Proceedings of the 6th South American Conference on Industrial Engineering and Operations Management
Sorocaba, Sao Paulo, Brazil, May 12-15, 2025

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/SA6.20250073
Published: May 12, 2025

Development of a Low Pressure Dense Phase Pneumatic Conveyor for Friable Products

Regis de Oliveira Dantas, MSc
PhD Candidate, Engineer
Universidade Federal do ABC
Santo Andre, Sao Paulo, Brazil
Regis.Dantas.@ufabc.edu.br

Ricardo Borges dos Santos, PhD
Researcher
Universidade Federal do ABC
Santo Andre, Sao Paulo, Brazil
Ricardo.Borges@ufabc.edu.br

Luis Alberto Martinez Riascos, PhD
Professor, Researcher
Universidade Federal do ABC
Santo Andre, Sao Paulo, Brazil
Luis.Riascos@ufabc.edu.br

Rodrigo Giacometti Ramos
Engineering Manager
Zeppelin Systems Ltda
São Bernardo do Campo, Sao Paulo, Brazil
Rodrigo.Giacometti@zeppelin.com

Abstract

This paper presents the development of a low-pressure (i.e. less than 1 Bar), dense-phase pneumatic conveyor system designed for the gentle handling of friable solid food products, such as extruded pet food kibbles. The primary challenge is minimizing product damage during conveyance, particularly at pipe bends where collisions and velocity changes occur. To address this, an empirical design methodology was employed, involving mechanical design, prototype construction, and industrial-scale testing of a feeder and piping system using an air blower. A key innovation is an improved pressure control valve, based on orifice plate theory, that adjusts conveying air flow and thus transport speed by managing pressure variations. The initial phase of development involved the characterization of pressure flow and stability of the precision air flow valves. Preliminary results demonstrate the valve's ability to maintain a consistent pressure differential is crucial for efficient and damage-free material conveyance. The next phase of this work will focus on comprehensive material transportation tests to quantify conveying capacity and energy efficiency, alongside further refinement of the pressure control valve. This research contributes to improved handling techniques for delicate materials in food processing and other industries.

Keywords
Pneumatic Conveying, Dense phase, Energy Efficiency, Friable Solids, Low Speed Conveying.

1. Introduction
Pneumatic conveying systems are widely used for transporting dry, bulk materials in various industries. These systems utilize a gas stream (typically air) to move materials through enclosed pipelines, offering many practical advantages such as versatility, enclosed handling thus no dust emissions , and flexible routing ***[Mills, D. et all 2004]***. They can handle a wide range of materials and are particularly valuable when dealing with materials that require containment or protection from contamination or in modifications to existing congested bulk material transportation systems.

More specifically, the pneumatic conveying of bulk particulate solids in industrial settings often presents challenges when handling friable materials, which are susceptible to degradation and dust generation during transport. High-velocity conveying, in particular, can induce unacceptable levels of product damage (Mills et all 2004). Consequently, low-velocity pneumatic conveying systems are frequently preferred for such materials to minimize attrition and maintain product integrity . Examples include the conveyance of carbon black pellets in rubber manufacturing and pet food kibbles in food processing. For these applications, the adoption of closed-piping pneumatic conveying is contingent upon maintaining sufficiently low conveying velocities and carefully designed pipe routing to mitigate structural damage to the pellets or kibbles and powder formation.

1.1 Objectives
This project focuses on developing a dense-phase, low-pressure pneumatic conveyor for transporting solid finished products in the form of kibbles or pellets , specifically pet food pellets, over short to medium distances. The primary goal is to find design and operating parameters so as to minimize material degradation during transport. A secondary goal is to measure energy specific consumption for different regimes and design options**.**
Thus, the main and secondary research questions are:

RQ1: Is it possible to convey friable food products using low speeds and low pressure air sources such as the pressure levels that are delivered by root blowers ?

RQ2*:* If it is possible to convey friable food products using low speeds and low pressures such as the pressure levels that are delivered by root blower, would this be energy efficient ?

2. Literature Review
2.1- Pneumatic Conveying System Classification; Theoretical and Operational Dynamics and Open Research directions - Pneumatic conveying systems play an important role in numerous industries, primarily because of their adaptability and their environmentally friendly characteristics. These systems can transport a variety of materials efficiently and with minimal environmental impact, making them a preferred choice in sectors such as food processing, pharmaceuticals, and bulk material handling ***[Giudice et al., 2016; Kwan et al., 2017; Zhang et al., 2020].*** critical technological approach for material transport in various industrial processes, with classification fundamentally rooted in the average particle concentration and flow characteristics within transportation pipelines. Several academic research gaps have been identified including "energy efficiency and sustainability, material degradation, and particle damage" ***[Abe et all 2023].*** The most accepted taxonomic framework presented by ***[Mills, D. 2016]*** distinguishes between two primary conveying modes: dilute-phase and dense-phase pneumatic transport systems:

Dilute-Phase Pneumatic Conveying: In dilute-phase systems, particles are suspended in high-velocity air streams, exhibiting significant particle-gas interaction and minimal particle-particle contact. The dilute-phase pneumatic transport mechanism uses high air velocities (typically 15-25 m/s) to keep the particles in suspension. This ensures continuous and uniform particle distribution along the entire pipeline. This regime is particularly suitable for spherical shaped particles, usually lightweight, non-fragile materials with minimal risk of degradation during transportation.

Dense-Phase Pneumatic Conveying: Dense-phase conveying represents a fundamentally different transportation mechanism, optimized for the low speeds needed by fragile, abrasive, or cohesive materials. The lower air velocities (3-10 m/s) and substantially higher material concentrations [kg of solid Particulate per kg of Air , allows this conveying mode to minimize particle to particle and particle to wall attrition and thus minimize mechanical stress and wear . The unique transportation dynamics in dense-phase systems involve distinctive flow patterns: a) Particle settling at pipeline bottom; b) Formation of characteristic "plugs" or "dunes"; c) Pressure-driven material propulsion; d) Reduced particle-wall interaction.

2.2 The Zenz Diagram

Introduced by Zenz (1949), offers a graphical methodology for analyzing the various modes of pneumatic conveying systems specific to solid particles, which remains valuable in contemporary applications. According to (Klinzing et al. 2010), the Zenz Diagram serves as a significant analytical tool for understanding the dynamics of pneumatic conveying. By plotting the pressure drop (ΔP) per unit length of the pipeline against the superficial gas velocity (m/s), while keeping the flow cross-sectional area or pipe diameter constant, the area under the graph is proportional to power, expressed as $\Delta P \times (V \times A) = (N/m^2) \times (m^2) \times (m/s) = (N \cdot m/s)$. This representation facilitates visual comparisons and aids in design decisions aimed at reducing steady-state power consumption [Gomes de Freitas et al., 2020; 2022].

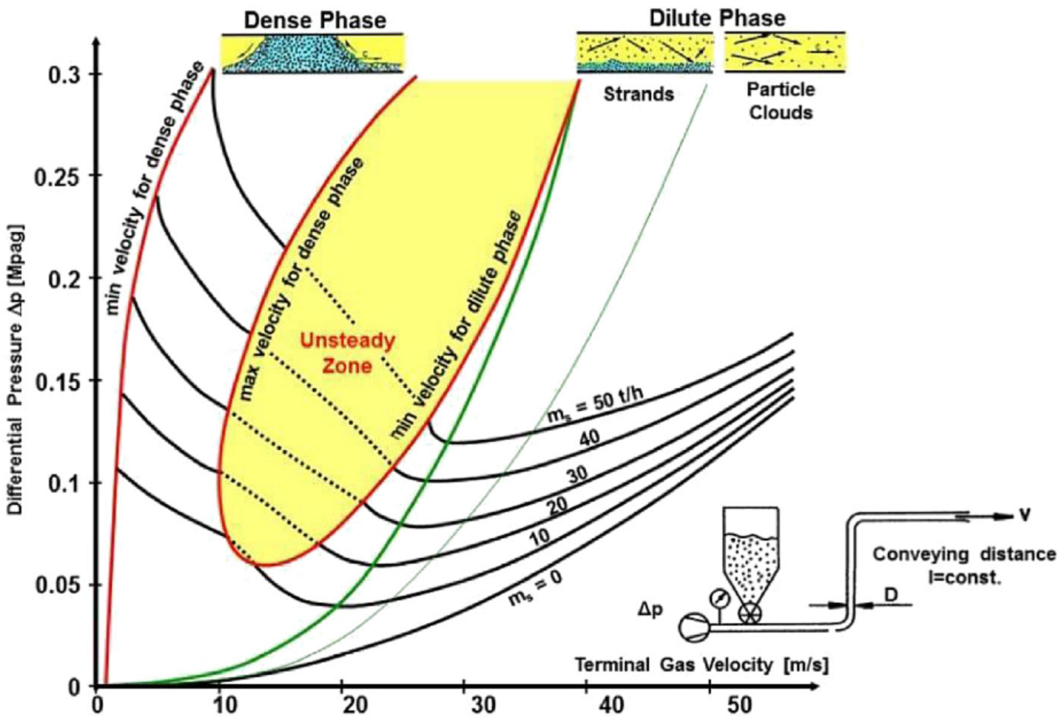

Figure 1. Zens Diagram for Dense, Unstable area, and Dilute Regimes (adapted from **[de Freitas et all 2022]**)

The Zens graphical representation delineates three primary conveying regimes according to **[Klinzing,G et all 2019]**: first a) *Dense Phase* regime with low gas velocities, high material concentration, minimal pressure fluctuations, reduced particle acceleration. b) The second area is characterized by an *Unsteady Zone* which is a transitional zone with high probabilistic risk of material blockages, Insufficient air velocity for consistent particle suspension and as such characterized by unpredictable flow behaviors. c) The third region is the *Dilute Phase* regime with high gas velocities, low material concentration, continuous particle suspension and maximized material-gas interaction.

2.3 Operational Implications and Material Considerations

The design selection between dilute phase or dense phase conveying depends on various critical parameters such as: conveyed material physical properties, particle size and shape distribution, particle mechanical fragility or wear and energy consumption considerations.

While the Zens diagram provides an important basis for understanding there are theoretical limitations to this approach. Recent research increasingly recognizes the complexity of pneumatic conveying dynamics. New findings through computational modeling techniques and advanced sensor technologies are continuously refining the understanding of particle-gas interactions and flow regime transitions. Pneumatic conveying system classification uses intertwining concepts from fluid dynamics, particle mechanics, and industrial engineering principles. The detailed understanding of these flow regimes enables optimized material transportation and energy savings for various specific industrial applications.

Figure 1 depicts the Zens diagram, illustrating the linear pressure drop (ΔP/l) versus superficial gas velocity (U), delineating dense-phase and dilute-phase conveying regimes. Material flow representations for each regime are shown schematically. The central region represents an unstable transport zone, characterized by a critical transition between dense and dilute phases. This instability emerges from reduced gas velocity concurrent with constant material feed rate. Under these conditions, insufficient air velocity prevents particle suspension, resulting in material precipitation and potential pipe blockage.

The unstable regime represents a mathematically intricate zone where particle-gas interactions become nonlinear, gravitational effects take precedence, and the efficiency of pneumatic transport significantly declines (Wypicht 2009***)***. In this region, the likelihood of mechanical obstructions increases exponentially. To mitigate these challenges, it is recommended to implement strategies such as precise velocity control, optimized material feed rates, dynamic pressure management, and the integration of advanced flow monitoring and control systems, commonly referred to as booster valves (Deng et al., 2021; Zhang et al., 2022).

3. Methodology

The methodology being used is empirical including extensive measurements at a test center in Sao Paulo. This was achieved by designing and setting to work a small industrial scale testing set up including feeding devices at a reasonable rate and reasonable distance of conveyance. Here the term "reasonable" indicates that these sizes exceed typical laboratorial dimensions and could be used for a small production facility.

This paper details the design process, empirical execution, and testing of several configurations of this conveying equipment. At the current stage, it presents preliminary results for the special pressure control valve developed. It is important to note that this valve is a key component to control pressure and flow during the conveyance and is for the system's performance.

4. Data Collection

The initial phases of the project focused on creating the necessary components for a dense-phase, low-pressure pneumatic conveyor system for the pet food industry. An industrial-scale prototype is being developed and tested at the Zeppelin Systems Latin America Ltda test center in São Bernardo do Campo, São Paulo , Brazil.

The first focus was on obtaining a flow regulating valve that could allow tests to validate the design, carry out several tests with different configurations, convey products, identify acceptable ranges and also eventually optimal operating range for material transport, and analyse possible continuous improvement opportunities.
The following set up was installed:

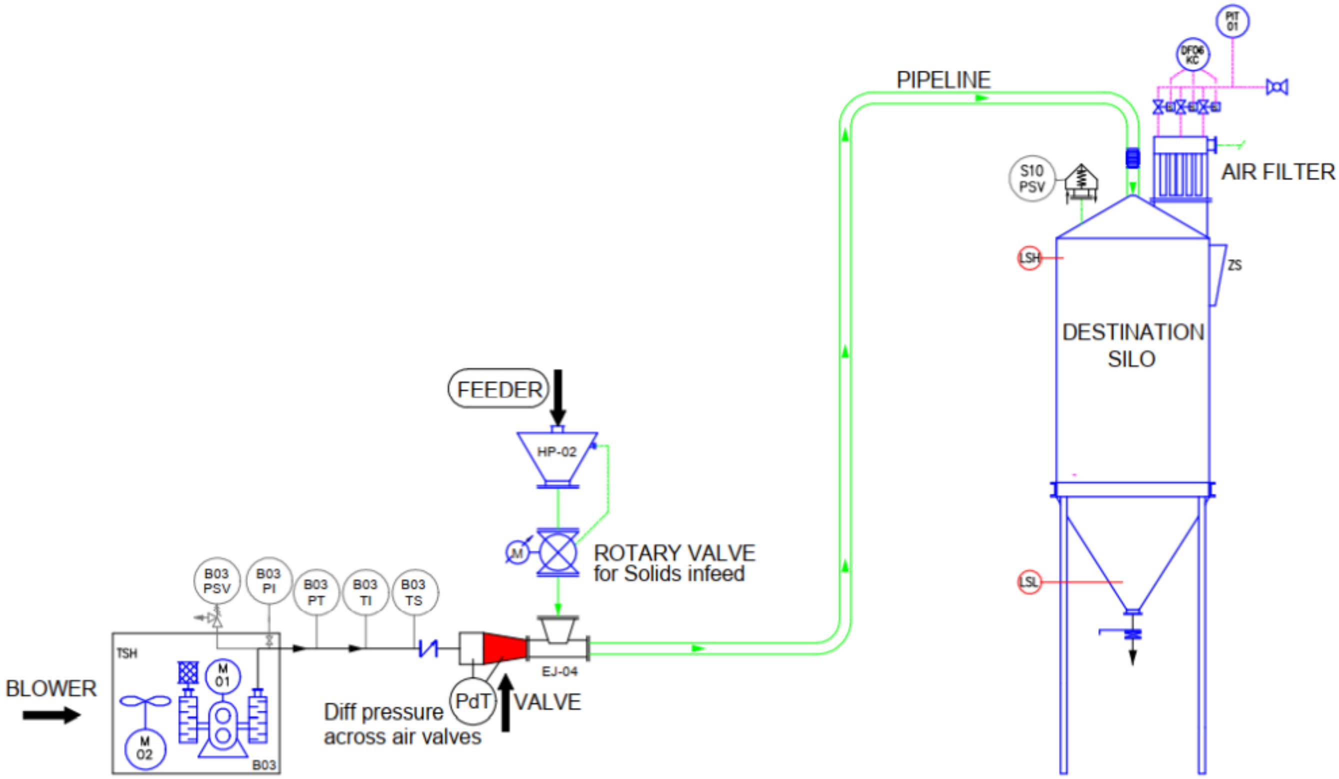

Figure 2. Schematic of test set up (by Authors)

The flow sheet for the test system is depicted in ***Figure 2.*** The set-up is designed for short to medium distance transport of finished goods or materials susceptible to damage. The manipulated variables are air flow volume and solids mass rate through a rotary valve. The measured variables are: Pressure differential across the air dosing valve , pressure at the beginning of the conveying pipe and mass in the destination silo (measured by load cells) Initial tests are conducted on a 3-inch diameter, 20-meter-long pipeline. This was later extended to a 4 inch pipe and a length of 60 m.

The choice of a rotary feeder for the feeding of granulated solid material is based on the established fact that the rotary valve is considered ideal for all non-abrasive applications with free flowing bulk solids. The rotary valve has become the choice for feeding of bulk solids into conveying lines, due to precision machining available today. Rotary valves with open rotors account for only small leakage air flow rates (Wilms, H; dosSantos, R 2002***)***.

A roots type air blower with an electric motor of 22 kW is used as the compressed air energy source, capable of generating up to 1 bar of pressure. The choice of a blower over a compressor was made due to its lower CAPEX (capital expenditure) costs, as well as due to lower operational and maintenance costs. A low-pressure transportation system based on a rotary blower should also achieve a more energy-efficient alternative as compared to a mid or higher pressure compressor.

Material is fed into the line using a rotary valve to ensure a continuous and metered flow. The system is designed to operate in dense phase near the critical velocity, making it susceptible to blockages caused by pressure fluctuations. A custom-designed pressure control valve minimizes pulsation in the conveying line by regulating pressure variations. Maintaining a small pressure differential (ΔP) across the control valve, measured before (PT1) and after (PT2) the valve, is crucial for proper operation. The objective is to maintain a constant transport pressure (PT2) downstream of the valve. This allows for precise control of transport velocity, minimizing material breakage and preventing blockages. The valve modulates pressure by opening or closing, stabilizing the total system pressure drop with minimal pulsation. The target range for ΔP variation is 80% to 95%.

The valve design is based on orifice plate theory, aiming for subcritical flow conditions during operation. This allows for pressure variations to maintain the desired line velocity. Calculations were performed considering the Nozzle type De Laval theory. An orifice plate is a flow restriction device used to measure fluid flow rates. It creates a pressure drop as fluid passes through a precisely sized opening. The pressure difference is then correlated to the flow rate using established equations, such as those in [ABNT NBR ISO 5167-2]. Orifice plates are simple, robust, and widely used in industrial applications for measuring the flow of liquids, gases, and vapors (Figure 3a 3b).

Figure 3A and 3 B- Research apparatus and set up under test showing Rotary Valve, Blower-Motor , Air Dosing Valve and surrounding piping (by Authors)

5. Results and Discussion

To characterize the valve's performance, tests and measurements of pressure drop were conducted across various pressure ranges to map its operating curves .

Results are presented in tabular form in Attachment 1 and in a graphical format below for the valve 100%, 75%, 50% and 25% open. Figure 4 shows four graphs of pressure drop (ΔP) as a function of flow rate (Q), displaying isobaric curves between 300 and 1000 mbar for valve openings of 100%, 75%, 50%, and 25%. The characteristic behavior of a De Laval nozzle is evident. The region of interest is on the left side of the graphs, where a small change in ΔP corresponds to a large change in flow rate. This represents the subcritical (unblocked) operating condition of the orifice plate. As the flow moves to the right, the critical region is encountered, where the flow rate becomes nearly constant, and ΔP decreases, resulting in near-vertical lines. This indicates a choked flow condition. Closing the valve reduces the maximum flow rate achievable for a given pressure range.

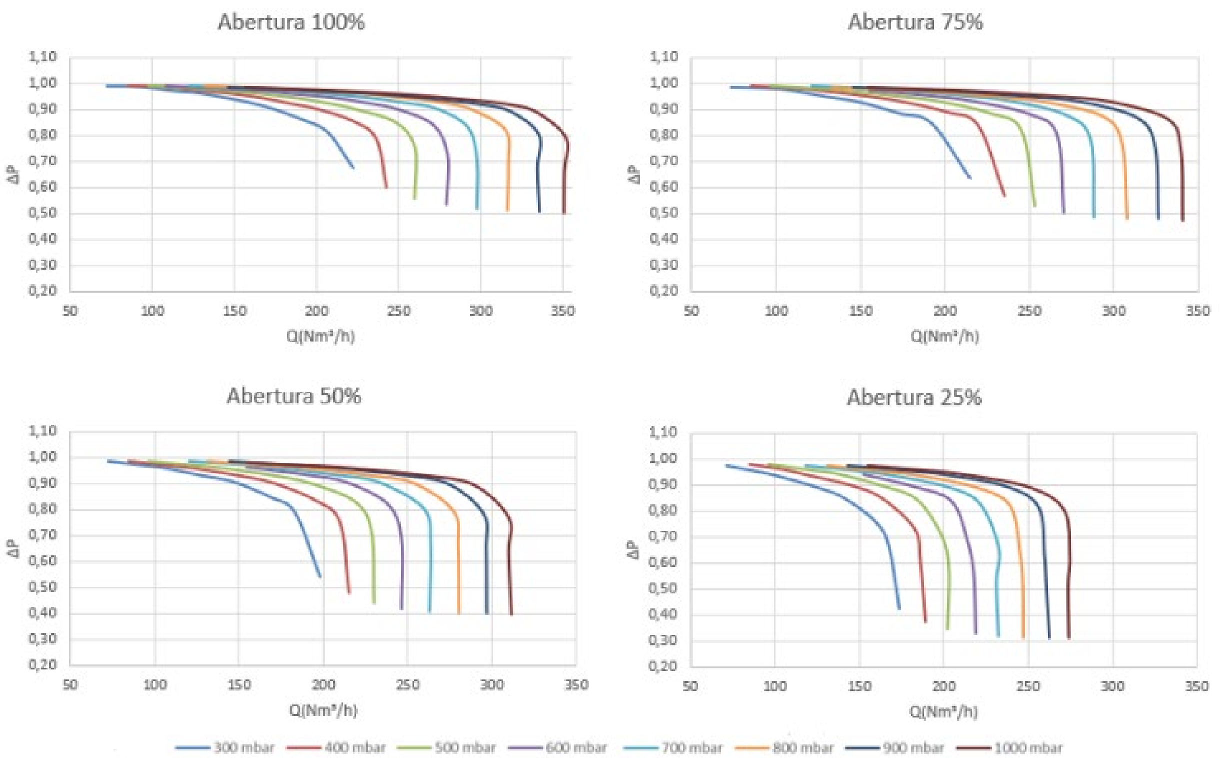

Figure 4. Characterization of Control Valve, note that the title "Abertura" means "Opening"(by Authors)

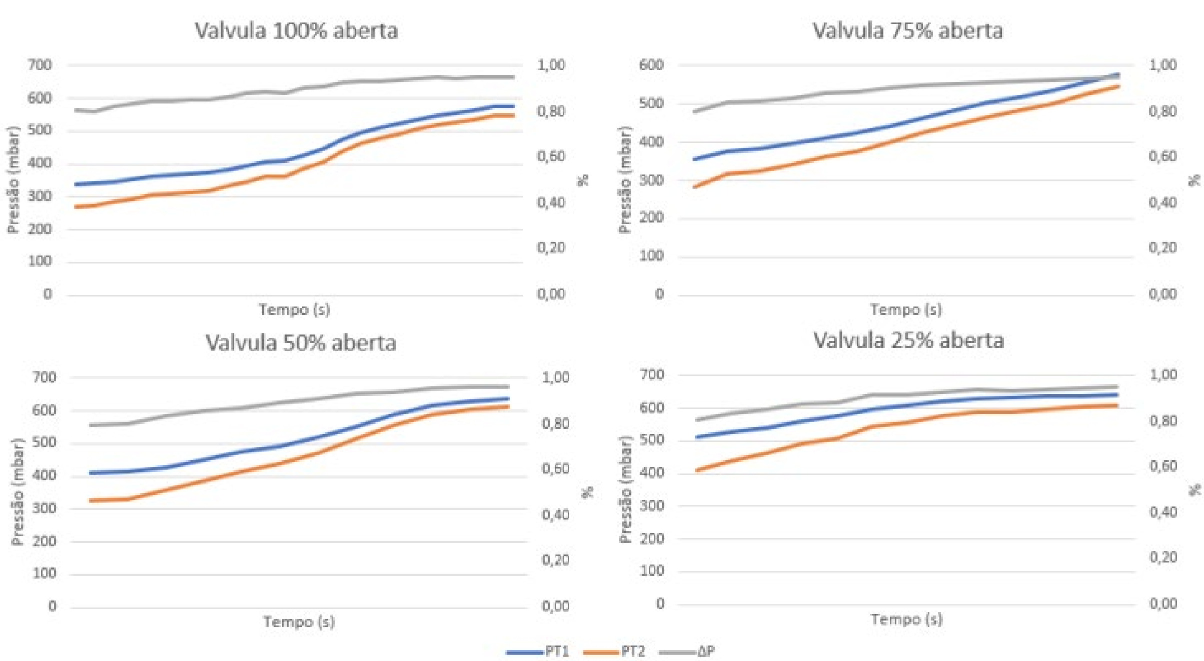

Figure 5. Operating Pressures and Pressure Drop for Blower Frequency of 30Hz with valve ("valvula") 100%,75%,50% and 25% open ("aberta") (by Authors)

Figure 5 presents results from the valve operating in conjunction with the blower at a frequency of 30 Hz, simulating an increasing pressure drop over time. The graphs highlight the region of interest, between 80% and 95% of ΔP. The blue curve represents the pressure upstream of the valve (PT1), and the orange curve represents the pressure downstream (PT2), which is the transport pressure of the system. The gray line represents the values of ΔP

As the pressure drop increases, due to material accumulation in the line, the downstream pressure rises. This requires a small increase in upstream pressure to initiate material transport. The graphs show that as the pressure drop increases, the values of PT1 and PT2 also change to maintain a constant transport velocity. During operation, both the valve position and the blower work together to stabilize the pressure drop, thus controlling the transport velocity.

The above data and graphical analysis allows us to expect a good quality of control of pressure drop and flow throughout the range of interest with respect to resolution and rangeability. In light of this, the tests of the system with different products such as grain (whole grains of corn dry) will soon be conducted.

6. Conclusion

This study explores a flow control valve to be integrated into a low speed low-pressure pneumatic conveying of friable products using a blower instead of a compressor to reduce costs and improve energy efficiency. The valve design aims to maintain minimal pressure drop and control transport velocity.

The valve demonstrated satisfactory performance, meeting the project's expectations. Its role in the pneumatic transport system is crucial, as it stabilizes the line pressure. When there is an increase in pressure, the valve opens, allowing more air to pass and providing time for the blower's frequency inverter to adjust the air flow, thereby preventing blockages. Once the pressure normalizes, the valve returns to its initial setting.

Preliminary results are promising, but additional testing with different granulate solids is needed to answer research questions RQ1 and RQ2.

Further Work

The next phase of the project involves tests of the system with different solid particulate materials. The tests with in-line materials. will be performed initially using corn grains, a granular material of greater hardness, which will allow us to gain experience and evaluate the system without compromising the raw material. Following this phase, tests will be carried out with friable products such as animal feed pellets, a product more sensitive to transportation. Mass flow results for different pressure- flow conditions will be collected and analyzed in order to evidence the system's effectiveness and validate its performance under real-world conditions. Further, the research will dive deeper in the evaluation of results and systematic improvement of the controls, valve and feeder. The results will be reported in a paper to be made public in the next few months.

Acknowledgements

The authors would like to thank Zeppelin Systems Latin America for the non financial support and use of their Laboratory for the research.

References

Abe, M.C.; Gelladuga, G.A.; Mendoza, C.J.; Natavio, J.M.; Zabala, J.S.; Lopez, E.C.R. Pneumatic Conveying Technology: Recent Advances and Future Outlook. Eng. Proc., 56, 205. 2023. https://doi.org/10.3390/ASEC2023-16267

ABNT NBR IS0 51 67-2:2011 - Medição de vazão de fluidos por dispositivos de pressão diferencial inseridos em condutos forçados de seção transversal circular Parte 2: Placas de Orifício ISBN 978-85-07-02758-4, 2011.

de Freitas, A. G., dos Santos, R. B., Pereira, L. M., Lima, Y. O., & Riascos, L. A. M. , Transporte pneumático de particulados –Otimização energética em um novo vaso de pressão [Not available in English]. In 2021 *14th IEEE International Conference on Industry Applications (INDUSCON) (pp. 999-1004). IEEE.*

de Freitas, A. G., de Oliveira, V. F., dos Santos, R. B., Riascos, L. A. M., & Zou, R, Optimization method for pneumatic conveying parameters and energy consumption performance analysis of a compact blow tank. *Journal of Pressure Vessel Technology*, 144(6), 064504, 2022.

Deng, H., Liu, H., & Zhang, Q, *The effect of carrier gas properties on pneumatic conveying performance. Materials Today: Proceedings,* 47, 3101-3106, 2021. *https://doi.org/10.1016/j.matpr.2021.05.456*

Giudice, A. L., Crea, D., & Rizzo, S, Industrial Applications of Pneumatic Conveying Systems. Chemical Engineering Transactions, 53, 835-840, 2016. doi:10.3303/CET1653140

Gomes de Freitas, A., Furlan de Oliveira, V., Oliveira Lima, Y., Borges dos Santos, R., & Alberto Martinez Riascos, L. , Energy efficiency in pneumatic conveying: performance analysis of an alternative blow tank. Particulate Science and Technology, 39(7), 868–876, 2020. https://doi.org/10.1080/02726351.2020.1850574.

Klinzing, G. et al. Pneumatic Conveying of Solids: A theoretical and practical approach. Third edition. [s.n.], 2010. ISSN 1567-827X. ISBN 978-90-481-3608-7.

Klinzing, G., A Review of pneumatic conveying status, advances and projections, 2020. https://doi.org/10.1016/j.powtec.2018.04.012

Kwan, S. Y., Chen, S. S., & Liu, C. Y, Environmental Impact of Pneumatic Conveying Systems in the Food Industry. Journal of Cleaner Production, 140(1), 119-128, 2017. doi:10.1016/j.jclepro.2016.05.083

Mills, D.; Jones, M. G.; Agarwal, V. K. Handbook of pneumatic conveying engineering. 1st edition. ed. [S.l.]:Marcel Dekker, 2004. 720 p. ISBN 0824747909.

Mills, D, Pneumatic Conveying Design Guide (Third Edition),Butterworth-Heinemann, 2016, Pages 595-616 ,ISBN 9780081006498, https://doi.org/10.1016/B978-0-08-100649-8.00026-3.

Zhang, Y., Wang, X., & Huang, J, Advances in pneumatic conveying technology: A review. Powder Technology, 373, 471-485, 2020. doi:10.1016/j.powtec.2020.08.017

Zenz F.A. Two-phase fluid-solid flow. Ind Eng Chem, 41(12):2801–6., 1949.

Wilms, H ; dos Santos, RB ; *Basics Of Pneumatic Conveying Systems Design*; 2002/3/18; International Congress on the Process Industries.

Wypych, P W, Pneumatic conveying of bulk solids. University of Wollongong. Thesis. 2009. https://hdl.handle.net/10779/uow.27646743.v1

Biographies

Regis de Oliveira Dantas is a Ph.D. candidate in Energy Engineering through the Industrial Academic Doctorate Program at the Federal University of ABC, in partnership with the German multinational Zeppelin Systems Latin America. His research focuses on the development of a new pneumatic transport equipment with an emphasis on energy efficiency. He holds a master's degree in Mechanical Engineering (2019), specializing in solid mechanics and the application of numerical methods in structures. He also earned a degree in Aerospace Engineering (2018) and a Bachelor's in Science and Technology (2014), all from the same institution. In the industry, he was part of the first cohort of researchers at Nestlé Brazil's Innovation and Technology Center (2020-2022), where he worked on research and development of innovative engineering solutions for manufacturing challenges.He has been conducting experimental research on Pneumatical Conveyance and Solid-Gas flow at the Pneumatic Conveying Laboratory of Zeppelin System Latin America in Sao Bernardo do Campo, Brazil since 2021

Ricardo Borges dos Santos is a post doc Researcher at Universidade Federal do ABC, Sao Paulo, Brazil. He earned his Master of Science Degree in Mechanical Engineering from the Penn State University, USA in 1989, and his PhD in Computer Science from the Center of Mathematics, Computation and Cognition of the Universidade Federal of ABC, Santo André, São Paulo (2020). His areas of research include Energy Efficiency, Pneumatic Conveying, Blockchain, Smart Contracts and Traceability, Food Supply Chain among others. From 1990 to 2024 Ricardo held executive positions in important German Machine and Equipment Manufacturing Industries. He is also a registered Lawyer in Sao Paulo Brazil. He was a member of the Board of the VDMA (German Machine and Equipment Manufacturer for Brazil for 7 years. He has been conducting and supervising research on Pneumatical Conveyance and Solid-Gas flow at the Pneumatic Conveying Laboratory of Zeppelin System Latin America in Sao Bernardo do Campo, Brazil since 2016 and has co-authored several international papers on the subject.

Luis A.M. Riascos is a Full Professor at the Universidade Federal do ABC, SP, Brazil. He has a Mechanical Eng. degree from Universidad del Valle, Colombia, he is also a MSc. and Dr Eng. degree from Universidade de São Paulo, Brazil. Holds a Post-Doc. from the Colorado School of Mines, USA. His research areas include Mechanical Design, Robotics, Manufacturing Systems, Fault Diagnosis, Energy Efficiency among others. He has been supervising research on Pneumatical Conveyance and Solid-Gas flow at the Pneumatic Conveying Laboratory of Zeppelin System Latin America in Sao Bernardo do Campo, Brazil since 2016 and has co-authored several international papers on the subject.

Rodrigo Giacometti Ramos is a Mechanical Engineer from Universidade Estadual Paulista (UNESP) – Bauru, São Paulo, with over 25 years of experience in engineering and industrial process optimization. Specializing in pneumatic conveying systems for bulk solids, he develops innovative solutions and executes industrial projects for material handling. Throughout his career, he has gained extensive expertise in the field, working for renowned companies and collaborating with leading technology centers in the United Kingdom and the United States. Currently, he conducts research at Zeppelin's test center and leads product and application engineering at Zeppelin Systems Latin America since 2020.