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Optimisation of air exchange and heat transfer using coaxial air ducts

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Abstract. In modern industrial premises, it is important to ensure effective air exchange with minimal energy consumption, which necessitates the optimisation of ventilation systems, particularly through the development of new air duct designs. The aim of this article was to develop a combined exhaust-supply air duct structure to improve the efficiency of air exchange in industrial spaces and reduce energy consumption for air heating. A comprehensive analysis was conducted of current scientific sources published in various countries, covering advanced technologies in air exchange, ventilation, and microclimate regulation. Theoretical justification of the design and mathematical modelling of heat transfer processes between the exhaust and supply air ducts were applied. Methods of heat conduction, convection, and radiation were also used to analyse the physical processes. As a result, a coaxial air duct structure was developed, consisting of an inner exhaust and an outer supply pipeline, with their diameter ratio optimised by the formula $D = 1.4 \cdot d$. Calculations confirmed the equality of exhaust and supply air volumes, ensuring stable air exchange. Modelling showed that the system effectively ensures uniform air distribution in the working zone, improving the overall performance of the ventilation system. A reduction in energy consumption was achieved by using the heat from the exhaust air to preheat the supply air. The calculations and modelling confirmed the effectiveness of the proposed design, which allows for a reduction in energy consumption for air heating and an improvement in air exchange in industrial spaces, contributing to the creation of comfortable working conditions. Overall, the developed ventilation system design is aimed at optimising air exchange processes in industrial premises and offers several advantages: energy efficiency – through the use of secondary heat resources; compactness – as the structure allows a reduction in the volume of ventilation equipment; versatility – since the system can be implemented across various industrial enterprises, including workshops with high levels of air pollution; improved occupational safety – as the new system contributes to the creation of comfortable conditions in the working area

Keywords: ventilation; industrial premises; heat conservation; aerodynamic characteristics; energy-saving technologies; air balance

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Introduction

Ventilation in industrial premises plays a key role in ensuring safe working conditions, particularly in the mining, metallurgical and chemical industries. The issue of removing harmful impurities and supplying clean air remains relevant for workshops where raw materials are processed, transported, and where finished products are manufactured. Existing ventilation systems are insufficiently effective. During the cold season, air requires heating, whereas in the warm season, it must be cooled. Moreover, such systems can be bulky and energy-consuming.

O. Lapshyn *et al*. (2022) described modern methods of maintaining an optimal microclimate, including air purification and recirculation technologies. They emphasise the importance of maintaining a proper balance between the supply of fresh air and the removal of polluted air. V. Korbut & S. Rybachov (2021) conducted experimental studies on the efficiency of dual-level air enclosures for industrial baths. They demonstrated that such a system significantly improves the removal of harmful emissions, which is especially important in production environments with high concentrations of contaminants.

V. Deshko *et al*. (2024) investigated the relationship between ventilation systems and the energy balance of buildings. Using EnergyPlus and DesignBuilder software packages, the authors modelled the impact of ventilation on building energy efficiency and indoor air quality. The results indicate the necessity of precise ventilation system design to ensure maximum efficiency. T. Tkachenko & V. Mileikovskyi (2020), in their studies, examined natural methods of improving indoor air quality. They focused on the influence of natural air ionisation, which makes it possible to significantly reduce the concentration of harmful substances in the air.

O. Voznyak *et al*. (2021) explored physical models of ventilation system elements under special conditions. They confirmed that adapting ventilation equipment to specific industrial conditions can significantly improve ventilation efficiency and enhance the microclimate in work areas. X. Wei *et al*. (2023) analysed the effectiveness of personalised air supply systems in reducing the impact of pollutants on workers. Their studies confirmed that a directed air stream improves air quality in the working zone.

E. Dudkiewicz & P. Szałański (2020) considered heat recovery technologies in ventilation systems of large industrial premises. They emphasised the significant potential for reducing heating costs by introducing heat exchangers into ventilation channels. N. Farouk *et al*. (2022) studied the influence of ventilation systems on CO_2 emissions in buildings equipped with phase-change materials. They concluded that energy-efficient ventilation solutions can substantially reduce greenhouse gas emissions while maintaining a comfortable indoor microclimate.

The reviewed scientific sources indicate the need for a comprehensive approach to optimising ventilation systems in industrial buildings. The main directions of research include the improvement of air duct designs, reduction of energy consumption, and enhancement of pollutant removal efficiency. The studies by V. Korbut & S. Rybachov (2021), O. Lapshyn *et al*. (2022), and V. Deshko *et al*. (2024) demonstrate that mathematical modelling is an effective tool for analysing air exchange parameters. At the same time, the studies by E. Dudkiewicz & P. Szałański (2020) and N. Farouk *et al*. (2022) confirm the feasibility of integrating heat recovery technologies into ventilation systems to reduce energy consumption.

However, the issue of optimising the design and parameters of air ducts in industrial premises remains insufficiently explored. Existing studies focus either on general aspects of ventilation or on local experimental research. The aim of this study was to develop a combined exhaust-supply duct design capable of ensuring effective air exchange in industrial premises while reducing energy consumption for air heating.

Literature review

Optimisation of ventilation systems in industrial premises is an important aspect of ensuring effective air exchange and reducing energy consumption. Research in this field covers various methods for improving ventilation processes, including enhancements to air duct design, the application of energy-saving technologies, and the use of mathematical models for analysing airflows.

A. Murga *et al*. (2020) conducted a study on hybrid emergency ventilation systems aimed at reducing the impact of pollutants in industrial spaces. Their work focused on evaluating the effectiveness of ventilation strategies in worst-case air pollution scenarios, such as accidental releases of toxic gases or particulate matter. The authors explored various air exchange regimes by modelling the spread of pollutants using CFD (Computational Fluid Dynamics). The results showed that integrating traditional mechanical ventilation systems with localised air purification sources can significantly reduce harmful emissions in the working zone. The study also highlights the need to consider the aerodynamic characteristics of the premises when designing emergency ventilation systems. The method proposed by the authors may be effective for industrial facilities with high contamination risks.

X. Zhao & Y. Yin (2024) in their study investigated modern pollution control strategies in industrial spaces and their impact on ventilation efficiency. They found that the most effective solutions were adaptive ventilation systems with dynamic regulation of airflow based on pollution levels. These systems use sensors to monitor the concentration of harmful substances, allowing automatic adjustment of airflow velocity and direction. The study placed significant emphasis on the relationship between microclimate parameters and worker productivity. The authors note that advanced ventilation strategies can not only improve air quality but also increase worker comfort, reducing the risk of occupational illnesses. The proposed pollution control methodology is considered promising for implementation in enterprises operating in challenging conditions, such as the metallurgical, chemical, and mining industries.

A. Pakari & S. Ghani (2021) analysed the effectiveness of various mechanical ventilation systems in cattle barns using CFD modelling and field measurements. They demonstrated that airflow optimisation contributes to improved microclimate conditions and animal productivity. Although their study relates to the agricultural sector, the findings may also be applicable to industrial premises. O. Tykhenko *et al*. (2024) investigated the factors influencing air ionisation in indoor spaces. They found that increasing the concentration of negatively charged ions promotes the removal of harmful particles, which is important for industrial facilities with high levels of dust pollution.

E. Zender-Świercz (2021) studied the impact of decentralised façade ventilation devices on indoor air quality. The author notes that such devices can effectively operate in combination with traditional ventilation systems, increasing the overall energy efficiency of buildings. T. Catalina & C. Lungu (2021) examined the effect of decentralised ventilation systems in classroom environments and their ability to maintain a high level of air quality. Their research showed that such systems can effectively remove air pollutants and improve comfort for occupants. M.I. Elhadary *et al*. (2021) carried out a comparative analysis of forced ventilation systems in industrial premises to improve worker comfort. They determined that combining mechanical ventilation with natural methods can significantly reduce heat loads and enhance working conditions.

Overall, the studies conducted by various authors expand the scientific understanding of alternative approaches to improving air exchange, including air ionisation, airflow optimisation, and the use of local ventilation devices. The relevance of energy-efficient ventilation is also confirmed by numerous studies. However, further development in this field requires the design of new, more effective technological solutions tailored to specific industrial conditions.

Materials and Methods

Regulatory documents such as the DSTN 3.3.6.042-99 (1999), DSTU-N B V.1.1-27:2010 (2010), and DBN V.2.5-67:2013 (2013) regulate the microclimate parameters in industrial premises, including permissible values for temperature, humidity, and air velocity. These requirements form the basis for the calculation and design of ventilation systems. Analytical and experimental methods were used in the study to evaluate the effectiveness of the proposed coaxial air duct (Patent No. 156625, 2024) in an industrial facility for the beneficiation of titanium-zirconium ores at the branch of the Vilnohirsk Mining and Pro cessing Plant of JSC UMCC, specifically in the drying workshop. The primary materials for analysis included design data of existing ventilation systems, results of laboratory measurements of microclimate parameters, and numerical modelling of airflow.

A comparison was made between the microclimate parameters specified in the above-mentioned regulatory documents and the actual values obtained during experimental measurements in the industrial facility. Parameters of the air environment (temperature, humidity, and airflow velocity) were measured using electronic anemometers, thermohygrometers, and gas analysers. The obtained data were subjected to mathematical processing to identify patterns and assess the effectiveness of the ventilation solutions. The solution to the heat exchange problem was performed using the Bernoulli method (formula 19) on a computer using Microsoft Excel. The equipment used included:

- anemometers for measuring airflow velocity;
- thermohygrometers for determining air temperature and humidity;
- gas analysers for monitoring carbon dioxide concentration and other harmful impurities;
- Microsoft Excel software for numerical modelling of the physical heat transfer process in the premises.

The applied methods made it possible to conduct a comprehensive analysis of the air duct system's effectiveness, assess its compliance with regulatory requirements, and develop recommendations for its optimisation.

Results and Discussion

The proposed air duct design consists of coaxially arranged exhaust and supply pipes: the exhaust duct has a diameter *d*, while the supply duct is determined using the formula (1), which ensures the required air exchange:

$$D = 1.4 \cdot d, \text{ m.} \quad (1)$$

The problem was solved by applying the formula for calculating the cross-sectional area:

$$Se = \pi \cdot d^2/4; \quad (2)$$

$$Ss = \pi \cdot D^2/4, \quad (3)$$

where *Se* – cross-sectional area of the exhaust air duct, m^2; *Ss* – cross-sectional area of the supply air duct, m^2.

This design provides uniform air exchange. The duct layout, as shown in Figure 1, includes exhaust and supply air ducts as well as a dispersing nozzle equipped with a swivel mechanism (coupling).

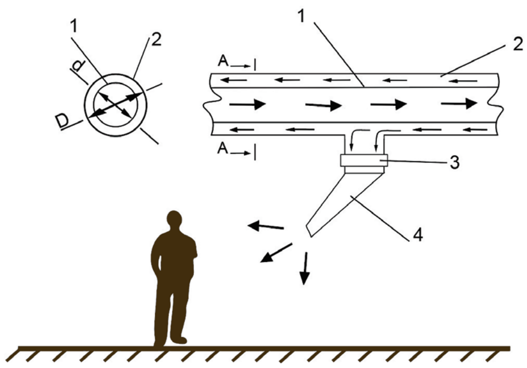

Figure 1. Combined air duct for ventilation of industrial premises

Notes: 1 – exhaust air duct; 2 – supply air duct; 3 – rotary mechanism (coupling); 4 – dispersing nozzle

Source: developed by the authors based on Patent No. 156625 (2024)

The operating principle of the air duct system is as follows. Polluted air from the source enters the exhaust duct via an extraction hood; the duct is located coaxially within the supply duct, and the air then flows through it to the air purification system. At the same time, clean air enters the room via the outer supply duct from the outside. Along the length of the supply duct, diffusing nozzles equipped with swivel mechanisms (couplings) are installed, forming clean air jets directed into the working zones of the industrial space.

The analysis and justification of air exchange parameters in industrial premises are carried out to verify the reliability of formula (1) and assess its applicability for ventilation system design. According to general regulations (DSTN 3.3.6.042-99, 1999; DSTU-N B V.1.1-27:2010, 2010; DBN V.2.5-67:2013, 2013), it is essential to maintain a balance between the volumes of extracted and supplied air in order to ensure effective ventilation in industrial environments:

$$Qe = Qs, \tag{4}$$

where Qe – volume of extracted air, m^3; Qs – volume of supplied air, m^3.

The thermal balance of the room is based on the law of conservation of energy, which states that energy is neither lost nor created, but only transformed or transferred between systems. Under industrial conditions, this balance takes the following form:

$$Qn + Qo + Qc = Qv + Qa, \text{J}, \tag{5}$$

where Qn – heat supplied through heating, ventilation, or solar radiation, J; Qo – heat generated by industrial equipment, J; Qc – heat from solar radiation, J; Qv – heat losses through enclosure structures and ventilation, J; Qa – heat accumulated in the building structures, J.

The main calculations of the air duct were carried out. To achieve thermal and ventilation balance, the geometric parameters of the air ducts were taken into account. According to the specified conditions, the diameter D of the supply duct was related to the diameter d of the exhaust duct by ratio (1). Given the exhaust duct diameter $d = 0.3$ m, the corresponding result was $D = 1.4 \cdot 0.3 = 0.42$ m.

Subsequently, the calculations were verified using several parameters:

1. Based on the cross-sectional areas of the air ducts.

Cross-sectional area of the exhaust air duct:

$$Se = \frac{\pi}{4} \cdot d^2 = \frac{\pi}{4} \cdot 0.3^2 \approx 0.07 \text{ m}^2. \tag{6}$$

Cross-sectional area of the supply air duct:

$$Ss = \pi/4 \cdot D^2 = \pi/4 \cdot 0.4^2 \approx 0.14, \text{m}^2. \tag{7}$$

The area of the annular section of the supply air duct was calculated as the difference between the supply and exhaust duct areas:

$$\Delta Ss = Ss - Se = 0.14 - 0.07 = 0.07 \text{ m}^2. \tag{8}$$

This indicated that the annular area of the supply duct (ΔSs) matched the area of the exhaust duct (Se), thereby ensuring air exchange balance.

2. Based on air volume:

The air velocities in both ducts were assumed to be equal:

$$\vartheta e = \vartheta s = 4 \text{ m/s}. \tag{9}$$

Volume of extracted air:

$$Qe = Se \cdot \vartheta e = 0.07 \cdot 4 = 0.28 \text{ m}^3/\text{s}. \tag{10}$$

Volume of supplied air:

$$Qs = \Delta Ss \cdot \vartheta s = 0.07 \cdot 4 = 0.28 \text{ m}^3/\text{s}. \tag{11}$$

Thus, the volumes of exhaust and supply air are equal: $Qe = Qs$. Calculations confirmed that formula (1) is reliable and may be applicable for the design of ventilation systems in industrial premises. The use of combined air ducts contributes to effective air exchange and reduced energy consumption, particularly through the utilisation of secondary heat. This was confirmed by experimental studies conducted under real conditions in the drying workshop of a titanium-zirconium ore beneficiation plant.

The physical process of heat transfer from the exhaust duct to the supply duct is based on the mechanisms of thermal conduction, convection, and possible partial participation of radiative heat exchange. Each aspect was therefore examined in detail:

1. Thermal conduction. The coaxial design, where the exhaust duct is located inside the supply duct, ensures thermal contact through their walls. The exhaust duct typically carries used warm air, the temperature of which may be significantly higher than that of the supply air. As a result, thermal energy is transferred through the walls of the inner duct to the supply air.

The heat transfer formula based on conduction is as follows:

$$Q = k \cdot A \cdot \Delta T/b, \text{J}, \quad (12)$$

where Q – amount of transferred thermal energy, J; k – thermal conductivity coefficient of the wall material, kg·m/(s³·K); A – heat transfer area, m²; ΔT – temperature difference between the exhaust and supply air, K; b – wall thickness, m.

2. Convection. The supply air in the outer channel moves and comes into contact with the walls of the exhaust duct. As a result, the thermal energy transferred through the walls is immediately absorbed by the flow of supply air. The convective process enhances the efficiency of heat transfer due to the continuous movement of air in the thermal contact zone. The formula for convection is as follows:

$$Q = h \cdot A \cdot \Delta T, \text{J}, \quad (13)$$

where h – heat transfer coefficient (dependent on the velocity and physical properties of the supply air), kg/(s³ · K).

3. Thermal insulation. The coaxial design reduces heat losses to the surrounding environment, as the outer air duct acts as an insulating layer. This increases the efficiency of thermal energy utilisation from the exhaust air to heat the supply airflow. The supply air duct ensures the heating of incoming air, which enters the room and improves working conditions in the personnel area. Simultaneously, the exhaust duct is cooled, which helps to maintain a balanced temperature. The total thermal balance of the system can be expressed as:

$$Qt = Qin - Qout, \text{J}, \quad (14)$$

where Qt – total thermal balance, J; Qin – heat from the exhaust air, J; $Qout$ – heat from the supply air, J.

Thermal radiation is a natural physical process whereby all bodies with a temperature above absolute zero (0 K) emit energy in the form of electromagnetic waves. In a coaxial air duct system, thermal radiation arises due to the temperature difference between the contacting surfaces:

- the exhaust duct (inner) has an elevated temperature due to the warm used air;
- the wall material emits thermal energy in the form of infrared radiation;
- the supply duct (outer) partially absorbs this energy, adding it to the overall heat transfer.

Thermal radiation is described by Planck's law and the Stefan-Boltzmann equation:

$$Q = \sigma \cdot \epsilon \cdot A \cdot (T_1^4 - T_2^4), \text{J}, \quad (15)$$

where Q – amount of transferred heat, J; σ – Stefan-Boltzmann constant (5.67 · 10⁻⁸ W/m² · K⁴); ϵ – emissivity coefficient of the material (ranging from 0 to 1); T_1 and T_2 – absolute temperatures of the surfaces, K.

It has been established that radiative heat transfer in the system does not always have a significant effect. If the inner duct wall has a high temperature and a low thermal conductivity coefficient, radiative exchange may contribute substantially to the overall heat transfer process. However, in most industrial ventilation systems, thermal conduction and convection remain the dominant mechanisms. In the system under consideration, radiative heat exchange functions only as an auxiliary mechanism, and its effect can be enhanced or diminished depending on material selection and design.

The development of a mathematical model of the air duct functioning as a heat exchanger enables the simulation of heat transfer processes within the working area (Spivak *et al.*, 2024). An important stage in building the model is the consideration of flow dynamics, which define the structure and parameters of the technological environment. Due to the complexity of hydrodynamic processes, it is typically only possible to formulate equations for single-phase flows (Navier-Stokes equations), the solutions of which are usually derived for individual cases. Therefore, simplified approaches are often applied during modelling, based on typical flow structures, such as ideal mixing or ideal displacement.

Flow models are described by systems of differential equations linking the key process parameters. For technological facilities, the most universal approach involves equations that describe changes in substance concentration or energy within the flow. In particular, when cooling or heating the workspace, it is appropriate to use the ideal mixing model, which assumes that the air entering the room is instantly distributed throughout the volume. In this case, the air temperature remains the same at any point in the room. To describe temperature changes over time in the mixing zone, the following notations are introduced: Tin – inlet air temperature, K; $T(t)$ – air temperature at any given time, K; Cp – specific heat capacity of air, m²/(s² · K); V – volume of the mixing zone, m³; V' – volumetric flow rate of the air, m³/s; Qin – amount of heat in the incoming air or at any given point, J. The heat exchange equation can be expressed as:

$$Q = V \cdot Cp \cdot T, \text{J}. \quad (16)$$

For changing inlet temperature conditions, the ideal model was described by the following equation:

$$\frac{dT}{dt} + \frac{1}{\tau}T = \frac{1}{\tau}Tin, \quad (17)$$

where $\tau = \frac{V}{V'}$ – the average residence time of air temperature in the mixing zone.

In the presence of a heat source Qs, the equation is modified:

$$\frac{dT}{dt} + \frac{1}{\tau}T = \frac{1}{\tau}Tin + \frac{Qs}{Cp \cdot V}. \quad (18)$$

Solving the equation using the Bernoulli method provides an expression for air temperature:

$$T(t) = Tin + (T_0 - T_{in})e^{-\frac{t}{\tau}} + \frac{\tau \cdot Qs}{Cp \cdot V}, \text{K}. \quad (19)$$

The solution to the resulting equation allows the determination of air temperature dynamics, accounting for variations in inlet temperature, thermal radiation from heat sources, and the average temperature retention time in the mixing zone. This makes it possible to describe in detail the thermal regime in working spaces and to assess the influence of key parameters such as the mixing zone volume, air velocity, and presence of heat sources. One of the most important factors determining the efficiency of ventilation and the achievement of the required temperature regime is the air exchange rate.

The analysis of temperature changes in a specific case involving ventilation of a drying workshop demonstrates that the air exchange rate ($n = \frac{V'}{V}$) significantly affects process efficiency. According to L. Amanowicz *et al.* (2023), the correct selection of air exchange rate is a key factor in reducing the energy consumption of ventilation systems. M. Bezrodny & T. Misiura (2020) emphasise that the use of heat pumps in ventilation systems allows significant improvement in temperature control and reduced heating costs.

A high air exchange rate indicates effective ventilation, which is essential for maintaining a healthy climate and reducing pollutant concentrations. H. Hetmanchuk (2024) notes that the level of natural air exchange depends on numerous factors, including internal and external environmental parameters, which must be considered when designing air ducts for ventilation systems. With increased air exchange rate, the time required to equalise temperature is significantly reduced, as confirmed by experimental calculations of V. Deshko *et al.* (2023).

According to V. Dzhedzhula (2021), ventilation systems of public buildings can serve as the basis for developing efficient industrial solutions. One of the critical aspects is the uniform distribution of airflows, which minimises heat loss and improves energy efficiency. As highlighted by V. Matviichuk *et al.* (2021), mathematical modelling of such systems is a crucial stage in developing optimal ventilation technologies.

The drying workshop of the beneficiation facility has technological equipment that emits a significant amount of heat, which directly affects the temperature regime in the premises and other microclimatic conditions. Under real operating conditions, the workshop has three drum dryers of various sizes, each equipped with two methane gas burners. The inlet temperature of these units reaches 600 ÷ 850°C, while the outlet temperature ranges from 80 ÷ 150°C. The volume of the room is a key parameter for determining the required air exchange rate. It is calculated using the formula:

$$V = H \cdot W \cdot L, \text{m}^3. \quad (20)$$

According to the parameters of the drying workshop, the premises have a height of H = 3.8 m, a width of W = 20 m, and a length of L = 30 m. Thus, its volume is V = 3.8 · 20 · 30 = 2,280 m^3. For service personnel, the recommended air supply rate is 30 m^3/h per person. These air supply standards for service personnel are based on the recommendations provided in DBN V.2.5-67:2013 (2013), which regulate the minimum volume of fresh air required to ensure a comfortable microclimate. Compliance with these standards is mandatory in the design and operation of ventilation systems to ensure healthy and safe conditions for work and rest. It should be noted that additional air exchange requirements may apply to different types of premises and activities and must be taken into account when designing ventilation systems. For example, if three people work in the drying workshop, the total required air volume for personnel is 90 m^3/h.

For drying premises, the air exchange rate depends on the type of contaminants and heat emissions. Recommended values range from 5 to 15 air changes per hour. Accordingly, the minimum required air volume for n = 5 is 11,400 m^3/h, while the maximum for n = 15 is 34,200 m^3/h. The total air volume, including personnel needs, at the minimum rate is 11,490 m^3/h, and at the maximum – 34,290 m^3/h. The air exchange rate in the actual conditions of the drying workshop of the beneficiation facility is: minimum – $n_{min} = \frac{11{,}490}{2{,}280} \approx 5$ 1/h; maximum – $n_{max} = \frac{34{,}290}{2{,}280} \approx 15$ 1/h.

This means that the entire volume of air in the premises must be replaced from 5 to 15 times per hour, depending on the intensity of work and microclimate requirements. The air exchange rate directly affects the temperature equalisation process in the premises. The more frequently the air in the room is replaced, the faster the temperature at any point approaches the supply air temperature. At the minimum rate of n = 5, the equalisation process takes more time due to the lower volume of fresh air. In the case of the maximum rate n = 15, thermal balance is achieved much more quickly, which is particularly important in rooms with high heat emissions.

In winter, the supply air temperature is usually increased to compensate for heat loss through walls, floors, ceilings, ventilation openings, and doorways. At a standard indoor temperature, the supply air temperature (*Tin*) in the air duct must be sufficiently high so that, after mixing with the indoor air or cooling, the required level is reached. The indoor temperature stabilises faster with a higher air exchange rate, as the supply air mixes more intensively with the internal air. For example, at n = 5, the temperature stabilisation time is approximately 12 minutes, whereas at n = 15, this time is reduced to 4 minutes. This enables more efficient maintenance of the required temperature regime and reduces the energy consumption of ventilation and air-conditioning systems. Thus, the optimal air exchange rate for a drying room should be from 5 to 15 times per hour. This ensures not only efficient ventilation but also rapid temperature equalisation, creating comfortable conditions for personnel and maintaining the necessary microclimate for technological processes. Table 1 and Figure 2 illustrate the dependence of air temperature on time for different air exchange rates. The results demonstrate that increasing the exchange rate accelerates temperature equalisation, ensuring effective ventilation of the premises.

Table 1. Calculation results of air temperature equalisation over time for different air exchange rates

t, min	*T* (*n* = 5)	*T* (*n* = 15)
0	10	10
10	21.37	28.37
20	26.27	29.87
30	28.39	29.99
40	29.31	30
50	29.7	30
60	29.87	30

Notes: the data presented in the table are the results of studies on temperature variation over time for different values of the air exchange rate parameter *n*

Source: developed by the authors based on original research

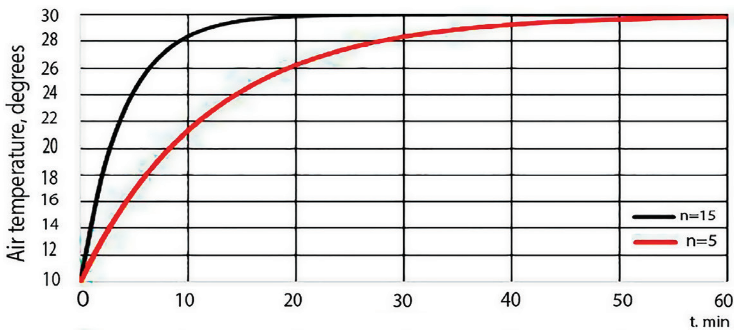

Figure 2. Graphs of air temperature versus time for different air exchange rates

Notes: the graphs show the dependence of air temperature on time for various values of the air exchange rate *n*; as the air exchange rate increases, the temperature stabilisation process accelerates

Source: developed by the authors based on original research

An increase in the air exchange rate contributed to faster temperature equalisation within the premises, which was particularly important under conditions of changing external thermal influences or the emergence of internal heat sources. At the same time, efficient ventilation ensured reduced adaptation time of the room to temperature changes, lower concentrations of pollutants, and the maintenance of a comfortable microclimate. The results of heat transfer modelling provided a basis for the development of workplace air shower systems (Fig. 1), aimed at ensuring thermal comfort and an optimal microclimate. When designing an air shower system, it was necessary to solve the problem of regulating airflow parameters depending on the season. In the warm season, the cross-sectional area of the air nozzle and the volume of supplied air were determined to ensure comfortable conditions. In the cold season, the air temperature at the nozzle outlet was calculated, taking heating into account. The following requirements were considered: the distance from the workplace to the nozzle should be ⩾ 1 m; the minimum cross-sectional area of the nozzle should be ⩾ 0.1 m^2; the air stream direction should be horizontal at chest level or at a 45° downward angle.

To reduce air temperature in summer, the evaporative cooling method with pre-humidification could be applied. The air passed through a humidifying filter, for example, a fabric filter moistened with water or a glycol solution, providing effective cooling. Heat exchangers were used to stabilise the process, maintaining the set air temperature. Porous inserts in the nozzle structure promoted uniform flow distribution and minimised turbulence. Evaporative cooling with pre-humidification was an effective method of reducing air temperature by evaporating water or aqueous solutions such as glycol. This process was widely used in various industries to improve indoor microclimate through air humidification and temperature reduction. The efficiency of such cooling depended on the area of wet surfaces and the rate of air flow over them. The use of porous materials moistened with water or solutions promoted intensive evaporation, resulting in a drop in air temperature. In the cold season, air showering through the nozzle ensured air heating to standardised temperatures in the working area. The calculations assumed a constant air supply velocity, allowing a balance to be maintained between comfort and system performance.

Thus, the proposed coaxial air duct system provided efficient transfer of thermal energy from the exhaust to the supply air, contributing to energy saving and improving conditions in industrial premises. Moreover, the proposed ventilation system was universal and could be adapted for operation in different climate zones, taking into account their specific characteristics. In regions with high average annual temperatures, the priority was to cool indoor air, which required significant energy input. The proposed system could be supplemented with integrated cooling modules based on the use of exhaust air, which typically had a lower temperature than the air in the working zone. Through the duct design, it was possible to organise cooling of the supply air without the use of additional cooling devices. The system could also include heat recovery modules, which enabled cooling of the supply air by exchanging heat with the exhaust air, reducing the thermal load on air-conditioning units. This solution reduced electricity consumption and maintained a comfortable microclimate even during periods of extreme heat.

In this way, the system was universal and could be configured to ensure energy savings under any climatic conditions. Based on the obtained results, it could be concluded that the use of a coaxial air duct system was advisable in facilities with various levels of heat emission, particularly in production workshops requiring significant air exchange. For premises with high heat loads, it was recommended to integrate additional cooling or heat recovery modules to reduce the load on air-conditioning systems. In areas with low heat emissions, the system could ensure an optimal balance between energy efficiency and comfort by minimising heat loss through ventilation. Proper sealing of joints between duct components had to be ensured to minimise thermal losses. It was recommended to additionally install an automated ventilation control system to monitor and optimise system performance in real time.

The study of the effectiveness of the coaxial air duct for industrial ventilation demonstrated its potential advantages in ensuring a stable microclimate and reducing energy consumption. Analysis of the obtained results enabled comparison of the effectiveness of the proposed design with traditional ventilation systems. Measurements of microclimate parameters showed a reduction in temperature gradients in the air exchange zone and uniform airflow distribution. It was established that the use of the coaxial duct allowed optimisation of thermal energy use, as confirmed by statistical data analysis (Table 1).

The analysis of literature sources by V. Korbut & S. Rybachov (2021) and O. Lapshyn *et al.* (2022) confirms that modern ventilation systems experience significant energy losses due to inefficient airflow distribution. The obtained results are consistent with the findings of E. Dudkiewicz & P. Szałański (2020), which indicate the feasibility of using combined air supply methods to reduce heat losses. The study by A. Murga *et al.* (2020) demonstrated the effectiveness of localised ventilation systems in reducing the impact of harmful emissions. A comparative analysis showed that the coaxial air supply configuration could serve as an alternative to traditional air exchange systems due to more efficient airflow distribution and energy saving.

The implementation of coaxial air ducts in industrial premises of various functions, particularly under elevated temperature conditions, makes it possible to ensure uniform air exchange, reduce the risk of local overheating, and optimise the use of energy resources. It has been established that the proposed solution can be integrated into existing ventilation systems without major structural changes, as the coaxial "pipe-in-pipe" design occupies less space compared to traditional ducts, enhancing its applicability in industrial settings. The study showed that the proposed ventilation system design has several advantages over conventional air exchange methods. L. Amanowicz *et al.* (2023) emphasise the importance of integrating energy-saving technologies into modern ventilation solutions. V. Deshko *et al.* (2023) highlight the feasibility of using parametric analysis of natural air exchange to assess system performance. The study by H. Hetmanchuk (2024) also confirms that natural ventilation can be significantly improved through adaptive technologies. Therefore, the conducted research confirms the effectiveness of the proposed ventilation system design and its potential for practical application in industrial facilities.

Conclusions

The proposed design of the combined air duct improves the efficiency of industrial ventilation by means of coaxial arrangement of the exhaust and supply ducts and provides a number of advantages, namely: the use of heat from the exhaust air to preheat the supply air significantly reduces heating costs, particularly during the cold season; the system can be implemented even in confined spaces, making it universal for use in various types of industrial workshops; the technology contributes to creating comfortable working conditions, reducing the risk of occupational illnesses and increasing overall workplace safety. Unlike traditional ventilation systems, the proposed design allows the integration of heat recovery mechanisms within a coaxial configuration while maintaining compactness and structural flexibility; it demonstrates high versatility, as it can be adapted to different climatic conditions and types of production; and it provides not only air exchange but also increases system energy efficiency by reducing heat loss. The combination of mathematical heat transfer modelling with engineering solutions for air shower systems enables optimisation of ventilation system parameters. This ensures effective thermal comfort in working spaces during both warm and cold periods. The results confirm the importance of correct selection of air exchange rate, nozzle area, and flow direction to achieve optimal microclimatic conditions. For future research, it is recommended to analyse system performance under various climatic conditions. In the warm season, it is essential to develop or refine automatic airflow regulation tools, such as systems for adjusting air velocity or volume, in order to maintain optimal parameters under changing industrial conditions. In the cold season, it is critically important to investigate heat transfer processes, particularly to determine how much heat is transferred to the supply air.

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Conflict of Interest

None.

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Оптимізація повітрообміну та теплопередачі за допомогою коаксіальних повітроводів

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Анотація. У сучасних промислових приміщеннях важливо забезпечити ефективний обмін повітря при мінімальних енергетичних витратах, що зумовлює необхідність оптимізації вентиляційних систем, зокрема шляхом розробки нових конструкцій повітроводів. Метою статті була розробка конструкції сумісного відсмоктувально-припливного повітроводу для покращення ефективності повітрообміну в промислових приміщеннях та зниження енергетичних витрат на підігрів повітря. Проведено ґрунтовний аналіз сучасних наукових джерел, опублікованих у різних країнах світу, що охоплюють передові технології повітрообміну, вентиляції та регулювання мікроклімату. Використано теоретичне обґрунтування конструкції та математичне моделювання процесів теплообміну між відсмоктувальним та припливним повітроводами. Також використовувалися методи теплопередачі, конвекції та випромінювання для аналізу фізичних процесів. У результаті розроблено конструкцію коаксіального повітроводу, що складається з внутрішнього відсмоктувального та зовнішнього припливного трубопроводу, співвідношення діаметрів яких оптимізовано формулою $D = 1{,}4 \cdot d$. Розрахунки підтвердили рівність обсягів повітря, що відсмоктується і подається, забезпечуючи стабільний повітрообмін. Проведене моделювання показало, що система ефективно забезпечує рівномірний розподіл повітря в робочій зоні, підвищуючи продуктивність вентиляційної системи. Зниження енергетичних витрат досягнуто завдяки використанню тепла від відсмоктувального повітря для підігріву припливного. Розрахунки та моделювання підтвердили ефективність запропонованої конструкції, що дозволяє знизити енергетичні витрати на підігрів повітря та покращити повітрообмін у промислових приміщеннях, що сприяє створенню комфортних умов для працівників. Загалом, розроблена конструкція вентиляційної системи спрямована на оптимізацію процесів повітрообміну в промислових приміщеннях, пропонуючи такі переваги: енергоефективність – за рахунок використання вторинних теплових ресурсів; компактність – конструкція дозволяє зменшити обсяг вентиляційного обладнання; універсальність – система може бути впроваджена на різних промислових підприємствах, включаючи цехи з високим рівнем забруднення повітря; підвищення безпеки праці – нова система сприяє створенню комфортних умов у робочій зоні

Ключові слова: вентиляція; промислові приміщення; теплозбереження; аеродинамічні характеристики; енергоощадні технології; повітряний баланс