Historical Review of Pneumatic Conveying[†]

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Abstract

This document attempts to cover the development of pneumatic conveying over the past 100 years or so. The individual researchers who worked in the field are highlighted along with their photograph which is included at the end of the document. As time progressed in the scientific and engineering developments of these years one sees a transition from a purely experimental approach with considerable empiricism to adapt to the development of numerical procedures in attempt to predict the flow characteristics. The basic physics of the phenomena of pneumatic still is not completely understood and new and novel experimental techniques are always welcome in the field.

Keywords: pneumatic conveying, dilute phase, dense phase, measurements, numerical

1. Introduction

Pneumatic conveying appears to have been in existence for well over 100 years. The literature indicates that grain was being unloaded from ships from 1856 to 1876 in the ports of London, Rotterdam, Hamburg and Leningrad. **Fig. 1** shows this operation of a Russian ship loading of grain in 1882. Possibly other applications did exist before this but this is the only one found to date. The Russian literature most likely exists but is difficult to discover.

2. Air movers

It is said that pneumatic conveying took off with the invention of the Roots Blower by the Roots brothers, Philander and Francis, in Indiana in 1859, Roll (1931). At that time the blowers were used in supercharging the internal combustion engine and first being employed in blast furnaces to help with the melting of iron. Undoubtedly compressors did exist before this so that high pressure air could be obtained to utilize in the pneumatic conveying operations. Vacuum conveying was also possible about the same time frame.

The vacuum pump is attributed to the Romans and later in the 13th century the Arabs were using suction pumps. The pumps surfaced in Europe in the 15th century. The first vacuum pump is attributed to Otto von Guericke in 1654.

Compressors have their early beginning in 1762 with John Smeaton followed by a compressor producing about 15 psi. Improvements were made in 1872 with a compound air compressor.

Thus one sees that the vacuum pumps and the air compressors pre-dates the air blowers so pneumatic conveying could have taken place in very early times. We have no record or mention of pneumatic conveying previous to the Russian grain unloading citation.

Fig. 1 Grain Unloading in 1882.

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3. Earlier pneumatic conveying studies

The earliest technical exploration into pneumatic conveying occurred in Germany by Gasterstadt (1924) at the Technische Hochschule Dresden. The work is reported in the German Engineering Journal, VDI. The work reported a linear behavior of the pressure drop in a straight section of pipe with the solids flow rate. The flow was dilute in nature. This concept was used by Cabrejos and Klinzing (1992) to develop a flow meter for measuring the solids flow rates with a system of transducers and valve to explore the full range of experimental conditions. Using the data from a large conveying system the linearity of the system pressure drop with the solids flow rate (**Fig. 2**) was constructed by Baker (1997).

Following this work the field seemed to be quiet with publications until after the Second World War when activity at Karlsruhe University began. The Karlsruhe group flourished under Rumpf, (Students-Leschonski, Molerus, Schwedes, Sommer, Werther), working in Process Technology. Teamed with Barth, (Students-Reh, Muschelknautz, Leineweber, Moller, Bohnet, Weber, Rizk), who worked in Conveying Flow Technology, to address all aspects of solids processing. Barth developed a solids friction factor term, λ_z which has been used extensively in the literature.

$$\text{Solids Friction} = \lambda_z (\text{velocity of the particle})^2 / 2D \quad (1)$$

Rizk (1973) through his dissertation work with Barth developed the first equation for the saltation velocity of polymer particles and explore the material of construction of the pipe to ascertain the frictional terms developed by the interaction of the particles with the wall. About the same time Zenz and Othmer published a book of Fluidization and Fluid-Particle Systems (1960). This work contained the first known experiments which Zenz performed in pneumatic conveying which according to legend were performed in his garage with a vacuum cleaner

Fig. 2 System Pressure Drop as a function of the solids flow rate. (With permission of the author.)

Fig. 3 Zenz diagram from pressure loss versus the conveying velocity at various flow rates, Rizk (1973) (With Permission of the author).

as an air source. Zenz was able to develop a phase diagram which is used extensively in the analysis of pneumatic conveying. See **Fig. 3**. In Japan pneumatic conveying blossomed under the direction of Morikawa who mentored such noted researchers as Tsuji and Tomita. Tomita began his contributions to pneumatic in 1971 and had a long and successful career at Kyushu Institute of Technology. His work was mostly experimental but he did delve into numerical simulation later in his career. He also addressed the issue of introducing swirl into the initial part of the pipe in order to enhance the transfer of particulate solids.

4. Germany

As noted above, before the 1950's Gasterstadt (1924) did some very basic studies in pneumatic conveying. His results of the pressure drop linearity with flow rate for dilute solid flow was the first flow meter of its kind. In addition he performed pneumatic conveying studies on a 100 m long horizontal pipe.

As noted above, in Germany the solids processing concept and its study began in earnest with Rumpf of Karlsruhe University along with other senior colleagues especially Barth who concentrated his studies in pneumatic conveying providing a rich source of students in solid processing. Almost all of the researchers in Germany in this solids processing through 1960's to 1990's came out of Karlsruhe. Many of the existing researchers can also trace their academic lineage back to Karlsruhe.

Professor Barth's untimely death did not stop the research machine from going. Some of the notables from Karlsruhe who populated Europe's elite of solids processing were Leschonski, de Silva, Schoenert, Loeffler, Molerus, and Schwedes. The Karlsruhe group spread throughout Europe taking professorships or senior re-

Table 1 Researcher from the Karlsruhe Group.

Last name	Affiliation
Leschonski	Clausthal Technical University
de Silva	Tel-Tek in Porsgrunn, Norway
Molerus	University of Erlangen
Rizk	BASF
Sommer	BASF—Technical University of Munich
Muschelknautz	Bayer—University of Stuttgart
Weber	Karlsruhe University
Bohnet	BASF—Technical University of Braunschweig

search positions in industry. Many started in industry and then moved on to universities.

Krambrock (1979–2004) is another German pneumatic conveying practitioner who has been prolific in the development of patents in pneumatic conveying and solids processing. He worked initially with Bayer collaborated with Muschelknautz who was also at the same firm at that time. He then joined Waeschle and from there formed his own firm eventually cooperating with Zeppelin and Wilms. Muschelknautz (1969, 1985) after the University of Karlsruhe started his industrial career with Bayer and then joined the University of Stuttgart.

Sommer (2009, 2011) from the Technical University of Munich and his students developed a clever way of measuring the wall stress in dense phase flow as well as exploring the structure of dense phase flow with two-dimensional tomographics. These results showed that the voidage is not uniform across the pipe cross-section.

Bohnet after working for BASF joined the faculty at the Technical University of Braunschweig and studied long distance conveying and cyclone operation in solids processing. He and his colleagues, Gottschalk and Morweiser (1997) produced a work on modern design of cyclones.

Molerus (1993) of the Technical University of Erlangen who also was Karlsruhe and Rumpf educated concentrated mostly on developing theories for solids processing operations including pneumatic conveying.

5. Japan

In Japan Inoya at Nagoya and Kyoto Universities assembled a team of students to begin to address the challenging area of solids processing from all levels. His lab produced many of the researchers in this field throughout Japan for the next 20 years or more. In fact it was challenging for other Japanese researcher who did not have the Nagoya or Kyoto stamp to advance. In pneumatic conveying Morikawa of Osaka University began to research

pneumatic conveying and added a well-known student to his research team; Tsuji. Morikawa (1982) and Tsuji did many projects together mostly experimental before branching out to numerical simulations.

Tsuji followed Morikawa as the Principal Professor at Osaka University and since has retired being followed by Tanaka, his student. They have produced a large volume of students who are world renown in the modeling and simulations area of solid processing and pneumatic conveying. After retirement from Osaka, Tsuji became the technical director of the Hosokawa Research Foundation. He still participates in symposium on numerical simulations although not formally attached in any entity.

In Japan there were a few other hot spots of pneumatic conveying research. Tomita of Kyushu Institute of Technology (1971) contributed extensively to the literature covering a wide spectrum of solids transport from pneumatic to hydraulic to capsule. As noted above he studied induced rotational flows to numerical simulations in dense phase flows. Tashiro was a student of his and he now at Kurume Technical University. Tashiro has done some fascinating work on the rotational motion of particle in dense phase flow.

At the large Nihon University Ochi has done pneumatic conveying research mostly in the dilute phase regime although he has also explored some dense phase work

At Kyoto University Masuda (2003) concentrated on trying to understand the electrostatic phenomena that occurs in pneumatic conveying. He performed some very basic work and also has explored measurement devices and flow measurement in pneumatic conveying. These are really fundamental in all electrostatic interactions.

6. United states

Much of the U.S. pneumatic conveying work did not come out of one font as was in Germany with Karlsruhe. With the importance of energy and coal, fluidizations studies were plentiful and many industrial companies and research organization developed extensive expertise in this field which is ancillary to pneumatic conveying. The work of Yang of Westinghouse and Knowlton at GRI and later PSRI are most noteworthy. Novel and creative experiments and devices were developed being placed almost immediately on the industrial scale. Expertise developed in the solids processing and fluidization area at Exxon, Texaco, Shell and others. Agrawal from Union Carbide was their resident expert in pneumatic conveying design with a specialty in dilute phase transport. Dow Chemical developed similar solids processing expertise under the leadership of Jacob and Dhodapkar. They fostered research in solids processing in the chemical industry making significant contributions to the state-of-

the-art. At Dupont Bell spearheaded the pneumatic conveying activities in their solids processing team lead by Reg Davies. Bell explored many relevant industrial issues including the use of multiple bends in conveying systems and particle attrition.

The area of consulting engineering cannot be forgotten when it comes to pneumatic conveying. Solt after many years with Fuller Company carried out extensive testing on a wide variety of materials and designs. Presently he is teamed with Hilbert in having webinars through the magazine Bulk Solids Engineering. Solt's **"Point to Ponder"** in the same magazine is classic with series now being sold separately. Solt did extensive short course offerings with the Center for Professional Development, AIChE and the University of Wisconsin. Jenike and Johanson is now also offering consulting services in pneumatic conveying. In Great Britain Bates has been an active contributor to the consulting field in addition to providing articles on practical guidelines on solids processing.

As mentioned before the field of pneumatic conveying did not spring from a single source but had a variety of different researchers at universities approach the topic. Michaelides (1984) did some interesting work on the solids friction factors. Soo developed unique mathematical analyses for pneumatic conveying with a heavy emphasis of electrostatic generation. Sinclair-Curtis (2015) probed both simulation and modeling proficiencies as well as experimental verification in her work. Sinclair-Curtis contributed heavily to the numerical simulations in solids processing including pneumatic conveying. Work in the area of constitutive models for stress/viscosity is noteworthy. She also carried out fundamental studies using Laser Doppler Velocimetry for both dilute and dense phase conveying. Most recently she is addressing the issue of particle shape which has been a challenge in the field from the beginning.

Klinzing and his students carried out experimental work in a wide scope of topics related to pneumatic conveying; electrostatics, drag reduction, meter development, long distance conveying, dense phase resulting in a number patents and copyrights. In collaboration with Rizk, Marcus and Leung a comprehensive book on pneumatic conveying was produced and is in its 3rd edition (2010).

7. Great Britain

Early work in Great Britain began with Rose and Duckworth (1969) who did research in pneumatic conveying at Kings College, University of London and City University London. Later, in the early 1970s, Mason developed a strong pneumatic conveying facility and expertise at Thames Polytechnic in London. He attracted Mills as a student who later developed into a trusted colleague

in pneumatic conveying Mills and Mason (1985). Mills has published widely and lectures often. Mills has had a close collaboration with Agarwal at IIT—Delhi in India in the transport of fly ash (1999, 2000). Reed also was part of the Thames group and took a real leadership role in research and administration later being part of Greenwich University. Mills initiate work with Mason on bend erosion started a long and productive career in pneumatic conveying provide a compendium of design procedures in the field developed from his many studies (1985). He focused on different feeders exploring the blow tank operation in considerable detail. He began his work at Thames Polytechnic and then at Glasgow Caledonian University and then private consultancy. Mills has work extensive with Agarwal of the Indian Institute of Technology in New Delhi on the transport of flyash. Extensive studies were performed under this partnership.

Bradley at the University of Greenwich has developed a large consultancy that goes under the name of the Wolfson Center (2008). While in Scotland, Mason with Jones and Mills attracted two researchers who developed some interesting basic concepts in measurements in pneumatic conveying: McGlinchey (1999), Pugh and Marjaovic. They continued to develop novel flow measurements devices and research in pneumatic conveying. During a sabbatical stay at Glasgow Caledonian University Levy collaborated strongly with David Mason and Marjanovic to produce three notable works in pneumatic conveying; Mason, Marjanovic (1998), Mason and Marjanovic (1998) and Mason and Levy (2001). In addition his work on a nozzles with Jones is also noteworthy; Levy, Jones and Das (1996).

At Cambridge University in Great Britain Nedderman supervised Konrad; Konrad, Harrison, Nedderson, and Davidson (1980), in theoretical and experimental analysis of dense phase conveying using the basic principles of soil mechanics. Their work is classic and the real beginning to the basic understanding of dense phase flow. Konrad had a brief stint at Virginia Tech to teach and then moved to Exxon changing fields somewhat. Lyndon Bates is a well-known consultant from Great Britain but his expertise is used widely around the world. He published review articles and guidelines often in the field of solids processing.

8. South Africa

South Africa came into the pneumatic conveying realm with a great force in moving large quantities of solids through large pipelines over long distances. Marcus began this effort through his dissertation work and continued on with a faculty position in Mechanical Engineering at Witwatersrand University. The mining industry and the coal

conversion activities of Sasol supplied a rich variety of challenging problems in pneumatic conveying. Marcus supervised about a dozen students who went on to continue in the field making contributions to industry and academia. The most successful ones were Meijer with Bateman (ELB, CEO) and Sheer (1995) who now is on the faculty at Witwatersrand (Wits) after working for a gold mining company. Unusual applications of pneumatic conveying were seen in carrying ice into gold and diamond mines for cooling. Long distance conveying processes were explored by Marcus and his students having some of the longest examples of actual commercial systems. Presently there is some work going on at Wits and the University of Johannesburg.

9. Australia and New Zealand

Australia has been a hot bed for solids processing lead by their vast mineral industry. Their ability to design large scale systems is found by their large scale experimental facilities both at Newcastle and Wollongong. Roberts started the bulk solids work in Australia before moving to the University of Newcastle in 1974. Arnold, Roberts' first research student, continued the work at Arnold at University of Wollongong in close communication with Roberts of Newcastle University. Arnold specialized in bin and hopper design as well as mechanical transport with belt conveyors. Wypych who studied with Arnold moved the progress forward in large scale pneumatic conveying. He always obtained data on experimental facilities that were comparable to industry. Wypych has been able to explore pneumatic conveying with realistic size conveying lines in both distance and pipe diameters. He has modelled dense phase transport with a two layer flow theory. The minimum transport boundary was studied with flyash and cement. He studied dense phase transport of various materials and probed the frictional term in pneumatic conveying as well as scale-up procedures. Wypych is active in his interactions with industry through consultancies.

Wypych guided a number of very talented students in his laboratory; Mi and Pan come quickly to mind. Pan has returned to China and leading a larger effort in China at this time, (2013, 2014, 2016)

About 15 to 20 years ago Newcastle University was able to attract Jones to their research group at The University of Newcastle Research Associates (TUNRA). Jones left the Mason group at Caledonian University in Glasgow, Scotland. Jones (1987, 1990, 1994), has been successful in leading the pneumatic conveying group at Newcastle and has grown the group into a well-recognized team. Jones served as the advisor and mentor to Williams and Krull both who have become recognized for their in-

novative studies. The Newcastle team is active in most of the solids processing conveying conference world-wide.

Jones explored various topics in pneumatic conveying. He and his colleagues probed the performance of blow tanks; product classification in relationship to pneumatic conveying; the effect of gas density on pneumatic conveying; bench scale tests for assessment of pneumatic conveying; blending and segregation of coals for pneumatic conveying; suction nozzles; fly ash, sand and cement properties in conveying; dense phase conveying; Behera, Das (2000)

In New Zealand Davies and Tallon (2006, 2014, 2015) collaborative work yielded a number of contributions to the field in measurements. Many of these resulted in patents for new devices using tracers in the flow and acoustic pulsations did considerable work on developing flow meters which a variety of sensors mainly based on acoustics. Davies and Gunabalan (1998) attacked the difficult problem of assessing the effect of back-to-back bends in conveying system. These meters have been proven to work in pneumatic conveying operation and in other solids processing applications. Many of the devices developed where applied to other solid processing systems.

10. Israel

A little later in the time line researcher in Israel began to explore the intricacies of pneumatic conveying lead by Kalman (1998, 1999). There were other researchers in two phase flow system in Israel who approached the topic in a fundamental basic analysis such as Hetsroni at the Technion and Taitel at Tel-Aviv University. Kalman spurred research to attrition, wear and threshold velocities and produced a number of students who advances these topics. Kalman's work in pneumatic conveying spans a number of different aspect of the technology. Besides his leadership in the International Conveying and Handling of Particulate Solids conferences and procedures he began with studies on size reduction and attrition phenomena is pneumatic conveying. He has explored the behavior of particles under different shear and impact conditions as well as multiple impacts. He probed deeper into this phenomena and was able to show the behaviors of stresses in particles over a wider range of temperatures. He and his students addressed the pickup and saltation velocities of particle in pneumatic conveying systems producing a generalized approach which is applicable for both pneumatic and hydraulic conveying. Some recent work in particle velocities in conveying both in bends and feeders has led to some interesting observations.

Kalman also works closely with Levy (2011) expanding their work to modeling and simulation with wide applications in solids processing; Han, Levy and Kalman (2003).

Kalman has questioned the basic premises on which most of pneumatic conveying is built and examined previous data assiduously. Most notable of Kalman's students have been Rabinovich, Goder, Portnikov, Shaul and others. The research of Levy (2000) concentrated on numerical simulations of pneumatic conveying and other solids processing operations. The effect of a bend on the particle cross-section concentration and segregation in pneumatic conveying systems and finite-volume for conservations of mass and momentum are a few examples.

11. Norway

When de Silva came to Porsgrunn in Norway to head up the solids processing group at Tel-Tek he began to construct a laborator he termed an insulated tent housing the pneumatic conveying facilities. De Silva organized a series of conferences on reliability of solids flow terms REPOWFLO. Some fundamentals studies were carried out as well as testing of powders and bins and hopper design. He worked closely with Enstad on particle characterization and behaviors. De Silva was able to attract Datta to his group to concentrate on pneumatic conveying and then followed by Ratnayake who is active today.

12. Chile

In Chile Francisco Cabrejos has been a force in pneumatic conveying working for Jenike-Johanson and also teaching at the Universidad Tecnica Federico Santa Maria in Valparaiso, Chile. His work has been mainly in the mining industry often carrying out transport at high altitudes where the mines are located. He has written a book on pneumatic conveying in Spanish entitled "Transport Neumatico" by Editorial USM (2013).

13. Interaction of pneumatic conveying with other solids processing operations and designs

Pneumatic conveying developed initially quite separately from other operations in solids processing although determination of the properties of the materials conveyed were always recognized as being an important parameter. The size, shape, distribution of both, true densities and bulk densities were essential in the analysis and experimentation. With the classification of Geldart (1973) into his A, B, C, and D type powders interest began in earnest to utilize this classification in reference to the ability and modes of conveying. It was quickly recognized as it was in the fluidization field that A type powders were one of

the easiest to be conveyed. The C—cohesive powder were a challenge with such materials as coal, flyash and cement being representative of these powders. The stresses that seen in dense phase conveying are similar to the analysis of bins and hoppers and Konrad (1980) under the direction of Nedderman recognized this and formulated the first attempt to understand dense phase conveying using first mechanistic principles. The feeder for pneumatic conveying systems vary from the simple to the very complex and their inter-relationship with bins and hoppers is imperative to understand. The same principles used in bins and hoppers and especially with outlet sizing is important to pneumatic conveying. In addition collection of the product at the end of the conveying lines requires knowledge of cyclone operation, filters and electrostatic separators depending on the size and characteristics of the solids being conveyed.

14. Modeling and simulation

Tsuji and Morikawa were the first to apply numerical techniques to the simulation of pneumatic conveying (1982). Since this beginning there has been a strong addition of more studies in the numerical simulation area which continues until today. Each investigator has refined the models that they employ and relaxed assumptions. In 2006 Tsuji gave a good summary of the status of modeling in pneumatic conveying and other solids processing operations. Theuerkauf in 2012 also presented a comprehensive survey of simulations and modeling in solids processing. Modelers have attempted to find experimental data with which to compare their findings with the work of Tsuji and Morikawa using LDV to measure the motion of particles in pneumatic conveying. Other researchers who explored the modeling and simulation from the use of discrete element methods to numerical fluid dynamics modeling have been Yu (2008), Tomita, Sinclair-Curtis (2012, 2013a, 2013b), Sommerfeld, Levy and others.

Tsuji (2006) has given an excellent summary of computational activities related to solids processing including pneumatic conveying. He noted that these computations can be separated into four groups; 1. gas-particle multi-phase flows, classification according to numerical analysis, 2. collision-dominated flow and Direct Simulation Monte Carlo methods (DSMC) and 3. the contact-dominated flow and 4. the Discrete Element Method (DEM).

Theuerkauf in his talk at Conveying, Handling of Particulate Solids-7 conference gave a good summary of modeling granular flows using the DEM. He also considered the DEM to be part of the modeling toolkit for design over the coming 10 years.

14.1 The need for further work

The reliable design of bulk solids storage systems was given a significant boost when Andrew Jenike and Jerry Johanson were able to develop a systematic design procedure based on bench scale bulk property testing. From a reasonable sized representative bulk sample of the material to be stored, material testing provides key parameters that can be used directly in an analytical design procedure. At present this is not possible in pneumatic conveying. Although many workers have attempted to classify bulk materials according to their pneumatic conveying mode of flow capability, none of the classifications can predict with certainty particularly around boundaries between categories of behavior. Neither can these classifications be used to establish the critical relationship between air flow rate, material flow rate and pressure gradient. This is an area of work that needs further development.

Many of the theoretical approaches that have been developed are empirically based. While this approach often yields good quality correlations for specific sets of circumstances it does little to further the real understanding of the mechanisms. The significant developments and reduction in cost of high quality instrumentation opens up many avenues for further investigation. An example of this is the miniaturization of technology which will allow the investigation of a much wider range of parameters in real time. An example of this is the work of Klinzing and Clarke (2012) in the development of the smart particle which will allow the direct measurement of particle acceleration. This will provide useful data to improve modeling and understanding of the mechanisms involved in pneumatic conveying.

15. Technical conferences related to pneumatic conveying

As noted previously, the literature in pneumatic conveying mostly like began in Germany with VDI and followed in the U.S. with the book on Fluidization and Fluid-Particle Systems by Zenz and Othmer (1960). Regular technical meetings began with Pneumotransport in 1972 lasting for about twelve years followed with Pneumatech lead by Stan Mason. Now-a-days the topic is regularly treated in most chemical and mechanical engineering journals along with specialized journals such as Powder Technology, Granular Matter, Multiphase Flow, Chemical Engineering Science and the American Institute of Chemical Engineers. The series of technical meetings lead by Kalman called Conveying and Handling of Particulate Solids (CHoPS) has provided a wide venue for researchers throughout the world. These conferences are

held every three years and CHoPS now beginning its 9th conference in 2018.

16. Future

Predicting the future is always dangerous because unforeseen development can surface which can upset the whole apple cart. At the present time there will undoubtedly more and more simulations and modeling approaches which can handle more and more particles that are not only spherical in nature. We have to address the non-spherical systems and multi-distributions and cohesive behaviors which occur in nature. In order to obtain the proper information to input into the models more basic physics must be explored experimentally. The ultimate goal is to be able to model a new system with new properties and guarantee that the behavior is realistic. When this occurs, we will have programs that can operate in a reasonable amount of time to give designs that are true to the nature of the material and the system. In many respects pneumatic conveying has the same future that all solids processing systems will have. To set a time frame for this will be a wild estimation but in 30 to 40 years we should be on our way to achieve our objective.

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Author's short biography

George Klinzing

Dr. George Klinzing is a professor of Chemical Engineering and served as the Vice Provost for Research at the University of Pittsburgh. He has directed 50 MS and 25 PhD dissertations in chemical engineering over a 53-year period with a focus on solids transport, handling, processing, and mass transfer.

He has been a consultant to DOE, Goodyear, Mountain State Energy, Allen-Sherman-Hoff, Kimberly-Clark, Dow Chemical, Certain Teed, U.S. Steel, Falconbridge, and Sarnoff.

His experience includes co-inventing the LICADO coal-cleaning process and two gas-solid flow meters; developing four software packages for pneumatic design; solid-liquid separation processing, particularly coal filtration and dewatering with an emphasis on solids characterization and analysis; research into fundamentals of coal-liquid and coal-gas transport as related to flow behaviors and energy requirements; coal-water slurry stability studies; and mineral filtration and dewatering process research into fundamentals of cake structure.

George Klinzing was the Chair of the Organizing Committee for the World Congress of Powder Technology-2006, has developed several patents, authored more than 254 publications, and has authored/co-authored two books on pneumatic transport.

He received a BS in Chemical Engineering from the University of Pittsburgh and a M.S. and Ph.D. degree in Chemical Engineering from Carnegie-Mellon University.

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