der Waals forces although the van der Waals forces are the dominant forces when particles are in contact. The electrostatic force may

be also comparable with the van der Waals forces when there are asperities on the particle surface (Krupp, 1967).

Humidity effect

An increase in the air humidity can greatly reduce the charge build-up. In the presence of moisture, water vapor adsorbs on the surface of the powder and forms a water layer. Since the dielectric constant of water is much larger than that of the powder, the conductivity of the surface increases and, therefore, fewer charges are likely to remain on the powder. The humidity can also affect the charging polarity. Coste and Pechery (1977) pulled polymer films over metal rollers at various relative speeds. They found that some polymer films subjected to surface slippage change their polarities but reverse to the original unipolar charging behavior when there is no relative motion. However, for some polymer films, such a phenomenon was not observed at zero slippage but partial reversion of the polarity occurred at very high relative humidities. The charge reduction often leads to weaker electrostatic forces. With an increase in the humidity, the attraction forces arising from liquid bridges can also occur. This is the reason why the electrostatic force can be neglected when compared with capillary forces in a humid environment. If the powder is exposed to high temperatures or pressures, the adhesion due to sintering can occur between powders when they are brought together and the effects of sintering are usually significantly larger than those of the electrostatic and van der Waals forces.

Charge measurement techniques

The charge on powder can be determined in various ways (Cross, 1987). The Faraday cup method measures the total charge on a certain amount of powder by using an electrometer. The charge determined in this way is usually expressed in terms of powder weight. The volume charge density of charged powder can be determined using an electrostatic field meter, which measures the surface potential, V , at a certain distance, d , from the surface. The electric field, E ($=V/d$) at the surface of the powder is obtained by the Gauss' law:

$$\int E dA = \Sigma q / \epsilon_0 \quad (1.4)$$

Although the above two are most commonly used techniques, the charge on an individual particle can not be determined. The method used to measure the charge on small particles is similar to the one developed by Millikan for determining the charge on an electron. The charged particle is injected into an electric field and its motion is recorded. By tracking the particle movement due to both the electrostatic and gravitational forces, the charge can be obtained.

A.2 Experimental

Figure 1.3 shows the schematic of the experimental set-up, which can be divided into two parts, the transport system and the charge measurement apparatus. For the transport system, the sorbent powders are transported by a Plexiglas feeder with powder flow coming from the side of the feeder. The tube for powder injection is placed horizontally and powder is carried into this tube from a small hole at the bottom. The powder flow rate can be adjusted by changing the size of the hole. Fitted at the bottom of the feeder is a tube for providing an air jet to loosen the powder. A solenoid valve hooked to a pulse generator/timer is connected to the air jet line to provide intermittent flow in order to prevent the formation of the channel flow in the vicinity of the small hole. Prior to conducting experiments, the powder was dried in a vacuum oven to eliminate the moisture factor and moisture content was also measured to assure the drying process was completed.

The transport line was designed such that tubes made of different materials can be installed and tested. The transport tube is of 0.635 cm OD and 100 cm length. Three kinds of tube materials were tested: brass, carbon steel and copper. Carbon steel was tested because it is one of the most commonly used materials in high temperature processes. High-purity nitrogen was used as a carrier gas to eliminate the humidity effect while studying the electrostatic properties of different sorbents. The gas flow controlled by needle valves ranges from 25 to 45 SCFH.

The charge measurement apparatus works as a Faraday cage, which is used to measure the net charges carried on powders. The Faraday cage is connected to the transport tube through a short copper tube. The Faraday cage essentially consists of two conductive containers. The dimensions of the inner and outer containers are 9 cm diameter x 30 cm long and 20 cm diameter x 40 cm long, respectively. The inner container is connected to Keithley electrometer

by a copper wire and is isolated from the outer container by highly insulating materials-PTFE. The distance between the inner and outer container is long enough to ensure there is no decay of charge. It is important to obtain the charge/mass ratio; therefore, a filter bag is installed inside the inner container to retain the particles and allow the gas to escape. Since the Sedigraph analysis for powder size distribution obtained in previous studies showed that approximately more than 95% of the sorbent powder is larger than 1 μ m and water. The humidity of gas can be adjusted by two ways: (1) adjust the depth of the tubing immersed into water. (2) mix the humidified gas with dry gas.

A thorough examination of various effects on the charging tendency and the charge polarity has been carried out for three sorbent materials: black river hydrate, CaCO_3 , and lignosulfonated hydrate. Effects investigated include sorbent material, gas flow rate, gas humidity, and tube materials.

A.3 Results and Discussion

It was noted that powder might be already charged before injected into the transport tube; therefore, experiments were also conducted without the transport tube in order to deduct the contribution of other sources from the total charge. Figure 1.5 shows the typical charging curves as a function of time for all three sorbents. It was found that the charge accumulation is independent of the quantity of powder transported. Figure 1.6 shows the variation of specific surplus charge with mass flow rate for Ca(OH)_2 transported through a brass tube at a gas flow rate of 25 SCFH. The specific surplus charge is defined as the ratio of the charge to the mass of the powder transported. The two curves on the top are experimental data without and with transport tube and the bottom curve represents the calculated values of charge generated solely due to the transport tube. The experimental data were fitted using the following equation:

$$Q' = a + b \frac{\ln M}{M} \quad (1.5)$$

where Q' and M are the specific surplus charge and the mass flow rate, respectively. After obtaining the fitting curves, the amount of charge on powder can be calculated simply by subtracting the values with the feeder only from those with both feeder and transport tube.

It was found that the values of the specific surplus charge range from 10^{-5} to 10^{-4} C/kg and $\text{Ca}(\text{OH})_2$ was charged positively. When particles are transported in an air environment, the maximum electric field a charged particle can give rise to is limited by the breakdown field strength of the air. By the Gauss' law, the value of the breakdown field strength is 3×10^6 V/m, although in practice higher field values can be observed for a nonuniform field (Bailey, 1984). For a $30 \mu\text{m}$ $\text{Ca}(\text{OH})_2$ particle, the maximum amount of charge it can acquire is 7.43×10^{-14} C if the Gaussian limit is reached. The corresponding specific surplus charge (charge-to-mass ratio) under this condition is 2.3×10^{-3} C/kg. It is apparent that the experimentally determined average values of specific surplus charge is smaller than the one based on the Gaussian limit. Cross (1987) pointed out that if powder flow has a high powder concentration or the transport tube has a very large diameter, the charge accumulated on powder can be reduced significantly. The results show that with increasing mass flow rate, the specific surplus charge decreases. Kittaka etc. (1979) studied the charging tendency of polymers in pneumatic transport and reported a similar trend of charges on powder varying with the solid loads. This tendency was thought to be caused by a decrease in the frequency of friction and collision between powder and wall for high powder mass flow rates. Powders acquire their charges mainly through the contact with the metal. At high powder mass flow rates (or powder concentrations), the distances between powder particles are smaller; therefore, the chances for particles to be deflected from its original path toward colliding with the metal wall become higher. As a result, the amount of charge per unit mass of powder decreases although the surplus charge of powder still increases as shown in Fig. 1.7.

The charging curves for the calcite and lignosulfonated hydrate were constructed in the same way. As shown in Fig. 1.8 and 1.9, calcite and lignosulfonated hydrate were charged negatively and positively, respectively. The same charging polarities for lignosulfonated hydrate and hydrate may be attributed to their similar molecular structures. These powders are hydrate-based sorbents. There has been a considerable amount of study on the relationship between the charging behavior and energy level for polymeric particles charged by the metal (Lowell, J. and Rose-Innes A. C., 1980; Medley, 1953). These results suggest that there is a strong dependence of the charge transfer on the side-groups of the polymer. Shaw (1917) found that, in general, basic materials tend to be charged positively and the acid materials negatively. Lowell and Rose-

Innes (1980) also pointed out that polymers with electron-donating groups such as OH^- tend to lose electrons during contact, while those with electron-accepting groups such as benzene ring obtain electrons. It is interesting to find that the sorbent powders also exhibit a charging behavior similar to the polymer. Figure 1.10 shows the comparison of the charge generation among the above three sorbent powders. Lignosulfonated hydrate was found to acquire the most amount of charges under the same operating conditions.

Figure 1.11 shows the results of the specific surplus charge on $\text{Ca}(\text{OH})_2$ transported in both dry N_2 and N_2 with a relative humidity of 50%. An increase in humidity was found to decrease the charge pick-up ability. As mentioned earlier, this phenomenon is caused by charge leakage enhanced by the humidity. It was observed that after the gas/powder flow was shut off, the reading of the charge on the electrometer remained approximately constant for the case of dry N_2 , while in the presence of moisture, a rapid decrease in the reading of charge was observed. The effect of gas flow rate on the specific surplus charge of $\text{Ca}(\text{OH})_2$ is shown in Fig. 1.12. The results show that the powder was charged more easily at higher gas flow velocities. It was also found that the effect of gas flow velocity was more significant at low powder mass flow rates. As discussed previously, the charging tendency of insulators by the conducting transport tube is a function of the materials of the transport tube. The comparison of the charge pick-up ability of $\text{Ca}(\text{OH})_2$ for three tube materials was conducted and the results are shown in Fig. 1.13. It was found that powder acquires charges the most when transported through brass tubes and the lowest when transported through carbon steel tubes.

In order to prevent electrostatic hazards, powder handling equipment is usually grounded. One question has been raised as to whether there is still charge build-up when the transport tube is grounded. Figure 1.14 shows the effect of grounding on the charging of $\text{Ca}(\text{OH})_2$ passing through a brass tube. It was found that grounding did reduce charge accumulation but some charges still remained on the powder.

In the second year, theoretical calculations of the van der Waals and the electrostatic forces were made for several ideal contact systems at zero separation, and the results show that the van der Waals forces dominate. In other words, if two particles stick together after colliding with each other, the van der Waals forces were the dominating forces responsible for keeping the formed agglomerate from breaking apart by shear forces. While these results demonstrated

that the electrostatic force can be neglected when particles are in contact, it is unclear whether this force still plays a minor role at a larger separation distance. In the following section, the dependence of both attraction forces on separation distance will be examined.

In Fig. 1.15, theoretical estimation of attraction forces for a sphere/sphere system (Ca(OH)_2) was plotted as a function of separation distance. The van der Waals forces are given as

$$F_{vdw} = \frac{AR}{12H^2} \quad (1.6)$$

where A is the Hamaker constant, which is 13.82 for Ca(OH)_2 , R and H are the sphere radius and the separation distance, respectively. Two sets of the electrostatic forces were estimated; one was obtained based on the breakdown field strength of the air and the other one was determined by the average values of charge in experiments. The electrostatic forces (image force) between a charged particle and an adjacent uncharged particle were considered. The particle size and the value of the specific surplus charge chosen are $30 \mu\text{m}$ and $5 \times 10^{-5} \text{ C/kg}$, respectively. Assuming particles are of a spherical shape and each particle is identical, the amount of charge on a particle can be obtained by multiplying the specific surplus charge with the particle volume, which is $1.57 \times 10^{-15} \text{ C/particle}$ in this case. The electrostatic force was then obtained using equation (1.3). Since the assumption of a point charge is valid only for a large separation distance, the electrostatic force was only calculated for separation distances down to one particle diameter. As particles move closer to each other, the extent of polarization increases, and a larger electrostatic forces can be expected. The upper bound of this force is in general determined by the break down field of the air. As shown in Fig. 1.15, the electrostatic forces based on the experimentally determined value of charge are larger than the van der Waals forces. However, as two particles are in contact, the van der Waals forces become larger than the maximum of the electrostatic force. In light of the above results, it is concluded that if particles are brought together over a larger range, the electrostatic force needs to be taken into account.

B. Modeling on Powder Dispersion

B.1 Introduction

In the previous three years, experimental studies have been conducted extensively on dispersion of sorbent particles in gas-solid injection nozzles and one optimum nozzle design (expansion nozzle with a two-jet booster jets) has been chosen for minimizing agglomerate size distribution. For better understanding and, furthermore, predicting the performance of the nozzle or agglomerate size distribution at the exit of the nozzle, previous studies on powder characterization and powder handling are integrated into a mathematical model.

General population-balance models have been extensively employed to simulate drop population variation in terms of drop size, age, concentration, etc. in liquid-liquid dispersion systems (Valentas and Amundson, 1966; Coulaloglou and Tavlarides, 1977; Ramkrishna, 1985; Tsouris and Tavlarides, 1994). This kind of model can also be applied to gas-solid systems (Yang et al., 1993). However, little has been reported on modelling of the particle size distribution variation in a dispersion of cohesive particles in turbulent gas-solid flows, i.e., sorbent conveying systems.

Although the effect of particles on the fluid turbulence may be important even under low particle concentration conditions, existing models for describing this influence are still incomplete (Sommerfeld, 1990). In literature, the mean flow field in turbulent gas-solid systems is assumed to be not significantly affected by particles in dilute systems and can be determined by standard $k-\epsilon$ model (Picart et al., 1986; Sommerfeld, 1990).

Agglomerate formation in sorbent conveying systems between primary particles are due to interparticle forces, such as van der Waals and electrostatic forces. Decrease in size increases the magnitude of these forces (Pietsch, 1984). Dispersion of aggregates can be achieved by different mechanisms, e.g., impacting and turbulence, etc. (Kousaka et al., 1979; Zahradnicek and Löffler, 1979). For turbulent gas-solid dispersion system, hydrodynamic forces, e.g. inertial force of fluid or by viscous shear force, are important. The magnitude of different kinds of hydrodynamic forces depends on the relative size of aggregates to eddies in turbulence (Kousaka et al., 1979).

The agglomerate size distribution is dependent on two simultaneous processes, i.e., coalescence and break-up of agglomerates. Both processes are controlled by hydrodynamic

forces and interparticle forces in the system, as shown in Figure 1.16. Therefore, to simulate the agglomerate size distribution variation, these two kinds of forces should be both taken into account.

B.2 Model for flow field

According to the literature review conducted, the turbulent flow in the sorbent conveying system is simulated by Eulerian conservation equations and k- ϵ turbulence model, from which the hydrodynamic forces can be calculated. The generalized equation for this model is:

$$\frac{\partial(\rho \bar{u} \phi)}{\partial x} + \frac{1}{r} \frac{\partial(r \rho \bar{v} \phi)}{\partial r} + \frac{1}{r} \frac{\partial(r \rho \bar{w} \phi)}{\partial \theta} = \frac{\partial}{\partial x} \left(\Gamma_{\phi} \frac{\partial \phi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left(r \Gamma_{\phi} \frac{\partial \phi}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left(\Gamma_{\phi} \frac{1}{r} \frac{\partial \phi}{\partial \theta} \right) + S_{\phi} + S_p q$$

The detailed equations are shown in Table 1.1.

The constants used in the k- ϵ model are: $C_{\mu}=0.09$, $C_1=1.44$ and $C_2=1.92$, $\sigma_k=1$ and $\sigma_{\epsilon}=1.33$. The boundary conditions are:

- i) $U_{in}=\text{constant}$, $U_{jet}=\text{constant}$, $k_{in}=\text{constant}$, and $\epsilon_{in}=\text{constant}$ at the inlet;
- ii) No-slip boundary conditions are used at the nozzle walls, i.e., $U=0$, $V=0$, $k=0$, and $\epsilon=0$;
- iii) $\partial \phi / \partial x = 0$ at the outlet.

Simulation results of the flow field show that turbulence intensity is very high in the nozzle ($10^2 - 10^5 \text{ m}^2 / \text{s}^3$) and drops exponentially along the nozzle, as shown in Figure 1.17. It is found that under conditions in previous experimental studies, most agglomerates are smaller than energy dissipation eddies (Kolmogorov eddies) in the turbulent flow and therefore, viscous shear stress is dominant.

B.3 Population balance model

The population balance model is expressed in terms of one-dimensional mass balance in this study. The mass balance for agglomerates of volume v over a differential axial location range from x to dx , under steady state condition, is

$$G_s \frac{\partial M_{(v,x)}}{\partial x} = \dot{M}_{B(v,x)} - \dot{M}_{D(v,x)}$$

where G_s , $M_{(v,x)}$, $\dot{M}_{B(v,x)}$, $\dot{M}_{D(v,x)}$ are the solid mass flow rate, the probability density distribution function (based on mass fraction) of agglomerates of volume v at axial location x , mass rate of birth and death rate of agglomerates, respectively. This equation can also be expressed in another form:

$$G_s \frac{\partial (v n_{(v,x)} / \alpha)}{\partial x} = \dot{M}_{B(v,x)} - \dot{M}_{D(v,x)} \quad (1.7)$$

$$\dot{M}_{B(v,x)} = \dot{M}_{B,C(v,x)} + \dot{M}_{B,B(v,x)}$$

$$\dot{M}_{D(v,x)} = \dot{M}_{D,C(v,x)} + \dot{M}_{D,B(v,x)}$$

The physical meanings of the last two equations are shown in Figure 1.18.

Coalescence of agglomerates

The reason for coalescence of agglomerates is adhesions of agglomerates upon the collisions between them due to the interparticle forces. In this study, only binary collisions are considered, since the probability of collisions among three or more particles is negligible.

Similar to the kinetic theory of gas, the collision frequency of agglomerates depends on the number density of the agglomerates $n_{(v,x)}$, averaged particle velocity fluctuations V_p' , and the size of collision agglomerates v_1, v_2 . Thus, the collision frequency between two agglomerates can be written as:

$$F_{C(v_1, v_2, x)} = k_1 n_{(v_1, x)} n_{(v_2, x)} V_p' (v_1 + v_2)$$

However, because interparticle forces are not strong, in some cases, enough to hold two agglomerates together, only a part of collisions lead to adhesion or coalescence. The controlling factors on the probability of adhesion include: interparticle forces (only van der Waals forces

considered) represented by Hamaker constant of the sorbent powder (A), size of particles (v_1 and v_2), and averaged solid velocity fluctuations V_p' .

$$P_{A(v_1, v_2, x)} = k_2 A / (V_p' v_1 v_2)$$

From the above equations, the mass rate of coalescence of two agglomerates of size v_1 and v_2 ($v = v_1 + v_2$) is:

$$M_{C(v_1, v_2, x)} = F_{C(v_1, v_2, x)} P_{A(v_1, v_2, x)} \cdot (v_1 + v_2) \rho_A$$

where ρ_A is the density of agglomerates. More specifically, the generation rate of agglomerates of size v by coalescence is:

$$\begin{aligned} M_{B, C(v, x)} &= \int_v F_{C(v', v-v', x)} P_{A(v', v-v', x)} \cdot [v' + (v - v')] \rho_A dv' \\ &= K_1 \rho_A A v^2 \int_{v_{min}}^{v-v_{min}} \frac{n_{(v-v', x)} n_{(v', x)}}{v' \cdot (v - v')} dv' \end{aligned} \quad (1.8)$$

And the disappearance rate of agglomerates of size v by coalescence is:

$$\begin{aligned} M_{D, C(v, x)} &= \int_v F_{C(v, v', x)} P_{A(v, v', x)} \cdot (v + v') \rho_A dv' \\ &= K_1 A \frac{\rho_A}{v} n_{(v, x)} \int_{v_{min}}^{v_{max}} \frac{n_{(v', x)} \cdot (v + v')^2}{v'} dv' \end{aligned} \quad (1.9)$$

Break-up of agglomerates

The break-up of agglomerates can be attribute to different reasons, e.g., hydrodynamic forces, impacting forces, thermal stress, and mechanical stresses. However, in this nozzle, only hydrodynamic forces are important to the break-up of agglomerates.

According to the theory of Hinze (1955), the generalized Weber number plays a dominant role in the deformation and breakup of a globule. Weber number means the ratio of hydrodynamic forces over surface tension of a globule. However, what is important in agglomerate breakup is interparticle forces rather than surface tension. Therefore, a similar number is defined as:

$$\Omega = \frac{\text{hydrodynamic forces}}{\text{interparticle forces}}$$

In this model, the viscous shear stress is dominant, as the simulation of the flow field shows:

$$\tau_s = k \sqrt{\rho_f \mu \epsilon_t(x)}$$

And, the van der Waals force is represented by Hamaker constant of the sorbent powder (A), since the packing of primary particles in a agglomerate is random. It is further assumed that the breakup frequency is proportional to Ω .

$$F_{Br(v, x)} = k_3 \frac{v}{A} \sqrt{\rho_f \mu \epsilon_t(x)} n_{(v, x)}$$

Hence, the mass rate of break-up of agglomerates of volume v is:

$$\dot{M}_{Br(v, x)} = F_{Br(v, x)} v \rho_A = -K_2 \frac{\rho_A}{A} \sqrt{\rho_f \mu \epsilon_t(x)} v^2 n_{(v, x)}$$

and the disappearance rate of agglomerates of volume v by break-up is in the same form:

$$\dot{M}_{D, B(v, x)} = -K_2 \frac{\rho_A}{A} \sqrt{\rho_f \mu \epsilon_t(x)} v^2 n_{(v, x)} \quad (1.10)$$

But, the generation rate of agglomerates of volume v by break-up is different:

$$\dot{M}_{G, B(v, x)} = \int_{v'} F_{Br(v', x)} v' \rho_A B_{vv'}(x) dv'$$

where $B_{vv'}$ is the probability of generation of agglomerates of volume v by break-up of larger agglomerates (v'). Since no experimental data for this term is available, it is assumed that:

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

Hence the generation rate of agglomerates of volume v by break-up of larger agglomerates is:

$$M_{B, B(v, x)} = K_2 \frac{\rho_A}{A} \sqrt{\rho_f \mu \varepsilon_t(x)} \int_{v+v_{min}}^{v_{max}} \frac{v'^2 n(v', x)}{v' - v_{min}} dv' \quad (1.11)$$

General and simplified form of this model

Substituting equations (1.8) - (1.11) into equation (1.7) yields the general form of the governing equation of this model:

$$\begin{aligned} G_s \frac{\partial \left[\frac{v n(v, x)}{\alpha} \right]}{\partial x} = & K_1 \rho_A A v^2 \int_{v_{min}}^{v-v_{min}} \frac{n(v-v', x) n(v', x)}{v' \cdot (v-v')} dv' \\ & + K_2 \frac{\rho_A}{A} \sqrt{\rho_f \mu \varepsilon_t(x)} \int_{v+v_{min}}^{v_{max}} \frac{v'^2 n(v', x)}{v' - v_{min}} dv' \\ & - K_1 A \frac{\rho_A}{v} n(v, x) \int_{v_{min}}^{v_{max}} \frac{n(v', x) \cdot (v+v')^2}{v'} dv' \\ & - K_2 \frac{\rho_A}{A} \sqrt{\rho_f \mu \varepsilon_t(x)} v^2 n(v, x) \end{aligned}$$

However, in this study, two factors contribute to simplifying this general equation: i) the solid volume fraction can be considered as a constant; ii) the solid volume fraction is so low ($< 1\%$) that the coalescence of agglomerates is negligible and the break-up of agglomerates is dominant in determining the agglomerate size distribution variation. The simplified governing equation is thus obtained:

$$\begin{aligned} \frac{\partial n(v, x)}{\partial x} = & \left(\frac{1}{G_s} K \frac{\rho_A \alpha}{A} \sqrt{\rho_f \mu} \right) \frac{1}{v} \sqrt{\varepsilon_t(x)} \cdot \left[\int_{v+v_{min}}^{v_{max}} \frac{v'^2 n(v', x)}{v' - v_{min}} dv' - v^2 n(v, x) \right] \\ = & C \frac{\sqrt{\varepsilon_t(x)}}{v} \cdot \left[\int_{v+v_{min}}^{v_{max}} \frac{v'^2 n(v', x)}{v' - v_{min}} dv' - v^2 n(v, x) \right] \end{aligned}$$

Simulation results

The simplified equation is solved by finite difference method. Figure 1.19 shows the comparison between the experimental data of the size distribution of agglomerates at the exit of the nozzle and the simulation results. From this figure, it can be seen that this model reasonably fits the experimental data.

III. POWDER MECHANICAL PROPERTIES

A. Introduction

The mechanical properties of calcium-based sorbents which characterize their behavior during handling and transport were investigated in this phase of the project. Problems associated with the process of handling and transport of sorbents can be avoided or at least be predicted if their flow properties are determined. Since these properties are not constant parameters for the sorbents, direct measurements are required to be performed in order to determine the flow properties of sorbents under different handling conditions. To achieve this objective, several sets of experiments have been conducted on different calcium-based sorbents using powder testing equipments (donated by Shell Development Company). Moisture content is one of the most important handling parameter that could strongly impede handling and transport processes of the sorbents. The effect of moisture content on the flow properties were also studied.

B. Experimental

The following Sections contain a summary of the experimental work performed in this phase of the project through the course of the fourth year.

B.1 Tested Sorbents

In the third year of this project, it was concluded that the addition of calcium lignosulfonate, an anionic surfactant, to the water of hydration improves the dispersibility and reactivity of the resulting modified product hydrate. Lignosulfonate is a waste product from the pulp and paper industry. In the Kraft pulping process, wood chips are cooked at elevated temperatures and pressures, using a mixture of sodium hydroxide and sodium sulfide. In this process, phenolic hydroxyl groups and carboxyl groups are inserted into the lignin structure, which is made up of phenylpropane units. Sulfonate groups are introduced into the alpha positions of the phenylpropane units (Sjöström, 1981). The resulting ionic molecule contains many sulfonate groups. Hydrates were made in the laboratory using reagent-grade (high purity) CaO and distilled water. In making the hydrates, a pre-measured amount of CaO powder is

placed in a beaker and excess distilled water in the range 70-80°C is added in one batch. The resulting mixture is found to bubble violently due to the exothermic reaction and is placed on a hot plate to boil off the excess water. After most of the excess water is boiled off, the cake is then dried in a vacuum oven at 50°C for 24 hours. The dried cake is then ground in a mortar and pestle. The calcium lignosulfonate used in these studies is made by Pfaltz & Bauer, Inc. and contains 80% calcium lignosulfonate, 9.2% sugars and 1% insolubles. For the modified hydrates, the necessary mass of calcium lignosulfonate to equal the final product mass percent is dissolved in the water of hydration prior to adding it to the CaO. Four modified hydrates with four mass percentages of lignosulfonate were examined in the tests: BRH (0.0%), LH-109 (0.5%), LH-108 (1.0%), CH-3-L (1.3%). Another type of calcium-based sorbent examined was the Delta calcium carbonate DCC.

B.2 Testing Equipment and Measured Properties

The following powder testing equipment were used for the measurements of sorbents flow properties:

- (1) Ajax cohesion tester for the measurements of the cohesive strength of the sorbents.
- (2) Jenike translatory shear tester for the determination of the angle of internal friction based on measurements of the yield locus of the sorbents.
- (3) Hosokawa powder characterization tester for the measurements of:
 - angles of repose, spatula, fall, and difference,
 - loose and packed bulk densities,
 - compressibility and Hausner ratio,
 - dispersibility and cohesion number,
 - degrees of flowability and floodability.
- (4) Moisture analyzer for the determination of the moisture content in the sorbents.

B.3 Definitions and Testing Procedures

Loose and packed bulk densities: The loose (aerated) bulk density is the bulk density of the powder when it is as loose as it can be. The packed bulk density is the bulk density of the powder when it is packed. The procedure in measuring these densities on the Hosokawa tester

is as follows. A bottomless container is fitted on top of a coarse screen (24 mesh) and mounted on the vibrating unit of the tester. The container is then filled with the powder. When the tester is set to vibrate, the powder flows through the screen and being collected in a cylindrical cup of a standard volume (100 cm³). The amplitude of vibration can be controlled by changing the voltage on the rheostat. As a standard, it is required to set the rheostat so that the flowing powder will heap above the edge of the cup in approximately 20-30 seconds. The powder is then leveled with the rim of the cup by, carefully, scraping the overflowing powder using a scraper. The net weight of the powder in the cup (in grams) divided by 100 is the aerated or loose bulk density of the powder (in gm/cm³). The test must then be continued to measure the packed bulk density of the same powder by placing the previously filled and leveled cup in the automatic tapping device of the tester. An extension cylinder is placed on top of the cup to allow adding more powder during the tapping process if necessary so that the powder will not pack below the rim of the cup. When the tapping device is turned on, it causes the filled cup to fall 180 times through a constant height. Again, after the tapping process is completed, the powder is carefully leveled with the rim of the cup and its net weight divided by 100 is the packed bulk density (in gm/cm³).

Compressibility and Hausner ratio: Compressibility, C , of a powder is defined as

$$C = 100 (P - A) / P \quad (\%) \quad (2.1)$$

where P and A are the packed and aerated bulk densities of the powder, respectively. Compressibility is a very important parameter in characterizing the flow behavior of a powder. As the compressibility of a powder increases, its flowability decreases. Powders with compressibility more than 20% will not be "free-flowing". Powders with compressibility 40 - 50% are very hard to flow and have the tendency to block the flow and form bridges.

Hausner ratio is defined as the ratio between the packed and aerated bulk densities of the powder (i.e. P/A). Studies on the fluidization behavior of fine powders (Geldart *et al.*, 1984; Rastogi *et al.*, 1993) classify powders according to this ratio as follows:

- i) Powders having Hausner ratio < 1.25 are considered as group A powders (i.e. free-

flowing easy-to-fluidize powders).

- ii) Powders having Hausner ratio > 1.4 are considered as group C powders (i.e. cohesive difficult-to-fluidize powders).
- iii) Powders having the ratio in the range 1.25 to 1.4 may have some properties of both groups A and C.

Results of the tests are shown in Fig. 2.1.

Angles of Repose, Fall, Difference, and Spatula: The angle of repose is the angle between the horizontal and the free surface of a powder poured freely on a horizontal surface from a given height. The angle of spatula is a rupture angle that is similar to the angle of internal friction of a powder. As will be shown later, it is very easy to quickly measure the angle of spatula without going through the lengthy shear tests required for determining the angle of internal friction of a powder. Both the angles of repose and spatula provide information about the flowability of the powder. Powders with low angles of repose and spatula are more flowable. Powders with angle of spatula less than 40 degrees are "free-flowing" powders. The angle of fall is the new angle of repose of a pile of powder which has been disturbed by a falling object. The angle of difference is the difference between the angle of repose and the angle of fall. The angles of fall and difference are important parameters in the evaluation of the floodability of a powder. A powder with low angle of fall is more likely to have an unsteady floodable flow. On the other hand, the greater the angle of difference of a powder is, the greater its potential for flooding or fluidization will be.

The standard procedure in measuring these angles on the Hosokawa tester is explained hereby. An arrangement of a bottomless cylinder fitted on a 24 mesh screen and a glass funnel is mounted on the vibrating unit in the tester, as shown in Fig. 2.2. A round platform is placed on a flat pan under this arrangement such that its center is aligned with the centerline of the funnel opening. The cylinder is filled with the powder. When the unit is set to vibrate, the powder flows through the screen openings and piles on the round platform forming a cone shape. The angle of the cone shaped pile is the angle of repose. Then, a shocker (of weight 111 gm and height 7 inches) is placed on the flat pan beside the previously measured pile of powder. The 111 gm weight is repeatedly permitted to fall on the pan from the 7" height for three times. This

shocking action disturbs the stable pile of powder and another angle is now measured, which is the angle of fall. Generally, the angle of fall is smaller than the angle of repose. Then, the angle of difference is calculated by subtracting the angle of fall from the angle of repose.

To measure the angle of spatula for a powder, a 7/8-in. wide spatula is placed in the flat pan and the powder is poured inside the pan so that the spatula is completely covered with several centimeters of the powder. By carefully lifting the spatula out of the pan, a considerable quantity of powder will be left on it. The angle of the powder on the spatula should be measured in different locations along the spatula and then the average is obtained. Then, the weight of the shocker is dropped on the spatula and the angle is measured again. The average of the two angles, before and after dropping the weight, is the angle of spatula for the powder. Results of the tests are shown in Fig. 2.3.

Dispersibility and cohesion number: Dispersibility of a powder is defined as the ratio of the weight of the dispersed portion of a sample of powder to the total weight of the sample when it is allowed to fall freely from a given height. Dispersibility is a measure for the potential of a powder to flood or be fluidized. The higher the dispersibility of a powder is, the more floodable it will be. Cohesion number is defined in this work as a percentage number rather than its conventional definition as the shear strength of a material under zero stresses.

A schematic diagram for dispersibility and cohesion measurements on the Hosokawa tester is shown in Fig. 2.4. To measure the dispersibility, a sample of 10 gm. of the powder is permitted to fall freely through a glass cylinder from a height of 20". The undispersed powder is collected in a watch glass of diameter 4". Dispersibility of the powder is then calculated as

$$\text{Dispersibility} = 10 \cdot (10 - \text{net weight of undispersed powder}) \quad (\%) \quad (2.2)$$

For cohesion number measurement, three mesh screens (# 60, # 100, # 200) are fitted on top of each other and mounted on the vibrating unit in the tester. These screens are chosen based on the average bulk density of the tested powder. A sample of 10 gm of the powder is placed on the #60 mesh screen. The unit is then set to vibrate for a period of time, T , given by

$$T = 20 + [(1.6 - W) / 0.016] \quad (\text{sec.}) \quad (2.3)$$

where T is the vibrating time and W is the working bulk density of the powder ($W = (P-A)C + A$). After the vibration is completed, the net weight of remaining powder on each screen is measured and the cohesion number is calculated as

$$\text{cohesion number} = 10 \cdot (W_{60} + 0.6 W_{100} + 0.2 W_{200}) \quad (\%) \quad (2.4)$$

where W_{60} , W_{100} , and W_{200} are the net weight of the remaining powder on the 60, 100, and 200 mesh screens, respectively. Results of the tests are shown in Fig. 2.5.

Degrees of Flowability and Floodability: The flow properties may be classified into two categories: i) properties which are measures of flowability (angle of repose, angle of spatula, compressibility, and cohesion number) and ii) properties which are measures of floodability (angle of fall, angle of difference, flowability, and dispersibility). According to Carr's evaluation (Carr, 1965), each of these properties is given an index number based on its value. Summation of these indices categorizes the corresponding degree of flowability or floodability of the powder over the range of 0 to 100. For example, a "free-flowing" material will have a flowability index (summation of corresponding flowability properties indices) of 90-100, while a material with "very bad" flowability will have a flowability index of 0-19.

Angle of internal friction and effective angle of internal friction: These angles define the relation between the normal and shear stresses in powders at failure and flowing conditions. The Jenike shear tester is used to determine the combined shear and normal stresses required to cause failure along a plane within the sorbent mass. The relation between normal and shear stresses along the failure plane is given by:

$$\tau = \sigma \tan \phi + c \quad (2.5)$$

where c is the cohesion, ϕ is the angle of internal friction, σ and τ are the normal and shear stresses, respectively. The curve represented by Eq. (2.5) is called the yield locus or the Mohr-Coulomb failure envelop for the material. The principle of operation for the Jenike shear tester is to apply a horizontal force to a prepared sample of the powder while a constant vertical load

is acting. The horizontal force is increased until shear failure of the specimen occurs. Then, the recorded values of the applied vertical and horizontal forces at failure give a point on the yield locus. The standard procedure described by the European Federation of Chemical Engineering (EFCE, 1989) is followed for these tests. The Jenike shearing cell, shown in Fig. 2.6, consists of a base, a ring, and a shearing cover with a bracket. The inner diameter of both the base and the ring is 3.5". The cell is filled with the sorbent and after proper consolidation of the specimen, three levels of vertical loads were applied to the specimen. The filled cell is mounted on the Jenike tester and for each vertical load, an increasing horizontal load is applied to the bracket by a mechanically driven stem which is driven forwards at a steady rate. The stem is attached to a force transducer which records the interacting horizontal force between the stem and the cell. When shear failure is noted on the recorder by a sudden drop in the reading, the maximum horizontal force gives the shear force at failure. This procedure is repeated three times in order to obtain three points on one yield locus. Two more yield loci are obtained by changing the consolidating procedure of the specimen. The slope of the yield locus gives the angle of internal friction, ϕ . The effective angle of internal friction, δ , is obtained by drawing a tangent to the three Mohr circles which touch the end point of each yield locus. The slope of that tangent gives the angle δ . Results of the shear tests are shown in Fig. 2.7.

Cohesive strength: The cohesive strength of a powder is the shearing stress in the powder when it is sheared under zero normal stresses. The capacity of powders to gain internal strength allows them to develop stable arches and resist gravity flow in the transport lines and handling facilities. The Ajax cohesion tester is used for the cohesive strength measurements 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. The test is repeated several times under different compacting loads. Results are shown in Figs. 2.8 - 2.12.

B.4 Effect of Moisture

Tests were conducted on the Hosokawa tester to study the effect of moisture content on the flow properties of the sorbents. Moisture content is defined as the weight ratio of the water contained by a sample of the powder to the original weight of the sample. Ambient humidity during storage and transport affects the moisture content of sorbents (Jozewicz and Gullett, 1991). Changes in the moisture content of powders affect most of their mechanical properties. In this work, the effect of moisture on the flow properties of sorbents was examined within the range of 0% to 6% moisture content. 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 tests are shown in Figs. 2.13 - 2.19.

C. Results and Discussion

Evaluation of the measured properties can be summarized, based on the results shown in Fig. 2.1 - 2.19, in the following concluding remarks:

- 1) All powders tested are of group C powders (Hausner ratio > 1.4) and are very compressible (47.5 - 52.7%). Accordingly, flow blocking must be highly expected. However, increasing the percentage of lignosulfonate slightly decreases the compressibility and Hausner ratio for the modified hydrates.
- 2) All sorbents have high angles of internal friction and gain more cohesive strength when compacted. . Accordingly, dense phase transport is not recommended.
- 3) The bulk density of the carbonate, DCC, is much higher than that of the hydrates (more than the double) which suggests that higher gas or air velocity is required for transportation of the DCC.

- 4) All tested powders have low angle of fall and high angle of difference. Hence, it is expected for these powders to have unstable and floodable flow. Also, increasing the percentage of lignosulfonate in the modified hydrates, increases the potential for flooding behavior, since the angle of fall for the modified hydrates decreases with increasing the lignosulfonate percentage. Also, the angle of difference increases with increasing the lignosulfonate percentage in the modified hydrate. This indicates that increasing the lignosulfonate percentage in the modified hydrate increases its tendency to be fluidized, yet uncontrolled flooding flow must be expected in this case.
- 5) The modified lignosulfonated hydrates are less cohesive than the BRH and the DCC.
- 6) The carbonate, DCC, has a very low dispersibility compared to the hydrate and modified hydrates. As was concluded in last year's work in project 1.2 on modified hydrates, increasing the lignosulfonate percentage improves the dispersibility of the modified hydrates.
- 7) For the modified lignosulfonated hydrates, sorbents with higher lignosulfonate percentage have lower angles of friction. This agrees with the conclusion that increasing the lignosulfonate percentage enhances the flow properties of the modified hydrates.
- 8) The cohesion number measurements are strongly affected by factors such as electrostatic attraction of particles, tendency to form balls on vibration, and coherence of smaller particles to larger particles. To overcome the effect of these factors on the measurements, each test has been repeated six to ten times and the results are averaged excluding odd ones.
- 9) Both of the angle of repose and the angle of spatula are considerably high for all tested powders. Accordingly, poor flowability is expected for these powders. Moreover, all the tested powders have "bad" degree of flowability (flowability index of 20-39). Also, all the tested powders have "fairly high" degree of floodability (floodability index of 60-79), except for the CH-3-L which has a "very high" degree of floodability (floodability index of 80-100).
- 10) Presence of moisture in the tested sorbents changes their flow properties. Cohesion and dispersibility were among the properties that have been greatly affected by moisture. This is because of the water bonds which increases the amount of cohesive forces in the

sorbent and causes the particles to agglomerate.

- 11) The degrees of flowability and floodability of sorbents decrease with the increase in moisture content. All tested sorbents have "bad" flowability based on the corresponding value of flowability index. Also, their tendency to flush is considered to be "fairly high" based on the corresponding value of floodability index.

IV. CONCLUDING REMARKS

The purpose of this study is to explain, using fundamental theories of interparticle forces, the difference in transport and dispersion between various sorbents. This project is closely tied with 1.1 through the focus of maximum utilization of sorbent materials used in the LIMB process. Interparticle forces lead to agglomeration or removal to transport tube walls of the sorbent fine particles, reducing sulfur removal capabilities.

The electrostatic properties of sorbent powders have been studied as a function of sorbent material, transport condition and transport tube material. The results suggest that the charge polarity is strongly dependent on the chemical structure of the sorbent materials. High gas flow rates and low humidities can result in more charge build-up on powder. The descending order of charging tendency of transport tube materials is brass, copper and carbon steel. Theoretical estimation of attraction forces shows that the electrostatic force dominates over a large range.

Mechanical testing equipments have been used to measure and analyze the flow properties of calcium carbonate, hydrate, and lignosulfonated hydrates under different handling and transport conditions. The tests performed showed that calcium carbonate has low flowability and dispersibility compared to the hydrates. Results proved also that increasing the lignosulfonate percentage improves the flow properties of the modified hydrates. Presence of moisture was shown to affect badly the flowability of the tested sorbents because of bonding between adjacent water layers which increases the cohesive strength of the sorbents.

A population balance model has been developed for the optimum nozzle design (an expansion nozzle with two-jet booster jets) conducted in the previous three years. The flow field inside the nozzle is simulated by a standard turbulent $k-\epsilon$ model and the dynamics of agglomerates size distribution variation are also considered. The performance of the nozzle can be quantified by this model. Simulation results show that this model reasonably fit experimental results.

V. REFERENCES

- Akande, A. R. and Lowell, J., "Contact electrofication of polymers by metals," *Journal of Electrostatics*, **16**, 147-156 (1985).
- Bailey, A. G. "Electrostatic phenomena during powder handling", *Powder Technology*, **37**, 71 (1984).
- Carr, R.L., "Evaluating low Properties of Solids," *Chemical Engineering*, January 18 163-168 (1965).
- Coste, J., and Pechery, P., 3rd Int. Cong. on *Static Electricity*, 4a-4f, Grenoble,(1997).
- Coulaloglou, C. A., and L. L. Tavlarides, "Description of Interaction Processes in Agitated Liquid-Liquid Dispersions," *Chem. Eng. Sci.*, **32**, 1289 (1977).
- Cross, J. A., *Electrostatics - principles, problems and applications*, Adam Hilger, Bristol, England (1987).
- Cunningham, r. G. and Hood, H. P., "The relation between contact charging and surface optential difference," *J. Colloid and Interface Sci.*, **32**, 444-448 (1970).
- EFCE, *Standard Shear Testing Technique for Particulate Solids Using the Jenike Shear Cell*, the Institution of Chemical Engineers, England (1989).
- Geldart, D., Harnby, N., and Wong, A.C., "Fluidization of Cohesive Powders," *Powder Technology*, **37**, 25-37 (1984).
- Harper, W.R., *Contact and Frictional Electrification*, Oxford (1967).
- Hinze, J. O., "Fundamentals of the Hydrodynamic Mechanism of Splitting in Dispersion Processes," *AIChE J.*, **1**, 289 (1955).
- Jozewicz, W., and Gullett, B.K., "The Effect of Storage Conditions on Handling and SO₂ Reactivity of Ca(OH)₂-Based Sorbents," *ZKG International*, **5**, 242 (1991).
- Kousaka, Y., Okuyama, K., Shimzu A., and Yoshida, T., "Dispersion Mechanism of Aggregate Particles in Air," *Journal of Chemical Engineering of Japan*, **12**, 2, 152 (1979).
- Krupp, H., "Particle adhesion theorey and experiments," *Adv. Colloid Interf. Sci.*, **1**, 111 (1967).

Table 1.1 The expressions of symbols used in the generalized equation.

equation	ϕ	Γ_ϕ	S_ϕ	S_p
continuity	1	0	0	0
momentum in x-direction	u	μ_e	$-\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}(\mu_e \frac{\partial u}{\partial x}) + \frac{1}{r} \frac{\partial}{\partial r}(r \mu_e \frac{\partial v}{\partial x}) + \frac{1}{r} \frac{\partial}{\partial \theta}(\mu_e \frac{\partial w}{\partial x})$	0
momentum in r-direction	v	μ_e	$-\frac{\partial p}{\partial r} + \frac{\partial}{\partial x}(\mu_e \frac{\partial u}{\partial r}) + \frac{1}{r} \frac{\partial}{\partial r}(r \mu_e \frac{\partial v}{\partial r}) + \rho \frac{w^2}{r} + \frac{1}{r} \frac{\partial}{\partial \theta} \left[r \mu_e \frac{\partial}{\partial r} \left(\frac{w}{r} \right) \right] - 2 \frac{\mu_e}{r^2} \frac{\partial w}{\partial \theta}$	$-2\mu_e/r^2$
momentum in θ -direction	w	μ_e	$-\frac{1}{r} \frac{\partial p}{\partial \theta} + \frac{\partial}{\partial x}(\mu_e \frac{\partial u}{\partial \theta}) + \frac{1}{r} \frac{\partial}{\partial r} \left[\mu_e r \left(\frac{1}{r} \frac{\partial v}{\partial \theta} - \frac{w}{r} \right) \right] - \rho \frac{w^2}{r} + \frac{1}{r} \frac{\partial}{\partial \theta} \left[\mu_e \left(\frac{\partial w}{\partial r} + 2v \right) \right] + \frac{\mu_e}{r} \frac{\partial w}{\partial r} + \frac{1}{r} \frac{\partial v}{\partial \theta}$	$-2\mu_e/r^2$
turbulent kinetic energy	k	μ_t/σ_k	G_k	$-\rho\epsilon/k$
dissipation rate of turbulent kinetic energy	ϵ	μ_t/σ_ϵ	$C_1 G_k \epsilon/k$	$-C_2 \rho \epsilon/k$

where $\mu_e = \mu + \mu_t$, $\mu_t = C_\mu \rho k^2/\epsilon$, $\Gamma_k = \mu_t/\sigma_k$ and $\Gamma_\epsilon = \mu_t/\sigma_\epsilon$.

$$G_k = \mu_t \left[2 \left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial r} \right)^2 + \left(\frac{1}{r} \frac{\partial w}{\partial \theta} + \frac{v}{r} \right)^2 + \left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial w}{\partial x} + \frac{1}{r} \frac{\partial u}{\partial \theta} \right)^2 + \left(\frac{1}{r} \frac{\partial v}{\partial \theta} + \frac{\partial w}{\partial r} - \frac{w}{r} \right)^2 \right]$$

Fig. 1.1 Theoretical attraction forces of various mechanisms for the sphere/plate system (from Schubert, 1981)

Fig. 1.2 Theoretical attraction forces between a $10 \mu\text{m}$ sphere and a plane surface as a function of separation distance (from Schubert, 1981).

Fig. 1.3 Schematic of the experimental set-up

Fig. 1.4 Configuration of bubble column

Fig. 1.5 Specific surplus charge of Calcite as a function of time, with transport tube

Fig. 1.6 Variation of specific surplus charge with mass flow rate for black river hydrate

Fig. 1.7 Variation of surplus charge with powder mass flow rate for balck river hydrate

Fig. 1.8 Variation of specific surplus charge with mass flow rate for Calcite

Fig. 1.9 Specific surplus charge of Lignosulfonated hydrate as a function of mass flow rate

Fig. 1.10 Relationship between specific surplus charge and powder mass flow rate

Fig. 1.11 Effect of relative humidity on the charge accumulation on balck river hydrate

Fig. 1.12 Variation of specific surplus charge with mass flow rate for black rive hydrate at three different gas flow rates

Fig. 1.13 Charging tendency of $\text{Ca}(\text{OH})_2$ for three different transport tubes

Fi.g 1.14 Effect of grounding on the charge pick-up ability of Ca(OH)_2 passing through a brass tube

Fig. 15 Comparison of theoretical values of the van der Waals and the electrostatic forces

Figure 1.16 Influence factors of agglomerates size distribution.

Figure 1.17 Axial variation of cross-sectionally averaged turbulent energy dissipation rate.

Figure 1.18 Dynamics of agglomerate size variation.

Figure 1.19 Comparison between the experimental data and simulation results.

Sorbent		Bulk Density (gm/cm ³)			Compressibility (%)	Hausner Ratio
		Aerated	Packed	Working		
Black river hydrate BRH		0.282	0.555	0.417	49.2	1.97
Modified black river hydrate	LH-109 0.5 %	0.334	0.703	0.527	52.7	2.10
	LH-108 1.0 %	0.317	0.627	0.470	49.5	1.98
	CH-3-L 1.3 %	0.321	0.611	0.459	47.5	1.90
Delta calcium carbonate DCC		0.756	1.523	1.142	50.3	2.00

Figure 2.1 Bulk densities, Hausner ratio and compressibility.

Figure 2.2 Measurement of the angles of repose and fall on the HOSOKAWA Tester

Sorbent		Angle of Repose (degree)	Angle of Spatula (degree)	Angle of Fall (degree)	Angle of Difference (degree)
Black river hydrate BRH		50	65	25	25
Modified black river hydrate	LH-109 (0.5%)	53	73	29	24
	LH-108 (1.0%)	54	72	22	32
	CH-3-L (1.3%)	55	72	21	34
Delta calcium carbonate DCC		54	75	23	31

Figure 2.3 Angles of repose, fall, spatula, and difference.

Figure 2.4 Dispersibility and cohesion number measurements.

Sorbent		Dispersibility (%)	Cohesion (%)
Black river hydrate BRH		35	45
Modified black river hydrate	LH-109 (0.5%)	33.3	44
	LH-108 (1.0%)	37.8	25
	CH-3-L (1.3%)	42.6	19
Delta calcium carbonate DCC		19.5	40

Figure 2.5 Dispersibility and cohesion number.

Figure 2.6 Jenike shearing cell

Sorbent		Angle of Internal Friction, ϕ (degree)	Effective Angle of Internal Friction, δ (degree)
Black river hydrate BRH		33	37
Modified black river hydrate	LH-109 (0.5%)	36	43
	LH-108 (1.0%)	35	41
	CH-3-L (1.3%)	34	40
Delta calcium carbonate DCC		33	38

Figure 2.7 Properties Obtained from Jenike shear tests

Figure 2.8 Cohesive strength of Delta Calcium Carbonate DCC.

Figure 2.9 Cohesive strength of Black River hydrate BRH (0.0% lignosulfonate).

Figure 2.10 Cohesive strength of modified lignosulfonated hydrate LH-109 (0.5% lignosulfonate).

Figure 2.11 Cohesive strength of modified lignosulfonated hydrate LH-108 (1.0% lignosulfonate).

Figure 2.12 Cohesive strength of modified lignosulfonated hydrate CH-3-L (1.3% lignosulfonate).

Figure 2-13 Moisture content vs. angle of repose

Figure 2-14 Moisture content vs. compressibility

Figure 2-15 Moisture content vs. Hausner ratio

Figure 2-16 Moisture content vs. cohesion number

Figure 2-17 Moisture content vs. dispersibility

Figure 2-18 Moisture content vs. flowability index

Figure 2-19 Moisture content vs. floodability index