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Enhancing the Efficiency of Pneumatic Conveying Systems by Optimizing Compressed Air Supply Modes

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Abstract: This study analyzes the issue of high energy consumption in industrial pneumatic transportation systems (PTS), which constitute an integral part of numerous technological processes. The objective of the research is to systematize and evaluate existing methodologies for optimizing compressed air supply in order to reduce operating costs and increase the overall energy efficiency of PTS. To this end, a review of specialized scientific publications over the past five years was conducted, devoted to the modeling, control and modernization of pneumatic transportation systems. The methodology is based on a comprehensive approach: theoretical foundations of two-phase flows are examined, the effectiveness of adaptive control systems (PID controllers, PLC, MPC) is compared, and the performance of modern compressor and peripheral equipment is evaluated. Based on the obtained data, a practical step-by-step framework for small and medium-sized enterprises is proposed, including an audit of the current state, digital modeling and implementation of optimization solutions. Within the study, specific recommendations are formulated regarding the selection of components and the configuration of operating modes, which allow achieving a reduction in specific energy consumption without significant capital expenditures. It is concluded that the integration of adaptive control algorithms and the precise selection of equipment constitute key factors in the pursuit of maximum energy efficiency. The information presented in this work will be of interest to engineers, production managers and researchers in the field of industrial energy efficiency.

Keywords: pneumatic transportation, compressed air, energy efficiency, optimization, control system, energy consumption reduction, two-phase flow, levitation

velocity, industrial automation, resource conservation.

Introduction

Pneumatic conveying systems constitute a fundamental element of the technological chain in industries such as chemical, food, pharmaceutical, construction, and mining. Their purpose is to transport bulk and powdery materials through pipelines by means of a compressed gas flow (commonly air). Despite advantages including containment of the process environment, the ability to route pipelines with a high degree of maneuverability, and a high level of process automation, pneumatic conveying systems exhibit significant energy intensity. It is estimated that systems for generating and conditioning compressed air account for approximately 10–15 % of the total energy consumption of industrial enterprises, with pneumatic conveying systems ranking among the largest consumers of this energy [1]. Against the backdrop of the global trend toward improved energy efficiency, reduced carbon footprint, and steadily rising energy tariffs, minimizing the operational costs of pneumatic conveying systems acquires particular importance [2].

The scientific problem lies in the insufficient systematization and integration of optimization methods for pneumatic conveying systems, especially those applicable to small and medium-sized enterprises (SMEs). Existing studies are predominantly focused either on in-depth mathematical modeling of complex hydrodynamic phenomena [3, 4], or on the assessment of the efficiency of individual system components [5], but rarely offer a holistic, practically implementable algorithm of actions for enterprises lacking a staff of specialized research engineers. As a result, many installations are designed with large safety margins in terms of power capacity and operate in regimes far from optimal, which inevitably leads to unjustified energy expenditure.

The aim of the research is to systematize and evaluate existing methodologies for optimizing the supply of compressed air in order to reduce operational expenses and enhance the overall energy efficiency of pneumatic conveying systems.

The scientific novelty consists in the formation of an integrated framework that unites: diagnosis of the current state of the system; selection of optimal transportation parameters based on the analysis of the properties of the material being conveyed; application of modern adaptive control systems for dynamic adjustment of the characteristics of the air flow.

The author's hypothesis is that the implementation of a comprehensive approach, combining fine-tuning of key operational parameters (airflow velocity, material concentration) and the use of automated control systems, will allow reduction of the specific energy consumption of pneumatic conveying systems without the need to replace major equipment units. This will not only lower direct production costs but also increase the reliability and stability of the technological process.

Materials and methods

In recent years issues related to the improvement of energy efficiency in compressed air systems have attracted the attention of both researchers and practitioners. In particular Dindorf R., Takosoglu J., Wos P. [1] conducted a systematic review of receiver tank designs demonstrating that optimal volume and reservoir geometry can reduce peak loads on compressors and smooth the system's energy peak demands. Concurrently analytical market reports by Smart Pneumatics underscore trends in digitalization and the use of intelligent sensors for real-time monitoring of air pressure and flow thereby creating prerequisites for adaptive optimization of equipment operating modes [2]. Practical guides such as Improving Compressed Air System Performance synthesize best engineering practices for balancing pipeline sizing selecting fittings and receiver operation strategies to minimize pressure losses and energy consumption [5]. Particular attention is paid to leak detection and elimination the CAGI guide describes methodologies for auditing pneumatic networks using ultrasonic and acoustic inspection enabling energy savings without significant capital expenditure [11]. At the stage of compressed air production Shao W. et al. [6] propose one-dimensional loss models for multi-stage centrifugal compressors in a supercritical CO_2-Brayton cycle demonstrating that the application of accurate loss coefficients significantly influences the assessment of installation energy efficiency at high pressures and temperatures.

Another body of work is devoted to mathematical modeling and experimental investigation of gas–solid mixture dynamics during pneumatic conveying. Using a hybrid CFD–DEM approach Hongtu Z. et al. [3] analyzed the influence of drill string rotation on flow characteristics in negative-pressure systems revealing that increased angular velocity reduces particle aggregation and aligns the flow velocity profile which can contribute to more stable material delivery. Alkassar Y. et al. [4] based on CFD modeling with consideration of particle size distribution demonstrated that wide gradations in D_{50} and D_{90} cause uneven distributions of local concentrations increasing turbulent losses and energy expenditures during dense-phase fly ash transport. Research on dilute pneumatic biomass feeding by Gomes T. L. C. et al. [9] showed that particle shape and surface roughness critically influence gas–dust flow formation which should be taken into account when selecting feed parameters for bioenergy installations. The review by Behera N. et al. [10] of pseudo-fluidized pneumatic conveying systems emphasizes the advantages of fluidization in reducing peak compressor loads and pipeline wear while indicating the necessity for precise calibration of operating modes for each specific material.

The third thematic group encompasses experimental developments for optimizing devices for pneumatic discharge and material accumulation. Thus, de Freitas A. G. et al. [7] applied a planar experimental design method to a novel solid particle feeder design demonstrating that optimization of the working channel geometry can reduce energy consumption by 12 % while maintaining the required feed productivity. Similarly, Gomes de Freitas A. et al. [12] evaluated an alternative dense-phase blow tank in pneumatic conveying documenting compressed air savings due to increased utilization of residual pressure in the container.

Finally, in the works of Chen Q., Li N. [8] a model predictive control MPC approach for optimizing radiant cooling systems is proposed which can be adapted to pneumatic systems for dynamic control of air pressure and flow based on forecasts of thermal loads and energy consumption. Errigo A., Choi J. K., Kissock K. [13] conducted a techno-economic-environmental assessment of industrial motor system energy audits developing a methodology for calculating the payback of measures to improve the efficiency of drive systems which is relevant for the implementation of energy-efficient solutions in compressed air systems of small and medium-sized enterprises.

Existing studies demonstrate a broad spectrum of approaches to enhancing the efficiency of pneumatic systems from optimization of hardware components receivers' compressors feeders and leak elimination to advanced CFD–DEM modeling and intelligent control systems. However, contradictions are observed in the literature regarding the assessment of the influence of particle size distribution variations on energy consumption. Moreover most experimental developments are performed on laboratory-scale installations with low throughput complicating the extrapolation of results to industrial scales. Insufficiently studied are the issues of integrating predictive real-time control considering the variability of fed material characteristics as well as the economic evaluation of comprehensive measures for pneumatic conveying optimization including analysis of payback periods and environmental benefits. These gaps represent promising directions for further research.

Results and Discussion

The optimization of pneumatic conveying systems cannot be achieved without a holistic consideration of both operational regimes and the configuration of mechanical elements. The primary objective is to reduce specific energy consumption (kWh/t) to the minimally necessary level. Achieving this goal requires precise delivery of compressed air in a volume sufficient to ensure the required throughput without generating excessive flow velocities and without the risk of pipeline blockages.

The total pressure drops in the system (and hence the energy expenditure) is determined by several components: air resistance during movement along the pipeline walls, friction of abrasive particles against the internal pipe surface, energy expended to accelerate particles to the air flow velocity, and energy losses associated with maintaining them in a suspended state. The dependence of the pressure drop magnitude on the air flow velocity is distinctly nonlinear and forms a U-shaped curve (see Fig. 1).

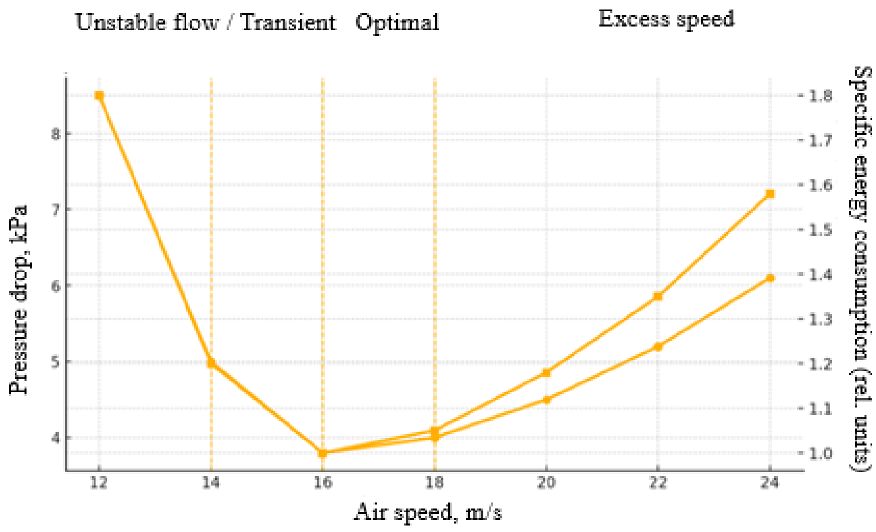

Fig. 1. Dependence of pressure drop and specific energy consumption on air velocity in the PTS (compiled by the author based on [2, 5, 8, 11]).

Analysis of the curvature of the pressure drop versus air flow velocity curve indicates that when the latter decreases the magnitude of the pressure drop initially decreases gradually reaching its minimum value in the vicinity of the critical conveying velocity (suspension velocity). Upon further reduction of velocity intense particle settling and formation of plugging agglomerates commence accompanied by a sharp increase in pressure indicating transition of the system into a failure mode. On the other hand, operation at velocities significantly exceeding the optimal leads to excessive energy consumption due to increased hydraulic losses accelerated wear of pipelines and fragmentation of the conveyed material. Thus, the key task in optimization is the selection and maintenance of an air flow velocity minimally exceeding the suspension velocity of the specific material at a given concentration

Based on a review of advanced methodologies the following stepwise framework has been developed (see Fig.2)

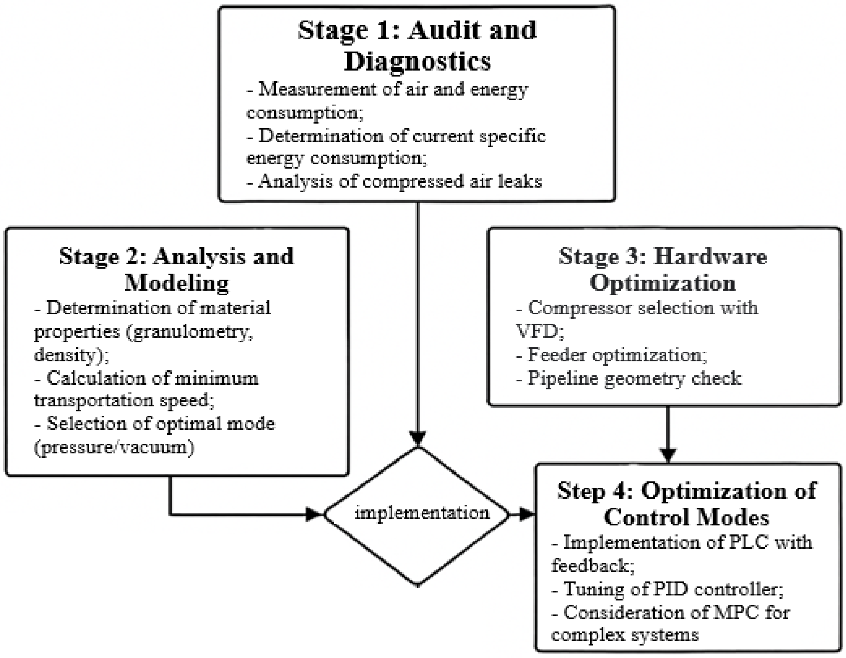

Fig. 2. Step-by-step framework for optimizing the energy efficiency of PTS for SMEs (compiled by the author based on [4, 8, 10]).

As can be seen from the figure, the first stage involves audit and diagnostics. At this stage, precise calibration of the baseline performance indicators of the compressor installation is carried out: air flowmeters are installed on the discharge lines and electrical energy meters on the compressor drives. A priority area of investigation is the detection and elimination of leaks, which, according to industrial practice, can reach 20–30 % of the total volume of compressed air generated [12].

In the next, second stage, analysis and modeling are performed. The key characteristic in this case is the minimum conveying velocity, which depends on the size, shape, and density of powder or granular materials. The values of these parameters are usually taken from specialized reference literature or determined under laboratory conditions. Based on the obtained data, the selection of the most appropriate configuration of the pneumatic conveying system is made (see Table 1).

Table 1. Recommendations for selecting the type of PTS and components for MSP (compiled by the author based on [8, 10, 13]).

Parameter	Low-pressure system (Dilute-phase)	High-pressure system (Dense-phase)
Operating principle	High air velocity (> 18 m/s), low material concentration (< 15 kg/kg)	Low air velocity (< 10 m/s), high material concentration (> 30 kg/kg)
Typical materials	Light, non-abrasive, non-fragile powders (flour, cement, plastic granules)	Fragile, abrasive, mixed materials (glass, sand, coffee beans, abrasives)
Advantages	Simple design, low initial cost	Low energy consumption, minimal pipe wear, preservation of material integrity
Disadvantages	High energy consumption, pipe wear, breakage of fragile materials	High initial cost, control complexity, risk of blockage
Recommended feeder	Rotary Valve	Pressure Vessel, Screw Pump
Compressor	Roots blower, low-pressure screw compressor	High-pressure screw compressor

The third stage, termed hardware optimization, follows. In this case, despite the fact that in many enterprises the compressor unit is centralized and serves several processing lines simultaneously, for high-throughput pneumatic conveying systems it is advisable to employ a dedicated compressor with a variable frequency drive (VFD). Such a configuration provides smooth regulation of air supply in accordance with actual demand and allows for a significant reduction in energy consumption compared to start-stop systems [5].

In the fourth stage, control mode optimization takes place. The implementation of a closed-loop control system based on a programmable logic controller (PLC) with feedback is considered the most effective solution. Pressure sensors installed at key points of the pipeline transmit data to the controller, which, through the compressor's VFD or a control valve, maintains pressure (and consequently conveying velocity) at the minimum permissible level.

The efficiency of investments in optimization measures manifests not only in the direct reduction of electricity costs but also in the decrease of expenses for maintenance, repairs, and the duration of forced equipment downtime. The accumulated experience in servicing heavy construction machinery provides the best confirmation of this. For example, in the operation of 750-ton Komatsu PC8000 excavators, failure of key components—hydraulic cylinders—entails multimillion-dollar losses due to downtime measured in days. In the traditional scheme, replacing a single hydraulic cylinder cost more than 100 000 $, whereas the implemented restoration technology, which includes restoring the geometry of the rod and barrel, overlay welding with a wear-resistant mixture, and subsequent precise machining, made it possible to reduce both financial costs and downtime by several times [7, 9]. Similarly, the restoration of swing frames assemblies of JCB and CAT excavators was optimized: instead of replacing an assembly costing approximately 5 000 €, a developed methodology of overlay welding and boring was applied, ensuring the return of the component to service within 3 days and reducing the downtime from 1,5 months to several days with a saving of about 4 000 € for the customer.

This experience illustrates a universal economic principle: investments in intelligent restoration and optimization technologies repay multiple times over through reduced operating expenses and the prevention of downtime. The same principle fully applies to pneumatic conveying systems. The initial costs for installing sensors, programmable logic controllers, and a compressor with a frequency converter may seem significant for small and medium-sized businesses; however, when compared to daily electricity losses due to systems operating at excess capacity, the payback period of such projects is estimated at one to three years, after which net savings commence [6, 7]. Thus, the modernization of a CAT-320D excavator, which increased its cost by 15–20 %, provided access to new types of work and fully paid for itself through the contract obtained. Similarly, the upgrade of the pneumatic conveying system, which reduced specific energy consumption by 20 %, enhances production profitability and increases the enterprise's competitiveness in the long term.

Thus, the results of the study emphasize the potential for improving the efficiency of pneumatic conveying systems, achievable not through a one-time implementation but through a systematic approach that includes thorough diagnostics, substantiated component selection, and, most importantly, the implementation of adaptive control systems that dynamically adjust operating modes to real conditions. The proposed framework provides enterprises with a structured algorithm of actions and ensures the achievement of measurable results in the field of energy conservation.

Conclusion

The conducted study emphasizes the importance of enhancing the energy efficiency of pneumatic transport systems and reveals a significant potential for its implementation. Systematic analysis of contemporary scientific literature and advanced engineering experience made it possible to delineate the main vectors for optimizing PTS.

The primary conclusion of the work is that maximum energy efficiency is achieved not through the isolated application of any single measure, but by means of a comprehensive, integrated approach, beginning with a detailed audit of the operating system. During the audit, precise measurement of actual energy consumption and identification of nonproductive losses, primarily compressed air leaks, are performed.

The central link in the optimization is maintaining the transport regime at minimum energy consumption, which is achieved at a flow velocity slightly exceeding the critical conveying velocity of the conveyed material. It has been confirmed that both underestimation and exceeding this velocity inevitably lead to significant energy overconsumption.

The step-by-step framework developed in the study includes stages of audit, analysis, hardware and regime optimization, as well as continuous monitoring. Practical implementation of this approach at small and medium enterprises is based on the introduction of modern feedback control systems (based on PLC) and the use of energy-efficient equipment, in particular compressors with variable frequency drives (VFD). This makes it possible to reduce specific energy consumption. The experience of implementing similar solutions in related sectors of heavy engineering demonstrates high profitability and a payback period of 1–3 years due to direct savings of energy resources and reduction of operating costs.

Thus, the aim of the study — justification and development of a comprehensive approach to improving the energy efficiency of PTS — has been fully achieved. The proposed recommendations and framework can serve as a methodological basis for modernization programs of industrial enterprises seeking to reduce production costs and increase competitiveness.

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