Dispersion of Solids Using Spinning Wheel Feeders

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Abstract

A particle feeder system is used to feed particles to a fluidized bed reactor. Interparticle Vander Waal forces cause the particles to conglomerate into a larger particle size than desired. A spinning wheel was added to the feeder system to shear the particles into smaller sizes. This study proves that the system works. It has also produced a successful basic model of the system. The experimental particle sizes compared well with the model particle sizes after the shear had been applied.

Introduction

A powder feeding system is used to feed fine particles to a transport tube reactor. This is a critical step since the reactor only provides for a few seconds residence time to react the powder. If inert gas velocity is used to shear a powder as it exits a feed tube, it will limit the throughput of the reactor by reducing the available residence time. Hence, methods to shear the powder mechanically, in order to prevent reduced process throughput, are desired. The objective is to feed a powder at its primary particle size rather than some aggregate size generated by an upstream screw or vibratory feeding device and to achieve such dispersion using minimized gas flow.

Interparticle Van der Waals forces cause the primary particles to agglomerate into larger particle sizes than desired. The particle feeder system is designed to shear the agglomerates back to the primary particle size as the powder enters the transport tube reactor. Powder is fed using a vibrating tube to where it drops onto a high speed rotating wheel. The rotating wheel accelerates the particles until the cohesion forces are overcome and the agglomerates are sheared. When the particles are on the spinning wheel, shear forces cause the interparticle forces to be broken, thus providing for smaller agglomerate sizes that approach the size of the primary particles for the system. The mechanically sheared powder is then swept with sweep gas into a lance that feeds the reactor system. Experimental results are presented for feeding Zinc Oxide (ZnO), Alumina (Al_2O_3), and Manganese Oxide (Mn2O3) into a flow tube. A pulsed laser imaging system is used to characterize the powder flow stream.

A basic model for the system was formulated. Simple force balances have been developed to describe the process. Vander Waals forces were calculated by using Hamaker theory with sphere-sphere being used as the geometry in the system. In addition, experimental particle sizes compare well with the model particle sizes after shear is applied.

Description of the system

A diagram of the feeder system may be seen in figure 1 below.

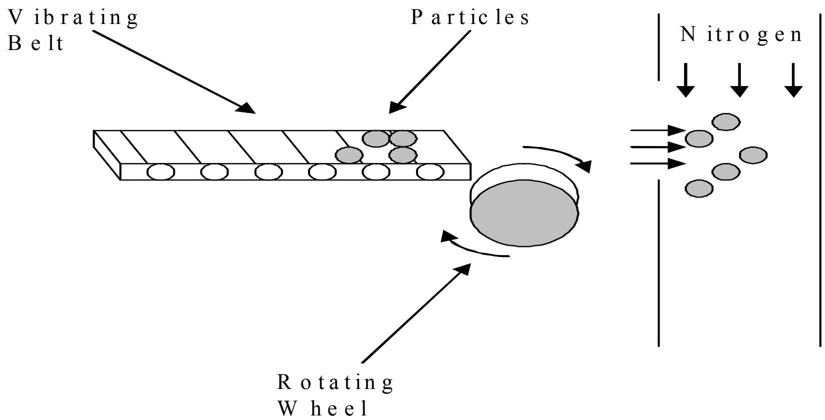

Figure 1: Diagram of the feeder system

The way the system works follows a basic pattern. Particles of are fed onto a vibrating bed where they are dropped on a rotating wheel. The rotating wheel accelerates the particles until the cohesion force with the wheel is overcome and thus the particles are thrown into the feeder shaft. When the particles are on the spinning wheel, shear forces cause the interparticle forces to be broken, thus creating smaller particles for the system. In the feeder shaft the particles are met by nitrogen gas, which assists the particles to flow into the reactor.

Literature review

A thorough search through the literature has revealed a belief that there are few, if any, systems published that are similar to the one that we invented. Some of the systems found use a spinning wheel to grind particles, opposed to shearing them like our system does [3-5]. An example of this use of wheels for grinding is the paper by Nikolov [4]. The theory by Nikolov is long, complicated, and would be very difficult to apply to our system. Nikolov uses statistical theory and advanced distribution functions to describe his system. In addition, this type of system would be unsuitable for our purposes, because we do not need a tensile load to break our particles; so it is believed that this would demand more energy than the system needs. The theories from Kapur et al [3] describe the impact grinding of a single particle. Problems arise in using this type of theory with our in model, in that the breakage function is based on impact energy as opposed to shear. The paper does use t-tests in determining particle size distributions after an impact. T-tests are something that we may consider adding to our model in the future, for an alternate means of determining size distributions. Finally, Potapov et al. [5] examined the particle distribution from dropping a ball onto a particle bed. Again, this is not the type of system we have, because we do not have an impact force like the system from Potapov has.

Continuing, there are other systems that use particles inside the rotating drums to shear the mixture [1,2,6]. This type of system is also unsuitable for our purposes in that it does not provide a reliable means to feed the particles into the system. Santomaso et al. [6] studied how the different rates of rotation in the drum affected the granular behavior. It is useful, because the effect of the rotation of the wheel on the particle sizes may be studied; however it is not useful in that the particles are in the drum as opposed to be on top of the drum. The system described by Ceylan et al [1] examines the size distribution inside of the rotating drum. When studying the size distribution different parameters are varied, like different feed sizes of particles and different entrance lengths into the drum. As may be inferred, this type of system and parameter variation does not apply to our system. Finally, Gray [2] looks at mixing of granular flows inside the drum. Again, this is system is close to ours, in that it models particle flow and the interactions the particles have with one another; however it is deficient in terms of comparison to ours in that the model does not look at shear the particles may undergo. The literature has shown that we have a novel system that may be one of the first of its kind.

Describing interparticle forces, the literature provides some fine examples. Seville et al. [7] provides a comprehensive chapter on interparticle forces. The chapter gets very detailed about Hamaker theory and Lifshitz theory and the difference between the two. The chapter provides equations for the Vander Waal forces for different types of geometries and looks at other types of effects that may create interparticle forces. Some the geometries include: two spheres interacting with one another, two cylinders, or two flat plates. The article by Visser [9] also provides further insights into interparticle forces. The review by Seville et al gets more into all of the types of interparticle forces occurring during fluidization and the review by Visser examines more of the Vander Waal force interaction between particles. The reviews by Seville and Visser provide a good outline on interparticle forces, but the Seville book provides the most useful information for the model we are creating.

Materials and Methods

Theory

Three forces act on the particles in the system and include a shear force from the wheel, a shear force from the nitrogen gas, and Vander Waal forces between the particles. In the case of this initial developing model, only the shear forces from the wheel and the Vander Waal forces will be considered.

Basic Hamaker theory will be used in developing the Vander Waal interaction forces between the particles. Hamaker theory describes the interactions between a particle and all of the other particles in a body as being additive and non-interacting. From this the net force or interaction energy may be found by integrating over the entire body of particles [7]. The Lifshitz theory improves on the Hamaker theory by relaxing the “pairwise interactions” assumption. This is done by ignoring the atomic structures of the bodies and treating them as continuous. The Lifshitz theory almost mimics a momentum balance where the dipole effect from one particle not only acts on one other particle, but all other particles and they in turn act on the original particle. These interactions are classified into a constant known as the Hamaker constant [7]. In the case of this paper, a combination of the Lifshitz and Hamaker theories will be used in the Vander Waal force equation.

There are different geometries that may be selected when choosing the type of Vander Waal force equation to use. Some examples of these include two spheres, two cylinders, or two flat plates. I have made the assumption that all of the particles are aligned in perfect sheets and are close enough together to use an equation for two spheres. A schematic of the alignment of the particles may be seen in figure 2.

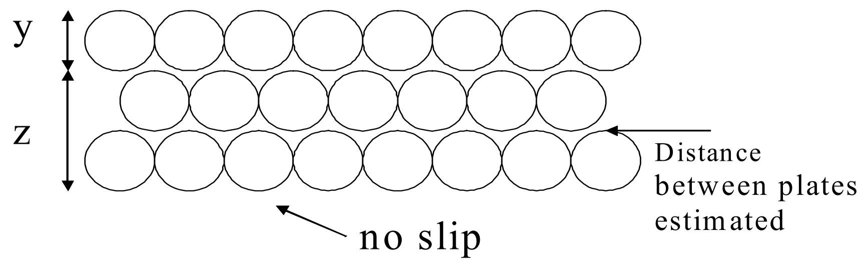

Figure 2: Schematic of the particle sheets; y and z are values that Matlab uses to calculate shear forces

Continuing with the development of the equation to describe the Vander Waal forces, it is assumed that there is no liquid bridging between the particles. This assumption is taken, because all data is taken in the dry climate of Colorado. Because the electrostatic force is what causes the particles to attract, equation 1 below describes this type of force between two particle spheres [7].

$$F = \frac{AR}{12D^2} \tag{1}$$

In equation 1, D is the distance between the two plates of particles in m, A is the Hamaker constant in J, and R is the radius of a sphere in m. To estimate the value for the Hamaker constant, it is assumed that there are no retardation effects in the interparticle force. If the no retardation assumption is relaxed, A will no longer be a constant. Calculated data from Israelachvili et al. [10] shows that the Hamaker constant with a metal oxide interacting with another metal oxide should be between 14 – 43 $*10^{-10}$ J. A least squares code was used to find the best fit Hamaker constant with a value from the Israelachvili range taken as the initial guess.

The theory of developing the basic equations for the shear force from the wheel is simple. First a force balance was performed on the model, as may be seen in figure 3 below.

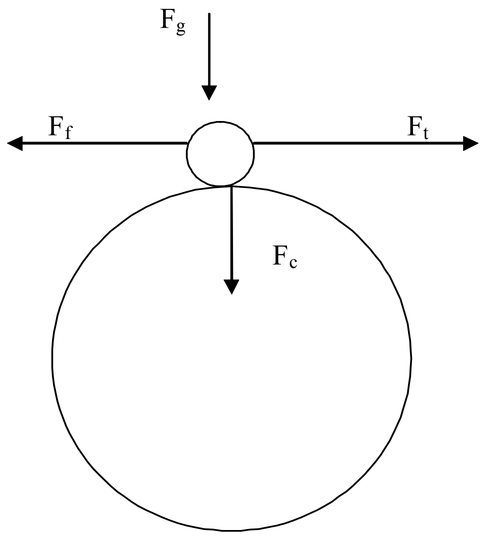

Figure 3: Schematic of the force balance; F_g is the gravitational force, F_f is the friction force, F_c is the centrifugal force, and F_t is the tangential force

As may be seen from figure 3, there are four different forces that have been identified as being important to the system, they are: F_g, the gravitational force; F_f, the friction force; F_c, the centrifugal force; and F_t, the tangential force. When applying a scaling analysis to determine the important forces in the diagram, the assumption that the particle is instantly accelerated to the velocity of the wheel is made. By making this assumption, the tangential acceleration may be ignored. Comparing the final three forces with a scaling analysis shows that the only significant force acting on the particle when on the wheel is the centrifugal force.

The centrifugal force may be broken up into two separate components. A diagram of the centrifugal acceleration from the wheel may be seen in figure 4.

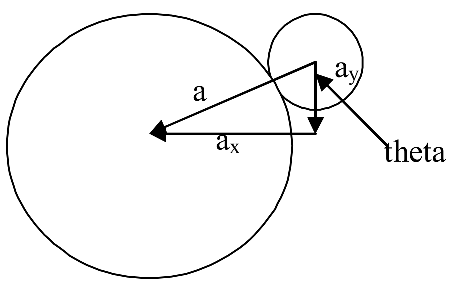

Figure 4: Schematic of the centrifugal acceleration components

Equations for the centrifugal acceleration components are derived from figure 4 in equations 2 and 3.

$$a_y = \omega^2 r\cos\theta \qquad (2)$$

$$a_x = \omega^2 r\sin\theta \qquad (3)$$

In equations 2 and 3, a_y and a_x are the centrifugal acceleration components in the y and x directions respectively in m/s^2, ω is the angular velocity of the wheel in rad/s, r is the radius of the wheel in m, and θ is the angle of the particle in radians, with the origin being defined as the top of the wheel. From the equations, it should be noted that only the radius of the wheel is being considered, because the radius of the wheel is much larger than the radii of the particles.

As may be seen in Figure 2, there is a no slip assumption being made on the wheel. Because of this assumption the y component of the centrifugal acceleration is only important in determining when the particle will fall off the wheel; however, the y component of the centrifugal acceleration decreases as theta increases, so it actually becomes irrelevant. Because of this the gravitational force will cause the particle to fall off at approximately π/2 radians. It may seem logically unreasonable to assume the particle will fall off at π/2 radians, but in favor of simplicity in the model, this assumption will not be relaxed.

The force in the x direction will be the major shear force that will counter the Vander Waal force and cause the particles to break apart. This is due in part to the assumption of the arrangements of the particles. The assumed arrangement of the particles may be seen in figure 2. The model will also calculate the amount of sheer in the y direction and compare it with the amount of sheer in the x-direction.

Matlab

Matlab was the computational program used to calculate the forces between the particles and forces due to the shear on the wheel. It would then calculate the size of the new particles and add them to a data file in order to create the particle distribution chart. The model is composed of two functions. One function calculates the forces, new particle size, and creates the histogram. The other function is simply a counter that arranges new particle sizes in the correct "bin" of particle sizes. There are a set of bins in which the particle sizes are arranged and in total there are ninety-seven bins. For example, bin 1 will contain all particles of size 10 μm and smaller; and the rest of the bins are increased at 10 μm increments.

The particle counter is an m file of if/else statements. A new particle size will be received from the shear function and a series of if/else statements finds which bin that the particle belongs in. There are no particles in the data set, which are being used in the Matlab code, that are larger than 960 microns. With bin sizes up to 960 microns there will always be a bin in which to place the new particle size.

The shear calculator is a more complicated code, than the particle counting function. It contains multiple while loops and if/else statements. A while loop causes Matlab to calculate the shear force in every bin. For example, it will first look at the data from bin 1 and then bin 2 and so on. Inside the first while loop there is an if/else statement which calculates whether or not there are any particles in the bin. If there are no particles in the bin, then the code will continue on to the next bin; however, if there are particles in the bin, the code will continue to the next while loop.

There is a while loop that will calculated the average amount of rows that a particle conglomerate will have. An average particle size is assumed to be 10 μm. This means an average conglomerate of size 40 μm will have 4 rows. As may be seen in figure 2, the function will calculate the mass of two rows when determining the shear force. Rows designated as y are the rows that will potentially come off the original particle and form a new particle. All other rows are designated as z and are considered to be part of the no slip condition. The shear force will is calculated in equation 4, as being the difference in the force from y rows and the force from z rows.

$$F = (M1 - M2) * a_x \tag{4}$$

Where in equation 4 M1 is the mass of z rows, M2 is the mass of y rows, and $a_x$is the centrifugal acceleration in the x direction. A similar balance is done in the y direction as well.

The final if/else statement compares the force calculated from equation 4, with the force from equation 1. If the force from equation 4 is greater than the force from equation 1, then a particle of size y is created, this particle is then sent to the particle counting equation described earlier and y begins again at a 1 row length. However, if the shear force is not larger than the interparticle force, then another row is added to the y row and a row is subtracted from the z row. This if/else statement is contained in the second while loop. A calculation is also done in the y direction. The program looks at which shear force is greater to determine where the “shear” on the particle will happen. All of these calculations will continue for every bin until a while loop has counted to π/2 radians, where a particle of size z plus y falls off the wheel due to gravity. The particle that falls off at π/2 radians is subsequently sent to particle counter function and added to the correct particle bin.

The shear function in Matlab finishes by summing the total number of particles in the system, after the shear force has been applied to each bin. After the total number of particles in the system has been calculated, every bin is divided by this sum; this creates a particle distribution of the data. The predicted data is saved to a data file and exported to excel where it is plotted.

Experimental Data

Data has been taking from three distinct spots from the system. The first is when the particles fall off the vibrating bed, the second is when the particles leave the wheel, and the last is when the particles leave the lance. When the data was taken from the first two locations, there was no gas flowing through the system. This was done to study the effect that the shear of the wheel had alone on the agglomerated particles. There is limited data thus far and it will be briefly presented.

Results and Discussion

Shown below in figure 5 is a series of pictures showing a particle falling onto the wheel and sheering.

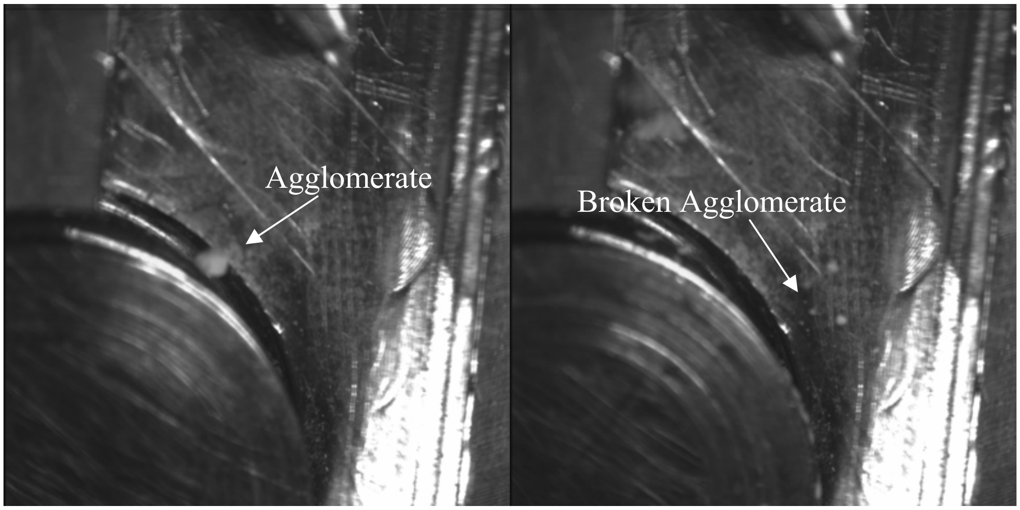

Figure 5: Agglomerate Broken on Spinning Wheel

As may be seen from the figure 5 the agglomerated particles are sheered on the spinning wheel. To further the proof of this the number distribution of the agglomerates falling off of the vibrating feeder are compared to those of the particles that are sheered on the spinning wheel. The comparison may be seen below in figure 6.

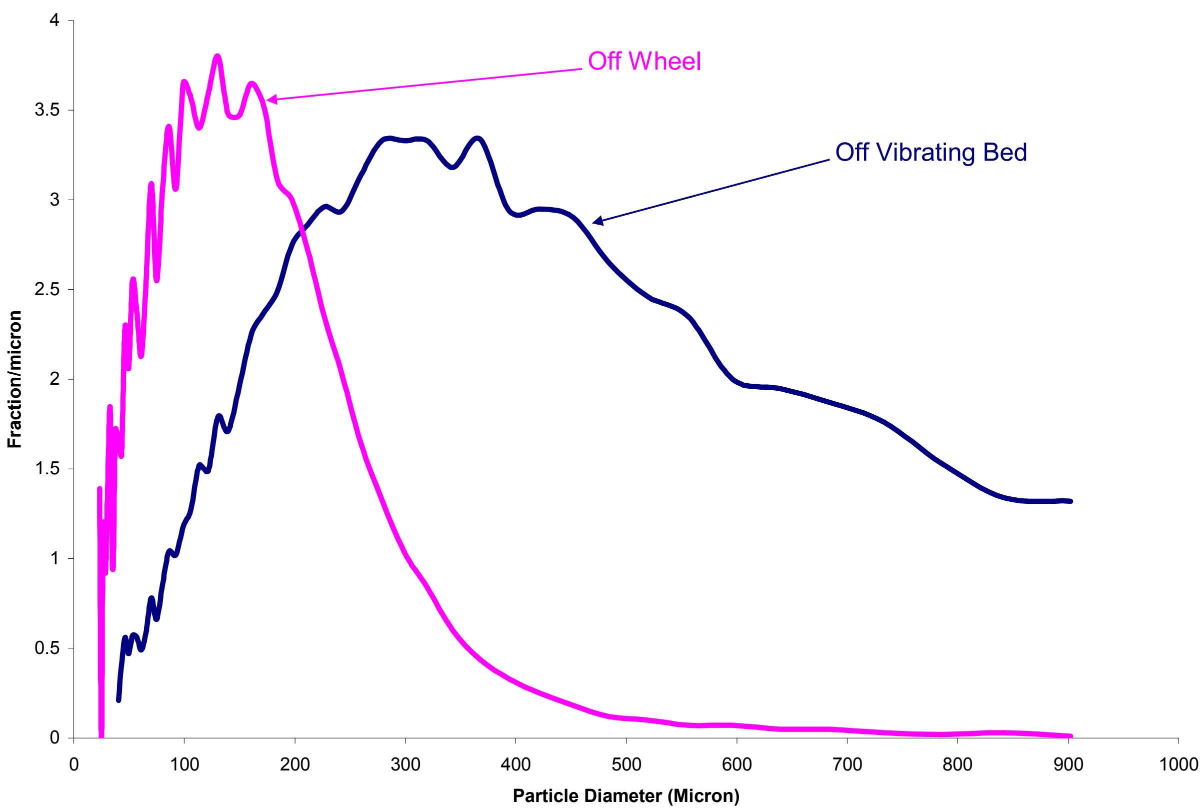

Figure 6: Particle Distribution Comparing Wheel Shear and No Shear

As may be seen from figure 6 when shear from the wheel is applied to the particles the curve shifts to the right, indicating that the particle diameters are now smaller. From the curve it may also be seen that the distribution for the particles falling off of the vibrating bed abruptly stops at about 960 microns. It is believed that this happens due to limitations in the equipment. From figure 5 and figure 6 it may be seen that the spinning wheel does sheer the particles down to a smaller diameter. Experiments will continue, eventually adding a gas flow rate in hopes of decreasing the average particle size.

The model that has been created will be applied to some of the data that has been collected. Results for the model applied to manganese oxide data may be seen below in figure 7.

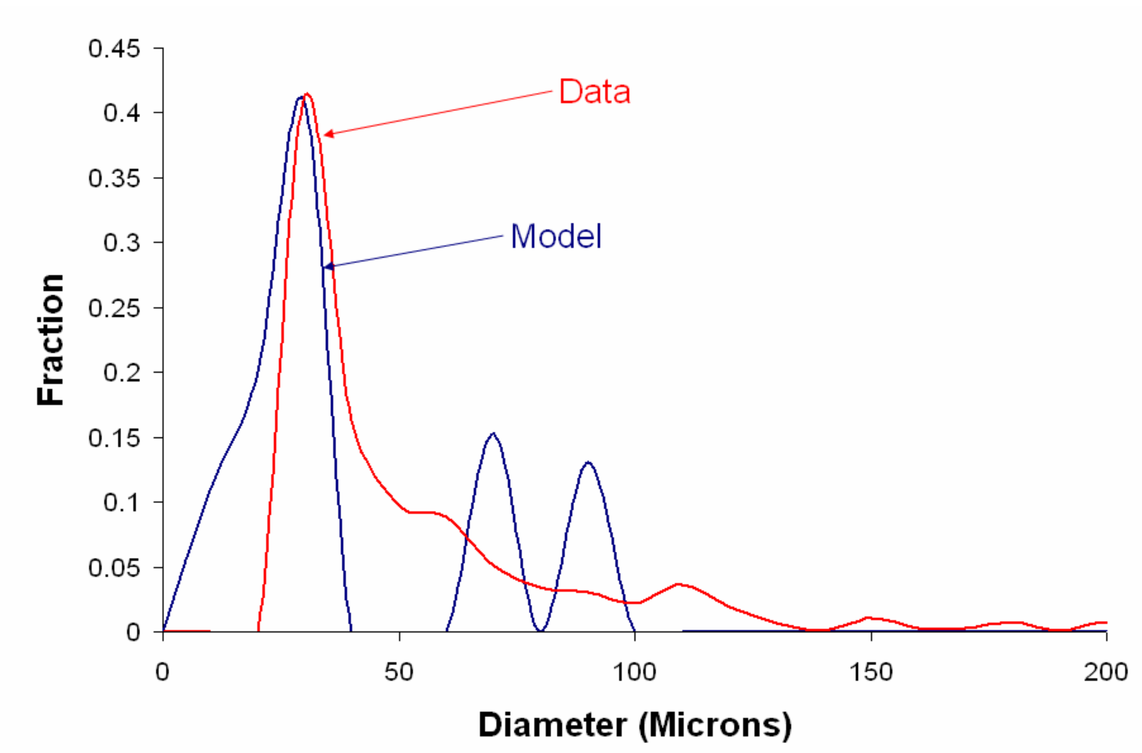

Figure7: Model vs. Experimental Data

As may be seen in figure 7 the model agrees well with experimental data. There is some static in the end of the model prediction, but it is expected that this static will go away as the model grows in complexity. The Hamaker coefficient and the distance between the plates were not known, so it they were determined by a best fit algorithm. The predicted values were then compared with values for metal oxides taken from Israelachvili [10]. The comparisons may be seen in table 1.

Table 1: Comparing predicted coefficients

	Separation Distance	Oxide Hamaker Constant	Metal Hamaker Constant
Model	3.6 nm	16 E-20 J	40 E-20 J
Experimental	0.2 - 1 nm	14E-20 - 43E-20 J	30E-20 - 50E-20 J

From table 1 it may be seen that the model is predicting Hamaker values that are in line with other metal oxide constants. The predicted separation distance is predicting a separation distance that may be a little high. Once again this is believed to come from some of the model assumptions and should go away when more complexity is added into the model.

Conclusion

Through pictures, particle distributions, and modeling we have shown that are powder feeder works. Though the study is not yet completed there is ample evidence that our novel feeding system works. Data has still yet to be taken for gas flows through the feeder, but preliminary experiments have shown that this will only improve the results by reducing the average particle diameter further. In addition the model has been found to agree with the data well. There are still some assumptions that need to be relaxed, but as the assumptions are relaxed the model is expected to become more reliable.

References

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