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Pneumatic Conveying Technology: Recent Advances and Future Outlook †

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Abstract: Pneumatic conveying is a vital technology for delivering bulk solids, powders, and granular materials in various industries. Significant advances in pneumatic conveying technology have occurred in recent years, spurred by the demand for sustainable and energy-efficient industrial processes. This paper explores the current advances in pneumatic conveying technology and their implications for the industry. First, the principles of pneumatic conveying are discussed. Then, two significant advances in pneumatic conveying technology are highlighted. Schenck Process, for example, has created the Enhanced Dilute Phase Pneumatic Conveying (EDIP) system, the E-Finity continuous dense phase system, and high-pressure systems utilizing Lontra's LP2 Compressor Blower. Second, Palamatic Process provides dense-phase vacuum conveying cyclones as well as powder pumps for nonabrasive dense-phase vacuum conveying. Several research gaps in pneumatic conveying technology are identified in the paper, including the integration of artificial intelligence and machine learning, the optimization of multiphase flow behavior, energy efficiency and sustainability, material degradation, and particle damage, handling of cohesive and difficult-to-convey materials, scale-up and design optimization, and real-time monitoring and control systems. The future outlook highlights the potential of sustainable practices to advance pneumatic conveying technology further. The integration of these technologies can lead to improved performance, energy efficiency, and sustainability in pneumatic conveying systems.

Keywords: pneumatic conveying; Schenck Process; Palamatic Process; cyclones

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1. Introduction

Pneumatic conveying is an essential technology for the efficient and dependable transportation of bulk solids, powders, and granular materials used in various industries. Pneumatic conveying systems use air or gas as the conveying medium, and the materials are transported through pipelines or ducts using a combination of pressure and airflow [1]. The advantages of pneumatic conveying include its ability to move materials over long distances, flexibility in routing, and transport materials in a closed system that minimizes dust and other environmental hazards. The use of pneumatic conveying is widespread and may be found in many facets of the solid manufacturing industry, from mining to handling food and polymers. According to the projections made by the solids processing sector, the global market for conveying systems is expected to exceed and grow after 3 to 5 years [2].

In recent years, there has been a significant increase in the demand for more sustainable and energy-efficient industrial processes. It is anticipated that creating sophisticated numerical models that accurately depict the surface charge distribution will improve the accuracy of the future modeling techniques of pneumatic conveying [3]. This has driven the development of new and improved pneumatic conveying technologies to meet these demands. Innovations in this field have led to the creation of novel systems, control strategies, and enhanced equipment designs that promise to revolutionize the way materials are conveyed pneumatically.

One of the most significant advances in pneumatic conveying technology is the development of high-pressure systems that allow for transporting materials over even longer distances. High-pressure systems use compressed air to move materials through pipelines, reducing the need for energy-intensive pumps or other mechanical devices. Additionally, these systems can be operated with lower flow rates, reducing energy consumption and improving overall efficiency. Another recent innovation in pneumatic conveying is advanced control strategies that allow for more precise control over the conveying process. These strategies incorporate real-time feedback mechanisms and predictive analytics, enabling operators to make real-time adjustments and optimize the process for maximum efficiency.

Enhanced equipment designs also contribute to advancing pneumatic conveying technology. For example, using new materials and coatings for pipelines and ducts can improve their durability and reduce wear and tear, minimizing maintenance and improving the system's longevity.

Overall, the recent innovations in pneumatic conveying technology have the potential to impact the way that materials are transported in various industries significantly. By providing a more energy-efficient and sustainable solution for material transportation, these advancements can help reduce costs, increase productivity, and minimize environmental impact. This will eventually help various industries deal with pneumatic conveying technologies, such as the pharmaceutical, food, cement, minerals, and power industries, among others. Ultimately, this paper aims to explore the recent innovations in pneumatic conveying technology, contextualize them within the broader material handling landscape, and examine their potential implications for industries worldwide.

2. Pneumatic Conveying

2.1. How It Works

Pneumatic conveying systems move air via pipelines, transferring a propelling force that transports bulk products from one end of the system to the other. Pneumatic conveying necessitates a pressure difference between the system's beginning and ending points, accomplished using compressors, fans, or blowers.

Two primary types of pneumatic conveying systems are the lean and dense phases. Each is utilized for a distinct purpose and has separate functions.

2.1.1. Lean Phase

Materials are moved using suspension, lean, or dilute phase pneumatic conveying using positive and negative pneumatic conveying methods. In a positive phase system, a fan produces pressure in the pipe and retains the product. A separator or filter is utilized to get rid of the material at the final point of the line. The velocity of materials ranges from 15 to 35 m per second (m/s). A pressure vessel and an input valve that cycles less and is not in perpetual motion are necessary for dilute system design.

Negative pressure systems, often known as vacuum systems, operate in reverse. They produce a vacuum and pull material through the line rather than pushing or blowing material through it.

2.1.2. Dense Phase

Dense phase conveying systems are suitable for moving sensitive or fragile materials. These systems can handle and transfer products at lower speeds, which helps prevent impact damage to the product. Dense phase systems use air pulses to force the product through, followed by another air and product pulse.

In contrast, to lean phase systems, dense phase systems necessitate more exact calculations for optimum design and timing. When using these systems, the overall density, particle size, and run or duration will assist and decide the air-to-product ratio.

Dense-phase pneumatic conveying may utilize "booster pulsers" to transport the product and liberate it from the piping walls. Many controls are installed through the constraints of the hopper section and the lining of certain pipe sections, which inputs small injections of air to manage the firmness of the product and keep the pipeline speed constant.

Although boosters improve the speed of the material being pushed, they also raise costs of upkeep and downtime and serve as a marketing ploy. Boosters should only be used when essential and when the circumstances justify it. Since the conveying pipeline is firmly packed, no air passes through the material, increasing efficiency. Because few material particles touch the piping or tube, pipe abrasion and wear are reduced.

2.2. Parts

A pneumatic conveying system's design uses cuts and pipes to move materials using air streams. An air mover is positioned at the system's starting point to force the materials through the line while providing pressure or a vacuum at the system's conclusion to pull materials through. The primary mover, conveying line, feeder, and separator are the four typical components of a pneumatic conveying system [4].

The Prime Mover is a device that initiates the flow and pressure of the air system. This allows the conversion of pressure energy into mechanical energy using the expansion of compressed gas. Equipment that can be considered for this is a blower, compressor, exhauster, vacuum pump, or fan [4].

The blower can be used to move materials using a pneumatic conveying system. When considering the system's design, the amount of pressure drop through the system is one of the relevant factors. This is most extensive at the end of the system. This enables the application of force that pushes material down the pipeline [4].

A vacuum pump is another piece of equipment used to move material. This can also be utilized in dense phase systems and is frequently used for a dilute phase system. The vacuum conveyor pulls the material through and is positioned to the right at the end of the pneumatic pipeline [4].

Compressors are used to supply airflow for all equipment in a system. There are two types of compressor. A positive displacement can be used to mechanically reduce the space occupied by air to increase the pressure in a system. Then a dynamic air compressor uses mechanical rotating impellers to convey pressure to the air. Meanwhile, the exhauster increases the speed and lowers back pressure, enhancing the system's performance. The fans are designed to reduce hazards, and it drives air motor fans at high speed, thus providing air to the system [4].

The feeder introduces bulk material in the gaseous stream without allowing any contamination in the storage. Equipment that can be considered is a venturi, screw, rotary valve, blow vessel, or feeder to introduce the solids under controlled conditions into the air streams [4].

The venturi is a section in a pneumatic conveying system that converts the pressure energy of a high-pressure air stream into velocity. Venturi eductors need positive pressure from a suitable blower to power the conveying operation. This substitutes rotary valves or electric pumps when powering the product conveyance.

The conveying line consists of pipework and fittings in which bulk materials are conveyed. Components comprise horizontal and vertical sections, straight branches, bends, and diverter valves. A separator is a subsystem that separates solid particles from air when materials are being conveyed to fill the storage. The components that can be used for storage are a receiver, silo/vessel, or cyclone to separate materials.

3. Innovations

3.1. Schenk Process

Schenk Process, a company from Doncaster, the UK, demonstrates competence in dense, injection, lean, and vacuum pneumatic conveying systems. The Enhanced Dilute Phase Pneumatic Conveying (EDIP) system, which employs air provided by Lontra's revolutionary LP2 Compressor Blower, and the company's newly patented E-Finity® continuous dense phase system is among the new advancements.

Dense phase conveying is an environmentally benign method of transporting delicate or abrasive materials through pipes at exceptionally steady yet low speeds, decreasing product degradation and equipment wear. Schenck Process is able to evaluate conveying ranges of up to 500 m using the conventional dense phase configuration, which may employ 80 mm, 100 mm, and 125 mm pipes. A range of options are offered with simple pipes, density stabilizers, and autoflow.

Schenck Process's E-Finity system is a proprietary continuous dense phase system that delivers the smooth and energy-effective transportation of granular and pellet materials. Conventional continuous dense phase systems include blowers and rotary valves, which can result in unsteady air leaks because of increased pipeline pressure. To address this issue, the E-Finity system employs accurate pressure monitoring to operate the valves and regulate the airflow, automatically adjusting for any leakage or temperature fluctuations. Schenck Process can evaluate conveying air, pressure, feed rate, leakage, and power usage using the E-Finity conveying system. It will offer 100 mm pipe routes up to 240 m with a 1 bar g blower or regulated compressed air supply for greater lengths. The substance will be supplied at a speed of up to 10 m3/h through a loss-in-weight hopper or a huge bag discharger.

Following the partnership with Lontra to deploy its LP2 blower, featuring their unique Blade Compressor® technology, lean phase conveying capabilities have also been strengthened. The pipes have diameters ranging from 50 mm to 125 mm and can transport up to 500 m at 10 ton/h rates, whereas the rotary values range from 200 mm to 300 mm. The Test & Innovation Center demonstrates the capabilities of the cutting-edge, highly efficient EDIP in relation to the conventional lean phase method using this new technology [5].

3.2. Palamatic Process

Palamatic Process is a company based in France that includes bulk material manufacturing lines in which pneumatic conveyors are included. Within the VFlow® product range, Palamatic Process provides five variants of vacuum conveying cyclones for dense phase pneumatic transfer. Their line for the dense phase is designed for abrasive materials to prevent damage to conveying lines and the disintegration of granules and friable powders. These systems, particularly if utilized with weighing systems, can be used with metering equipment to feed raw materials into the manufacturing process in a regulated manner.

The latest generation of powder pumps from the Palamatic Process design office provides nonabrasive dense phase vacuum conveying, which minimizes material deterioration and the development of additional dust inside powder managing industrial processes. This cyclone is well suited for problematic materials (abrasiveness, explosive, poor circulation, or friability), and it is placed in the process with expansion options to meet its manufacturing needs. Clean-in-place conveying, line purge vacuum systems, and hygienic vacuum-conveying equipment are alternatives. The conveying system might be configured with many feed locations and destinations in the process. Systems can also feed material into a pressurized reactor vessel without extra air.

This company provides V-Flow®, the vacuum transport system, which operates on the tenet of the dense phase. Bulk material is gathered using an electric or pneumatic vacuum pump to a tangential arrival cyclone.

It is then vacuumed via a pneumatic conveyor gearbox located at its point of recession until it reaches the vacuum cyclone, which comes with small-sized filters to differentiate the product from air. The vacuum cyclone is outfitted using a butterfly valve and a level probe, enabling regular emptying. This type of powder pump achieves speeds ranging from 5 to 10,000 L per hour while consuming little energy and requiring little maintenance. The table in the section below shows the specifications for this technology [6].

4. Research Gaps

Recent advances have been seen in the world of pneumatic conveying, where we have observed improvements concerning low-energy consumption levels while also leading to high-material handling accuracy rates due to efficient mechanisms introduced via technology. However, even with all these advances thus far, it is still apparent that several research areas need examination if we are ever going to elevate further how we approach pneumatic conveying. These research gaps include, but are not limited to, the integration of artificial intelligence and machine learning techniques, optimization of multiphase flow behavior, energy efficiency and sustainability, material degradation, and particle damage, handling of cohesive and difficult-to-convey materials, scale-up and design optimization, and real-time monitoring and control systems. Thus, in this review paper, we seek to learn about these research gaps while assessing how each can impact the field of pneumatic conveying.

Artificial intelligence (AI) and machine learning (ML) approaches represent one significant research gap in recent developments in pneumatic conveying. The effectiveness and performance of pneumatic conveying systems have improved significantly, but there is still room for improvement in utilizing AI and ML algorithms to optimize different parameters. Real-time data analysis, predictive modeling, and adaptive control can be made possible by applying AI and ML in pneumatic conveying, improving system performance, lowering energy use, and increasing reliability. In a study that tackled the CFD-DEM approach regarding its simulation, it was shown to be currently the most promising in generically addressing a variety of complex phenomena, given the rapidly advancing state of computer technology. This method has been quickly developed and deployed to research pneumatic conveying in recent years, including everything from flow dynamics to process performance [7].

Another gap focuses on the optimization of multiphase flow behavior. In pneumatic conveying, solid particles interact intricately with a gas medium, changing several characteristics, including the trajectory of the particles, the pressure drop, and the interactions between the particles and the walls. Despite recent advances, the behavior of multiphase flow in pneumatic conveying systems still needs to be better understood and characterized. Part of this is investigating how particle size distribution, shape, material characteristics, and gas flow dynamics affect system performance and conveying efficiency. Optimizing the multiphase flow behavior can also reduce particle deterioration or damage, increase energy efficiency, and reduce the wear and tear of conveying equipment. It is strongly advised to incorporate new collision terms into the multiphase particle-in-cell (MP-PIC) approach for forecasting dilute-phase flows [8]. By bridging this research gap through experimental studies, advanced modeling techniques can aid in creating more effective and dependable pneumatic conveying systems.

Recent developments in pneumatic conveying have left a significant research gap focused on energy efficiency and sustainability. Even though pneumatic conveying systems have seen tremendous improvements in their overall performance, there is still a need to address these processes' energy usage and environmental impact. Investigating cutting-edge strategies to improve energy effectiveness, lower carbon emissions, and promote sustainable practices in pneumatic conveying systems is critical. To reduce energy waste, this entails researching the utilization of renewable energy sources, improving compressor technology, putting energy recovery systems in place, and creating sophisticated control procedures. In a study [9], a novel industrial bulk solids feeder called Batchpump is experimentally characterized as a feeding mechanism for dense phase pneumatic conveying. Although it has smaller dimensions and a simpler operating system than conventional blow tank versions, the created device was found to have equivalent performance parameters. This has significant benefits for retrofits and implementing a new conveyor line.

Additionally, research efforts should concentrate on assessing the environmental impact and life cycle analysis of pneumatic conveying systems, considering resource use, material degradation, and carbon emissions.

Understanding and minimizing material deterioration and particle damage are vital research gaps in light of the recent advancements in pneumatic conveying. Many materials, including delicate or abrasive particles that may degrade or be damaged during the conveying process, are frequently transported using pneumatic systems. There is still a need for study in regard to avoiding particle breakage, reducing the wear and tear of conveying equipment and optimizing the conveying parameters to maintain material integrity despite improvements in system design and material handling procedures. According to a study on biomass degradation in pneumatic conveying systems, it can be difficult to assess the degradation of bulk biomass materials since the particle velocity in pipe bends might vary greatly depending on the kind of material [10]. This research gap encompasses investigating novel methods to lessen particle damage, including developing protective coatings, using sensitive conveying technologies, and incorporating cutting-edge sensors for real-time particle behavior monitoring; furthermore, by understanding how particle characteristics like size, shape, and composition impact deterioration and damage, scientists may be able to develop customized handling methods for a variety of materials. In pneumatic conveyors, an increase in particle velocity leads to an increase in solid particle disintegration due to an increase in air mass flow rate, according to the study by Singh et al. [10]. Reduced material deterioration is made possible by increased solid feed rates or pipeline particle concentrations.

When handling materials with a high moisture content, small particles prone to aggregation, or cohesive powders, pneumatic conveying systems frequently encounter difficulties. Although pneumatic conveying technology has made significant strides, there is still a need to investigate cutting-edge methods to enhance the flowability and conveyability of such materials. It is acknowledged that, regarding pneumatic conveyors, this system would have difficulty handling cohesive materials. In a study by Olaleya et al. [11] wherein they study the processes of a cohesive particle, or in their case, cohesive dairy powders, cohesive dairy powders quickly re-aggregate after the second 90-degree bend and deposit at the bottom of the horizontal pipe at low gas velocities. Even at larger loading ratios, their results reveal intermittent particle dispersion at higher gas velocities and reduced particle deposition.

Though there have been many improvements in small-scale applications and laboratory research, there is still a need to bridge the gap between these studies and large-scale industrial implementations. When scaling up pneumatic conveying systems, several variables, such as system geometry, material qualities, and operational parameters, must be carefully considered. Additionally, design optimization is essential for increasing system effectiveness, reducing pressure drop, and assuring dependable and secure operation. Several studies have vouched for optimization and proper scale-up data but with varying results [12–14].

The creation and use of real-time monitoring and control systems focus on a large research gap in recent developments in pneumatic conveying. Although pneumatic conveying system performance and efficiency have improved significantly, more real-time monitoring capabilities and sophisticated control strategies are still required. Systems for real-time monitoring can offer insightful information about the operating circumstances, performance metrics, and potential problems in the pneumatic conveying system. There are few control system studies, the most notable being developed by Euh et al. [15], wherein the researchers made a control system for a sawdust pneumatic conveyor dryer in pellet production.

5. Future Outlook

There is immense potential for innovative advances in pneumatic conveying technology. Recent innovations have prepared this field for an entirely new phase of innovation, advancing this area to unprecedented levels of automation, sustainability, and efficiency. Pneumatic conveying systems are expected to undergo a revolution as the industry looks for more affordable and dependable material handling solutions by incorporating modern technologies such as machine learning, artificial intelligence, and renewable energy sources. This article examines the exciting prospects ahead and their significant effects on industries worldwide as it examines the future outlook for pneumatic conveying technology.

Pneumatic conveying technology has immense space for improvement and advancement with the addition of artificial intelligence (AI) and machine learning (ML). AI systems can detect problems before they lead to equipment breakdowns or disruptions by monitoring characteristics like temperature, air pressure, and vibration. Predictive maintenance reduces downtime, lowers maintenance expenses, and raises overall system reliability [16]. The improvement of material flow is another key application. AI and ML continually assess and modify system settings based on real-time information, sensor inputs, and historical data [17]. AI and ML technologies increase system effectiveness, decrease energy consumption, and improve product quality by optimizing material flow through intelligent decisions to alter the control variables [18]. Pneumatic conveying integration also requires adaptive control systems, which AI and ML make possible. By learning from prior experiences, these systems dynamically modify system parameters in response to changing conditions. They increase the efficiency and flexibility of pneumatic conveying operations because they can instantly react to changes in material qualities, system disruptions, and other factors [19].

Advanced measuring approaches, such as high-speed photography, advanced particle tracking techniques, and non-intrusive sensors, will improve multiphase flow characterization and provide more precise and in-depth information on flow behavior and particle dynamics. These developments will effectively simulate and comprehend complex multiphase dynamics [7]. To maximize multiphase flow in pneumatic conveying systems, computational modeling and simulation approaches, such as computational fluid dynamics (CFD) and numerical simulation, will be essential. These developments will improve system designs and allow more precise predictions. Systems for pneumatic conveying can operate more effectively and efficiently by combining data-driven methodologies. Multiphase flow in pneumatic conveying must be optimized, which calls for real-time monitoring and control systems. These systems can adjust and improve their performance in response to changing conditions by incorporating advanced sensors, feedback control loops, and algorithms for optimization. System effectiveness will increase, energy consumption will be reduced, and overall performance will be improved with real-time control and monitoring [20].

Optimization strongly emphasizes sustainability and environmental factors in addition to performance gains. This entails limiting energy use, decreasing emissions, and improving system designs to provide effective material transport while considering the environment. Future research will concentrate on creating ecologically friendly and sustainable solutions [21]. Automated control systems and optimization algorithms must be included to increase the energy efficiency of pneumatic conveying. Predictive designs and feedback control loops can optimize system parameters, including air pressure, velocity, and material flow rates, to reduce energy usage while maintaining optimal efficiency. Future pneumatic conveying systems might also encompass energy regeneration and recovery technology. These innovations reduce total energy consumption and increase sustainability by capturing and recycling energy from different components, including air compressors and braking systems. Investigating and deploying alternative energy sources are part of pneumatic conveying's attempts to be sustainable and energy efficient. Utilizing solar or wind energy in pneumatic conveying systems can help reduce the dependency on conventional fossil fuels and greenhouse gas emissions [22].

Moreover, there will be a stronger focus on every phase of the lifecycle of pneumatic conveying systems, from production to disposal. The production of more sustainable systems will be guided by lifecycle assessment methodologies and eco-design principles, considering elements like raw material preference, energy consumption, waste production, and recyclability [23]. Future research will also concentrate on discovering and utilizing materials that are resistant to deterioration and particle harm. To do this, improved coatings, liners, and wear-resistant materials must be investigated [24]. These materials must resist the abrasive nature of particle flow and reduce the damage to particles and equipment surfaces. The prediction and comprehension of material deterioration and particle damage will progress due to computational technologies like discrete element modeling (DEM) and finite element analysis (FEA). Using these models, engineers can optimize system designs and reduce damage risks by simulating particle movements, impact forces, and wear patterns. Future development and research projects will concentrate on creating novel parts and systems that reduce the degradation of materials and particle damage. To improve particle handling and reduce wear, this includes creating specific flow modifiers, impact-reducing mechanisms, and particle separators [25]. Real-time condition tracking and proactive maintenance methods are made possible by integrating cutting-edge sensors, statistical analysis, and machine learning approaches. Continuously tracking system variables, including vibration, temperature, and wear patterns, enables early detection of potential problems, enabling proactive maintenance to stop the corrosion of materials and failures of equipment [26].

Cutting-edge material conditioning techniques such as pre-conditioning, de-agglomeration, and surface treatment are being developed and utilized to alter the properties of cohesive materials and improve their flow characteristics. Additionally, to reduce material build-up, encourage material flow, and avoid obstructions, optimal pneumatic conveying system designs with specific elements like airlocks, feeders, and hopper designs are being created [10]. The design of conveying systems will be further improved by better understanding the mechanisms governing air–solid interactions, including the effects of variables like air pressure, particle size, and material qualities on cohesive materials [27]. By integrating cutting-edge sensor technologies, cohesive materials may be monitored and characterized in real time, allowing for the adjustment of system settings and a constant flow of material. The conveying process can be optimized by simulating particle behavior and forecasting material flow patterns using computational modeling and simulation approaches, such as discrete element modeling (DEM) and computational fluid dynamics (CFD). Using efficient procedures, case studies, and lessons learned, researchers, engineers, and industry experts continuously enhance and share knowledge to encourage successful conveyance strategies [28].

The prediction and optimization of the behavior of large-scale systems will be greatly aided by scale-up modeling and simulation approaches like CFD and DEM. To validate simulation results and optimize system characteristics, validation by experimentation of scale-up designs will continue to be essential. Design optimization will balance performance metrics and limitations by considering material characteristics, air–solid interactions, and system elements using cutting-edge approaches like multi-objective optimization [29]. Performance will be optimized, and human intervention will be minimized by integrating automation, robotics, and advanced monitoring and control systems. Industry stakeholders working together will make it easier to share knowledge and create standardized rules and design approaches for effective scalability and optimization. These future developments highlight the industry's focus on advancing pneumatic conveying technology for more dependable and efficient operation at higher sizes [30].

Future research will concentrate on incorporating sophisticated sensor technologies into pneumatic conveying systems, allowing for the real-time monitoring of various parameters. Data analytics and machine learning techniques will make it possible to meaningfully extract the massive amounts of data produced by real-time monitoring systems, improving the system's efficiency and proactive decision-making [2]. Implementing adaptive control techniques will optimize conveying performance by dynamically adjusting system parameters based on real-time sensor feedback. Furthermore, operators can remotely monitor system performance, run diagnostics, and receive alerts for unusual conditions, decreasing downtime and increasing system reliability. Pneumatic conveying processes will be completely controlled and optimized thanks to seamless interaction with automation technology and industry principles. Strong safety precautions and data protection protocols will also be given priority to guarantee the confidentiality and authenticity of the acquired data.

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