Transformative Research in Pneumatic Conveying

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Abstract

This paper address the need to be more risky and exploratory in our research endeavors when studying pneumatic conveying. The term transformative research is the strategy that has been adopted by many of the funding agencies. Significant resources have been spent to provide new research but mostly for projects that provide incremental advancement in our knowledge. This analysis reviews what knowledge that can be considered as transformative advances in the field of pneumatic conveying over the past sixty + years and projects what avenues and areas we can explore to make great future advancements.

1. Transformative Research

In order to advance and improve the operations of any solids processing plant or a particular piece of solid handling equipment knowing the basic factors and physics that contribute to the unit's operation is required. The more involved the process and the equipment the less one seems to know how the unit will operate when material types and sizes vary. As always, knowing the operating characteristics and performance of the materials before the operation is implemented and constructed is most desirable and essential. What is needed to make a significant impact on process and product improvement is to employ research that yields transformative results. Knowing the basics is one step towards this objective. Transformative results are results that give breakthroughs in the field that affect the entire system not just providing small incremental changes. This may sound like a very high risk endeavor and the results may lead to difficulty in obtaining adoption in normal plant operations. The research community is being encouraged to take this risk with transformative research and make the leap. It is understood that not all such transformative research explorations will be successful and there will be failures along the way.

In the U.S. Federal government and other funding agencies transformative research is now being stressed. Incremental research that yields small advances has been assailed by the funding community as not being acceptable. This is probably driven by reviewing the large amount of resources that have been expended to make small advances in science and engineering and the desire to drive the agenda faster and more effectively. The research community has learned how to write proposals that are fundable by suggesting small changes but which are not generally transformative in nature. The researchers please the reviewers by not being too innovative and not too exploratory. It has been a real danger to be transformative in a proposal because reviewers will not write favorable reviews saying that these ideas of too high risk. The Science Board Chair of the National Science Foundation, Steve Bering, who is the former President of Purdue University has been driving the National Science Foundation agenda with the transformative message. The National Institutes of Health are also giving the same message to the research community on the kind of transformative research they want and will fund.

What is proposed here is to review developments in the area of pneumatic conveying and assess that may be considered as transformative research that has taken place in the past to help advance new research in the field. The assessment of these advancements is one in which the author takes full responsibility for choosing the transformative topics and wishes to apologize if other developments which the reader may think as transformative are not considered. It is hoped by reviewing the past we can project into the future with an agenda that will permit us to employ transformative research in an effective manner.

2. Transformative Research Concepts from the Past

- Zenz Diagram – One of the very first people to represent the whole of the pneumatic conveying scope was suggested by Zenz (1962) in his proposing the state diagrams that now often bear his name. The pressure loss per unit length is found to vary with the transport gas velocity at constant solids flow rates. Figure 1 is very informative in providing an understanding of the operational limits of pneumatic conveying. These plots give the designer some insight on where to operate in order not to have an unsteady operation or to have a line plug in their operations. The inherent instability of denser phase flows can be shown to exist at crucial points in these diagrams. It is noteworthy that Zenz performed many of his first experiments in very small equipment located in his garage and using a vacuum cleaner as the air source.

- Barth Analysis - Barth (1954) was also one of the pioneers of pneumatic conveying who reduced the analysis of complex flows into basic physics trying to ascertain the parameters needed in order to develop a predictive model for design. He focused on additional pressure drop due to the presence of solids in addition the standard contributions from the gas flow friction and the gravitational forces. This additional pressure drop is written as

$$\Delta p_z = \mu \lambda_z \frac{\rho}{2} v^2 \frac{\Delta L}{D}$$

Over the years the evasive term (λ_z) has been investigated by many researchers. For the dilute phase operations we have an adequate representation for this value.

- Saltation Analysis – Rizk (1973) working with Barth in his first foray into pneumatic conveying understood that a predictive tool was needed to establish when particles would salt out of the flow. His basic, simple experiments proved to be easily applied to the industrial scene. Further refinement have taken place but Rizk was the first to give us a tool. This work was one of the first that Rizk employed in the career in pneumatic conveying studies and design. The basic salutation equation is given as

$$\mu = \frac{1}{10^{\delta}}\left(\frac{v_s}{\sqrt{gD}}\right)^{\chi}$$

$\delta = 1.44d + 1.96$

$\chi = 1.1d + 2.5$

- Konrad Dense Phase Analysis – In his Ph.D. dissertation Konrad opened the door for a basic analysis of dense phase flow incorporating much of the field of solid mechanics to these conditions. Using the moving packed bed analogy he provided a basic understanding of dense phase conveying. This blend of fluid and solid mechanics was a step forward in attempting to required that one had to test each and every dense phase system in order to have systems that would function. Konrad (1984) incorporated some of the basic findings of Jenike in his analysis. One can note that the common terms developed by Jenike for bin and hopper are part of the models.

- Jenike Shear Cell – As mentioned above Konrad incorporated the finding of Jenike (1964) in his dense phase model development. This provided significant advancement to the understanding of dense phase conveying and is employed extensively today. The Jenike Shear Cell (2008) has been improved continually and a photo of a recent unit offered by the firm, Jenike and Johanson is seen in Figure 2.

- Muschelknautz Dense Phase Analysis – Muschelknautz (1969) was one of the first who addressed dense phase conveying and carried out considerable testing and analysis in this field. His models tend to follow an overall system approach which has had some success in applying to industrial situations. The model he and Krambrock suggested is given as

$$P_1 = P_2 e^{\frac{g \cdot \mu \cdot \beta_o \cdot L}{R \cdot T \cdot c / v}}$$

One noted the term (β_0) term as the product friction coefficient unique to the product conveyed.

As mentioned, Muschelknatuz was one of the pioneers in pneumatic conveying and his thinking about the basic frictional term in the overall analysis and modeling of pneumatic conveying led him to project that the gravitational forces had a significant effect on the basic friction. He was able to be first in carrying out pneumatic conveying in outer space aboard the space shuttle in order to remove the gravitation forces from the basic expression. This was a very ambitious project and while the overall results never did not completely materialize the studies and data obtained pointed to the direction to follow.

- Geldart Diagram – Another development that can be considered transformative that developed in another field of solids processing is the Geldart Diagram conceived with the idea of understanding how particles with different characteristics behaved in the fluidization operation. I believe that Geldart (1973) while working dominating in fluidization had an impact on the whole solids processing field including pneumatic conveying. Through his classification of the various type of solid powder and their flowability conditions and results in pneumatic conveying can often be interpreted. Figure 3 presented here was recently proposed by Yang (2007) in his attempt to expand the analysis to high temperature and high pressure fluidization operations.

- Tsuji Simulation of Dense Phase Flow - Tsuji began his efforts in pneumatic conveying under the tutelage of Morikawa with very classic experimental findings especially in the use of hot wire anemometry. This data has set the standard for many modeling and simulation analyses that followed. Tsuji (1992) branched out into the simulation and modeling arena and began to carry out very basic simulations of complex pneumatic conveying conditions. When his result started to be similar to those found in the laboratory, attention was drawn to him and the field which holds such promise. This is a transformative result. One notes in Figure 4 the similarity to actual experiments.

  Following the modeling and simulation approach Sinclair (1995) has employed detailed fluid and solid mechanics behaviors to provide amazing predictions of actual flow situations.

- Large Scale Systems – Marcus et al. (1986) and Wypych (1999) both took the realm of pneumatic conveying research from what some industrial practitioners call tools to reality by implementing large scale testing with industrial size pipeline both in diameter and length. Industry had to listen to these researchers and could not just pass off University work as cute and that is a nice toy. These studies have been transformative in providing more respect for University scale research because they did show that the smaller scales could provide interesting and useful information for industry. Understanding the scaling parameters can be credited to their transformative work.

- Pressure Fluctuations – Solt was the first to my knowledge that suggested the idea that the noise generated by pneumatic conveying could be used in diagnostics of the problems which such systems experienced. Dhodapkar and Klinzing (1993) took this idea and applied signal analysis of the pressure fluctuation to such flows in order to predict the flow regimes and operations. This type of analysis could be done on-line in the plant. The results point to very distinct signals of the pressure fluctuations depending if the flow is homogenous in nature of is a moving wavy bed. Figure 5 shows one such signal for stratified flow.

  Utilizing pressure measures and other noise analysis techniques has been pioneering by Davies (1987) applying many of his ideas and invention to actual industrial usage.

- Wavelet Analysis – Building on the foundations of signal analysis in electrical engineering Pahk and Klinzing (2008) tried to analyze the signal of the pressure fluctuation in order to what actually made up these fluctuations and could can we indeed read this signal in a more intelligent manner. Detailed analysis using the wavelet approach indicates that the various contributions of the pressure fluctuations can be filtered out of the signal to provide a more detailed analysis of the system. Figure 6 is one result of this analysis which distinctly picks out the blower, feeder, turbulence and solids interactions terms.

- Particle Interactions – In a fundamental analysis of the friction generated in pneumatic conveying it naturally comes down to what the particles are doing between themselves and in their impacts with the wall of the pipe. These questions were first addressed by Louge et al. (1989) who looked at impacts of large particles to gain some insight into how to model and quantify these interactions. Borzone and Klinzing (1990) have shown that the condition of the wall surface can intimately affect the particle impact behavior. One can note in Figure 7 below the unique impact and reflection angles can occur when the surface roughness is varied. In more recent work Vasquez et al. (2008) showed the unusual behavior of flexible particles and their interactions with the wall and themselves. These particles produce considerable rotation as well as unique interactions with the wall even bouncing backward against the main flow stream. The cartoon of this behavior is seen in Figure 8. Are these particle behaviors transformative? I believe the observations challenge us to think of new ideas and models and present to us opportunities to explore the basics more carefully.

- Electrostatics – Richardson and McLeman (1960) explored pneumatic conveying with particles that produced considerable electrostatic forces that presented themselves as an increased in the pressure drop in a recirculation system. See Figure 9. This unique observation focused the community at exploring the cause of such behaviors. Klinzing probed electrostatics first in trying to eliminate the effect but the fascination of the phenomenon led to several experiments trying to establish its amount, direction and conditions for occurrence. Use of the phenomenon in a positive manner was also explored in the metering of flow. Figures 10 shows how the electrostatic effect can give completely different flow behaviors and patterns as such causing considerably more energy to be expended in conveying as well as being dangerous in operation.

- Pickup – Following on the original work of Rizk on saltation Cabrejos and Klinzing (1994) worked in order to determine if there was a broader scope of pick-up and saltation expressions that could be used for a wide cadre of materials. Some interesting results emerged in these studies to show a hysteresis seen between the two phenomena and how difficult determining the exact values for fine particle behaviors could be. Kalman (2008) and his students have explored even further into these phenomena and have developed new generalized correlations for us all to use. Figure 11 shows the Cabrejos experimental findings.

- Tomography - In order to understand the details of the internal structure of pneumatic conveying Dyakowski, Williams and their colleagues employed tomography to obtain a three dimensional view of pneumatic transport including dense phase conveying. They were able to show that the internal structure of this type of flow is complex and unsteady pointing to the reasons correlations are difficult to employ and duplicate. Dyakowski and Williams in 1993 published a paper in Powder Technology which was the beginning of the use of tomography to explore the details of pneumatic conveying with the measurement of the particle velocity distributions in a vertical channel. This technique has blossomed under their direction and attracted other researcher to the field to explore the details of the flows often showing the non-homogeniety of the flow structure. This work has been transformative to the field. See Figure 12.

- Ice, Space and Chickens – Transformative or Just Different

I believe that the next three examples are most unusual and point to the creativity of humans to apply principles completely outside the normal applications and lead to new technologies. In my estimation this type of thinking is transformative. Sheer (1995) met a challenge which came from the need to cool the air in deep mining operation which led to the suggestion to conveying ice from ground level down about 1 kilometer to the mining where the latent heat of melting would be released and cool the air for workman to function in the deep mines. In this application success was achieved by using plastic piping in the operation since metal piping formed a strong bond between the ice and the metal so that plugs of ice would block the pipeline. This points to the strong dependence of the inner piping surfaces to operations including friction. Figure 13 shows the ice plug in the application.

NASA has had a keen interest in moon explorations and as such has carried out a number of tests already on how particles would behave under reduced gravity conditions. The use of a KC135 jet airplane to simulated reduced gravity during the diving operations has been employed to assess the effect of reduced gravity of saltation a pickup and well as fluidization and pressure drop in pneumatic conveying. NASA also has the idea of mining the moon in order to generate oxygen to sustain life. One such process is shown in Figure 14. Actual NASA data on choking under reduced gravity conditions is seen in Figure 15.

It is not uncommon to see pneumatic conveying applied in the food industry. Handling these material pneumatically provides many advantages to the over handling problems of bulk food moving. One lesser known application in the food related industry involved the conveying of live animals as seen in Figure 16. Again, are these transformation developments?

3. Conclusions and a Proposed Future Strategy

One can see that there have been a number of developments over the years that could be called transformative in the field of pneumatic conveying. Sometimes these have occurred within the community itself and sometimes information and discoveries in other fields have enriched the field and brought welcome information and change.

I believe the call is to take a chance and be little riskier is our future approaches.

Some of the topics that appear to be ripe for consideration are:

- Friction – The friction experience between the solids and the wall of the conveying enclosure along with the inter-particle behaviors and the gas turbulence and solid interaction all lead to an energy loss seen in pneumatic conveying. There have been attempts to describe each of these forces and losses (Molerus, 1996) but little success in quantifying these losses in a most general way as to applicable to all conveyed particles . This all point to a more thorough understanding of the basic physics of the process. Because pneumatic conveying operations occur in turbulent flow regimes we are even more challenged to probe turbulence and all its nonlinear behaviors in the presence of particles. We have resorted to many correlations for specific materials and tried to generalize with limited success. Trying to isolate the contributions are being explored and hopefully with new experimental methods and new analyses borrowed from other branches of science and engineering friction will be less of a mystery to us.

- Other Forces – As mentioned, friction does involve several different components that can be broken down into linear forces but also one must anticipate nonlinearities in these considerations. The forces that contribute to the overall energy loss must be considered in trying to understand and analyze the pneumatic conveying. There are the particle-particle, particle wall impacts, rotational spins, turbulence contributions both amplifying and damping components and of course the ever present electrostatics which is often termed “black magic.” Our models must determine if these forces have a significant contribution to the overall models both analytical and numerical and fortunately in engineering analysis we can often times reduce or eliminate the significance of some of these forces in our analyses.

- Simulation and Modeling - There has been particularly impressive progress that has taken place in the simulation and modeling arena. It just seems like a few years ago when this approach was being conceived several people would say under their breath, “This will never work.” These same people are changing their minds as the field has become more sophisticated and comprehensive in the approaches. We will see more success in this field in the future when we can insert the correct physics into the models

- Industry Perspective – Industry has taken an approach to research in pneumatic transport that is a blend of incremental advances and transformative research. The transformative part has come about when industry must act because of a serious upset to a process that can be pointed at pneumatic conveying. Chances can be taken because if action is not taken even more serious financial losses will occur.

- Films Records – With the advances in recording the physics processes of particle flow with cine and fast videos we have at our disposal the ability to probe the mechanism and slow down their actions that we can address a more realistic model. There are fast video cameras and other photographic techniques available to us at prices that we can afford that hold the potential to unlock some basic observations and information. Use of tracers in the flow can permit possible quantification of particle behaviors.

- Data in the Files – In conversations with various industrial practitioners of pneumatic conveying the topic of having carried out tests before and not really having a chance to analyze these data with newer techniques and concepts often emerges. There is a feeling that there is a wealth of information still sitting in filing cabinets and if we could only go through this data systematically we could provide new incite to existing problems. While in concept this may sound easy, implementing this process is a challenge but I do believe it would be a worthwhile adventure.

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5. Nomenclature

ΔP : *Pressure difference, (Pa)*
L : *Pipe length, (m)*
H : *Pipe height, (m)*
F : *The stress on the front end of a plug*
D : *Pipe Diameter, (m)*
ρ_B : *Bulk density*

$$\rho_B = \rho_S(1-\varepsilon)$$

ρ_S : *Solid Particle density*
ε : *Voidage, (-)*
g : *Gravitational force, (9.8 m/s^2)*
P_2 : Downstream Pressure, (Pa)
P_1 : Upstream Pressure, (Pa)
g : Gravitational force, (9.8 m/s^2)
c/v : Velocity Ratio (Particle/gas), (Between 0-1.3)
μ : Mass flow ratio, (Solid mass flow rate (m_s)/Gas mass flow rate of pipe (m_g)) (Between 50-300)

$$\mu = \frac{m_s}{m_g}$$

T : Temperature
R : Gas Constant
β_D : The value of β_D Weber derived from experiments. Values of β_D=0.6 can be assumed for horizontal dense phase conveying. (16)

$$\beta_D = \sin\delta + \mu_R \cos\delta$$

where:
δ : Angle of inclination
μ_R : Coefficient of sliding friction

β_o : The product frictional coefficient β_o proposed by Muschelknautz and Krambrock can be determined by the previous conveying test from the expression:

Recommended estimating β_o:
β_o = 3 to 5 for plastic pellets
β_o = 4 to 6 for plastic powders at terminal velocities of about 6 to 10 m/s.

Figure 1

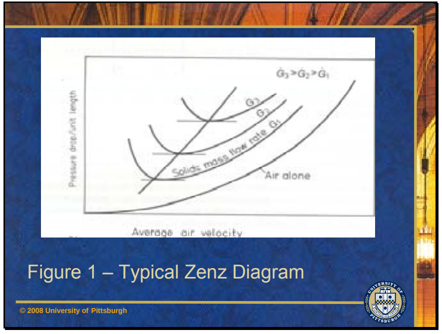

Figure 1 – Typical Zenz Diagram

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Figure 2

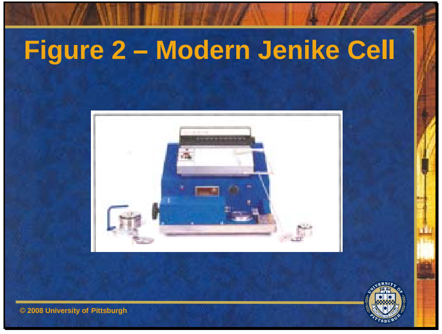

Figure 2 – Modern Jenike Cell

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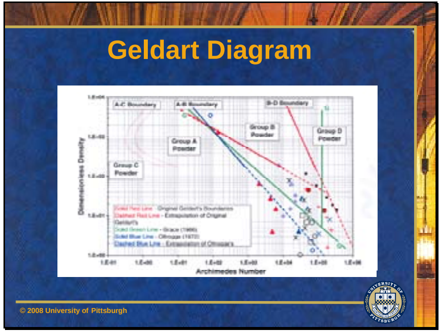
Figure 3



Geldart Diagram

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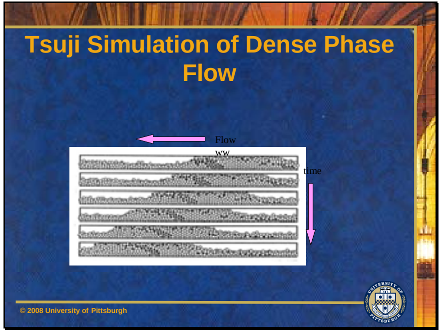
Figure 4



Tsuji Simulation of Dense Phase Flow

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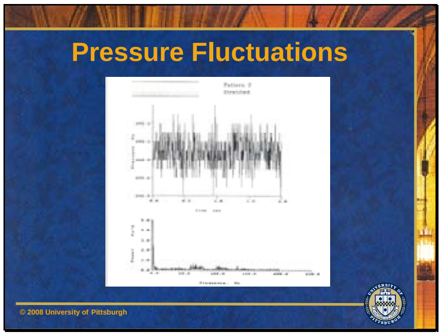

Pressure Fluctuations

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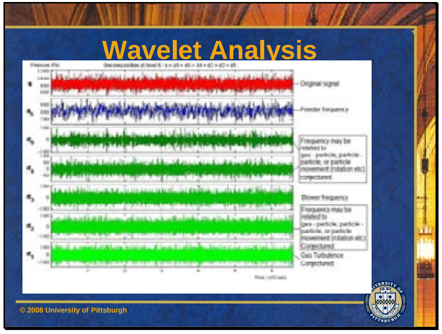
Figure 5



Wavelet Analysis

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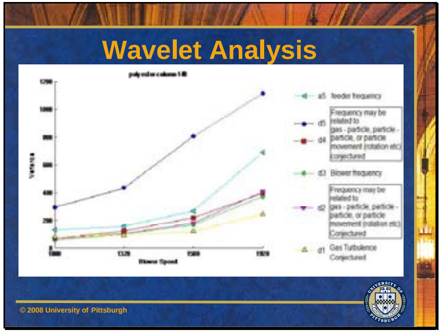
Figure 6-a



Wavelet Analysis

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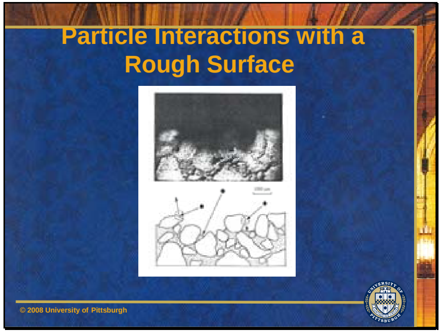
Figure 6-b



Particle Interactions with a Rough Surface

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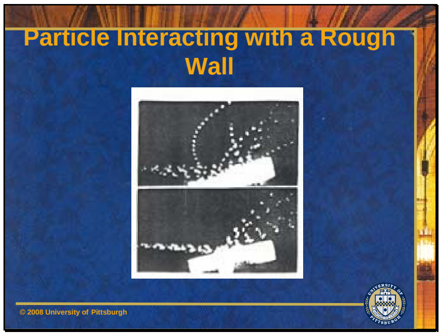
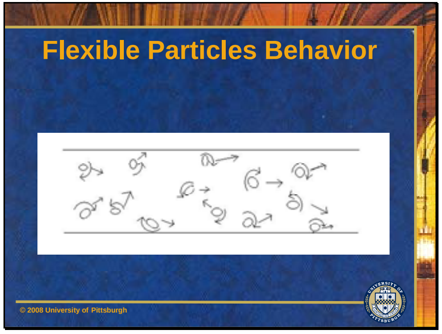
Figure 7-a



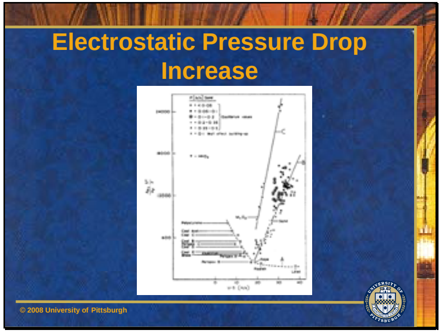
Particle Interacting with a Rough Wall

Figure 7-b



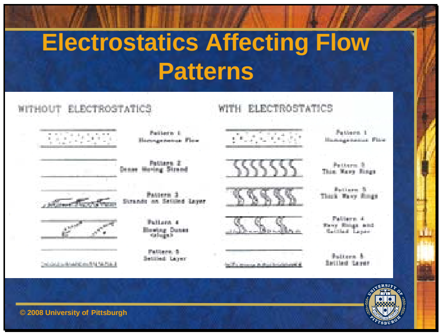
Flexible Particles Behavior

Figure 8



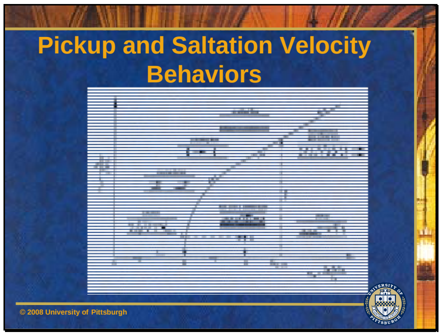
Electrostatic Pressure Drop Increase

Figure 9



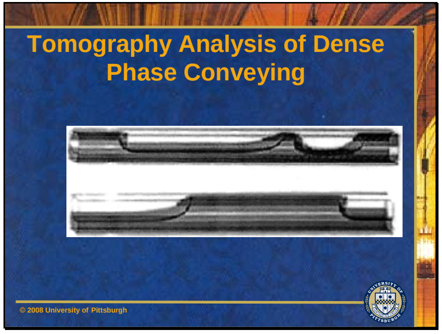
Electrostatics Affecting Flow Patterns

Figure 10



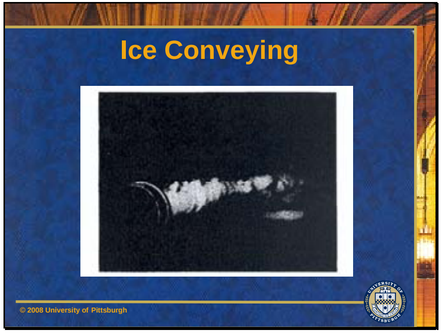
Pickup and Saltation Velocity Behaviors

Figure 11



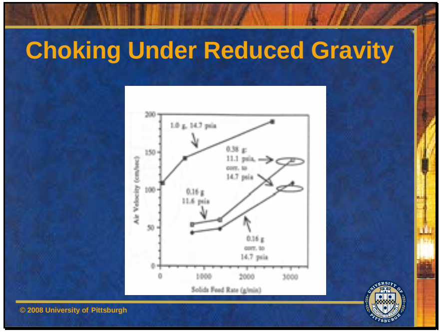
Tomography Analysis of Dense Phase Conveying

Figure 12



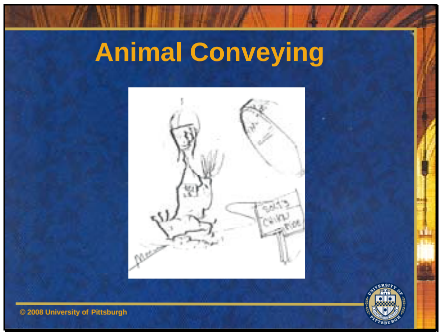
Ice Conveying

Figure 13



Choking Under Reduced Gravity

Figure 14



Animal Conveying

Figure 15