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Comprehensive methodology for creating enhanced datasets for modelling the process of magnetic separation of iron ore

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Abstract. The study presents an innovative approach to creating extended datasets for modelling magnetic separation of iron ore, which is crucial for enhancing efficiency and automating enrichment processes in the mining industry. The aim of the research was to develop a methodology for creating extended datasets for modelling magnetic separation of iron ore that takes into account the specifics of Ukrainian deposits and allows for the generation of representative data in conditions of limited real production data by integrating physical modelling with machine learning methods. Research methods: modelling using mathematical learning, simulation based on physical processes, statistical analysis. The study examined the use of the USIM PAC simulator for modelling the iron ore enrichment system and adapting data for magnetic enrichment, ensuring the accuracy of modelling technological enrichment processes. The simulator was used to obtain a dataset from physical modelling of part of the enrichment process based on data from the Valyavkinske deposit. Primary modelling of the dataset was analysed, including statistical characteristics, distribution shape, and normality tests to identify fields requiring correction. Based on the analysis results, specific requirements for data distribution in the new dataset to be formed for further use were established. In accordance with these requirements, several mathematical models were implemented to reproduce the specified criteria and parameters. For each data field, the best model was carefully selected, and the dataset was corrected based on its data to bring the distribution as close as possible to the desired one. Comprehensive validation of the resulting corrected data was conducted, emphasising the preservation of the physical validity of the data and their correspondence to real enrichment processes. A detailed analysis of the corrected data was performed, as well as the statistical characteristics of the resulting dataset, confirming the effectiveness of the developed comprehensive methodology for modelling and adapting data for magnetic enrichment of iron ore. The methodology holds practical value due to its innovative approach to creating extended datasets for modelling magnetic separation of iron ore, enhancing the efficiency and automation of enrichment processes while considering the specifics of deposits and generating representative data in conditions of limited real data

Keywords: nonlinear modelling of enrichment; separation control; machine learning in enrichment; automation of enrichment processes; simulation of technological parameters

Introduction

The relevance of this work is determined by the necessity to improve the processes of modelling magnetic separation of iron ore under conditions of limited real data, especially for Ukrainian deposits. The specifics of Ukrainian iron ore deposits, particularly in the Kryvyi Rih basin, require the development of special

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extraction and processing technologies. The development of a comprehensive methodology for creating extended datasets will help overcome these limitations, taking into account local geological conditions and ensuring more effective modelling of the magnetic separation process. This will contribute to the optimisation of enrichment processes, improvement of concentrate quality, and reduction of energy consumption in the mining industry of Ukraine.

Current trends in modelling magnetic separation are characterised by a comprehensive approach that integrates various computational and analytical methods. These approaches encompass a wide range from classical numerical methods to advanced techniques in machine learning and multiphysics modelling. Significant progress has been made in developing methods that allow for the simultaneous consideration of complex interactions between different physical processes inherent in magnetic separation. Concurrently, optimisation methods for control are being developed, aimed at enhancing the efficiency of enrichment processes. The integration of these diverse approaches creates a powerful foundation for developing adaptive and high-precision models capable of functioning under conditions of limited experimental data and accounting for the specifics of local conditions.

In the study by V.V. Shenoy *et al*. (2024), the influence of the magnetic field on flow behaviour in a step geometry is examined. Using modern computational fluid dynamics methods, particularly the open-source package OpenFOAM, the authors investigated the interaction between magnetic forces and geometric factors affecting flow characteristics. The study revealed important patterns in flow behaviour under the influence of the magnetic field and geometry. The proposed mathematical models allow for the prediction of key flow parameters under various conditions. The results of this CFD work have the potential for application in a wide range of engineering tasks related to magnetohydrodynamic flows and boundary layer control.

In the work by R. Chowdhury *et al*. (2024), a comprehensive method for optimising medium parameters for effective material separation in a hydrocyclone separator is proposed, combining theoretical approaches and CFD modelling. The use of CFD allowed for a detailed analysis of the impact of medium density on the separation of PVC and PET particles, visualising and assessing key process parameters. Although the study focused on plastics, the methodology can be applied in various fields, including magnetic enrichment, where consideration of medium and particle properties is critical for optimising separation.

M.E. Kinaci *et al*. (2020) investigated the process of indirect reduction of iron ore in fluidised beds using the discrete element method (DEM) in conjunction with computational fluid dynamics. The developed model can be applied to simulate the processes of iron ore reduction in industrial reactors, optimising process parameters and developing new iron production technologies. J. Liu *et al*. (2021) studied the magnetic separation process in an aerodynamic drum magnetic separator (ADMS) using the finite element method and multiphysics modelling in COMSOL Multiphysics software. The modelling of the magnetic field, airflow, and particle movement in the separator was conducted. The influence of various parameters (air velocity, magnetic field intensity, positioning of magnetic poles) on the separation efficiency of magnetic and non-magnetic particles was demonstrated. The simulation results were verified through experimental measurements and calculations. The proposed model allows for the prediction of particle trajectories and extraction probabilities under different conditions, which can be useful for precise control of the magnetic separation process using combined force fields.

Moreover, there is a growing interest in the application of machine learning methods, particularly convolutional neural networks (CNNs), which open new opportunities for predicting separation efficiency under complex conditions. Research conducted by Y. Li *et al*. (2022) demonstrates the successful use of CNNs for modelling grinding processes in ball mills, based on externally measured process variables. These approaches can be adapted for magnetic separation, enhancing prediction accuracy and reducing the need for large volumes of experimental data. The implementation of machine learning fosters the development of hybrid models that combine theoretical knowledge with data from discrete element method simulations, providing more effective and rapid modelling of complex systems.

N. Yang *et al*. (2022) analysed the development of modelling methods for mineral deposits, emphasising the transition to three-dimensional digital models and the importance of understanding ore formation processes. The authors highlighted the application of machine learning methods, particularly convolutional neural networks, for predicting hidden deposits. They stressed the issue of data scarcity and proposed the use of advanced machine learning techniques to process incomplete data, underscoring the importance of integrating expert knowledge. Despite progress in modelling magnetic separation, there remains a need for the development of comprehensive methodologies for creating accurate models under conditions of limited real data.

V. Morkun *et al*. (2020) investigated the identification of nonlinear dynamic enrichment objects using a second-order Volterra model and its projection onto orthonormal Laguerre basis functions. This potentially impacts the improvement of modelling accuracy for iron ore enrichment processes, reducing model complexity and sensitivity to noise. O. Porkuian *et al*. (2019) considered the development of a predictive control system for the iron ore enrichment process based on a hybrid Hammerstein model. The model combines a fuzzy nonlinear block and a crisp linear dynamic block for effective approximation of nonlinear, dynamic, and non-stationary properties of enrichment line objects. The proposed algorithms ensure rapid real-time identification and optimal control considering constraints, leading to improved concentrate quality and reduced energy consumption.

S. Rajendran & C.V.G.K. Murty (2023) reviewed modern approaches to numerical modelling of enrichment processes for coal, iron ore, chromite, and bauxite. This allows for a better understanding of key process variables affecting the efficiency of enrichment equipment and the potential for optimising technological operations. The work provides tools for predicting the behaviour of complex mineral enrichment systems, contributing to the development of more effective mineral processing methods.

The aim of this research was to develop an innovative methodology for creating extended datasets for modelling magnetic separation of iron ore, taking into account the specifics of Ukrainian deposits and the limitations of available information.

Materials and Methods

Justification for the choice of modelling method. An analysis of existing methods for modelling the magnetic separation process revealed the necessity of applying a comprehensive approach to address the task at hand. Considering the complexity and non-linearity of the magnetic separation process, as well as the specifics of the available data and tools, particularly USIM PAC – a commercial simulator for technological processes developed by CASPEO (Brochot *et al*., 1995) – and the Python Spyder IDE development environment (n.d.), the decision was made to employ a hybrid modelling method (McCoy & Auret, 2019). The main arguments in favour of choosing the hybrid method are as follows:

1. Complexity of data processing. The proposed hybrid method combines physical modelling of magnetic separation with machine learning techniques. Initially, data is obtained from a model built on physical principles using the USIM PAC technological process simulator. This model is based on fundamental physical laws and empirical relationships that describe the magnetic separation process. Subsequently, this data is sequentially expanded and restructured using machine learning algorithms. In particular, neural networks are employed to uncover hidden patterns, clustering methods are used to group similar results, and regression algorithms are applied to predict process efficiency under various conditions. This combination of physical modelling and machine learning methods allows for effective processing of complex, non-linear relationships in magnetic separation data, significantly enhancing the capabilities of the initial physical model.

2. Adaptability to different conditions. In the study, data from the Valyavkinske deposit (Bogdanov, 1984) was used as an example for initial modelling. The deposit was chosen due to its typical characteristics, which well represent the general conditions of iron ore deposits in Ukraine. However, the developed approach aims to create a general model of the enrichment system that can be adapted to various mining and processing plants. The hybrid method provides the necessary flexibility for such adaptation, allowing the model to be tailored to the specific conditions of other deposits and mining and processing plants (MPP). A key aspect of this adaptability is the ability to replace the technological parameter data of MPPs and deposits. This allows for the modelling results to be aligned with the conditions of different MPPs. For example, by changing parameters such as ore characteristics, equipment configuration, or operating modes, the model can be adapted to the specifics of a particular plant. Such flexibility is especially useful when optimising processes at new deposits or modernising existing MPPs. The hybrid method, by combining physical modelling with machine learning techniques, allows for rapid retraining of the model on new data while maintaining a fundamental understanding of the physical enrichment processes.

3. Working with limited data. In conditions of limited access to real production data, the hybrid method allows for the effective use of artificially generated data while preserving the physical validity of the model through the use of USIM PAC. The effectiveness of this approach is supported by general principles of using simulators in modelling enrichment processes, as detailed in the work of A. Karpatne *et al*. (2017), where the authors emphasise the importance of integrating physical models and machine learning methods to enhance prediction accuracy in complex systems. However, further validation on real production data remains an important step for fully confirming the accuracy and reliability of the developed model.

4. Preparation for the development of a control system model. Based on a limited initial dataset obtained from the operation of USIM PAC, an expanded dataset is created. This expanded dataset is characterised by a significantly larger volume while preserving key relationships between fields that correspond to the mathematical dependencies of the USIM PAC simulation system. Such an approach potentially allows for the generation of a more diverse data sample, which can serve as a foundation for the further development of a predictive automated control system for the non-linear iron ore enrichment system. However, to confirm the effectiveness of this approach, thorough validation of the expanded dataset is necessary. As noted by T. Hastie *et al*. (2009) in their foundational work on statistical learning, it is important to conduct comprehensive statistical analysis to verify the preservation of key relationships and to perform testing on real data where possible. This ensures the reliability and practical applicability of the developed model.

5. Potential for further development. The hybrid method leaves room for the integration of additional modelling methods in the future, which may be beneficial for further research and improvement of the system.

Characteristics and structure of the enrichment system model. The enrichment system model is based on geological and mineralogical data from the Valyavkinske deposit of iron quartzites (Bogdanov, 1984; Kupin, 2008). This data includes ore characteristics such as iron content, mineral composition, textural-structural features, and physical properties, which are crucial for designing the enrichment process. Although the data is derived directly from the deposit, it has been adapted for modelling the first stage of magnetic enrichment, typical of most Ukrainian MPPs (Sokur *et al.*, 2022). This allows for the creation of a model that reflects the typical conditions for enriching iron quartzites in Ukraine. The overall structure of the studied part of the iron ore enrichment system is presented in Figure 1.

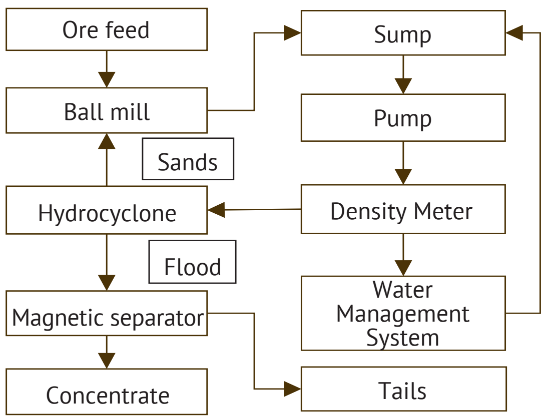

Figure 1. Technological scheme of iron ore enrichment with control of the solid density in the hydrocyclone
Source: developed by the author based on typical technological process schemes presented in M. Sokur *et al.* (2022)

The key input parameters of the model include the percentage of solids entering the hydrocyclone (25-35%), the flow rate of additional water (180-393 m^3/h), and the iron content in the incoming ore (36-38%). The output parameters encompass the iron content in the concentrate (52.5-55.5%) and tails (12.6-12.7%), as well as the mass flow rate of the concentrate (55-60 t/h) and tails (40-45 t/h). The selected characteristics of the deposit include an average rock density of 3.2-3.4 t/m^3, the grain size of magnetite inclusions of 0.074-0.044 mm, and the ratio of magnetic to non-magnetic minerals of 45-55.

The technological process, illustrated in Figure 1, consists of the following operations: the feed ore is supplied by a feeder to a ball mill for fine grinding. The resulting ore pulp is directed to the hydrocyclone for hydraulic classification by size. The overflow from the hydrocyclone is sent to a magnetic separator, where the material is separated based on magnetic properties into a magnetic product (concentrate) and a non-magnetic fraction (tails). The sands from the hydrocyclone are returned for regrinding in the ball mill, forming a closed grinding circuit. Control is achieved by adjusting the percentage of solids entering the hydrocyclone within the range of 25-35%, which affects the flow rate of additional water and ensures the quality of the concentrate (specifically, the iron content) in accordance with the target indicators established in the technological maps of the MPPs. This model provides a foundation for the development of automated control systems tailored to the specifics of Ukrainian iron ore deposits.

The use of the USIM PAC simulator. The technological process simulator USIM PAC from CASPEO was chosen to create the initial model of the iron ore beneficiation system. USIM PAC stands out among alternatives due to its greater number of equipment prototypes, the ability to use different models for circuit elements, and advanced result analysis. Its reliability is confirmed by widespread application in metallurgy and chemistry (Brochot *et al.*, 2002). For modelling the iron ore beneficiation process, the internal base Model 140 – "Feed Liberation" was utilised, which is an integral part of the commercial USIM PAC simulator (Fig. 2).

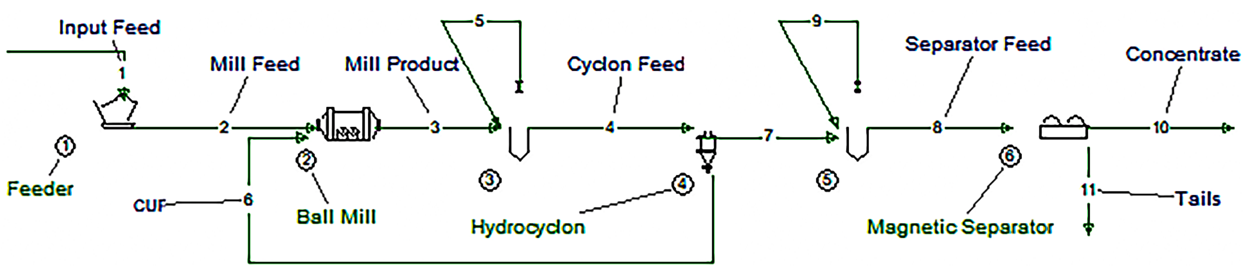

Figure 2. Iron ore enrichment system based on the Model 140 USIM PAC
Source: image of a typical educational Model 140 that is part of the USIM PAC

This model was chosen for its effectiveness in simulating the early stages of ore processing, making it particularly valuable for modelling the enrichment of iron ores from Ukrainian deposits. Model 140 is based on the method of R.L. Wiegel (1975) and the liberation model of A.M. Gaudin (1939), which allows for an accurate description of the mineral liberation process during grinding. It operates with key parameters: the dilution factor with waste rock, the content of the valuable mineral, and the effective grain size of the mineral. An important advantage of Model 140 is that the composition by liberation classes does not depend on the size distribution, making it especially useful at the beginning of the technological scheme. This corresponds to the actual operating conditions of Ukrainian MPPs. When applying Model 140 to the Valyavkinske deposit, specific characteristics of the local ores were taken into account, particularly the average magnetite inclusions and the typical mineralogical composition.

Description of model parameters. The modelling of the iron ore enrichment process was carried out based on data obtained using USIM PAC. Key model parameters, including input and output variables, their ranges, and units of measurement, are presented in Table 1.

Table 1. Key parameters of the iron ore enrichment process model

Parameter	Description	Range of values	Units of measurement
	Input parameters		
solid_feed_percent	Percentage of solids at the hydrocyclone inlet	25-35	%
water_add_mass_flow*	Additional water flow rate	180-393	m^3/h
feed_fe_percent	Iron (Fe) content in the feed ore	36-38	%
	Output parameters		
concentrate_fe_percent	Iron (Fe) content in the concentrate	52.5-55.5	%
tailings_fe_percent	Iron (Fe) content in the tailings	12.6-12.7	%
concentrate_mass_flow	Mass flow rate of the concentrate	55-60	t/h
tailings_mass_flow	Mass flow rate of the tailings	40-45	t/h

Notes: * – in fact, at this stage, the flow rate of additional water, despite being an input parameter, should be calculated
Source: developed by the author based on the data from O. Bogdanov (1984)

Modelling the distribution of iron content in incoming ore. The initial assumption for modelling the distribution of iron content in incoming ore was based on a normal distribution. This assumption is supported by the research of J.C. Davis (2002), who demonstrated that the natural variability of geological processes and the effects of ore mixing during extraction and transportation contribute to the formation of a normal distribution of valuable component content. This approach is also reinforced by the central limit theorem, which is relevant for many geostatistical processes. Thus, adopting this assumption is justified and beneficial for modelling iron ore enrichment processes.

To improve the fit of the data to a normal distribution, various transformation methods were explored. Among them, mathematical transformations (power, logarithmic, exponential) were applied, as well as statistical transformations such as the Box-Cox method (Box & Cox, 1964) and Yeo-Johnson method (Yeo & Johnson, 2000). Additionally, data processing methods were utilised, including outlier removal and the calculation of moving averages, as well as more complex approaches such as kernel density estimation (Silverman, 1986), principal component analysis (PCA), and rank normalisation. The chosen transformation method was applied to create a dataset with iron content distribution that closely aligns with a normal distribution. This provided the necessary foundation for further modelling of iron ore enrichment processes.

Generation of solid percentage values at the hydrocyclone inlet. The solid percentage at the hydrocyclone inlet (solid_feed_percent) is a key control parameter in the developed model. A comprehensive methodological approach was employed for its analysis and generation. Initially, a statistical investigation of the distribution of solid_feed_percent values in the primary dataset was conducted. The Kolmogorov-Smirnov tests (Massey, 1951) and Shapiro-Wilk tests (Shapiro & Wilk, 1965) were used to verify the normality of the distribution. The coefficient of variation, skewness, and kurtosis were also calculated to characterise the shape of the distribution, using methods described by T. Hastie *et al*. (2009).

To fill in missing data, two methods were developed and compared: kernel density estimation (KDE) and random filling within quantile constraints (RFQL). The KDE method, described by B.W. Silverman (1986), uses kernel density estimation to model the distribution of existing data. This method fills in gaps with random values within defined quantile constraints, preserving the statistical structure of the data while filling in the gaps. After generating data using both methods, a comparative analysis of their statistical characteristics was conducted. Mean values, data dispersion, distribution shape, and the presence of outliers were assessed using methods described in T. Hastie *et al*. (2009). This analysis allowed for the identification of the most suitable method for filling in missing solid_feed_percent values, ensuring the accuracy and representativeness of the data for further modelling. The chosen method was applied to create an extended dataset that includes both original and generated solid_feed_percent values. This approach ensures the preservation of the statistical structure of the original data while simultaneously expanding the dataset for more accurate modelling of the enrichment process.

Determining additional water flow values. In the model structure, the parameters of solid percentage in the hydrocyclone (solid_feed_percent) and additional water flow (water_add_mass_flow) have a close yet nonlinear relationship. To determine this relationship and fill in missing water_add_mass_flow values, the following methodology was applied. Initially, an analysis of the primary dataset was conducted to study the nature of the relationship between solid_feed_percent and water_add_mass_flow. It was established that this relationship is most accurately described by a second-degree polynomial dependence. A subset of records with incomplete data containing values for both parameters was extracted from the full dataset. Four methods were chosen for training and prediction: Gradient Boosting (Friedman, 2001), Random Forest (Breiman, 2001), Linear Regression (Hastie *et al.*, 2009), and Ridge Regression (Hoerl & Kennard, 1970). The selected methods provide a variety of approaches to data modelling, allowing for the capture of both complex nonlinear and linear dependencies. The models were trained on a sample of complete records. Quality metrics were calculated for each model, enabling a comparative analysis of the methods' effectiveness. This approach allows for the identification of the most accurate method for filling in missing water_add_mass_flow values and ensures data integrity for further analysis of the enrichment process.

Determining dependant parameters. To determine the iron content in the concentrate and tails, as well as the mass flow rates of the concentrate and tails for incomplete records in the dataset, the following methodology was applied. Initially, models were trained based on the complete dataset to fill in missing values in incomplete records. Six machine learning methods were used for this purpose: eXtreme Gradient Boosting (XGBoost) (Chen & Guestrin, 2016), Support Vector Machines (SVR) with a Laplace kernel (Cortes & Vapnik, 1995), Random Forest (Breiman, 2001), Multilayer Perceptron (MLP) (Rumelhart *et al.*, 1986), Ridge Regression (RR) (Hoerl & Kennard, 1970), and k-Nearest Neighbours Regression (kNN) (Altman, 1992). The choice of these methods is due to their ability to effectively work with multiple input/output (MIMO) models and address approximation tasks. Subsequently, the parameters of each model were optimised to enhance its performance. Based on the optimised parameters, final models were formed for further use in the enrichment process. This approach ensures the creation of an extended dataset with complete data for further analysis and modelling of the enrichment process.

Results and Discussion

Development of the functional diagram. To better understand the relationships between the model parameters and their roles in the iron ore beneficiation process, a functional diagram has been developed (Fig. 3). This diagram is based on the technological scheme of iron ore beneficiation with solid density control in the hydrocyclone (Fig. 1) and the iron ore beneficiation system based on Model 140 USIM PAC (Fig. 2). It visualises the main input and output variables, as well as their impact on various stages of the beneficiation process, integrating information from the previous diagrams into a more detailed functional model.

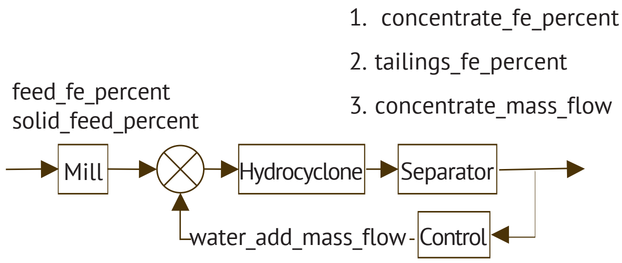

Figure 3. Functional diagram of the relationships between the parameters of the iron ore enrichment process model

Source: author's own development after processing the Model 140 USIM PAC

The functional diagram (Fig. 3) illustrates the key variables of the model and their interrelationships, which are crucial for understanding the iron ore beneficiation process. It demonstrates how the percentage of solids at the inlet of the hydrocyclone and the flow rate of additional water affect its operation, which in turn impacts the efficiency of magnetic separation. J. Svoboda (2004) notes that these factors are critical for achieving optimal results in the separation process, as they determine how effectively the useful components are separated.

The iron content in the incoming ore directly influences the quality of the obtained concentrate and tails, which is an important aspect for assessing the economic efficiency of beneficiation. This functional diagram not only summarises information from previous figures but also expands it by showing detailed interrelationships between parameters and their impact on each stage of the beneficiation process. As a result, it allows for a better understanding of how changes in one parameter can affect other aspects of the process. This knowledge is critically important for optimising the operation of the iron ore beneficiation system, as emphasised by T.J. Napier-Munn *et al.* (2014). Thus, the functional diagram serves as an important tool for analysing and improving technological processes in the mining industry.

The interrelationship between parameters is key to understanding the dynamics of the iron ore beneficiation system. The parameter feed_fe_percent reflects the percentage of iron content in the ore being fed into the system. When this value is constant, the system remains stable, but output parameters, such as concentrate quality and product yield, which constitute the objective function, do not reach their optimal values. To optimise the process, it is necessary to adjust the parameter solid_feed_percent, which represents the percentage of solid material in the pulp. This parameter is regulated through water_add_mass_flow, i.e., the mass flow rate of water added to the system. Increasing or decreasing the water supply alters the pulp density, which directly affects the efficiency of the beneficiation process. Thus, the correct adjustment of solid_feed_percent allows the system to achieve an optimal state, maximising concentrate quality while maintaining a high product yield. In the modelling process, solid_feed_percent and feed_fe_percent are set within defined constraints, while other parameters are calculated based on the mathematical model of the process.

The choice of these parameters is driven by the primary objective of the work – generating a dataset that describes the nonlinear process of iron ore beneficiation for further use in creating a predictive control system (Hodouin, 2009). The selected set of input, output, and influencing parameters provides an adequate description of the process to achieve this goal. Determining the optimal size of the expanded dataset is a key stage in modelling iron ore beneficiation, ensuring a balance between data representativeness and computational efficiency. This is critically important for the accuracy of the model, avoiding overfitting, and effectively utilising resources.

As noted by B.A. Wills & J.A. Finch (2015), optimising the dataset size is an important aspect for achieving high model accuracy and preventing overfitting. This optimisation requires consideration of the specifics of the iron ore beneficiation process, particularly the nonlinear relationships between parameters and the variability of process conditions. Methods for determining the optimal size may include learning curve analysis, cross-validation, and assessing the statistical significance of sample size increases, as described in the work of G. James *et al.* (2021). The application of these methods allows for the determination of the optimal dataset size that provides sufficient data representativeness for accurate modelling of the nonlinear iron ore beneficiation process while maintaining computational efficiency.

Determining the optimal size is an iterative process that requires constant balancing between accuracy and efficiency. Evaluation criteria may include model quality metrics (e.g., RMSE, R^2) and computational costs. A typical dataset size for modelling beneficiation processes can range from several thousand to hundreds of thousands of samples, depending on the complexity of the process and accuracy requirements (Napier-Munn *et al.*, 2014). It is also important to consider specific challenges associated with iron ore beneficiation data, such as the uneven distribution of ore quality classes and the potential presence of outliers, which may affect the representativeness of the sample.

Analysis of the results of the initial modelling and characterisation of the generated dataset. As a result of the preliminary modelling using the commercial software USIM PAC (Brochot *et al.*, 1995), 915 data records were generated. The analysis of the statistical parameters of the primary dataset demonstrates the following features (Table 2).

Table 2. Statistical characteristics of the initial dataset

	solid_feed_ percent	water_add_ mass_flow	feed_fe_ percent	concentrate_ fe_percent	tailings_fe_ percent	concentrate_ mass_flow	tailings_ mass_flow
Key indicators of central tendency							
Mean	29.76	272.82	36.65	54.29	12.65	57.62	42.37
Med	29.53	267.84	36.63	54.31	12.65	57.60	42.42
Dispersion indicators							
Std dev	2.97	62.26	0.79	0.70	0.03	1.21	1.18
Min	25.01	180.44	35.30	52.67	12.60	54.88	39.87
Max	34.99	393.80	38.02	55.86	12.70	60.18	44.97
CV	0.1000	0.2282	0.0216	0.0128	0.0020	0.0210	0.0279
Distribution shape indicators							
Kurtosis	-1.24	-1.13	-1.24	-0.70	-1.18	-0.82	-0.86
Skewness	0.09	0.28	0.06	-0.01	0.05	0.01	-0.02
Normality tests							
Shapiro-Wilk	2.21E-17	2.72E-18	6.20E-17	2.12E-06	4.25E-15	3.49E-08	6.04E-09

Notes: the most significant indicators were taken for the fields
Source: author's own calculations when processing the data

The solid phase content in the hydrocyclone liquid (solid_feed_percent) is characterised by a mean value of 29.76% and a median of 29.53%, indicating a typical level of solid phase content and a relatively symmetrical distribution of the data. The standard deviation of 2.97 and the coefficient of variation of 0.1000 indicate moderate variability of the parameter. The range of values from 25.01 to 34.99% demonstrates significant amplitude of fluctuations. The skewness coefficient of 0.09 indicates slight right-side skewness, while the kurtosis coefficient of -1.24 suggests a flatter distribution compared to normal. These characteristics indicate a stable, yet not static, process of solid phase feeding, with certain distribution peculiarities that should be considered in further analysis and modelling.

The water flow rate (water_add_mass_flow) has a mean value of 272.82 and a median of 267.84, indicating slight right-side skewness of the distribution. The high standard deviation of 62.26 and the coefficient of variation of 0.2282 indicate significant variability of this parameter. The wide range from 180.44 to 393.80 demonstrates substantial fluctuations in water flow, which may be related to different operating modes of the hydrocyclone or changes in the input raw material.

Iron content indicators (feed_fe_percent, concentrate_fe_percent, tailings_fe_percent) demonstrate high stability. Low coefficients of variation (0.0216, 0.0128, 0.0020 respectively) and narrow ranges of values indicate the stability of the enrichment process and the effectiveness of separating iron-containing components. The closeness of the mean values and medians for these indicators suggests the symmetry of their distributions, which is a sign of a stable technological process.

The mass flows of concentrate and tailings (concentrate_mass_flow, tailings_mass_flow) are characterised by low coefficients of variation (0.0210 and 0.0279 respectively), indicating the stability of the separation process. The proximity of the mean values and medians, as well as relatively narrow ranges of values, confirm the stability of mass flows, which is an important indicator of the hydrocyclone's operational efficiency. The analysis of the distribution shape shows that all variables have negative kurtosis coefficients (ranging from -0.70 to -1.24), indicating a platykurtic distribution. This means that the distributions have a flatter shape compared to a normal distribution, which may indicate greater uniformity of values in the central part of the distribution. The skewness coefficients are close to zero (ranging from -0.02 to 0.28), indicating relatively symmetrical distributions for all parameters.

The results of the Shapiro-Wilk normality tests (Shapiro & Wilk, 1965) show very low P-values for all variables. This indicates a statistically significant deviation from normal distribution for all studied parameters. Such results may be a consequence of the specifics of the technological process or the presence of certain constraints or controls over the parameters.

Overall, the analysis of statistical characteristics demonstrates a stable distribution of most studied indicators with moderate variability. Such results correspond to typical observations for technological processes, as noted by D.C. Montgomery (2021) in his work on statistical methods analysis in industry. Deviations from normal distribution and platykurticity are important features that need to be considered in further analysis and modelling of the data. These characteristics may influence the choice of statistical analysis and modelling methods, as well as the interpretation of the results of iron ore enrichment process studies. A visual analysis of the statistical parameters of the primary dataset, presented through histograms and distribution density curves, is shown in Figure 4.

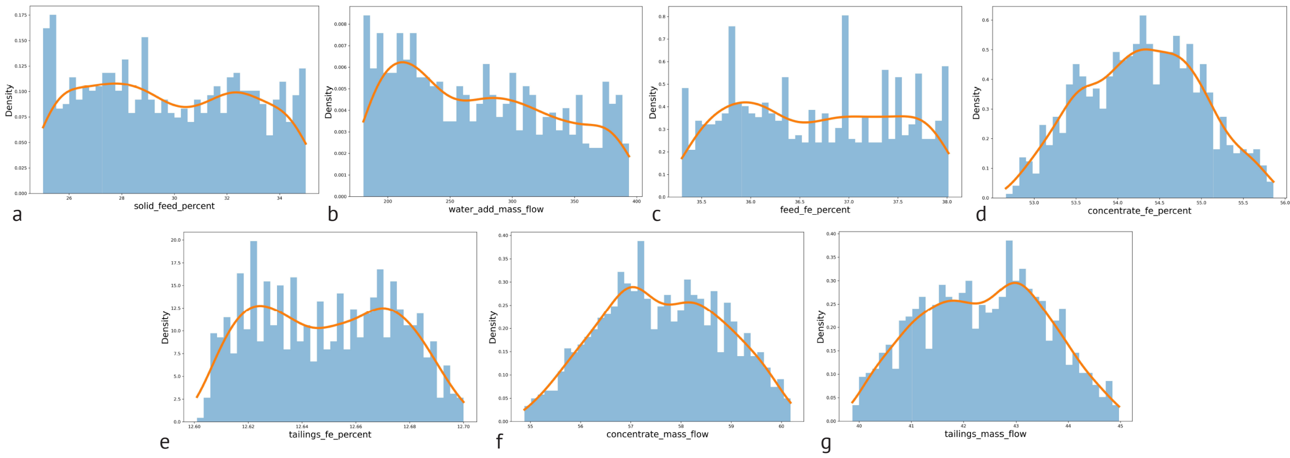

Figure 4. Histograms and density distribution curves of the main parameters of the primary dataset

Notes: a – solid phase content in the hydrocyclone liquid; b – water flow rate; c – iron content in the feed ore; d – iron content in the concentrate; e – iron content in the tailings; f – mass flow rate of the concentrate; g – mass flow rate of the tailings Bar chart – histogram, line graph – density curve of the corresponding parameter

Source: author's own development based on conducted calculations

Modelling the distribution of iron content in the incoming ore. In the process of modelling the distribution of iron content in the incoming ore, an initial assumption was made regarding the normal distribution of the data. This assumption was based on theoretical considerations and widely accepted practises in the field of ore enrichment. However, as previously demonstrated (Table 2; Fig. 4), the analysis of the primary model data revealed significant deviations from the expected normal distribution. The primary cause of this deviation was identified as the manual entry of data for the relevant variable, which led to an uneven distribution. Consequently, the task arose to adjust the distribution of this field to normal, which is critically important for the accuracy of further modelling of the enrichment process.

To address this issue, a number of distribution correction methods were proposed and analysed. Among them were: logarithmic transformation, exponential transformation, the Box-Cox method (Box & Cox, 1964), the moving average (MA) method, Kernel Density Estimation (Rosenblatt, 1956), and Principal Component Analysis (PCA) (Pearson, 1901). The results of applying these methods are presented in Figure 5.

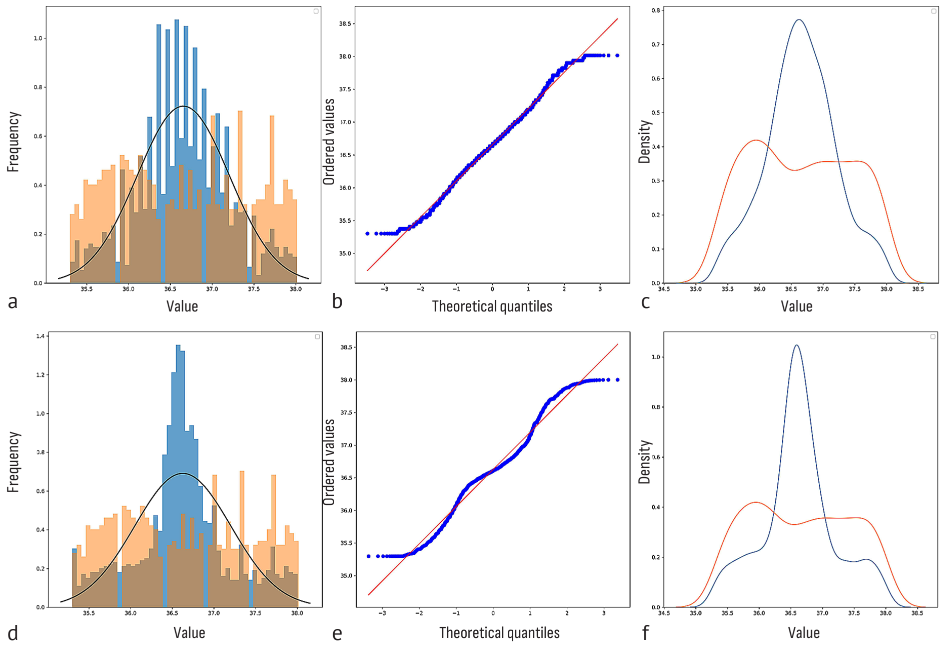

Figure 5. Results of transformation using different methods

Notes: a – Log; b – Exp; c – Box-Cox; d – MA; e – KDE; f – PCA. Distribution of diagrams in the group from left to right, top to bottom: 1. Histograms of the original (orange) and modified (blue) distributions; 2. Q-Q plot after modification; 3. Density curves of the original (orange) and modified (blue) distributions

Source: author's own development based on conducted calculations

Based on a comparative analysis of quality metrics (Table 3), the moving average method with automatic parameter optimisation was selected. This method provided the best balance between achieving normality of the distribution and preserving key characteristics of the original data. Specifically, the MA method showed optimal results across four of the five key criteria: multiplier, skewness, kurtosis, and preservation of the original data. Although the method did not achieve optimal results for P-value, automatic optimisation helped minimise undesirable effects of the transformation.

Table 3. Comparison of data transformation methods

Method	Multiplier	P-value	Skewness	Kurtosis	Original data percentage
Optimal	⩽10	0.05	0.5	0.5	⩾10%
Log	3	0.0950	0.0309	0.1721	25.03%
Exp	1	0.2364	-0.0065	0.2006	50%
Box-Cox	8	0.8050	-0.0009	-0.1157	11.11%
MA	2	0.1725	0.0265	0.1731	33.38%

Notes: the first line is the optimal indicators that needed to be achieved during the automatic search for parameters

Source: author's own calculations when processing the data

The application of the chosen method allowed for the creation of a new dataset, which includes 730 complete and 2,026 partially filled records, demonstrating an approximate Gaussian distribution of iron content (the filled data column feed_fe_percent with 2,756 values). This created a reliable foundation for further analysis and modelling of the enrichment process. It is important to note that correcting the distribution of iron content in the incoming ore is critical for the accuracy of the entire enrichment model. This enables more accurate forecasting of process outcomes and optimisation of control parameters, ultimately enhancing the efficiency of the entire iron ore enrichment process.

Generation of solid feed percentage values at the hydrocyclone inlet. The solid feed percentage at the hydrocyclone inlet (solid_feed_percent) is a key control parameter in automated iron ore beneficiation systems. B.A. Wills & J.A. Finch (2015) emphasise that this parameter significantly affects the efficiency of the beneficiation process and the optimisation of target indicators, such as concentrate quality and product yield. A statistical analysis of the primary dataset revealed that the distribution of solid_feed_percent has a flat structure. This feature creates favourable conditions for exploring various operating modes of the system (Fig. 4). Two methods were employed to fill in the missing data: Kernel Density Estimation (KDE) (Rosenblatt, 1956) and Random Filling with Quantile Limits (RFQL) (Hastie *et al.*, 2009). The results of the transformation of the solid_feed_percent distribution using these methods are presented in Figure 6, which visually demonstrates the differences between the KDE and RFQL methods: the KDE method provides a smoother distribution, while RFQL better preserves the structure of the original data. This visual comparison is complemented by a detailed analysis of statistical indicators presented in Table 4.

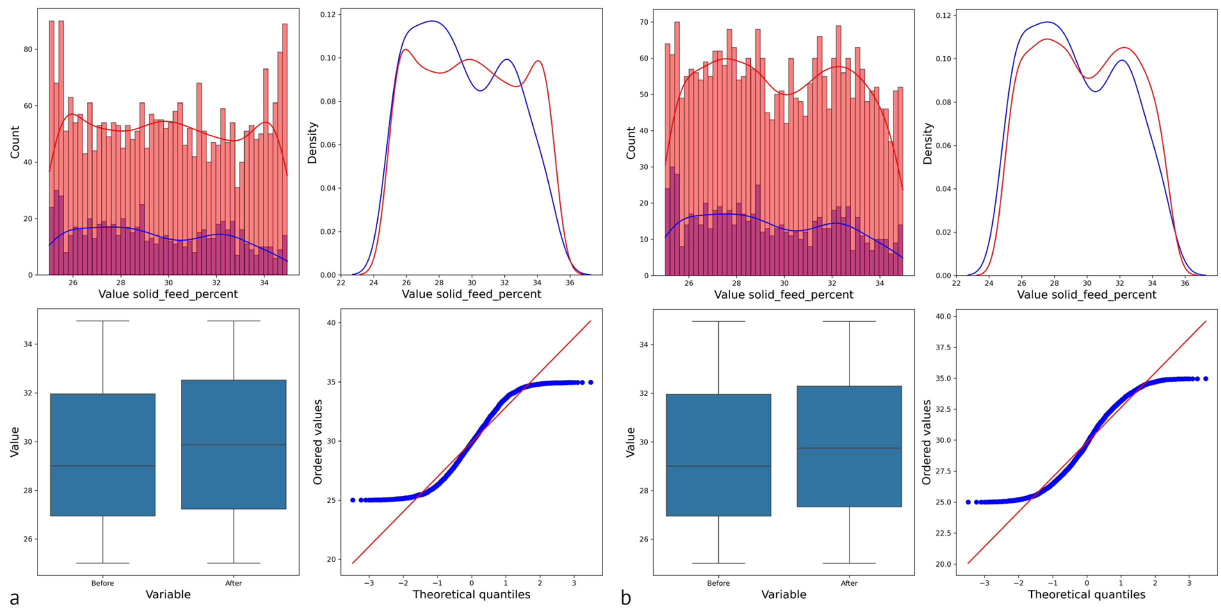

Figure 6. Transformation of the solid_feed_percent distribution due to gap filling

Notes: a – use of the KDE method; b – use of the RFQL method. Distribution of diagrams in the group from left to right, top to bottom: 1. Histograms of the original (red) and modified (orange) distributions; 2. Density curves of the original (blue) and modified (red) distributions; 3. Box plot of the value distribution; 4. QQ plot of the residuals

Source: author's own development based on conducted calculations

Table 4. Comparison of statistical indicators of missing data imputation methods

Metric	RFQL	KDE	Difference
Mean	29.8897	29.8905	0.0008
Std dev	2.8954	3.0256	0.1303
Med (50%)	29.8870	29.8740	-0.0130
25th percentile	27.3300	27.2000	-0.1300
75th percentile	32.3650	32.5003	0.1352
Skewness	0.0329	0.0472	0.0143
Kurtosis	-1.1982	-1.2442	-0.0460

Source: author's own calculations in data processing

The data analysis in Table 4 shows that both methods demonstrate similar results regarding means, dispersion, and skewness. However, the RFQL method proved to be more stable, with a lower tendency to create outliers. While KDE offers a broader coverage of possible values, RFQL better maintains the realistic characteristics of the process, which is critical for the accuracy of the model, as discussed in the work of T. Hastie *et al*. (2009). The choice of the RFQL method for further work is justified by its ability to preserve the statistical structure of the original data, which is particularly important for modelling complex technological processes. This method allows for the generation of data that not only fills in gaps but also retains the characteristics of the actual beneficiation process, as noted by A. Gelman & J. Hill (2006). It is important to note that changes in the solid percentage significantly impact the efficiency of the beneficiation process, and optimal control of this parameter can lead to improved concentrate quality and reduced losses of valuable components in the tails.

Determining the values of additional water consumption. The parameters of solid feed percentage (solid_feed_percent) and additional water flow rate (water_add_mass_flow) were found to be non-linearly interrelated. Solid_feed_percent serves as an indicator of the system's control mode, while water_add_mass_flow regulates this mode (Wills & Finch, 2015). An analysis of the initial dataset confirmed the non-linearity of the relationship between solid_feed_percent and water_add_mass_flow, which is most accurately described by a second-degree polynomial dependence. From 730 complete records containing values for both parameters, a model was developed to predict water consumption for 2,026 records lacking this value. Four machine learning methods were applied for modelling: Gradient Boosting (Friedman, 2001), Random Forest (Breiman, 2001), Linear Regression, and Ridge Regression (Hastie *et al*., 2009), providing a variety of approaches to data modelling. The effectiveness of each method was evaluated using key metrics (Table 5) and visualised in Figure 7.

Table 5. Comparison of the effectiveness of machine learning methods for modelling

Method	MSE	MAE	R^2
Gradient Boosting	0.9691	0.7396	0.9997
Random Forest	0.7237	0.6129	0.9998
Linear Regression	1.6805	1.0276	0.9996
Ridge	4.1035	1.5272	0.9989

Source: author's own calculations in data processing

The analysis of results showed that the Random Forest method demonstrated the best performance with the lowest MSE and MAE values, as well as the highest R^2 (James *et al*., 2021). This indicates its high accuracy and ability to effectively model complex non-linear dependencies between the parameters of the enrichment process. The obtained results have significant practical implications for optimising the enrichment process. They allow for more accurate forecasting and control of the solid percentage at the inlet of the hydrocyclone, which is crucial for enhancing the efficiency of the entire iron ore enrichment process. B.A. Wills & J.A. Finch (2015) emphasise in their work that precise control of this parameter can significantly impact the quality of the final product and reduce processing costs.

Definition of dependant parameters. To search for missing values in the fields of iron content in the concentrate, iron content in the tails, mass flow rate of the concentrate, and mass flow rate of the tails, an approach is employed that utilises a complete dataset to train machine learning algorithms that fill in the missing values. This enhances the integrity of the extended dataset, which is critically important for further analysis and modelling of enrichment processes. Six machine learning methods were selected for this purpose: eXtreme Gradient Boosting (Chen & Guestrin, 2016), Support Vector Machines with Laplace kernel (Cortes & Vapnik, 1995), Random Forest (Breiman, 2001), Multilayer Perceptron (Goodfellow *et al*., 2016), Ridge Regression (Hoerl & Kennard, 1970), and k-Nearest Neighbours Regression (Altman, 1992). These methods are distinguished by their ability to effectively solve approximation tasks using MIMO models. Each of these methods was optimised to ensure maximum efficiency, allowing for the creation of models for accurate modelling of technological enrichment processes. The analysis results presented in Table 6 show that the Multilayer Perceptron demonstrates the best performance. This model has the lowest error values and the highest coefficient of determination R^2, indicating its high accuracy and effectiveness in generalising data, as detailed by I. Goodfellow *et al*. (2016) in their work on deep learning.

Table 6. Comparison of metrics for mathematical learning systems

Method	MSE	RMSE	MAE	R^2
XGB	0.0021	0.0460	0.0288	0.9977
SVR	0.0015	0.0383	0.0188	0.9989
RF	0.0032	0.0564	0.0336	0.9973
MLP	0.0013	0.0361	0.0208	0.9990
RR	0.0016	0.0396	0.0247	0.9986
kNN	0.0030	0.0540	0.0329	0.9972

Source: author's own development based on the calculations performed

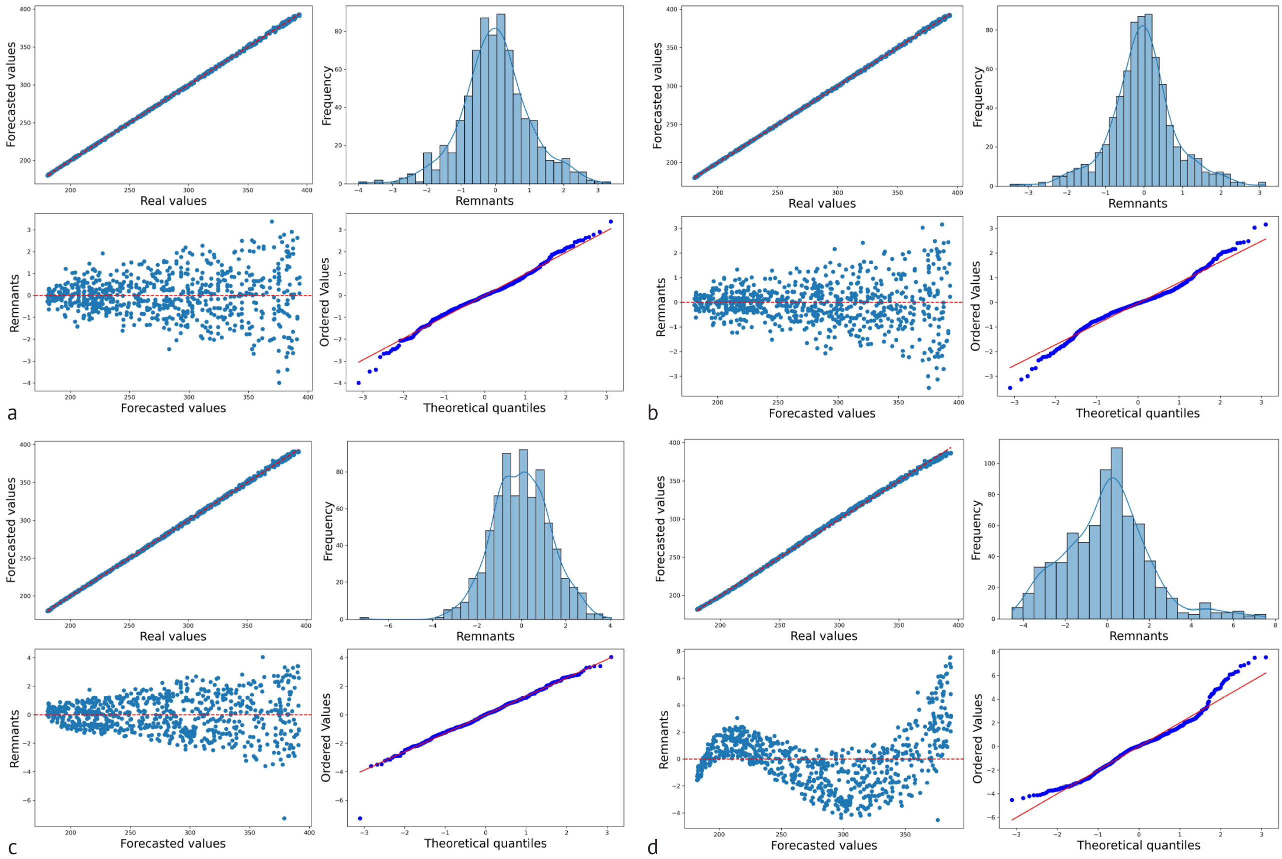

Figure 7. Quality metrics for forecasting using different forecasting methods

Notes: a – Gradient Boosting; b – Random Forest; c – Linear Regression; d – Ridge. Distribution of diagrams in the group from left to right, top to bottom: 1. Actual and forecasted values; 2. Distribution of residuals; 3. Residuals of forecasted vs. values; 4. QQ plot of residuals

Source: author's own development based on the calculations performed

Additionally, the SVR method with Laplace kernel also showed competitive results. With a high R^2 value and low error values, SVR is a reliable alternative for modelling, especially when neural networks are overly complex or resource-intensive. This method offers a balanced solution between model complexity and accuracy, making it very useful for real production conditions. Figure 8 illustrates the residuals when using machine learning methods. MLP demonstrates the most consistent results without significant deviations, while SVR also proved to be stable, confirming its reliability. MLP is the optimal choice for high-precision solutions to complex enrichment technological tasks, while SVR with Laplace kernel can be a practical option for situations where a combination of efficiency and simplicity is required.

Figure 8. Visualisation of residuals when using different learning methods

Notes: a – XGBoost; b – Support Vector Regression; c – Random Forest; d – Perceptron Neural Network; e – Ridge Regression; f – k-Nearest Neighbors Regression. Fields in the group from left to right, top to bottom: concentrate_fe_percent, tailing_fe_percent, concentrate_mass_flow, tailing_mass_flow

Source: author's own development based on the calculations performed

Analysis of extended data. As a result of working with the data, an extended dataset was obtained with several modified distributions. The total number of records in the new dataset amounted to 2,756 records, which was determined by the initial requirements for automatic parameter selection when working with the feed_fe_percent field. Further expansion of the data array can be conducted through an iterative cycle according to the developed methodology. The statistical indicators of the new dataset are presented in Table 7.

Table 7. Statistical characteristics of the resulting dataset

	solid_feed_ percent	water_add_ mass_flow	feed_fe_ percent	concentrate_ fe_percent	tailings_fe_ percent	concentrate_ mass_flow	tailings_ mass_flow
Key indicators of central tendency							
Mean	29.86	270.02	36.65	54.28	12.65	57.65	42.34
Med	29.82	261.65	36.66	54.28	12.65	57.7	42.32
Dispersion indicators							
Std dev	2.86	59.66	0.54	0.55	0.02	0.91	0.87
Min	25.01	180.58	35.3	52.66	12.6	54.88	39.98
Max	34.96	393.8	38.02	55.86	12.7	60.09	44.96
CV	0.0956	0.221	0.0148	0.0101	0.0014	0.0157	0.0206
Distribution shape indicators							
Kurtosis	-1.18	-1.03	0.01	-0.27	-0.04	-0.16	-0.1
Skewness	0.04	0.35	0.04	0.05	0.06	-0.14	0.11
Normality tests							
Shapiro-Wilk	7.51E-28	1.82E-30	5.55E-10	7.06E-03	4.82E-07	1.64E-04	1.06E-03

Source: author's own development based on the calculations performed

The main indicators of central tendency, such as the mean and median, remained virtually unchanged for most indicators, indicating the preservation of the overall data structure. However, slight changes were observed in the indicators of water_add_mass_flow and concentrate_mass_flow, which may be related to the modification of the distribution of these fields. The analysis of dispersion indicators revealed that the standard deviation decreased for most indicators, indicating a reduction in data spread. The coefficients of variation also decreased, suggesting an increase in data homogeneity.

The study of distribution shape indicators demonstrated that the coefficients of excess and skewness underwent slight changes, indicating the preservation of the overall shape of the distribution. However, for some indicators, such as feed_fe_percent, concentrate_fe_percent, and tailings_fe_percent, a decrease in excess was observed, which may indicate a convergence towards a normal distribution. The results of normality tests, particularly the Shapiro-Wilk test, indicate that the distribution of most indicators remains non-normal. However, for some indicators (concentrate_fe_percent, tailings_fe_percent), a slight approach to normality is observed.

In general, it can be concluded that the modification of the distribution of certain fields led to minor changes in the statistical characteristics of the dataset. The main indicators of central tendency remained virtually unchanged, while the dispersion and shape indicators experienced slight improvements. This suggests that the overall data structure has been preserved, but their homogeneity and approach to normal distribution have somewhat increased. The visual distribution of the resulting dataset, presented through histograms and density distribution curves, is shown in Figure 9.

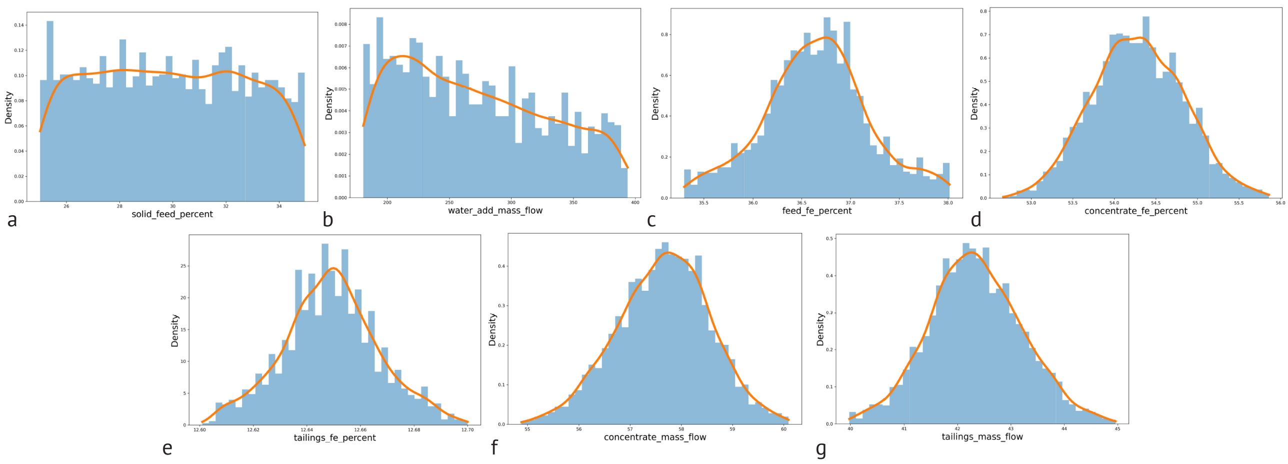

Figure 9. Histograms and density curves of the data distribution of the main parameters of the primary dataset

Notes: a – solid phase content in the hydrocyclone liquid; b – water flow rate; c – iron content in the feed ore; d – iron content in the concentrate; e – iron content in the tailings; f – mass flow rate of the concentrate; g – mass flow rate of the tailings. Bar chart – histogram, line graph – density curve of the corresponding parameter

Source: author's own development based on the calculations performed

As a result of the conducted analysis, an extended dataset was formed while preserving the overall structure of the original data. The modification of the distributions of certain parameters led to minor changes in the indicators of central tendency and an improvement in the homogeneity of the data. The presented statistical characteristics and visualisations confirm the increased proximity of the distributions to normality. The developed methodology for creating extended datasets for modelling magnetic separation of iron ore demonstrates significant potential for enhancing enrichment processes in the mining industry. The hybrid method used in the study has the potential to integrate aspects such as modularity, which, as defined by S. Shalev-Shwartz & S. Ben-David (2014), allows for the updating of components without the need to rebuild the system, ensuring adaptation to new requirements.

The use of the USIM PAC simulator for generating the primary dataset aligns with the approach described in the work of T.J. Napier-Munn *et al.* (2014), who emphasise the importance of applying specialised simulators for modelling enrichment processes. However, unlike their study, this work identified deviations from the expected Gaussian distribution, highlighting the necessity of validating theoretical models against real data, as noted by B.A. Wills & J.A. Finch (2015). The application of the moving average method with automatic parameter optimisation for data distribution correction is an innovative approach that has not been widely covered in previous research. This method demonstrated better results compared to traditional data transformation methods, such as logarithmic and exponential transformations, as described in the work of T. Hastie *et al.* (2009), which discusses various data processing techniques to improve their quality.

The use of the Random Forest with Quantile Limits method for filling in data gaps shows similarities to the approach proposed by L. Breiman (2001), but with additional constraints to ensure the physical validity of the data. This enhancement allows for better preservation of the characteristics of the actual enrichment process, which is a critical aspect emphasised by A. Gelman & J. Hill (2006). A comparison of different machine learning methods for modelling the relationships between parameters of the enrichment process revealed the superiority of the multilayer perceptron over other methods. This aligns with the findings of A. Karpatne *et al.* (2017), whose authors also noted the effectiveness of neural networks for modelling complex nonlinear processes in the mining industry. However, unlike their work, this study also found high effectiveness in the SVR method with a Laplace kernel, which may serve as a useful alternative in conditions of limited computational resources.

The developed methodology for creating extended datasets corresponds to the current trends of Industry 4.0, as mentioned in the research by H. Lasi *et al.* (2014). It provides modularity in the approach, allowing for the integration of new methods and data sources (Khaleghi *et al.*, 2013). It is important to note that this research focuses on the specifics of Ukrainian iron ore deposits, particularly the Kryvyi Rih basin, which distinguishes it from many international studies. This allows for consideration of local geological conditions and technological features, which are critical for the practical application of the results. Overall, the obtained results lay the foundation for further development of automated control systems for enrichment processes, aligning with the research directions outlined by P. Kadlec *et al.* (2009) and I.E. Grossmann & G. Guillén-Gosálbez (2010), who detail the importance of automation in managing technological processes and its impact on production efficiency. In particular, a promising direction is the integration of the developed methodology with decision-making systems and energy consumption optimisation.

Compared to existing studies, the developed methodology offers a comprehensive approach that combines physical modelling, statistical methods, and machine learning. This allows for overcoming the limitations associated with the lack of real production data while maintaining the physical validity of the model. Such an approach opens new opportunities for optimising iron ore enrichment processes and enhancing production efficiency in the context of Ukrainian mining and enrichment plants.

Conclusions

As a result of the research, a comprehensive methodology for creating extended datasets for modelling the magnetic separation process of iron ore has been developed, taking into account the specifics of Ukrainian deposits and the limitations of available information. Key achievements include: the creation and validation of an extended dataset based on the technological simulation USIM PAC; the development of a method for correcting data distribution with automatic parameter optimisation; and a comparative analysis of machine learning methods, where the multilayer perceptron demonstrated the highest prediction accuracy. The scientific novelty of the research lies in the development of an innovative methodology that combines technological simulation, statistical data correction methods, and modern machine learning algorithms for modelling the processes of magnetic separation of iron ore. This approach allows overcoming the limitations associated with the lack of real production data while maintaining the physical validity of the models.

The work provides opportunities to enhance production efficiency and product quality at Ukrainian mining and beneficiation plants. The developed methodology creates conditions for more precise tuning of technological processes, which is particularly important in the early stages of design and in conditions of limited access to technological data. Furthermore, this methodology represents a significant step towards improving the efficiency and competitiveness of Ukrainian MPPs. This innovative approach opens new possibilities for optimising production and enhancing product quality in the field of iron ore beneficiation, contributing to the overall progress of the industry and strengthening Ukraine's position in the global iron ore raw materials market.

Nevertheless, an important direction for further research is the integration of the developed models into comprehensive automated control systems for technological processes, which will promote an increase in the level of automation and optimisation of management in enterprises. The application of deep learning methods to improve the accuracy of predicting beneficiation process parameters will enable the creation of more precise and reliable models for decision-making, while the development of adaptive control algorithms and optimisation of energy consumption will contribute to cost reduction and enhanced environmental safety in production.

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Conflict of Interest

None.

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Комплексна методологія створення розширених датасетів для моделювання процесу магнітної сепарації залізної руди

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Анотація. Дослідження пропонує інноваційний підхід до створення розширених наборів даних для моделювання магнітної сепарації залізної руди, що є важливим для підвищення ефективності та автоматизації процесів збагачення в гірничодобувній промисловості. Мета дослідження полягала в розробці методології створення розширених наборів даних для моделювання магнітної сепарації залізної руди, яка враховує специфіку українських родовищ та дозволяє генерувати репрезентативні дані в умовах обмеженості реальних виробничих даних шляхом інтеграції фізичного моделювання з методами машинного навчання. Методи дослідження: моделювання з використанням математичного навчання, симуляція на основі фізичних процесів, статистичний аналіз. У дослідженні розглянуто використання симулятора USIM PAC для моделювання системи збагачення залізної руди та адаптацію даних для магнітного збагачення, що забезпечує точність моделювання технологічних процесів збагачення. Застосуванням симулятору отримано набір даних фізичного моделювання частини процесу збагачення на основі даних Валявкінського родовища. Проаналізовано первинне моделювання набору даних, включаючи статистичні характеристики, форму розподілу та тести на нормальність для виявлення полів, що потребують корекції. На основі результатів аналізу визначено конкретні вимоги до розподілу даних у новому датасеті, який має бути сформований для подальшого використання. Відповідно до цих вимог реалізовано декілька математичних моделей, що відтворюють задані критерії та параметри. Для кожного поля даних ретельно підібрано найкращу модель та виконано корекцію датасету за її даними, щоб максимально наблизити розподіл до бажаного. Для отриманих скоригованих даних проведена всебічна валідація результатів з акцентом на збереженні фізичної достовірності даних та їх відповідності реальним процесам збагачення. Проведено детальний аналіз відкоригованих даних, а також статистичні характеристики результуючого датасету, в результаті чого підтверджена ефективність розробленої комплексної методології моделювання та адаптації даних для магнітного збагачення залізної руди. Методологія має практичну цінність завдяки інноваційному підходу до створення розширених наборів даних для моделювання магнітної сепарації залізної руди, що підвищує ефективність і автоматизацію процесів збагачення, враховуючи специфіку родовищ та генеруючи репрезентативні дані в умовах обмеженості реальних даних

Ключові слова: нелінійне моделювання збагачення; керування сепарацією; машинне навчання в збагаченні; автоматизація збагачувальних процесів; симуляція технологічних параметрів

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Overview of promising research in the field of solid waste recycling for further use as solid fuel materials

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Abstract. The relevance of the stated topic of this research is the global increase in environmental problems, including resource depletion and pollution, which has led to an urgent need to develop solutions for sustainable waste management. This study is concerned with municipal solid waste processing, with a particular focus on the conversion of waste into solid fuel materials. A comparative analysis of the literature for the period up to 2024 was carried out to identify the most efficient waste-to-energy technologies. The findings highlight two key societal issues: environmental degradation due to inadequate waste management practices and resource scarcity caused by urbanisation and industrialisation. Among the notable results is the identification of waste incineration and pyrolysis as promising technologies for energy recovery, landfill reduction and environmental mitigation. In particular, it was shown that pyrolysis produces more energy and emissions than traditional incineration. In addition, the analysis showed the potential of waste-to-energy and microbial fuel cells as innovative approaches to sustainable energy production from waste. These technologies can provide additional sources of energy for domestic and industrial needs, while reducing the environmental impact of waste disposal. The practical value of this research lies in its potential to develop advanced technologies for processing municipal solid waste for energy, which can improve resource efficiency and energy sustainability

Keywords: energetic resources; waste sorting; global warming; industrial processing

Introduction

Any waste is an inevitable product, the amount of which is rapidly increasing due to population growth. This in turn pushes for an increase in demand for waste disposal. There are various kinds of waste in the world, for example, non-hazardous waste that occurs in everyday life – plastic, paper, food, etc., which are generally called municipal solid waste (MSW). The MSW content usually consists of a diverse mixture of materials, but, however, the main share is organic content. Until 2024, the most widely used methods of solid waste recycling were landfill disposal and incineration, which seem to have reached maximum occupancy. Such waste disposal options have a detrimental effect on the environment, i.e., to environmental and social problems, for example, to soil and sea pollution, and this leads to a deterioration in water quality, the spread of pests and various diseases and viruses, the emergence and spread of unpleasant odours, etc. The reason for this is the release of substances that include polychlorinated dibenzo-p-dioxins and dibenzofurans, including methane. S. Khan *et al.* (2022) noted that all these pests belong to persistent organic pollutants (POPs) – toxins that have a harmful effect on human health and the environment, and can also be sources of greenhouse gases. It should

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also be borne in mind that when burning household waste, incomplete combustion of hydrocarbon fuel occurs, in which soot particles are released. In turn, they negatively affect the environment, because they are carriers of toxic substances. J. He *et al.* (2022) conducted a study of the morphology of soot particles that are formed during the combustion of solid household waste, namely paper, kitchen waste, plastic and textiles. The results of the study showed a significant influence of the composition of waste on the physical properties of soot particles. This kind of work can provide valuable information for modelling carbon black nanostructures and heat transfer in the furnace. In particular, the study did not present a comprehensive account of the long-term stability and degradation behaviour of carbon black nanostructures under varying thermal conditions. Moreover, the interaction mechanisms between soot particles and diverse furnace materials, which may markedly influence heat transfer efficiency, remain insufficiently explored.

There are other traditional methods of municipal solid waste disposal – these include recycling, reuse, incineration without energy generation, gas production as a result of pyrolysis and industrial incineration with the use of released energy. However, the heterogeneity of the composition of waste to some extent may limit the use of traditional approaches. K. Lin *et al.* (2022) noted that incineration, pyrolysis, gasification, anaerobic digestion and landfill disposal are fraught with a potential risk of explosion during operation. The household also has a significant impact, since it is one of the largest sources of solid waste in the world. In the course of the H. Alhassan *et al.* (2020) study, the factors determining the characteristics of households for waste separation and disposal options were studied. It was identified that the most and least separable solid waste are bags and food waste, respectively. In addition, the most significant factor motivating and hindering the activity of households to separate sources is the financial incentive. H. Alhassan *et al.* (2020) also found that the government should develop and implement a waste minimisation policy and it is necessary to provide and make waste separation facilities accessible and convenient, since this can contribute to waste separation behaviour.

The introduction of innovative waste-to-energy conversion technologies can help in the management of solid waste while maintaining a relatively stable level of energy scarcity. The study by S.K. Awasthi *et al.* (2022) proved that the number of patents in the field of solid waste processing continues to grow rapidly, which stimulates the use of methods to combat solid waste pollution. Energy extraction as a result of waste disposal is the most preferable and profitable, because this will reduce the amount of waste, and reduce the production of thermal energy. Much attention of S.K. Awasthi *et al.* (2022) has been devoted to the issue of a more profitable technology for processing solid waste with the conversion of solid fuel materials, which solves most of the problems associated with the environment. In this regard, the purpose of this work is to analyse the latest and current research with an overview of effective methods of processing municipal solid waste for further use as solid fuel materials.

M. El Alouani *et al.* (2024) investigated the potential of utilizing bulk solid waste in the creation of flame retardant materials. This approach offers an alternative avenue for the utilization of solid waste beyond its conventional use in fuel production. Such materials can be integrated into industrial processes, thereby reducing the necessity for the utilization of primary resources while simultaneously enhancing the sustainability of the process. Similarly, A. Machín *et al.* (2024) demonstrated the potential of solid waste in improving the hydromechanical behaviours of soils, thereby contributing to more stable construction practices and offering another avenue for waste utilisation in infrastructure development. Furthermore, Y. Xiong *et al.* (2024) investigated the recycling of hazardous lithium-ion batteries, demonstrating the potential to transform these materials into catalytic substances with high added value. This work emphasises the necessity for recycling technologies that address both environmental concerns and resource recovery, particularly in the context of hazardous materials.

The objective of this research was to investigate innovative approaches to municipal solid waste management, with a particular focus on the conversion of waste into solid fuel materials. This approach has the potential to address both environmental and energy concerns.

Materials and Methods

The basis of the methodological approach in this scientific study is a combination of the method of comparative analysis of the results of available literary sources in the field of assessing current achievements in the field to processing municipal solid waste, with an analytical study of the best options for their disposal. In addition, when conducting this scientific study, the conditional division of municipal solid waste into four key categories was taken into account, with the addition of two auxiliary categories – production waste, which is formed exclusively as a by-product during the production of the main product, as well as consumer waste, which is unusable for use in everyday life.

The work also considers solid fuel materials obtained by processing solid waste were studied. One of these most common materials is considered to be Resource Description Framework (RDF). In turn, RDF is classified in accordance with the standards established to accelerate the sale of this fuel for energy use and increase its calorific value (Chavando *et al.*, 2022). Among the key standards that were considered in this study are:

▼ ASTM International Standard No. E856-83(2004) (1998): RDF is officially defined by the American Society for Testing and Materials (ASTM) through the ASTM E-38-01 Committee on Resource, Energy Recovery. This standard is used and applied mainly in the incineration industry;

▼ UNI 9903-1:2004 (2004) is a European standard used mainly in Italy for the incineration and cement industries. This standard also establishes the physical and chemical characteristics of solid fuel obtained from waste (conventionally called RDF), including general requirements for its storage, processing and transportation.

The practical application of the method of comparative analysis of the results of the study of modern achievements in the field of solid waste processing made it possible to assess the real need to develop measures to introduce rules and prepare laws on solid waste processing. This subsequently makes it possible to create an integral structure for ensuring the proper level of environmental cleanliness, which has been introduced to 2024 in a number of large cities around the world, as well as to create the proper conditions for the separation and processing of solid household and other waste.

An analytical study of the best available options for the processing and disposal of municipal solid waste made it possible to give a comprehensive assessment of the traditional methods, such as incineration, burial, composting and anaerobic digestion, as well as non-traditional ones, among which pyrolysis, gasification, plasma gasification, hydrothermal carbonization should be noted and torrefaction. This made it possible to evaluate the effectiveness of the currently used technologies for the processing of municipal solid waste and to make a choice of the most preferable of them in various time perspectives.

Results and Discussion

Solid household waste is mainly classified into 4 categories – residual, recyclable, food, and hazardous. However, waste can be divided into two large groups: the first includes production waste, which is formed as a by-product during the development of the final product, and the second – consumer waste, products that are not suitable for use in everyday life and agriculture. Waste also belongs to the hazard classes: extremely dangerous; highly dangerous; moderately dangerous; low-risk; practically harmless. To understand the correctness of the ratio of waste products, a detailed classification is listed below, considering the most common with examples and MSW compositions:

▼ organic products – food and plant residues (leftovers and scraps from fruits, scraps, bones, leaves, manure, grass, etc.);

▼ plastic – plastic materials (wrapping films, plastic bags and bottles, polyethylene, hoses, packaging materials from hygiene products, including cosmetic and decorative, disposable tableware);

▼ glass – glass materials and products (bottles, dishes, light bulbs, mirrors, ceramic and porcelain materials, and products where organic impurities such as sand and clay are present);

▼ cardboard napkins, office paper, all paper products, newspapers, boxed products.

It is also necessary to attach importance to the influence of the time of year, the financial situation of the country on the quantity, composition and nature of solid waste. A proper understanding of the composition, classification and quantity of waste contributes to proper management practices and gives an approximate idea and understanding of how much energy can be extracted from solid household waste.

Solid particles contained in food, beverages and air carry heavy metal pollutants into the human body. These pollutants can enter the body in three ways: by swallowing the product, inhaling the smell or by skin contact. The amount of a contaminant inside the body can be toxic to humans, and the consequences may not appear immediately, but with the accumulation of such substances. It is also worth paying attention to the problem of handling solid waste from the standpoint of mechanical safety, because the risks of skin damage are also high, for example, fragments from glass products can provoke bruises/wounds, etc. The working class, which is engaged in solid waste processing, has the greatest probability of encountering such dangerous cases.

To eliminate and pre-mitigate the increasing environmental pressure, countries need to develop policies and introduce rules and laws on the issue of solid waste recycling. A small method that is already used in almost all developed countries can be cited – waste sorting. With the introduction of a separate garbage sector for waste in cities, the collection, transportation and processing of garbage is reduced, which leads to mitigation of climate change. It should also be borne in mind that the separation of waste should be at the home, household level. It is necessary to educate people about the proper sorting of garbage – to separate paper from glass, and to fold plastic separately. Thus, it is necessary to modernise the waste sorting system. According to D.G. de arros Franco *et al.* (2022), an effective waste management system is proposed that has a beneficial effect on society, while simultaneously attracting economic, environmental and medical benefits. This study has shown the possibility of improving public and private waste disposal systems at the regional level. That is, the elementary separation of waste into inert ones can have the most favourable and beneficial effect on the environment. In combination with waste-to-energy conversion technologies, this provides numerous benefits, such as energy production, recycling of materials for secondary use and reduction of landfills and landfills. After all, it is worth giving the main importance to the fact that a number of materials, turning into solid household waste, can store energy in chemical bonds, when they break, a huge amount of energy is released.

Given that waste management is a societal issue, it is imperative that the general public is made aware of the issues surrounding waste and that those responsible for implementing recycling programmes are adequately trained. J. Sun *et al.* (2023) demonstrated that the promotion of waste sorting, recycling and the utilisation of innovative technologies, such as microbial fuel cells and refuse-derived fuel, may be impeded in the absence of comprehensive public education and the provision of training for relevant personnel. Moreover, the accessibility and comprehension of waste management practices at all levels of society directly influence the extent of participation and the overall efficacy of recycling initiatives. It is therefore evident that government intervention in the form of educational campaigns and the integration of informal waste collectors into formal waste management systems is necessary. These measures will facilitate the acquisition of knowledge and the allocation of resources, thereby overcoming the current impediments to the development of comprehensive waste recycling systems.

The incineration method is the most economical and reliable. As a result of municipal solid waste incineration, two main products are formed – fly ash and bottom ash. The fly ash is collected after the filtration process and carefully sealed to avoid contamination of the local surroundings, which are then moved to completely closed "hazardous landfills" that do not allow leaching into the environment. Bottom ash is the main by-product, accounting for almost 80% of the total volume of ash produced. It also consists of inert, non-combustible materials and metals. A.M. Matos & J. Sousa-Coutinho (2022) investigated the possibility of using shredded bottom ash from municipal solid waste incineration as an additional cementitious material for concrete mixtures. The results showed a good potential for use in the construction sector, but the adverse effects of the presence of metallic aluminium were also noticed. C. Zhao *et al.* (2022) demonstrated the features of chlorine and metal ions during the heat treatment of fly ash, which demonstrate a significant effect on the harmlessness and resource of fly ash. The results showed that it is possible to remove chlorides and heavy metals at a firing temperature above 750°C. According to C. Li *et al.* (2022), an analysis of previously undetected organic pollutants formed and released during municipal solid waste incineration was carried out. The authors identified their identity, and carried out a toxicity assessment and provided recommendations for a detailed study conditioned upon their highly dangerous toxicity. Pollutants were found in both flue gas and fly ash from various types of incineration activities. Conditioned upon the pandemic caused by COVID-19, clinical waste has increased dramatically. They were disposed of mainly by co-incineration with solid waste, which causes an increase in the main elements and non-volatile heavy metals in polluted air. D.-Y. Lan *et al.* (2022) showed that with such combustion, the content of alkali metals and HCl in the flue gas increases, which contributes to the potential corrosion of the boiler. Thus, the incineration method is a good choice only by reducing the volume of waste, which can reach up to more than half, but there are also negative sides – air pollution, bottom and fly ash.

The burial method is quite old and cheap; however, it occupies a large area of the land resource and can cause secondary contamination of soil and groundwater. Therefore, this technology has been mostly neglected. Basically, there are 3 main alternatives:

- direct disposal of unprocessed waste in a landfill;
- recycling of waste before final disposal;
- recycling of waste to extract resources (materials and/or energy, followed by the disposal of residues.

Direct transportation (the first option) to a landfill is usually the cheapest disposal option. However, every day the places on landfills are decreasing, which leads to a significant increase in the cost in settlements. The second option serves to reduce the amount of waste. The third option involves processes that recover energy or materials from solid waste, which eventually gives only their residues. All of this energy and/or material extraction systems involve significant capital and operational costs. However, the sale of both energy and materials reduces the net cost of restoration. Such methods allow conserving resources, and waste residues require much less space to be placed on the ground than unprocessed waste (Daskalopoulos *et al.*, 1997). In an open environment, various biochemical reactions naturally occur from waste, which leads to the development of landfill gas. Such gas can be used for energy purposes; however, such a process is time-consuming. P. Sharma & S. Kumar (2021) found various organic compounds that remain stable and unchanged in the medium even after a long stay. The work proves that various organic polymers, metals and other related pollutants pose a danger to the environment. Thus, the main advantage of choosing a method of solid waste disposal is the simplicity and cheapness of the technology itself, but the main disadvantage is that the territory on Earth is limited, and land pollution can reduce it altogether.

There is also a common method of thermal decomposition of waste (pyrolysis), in the complete absence of air and creating products in three states, such as solid carbon residues, bio-oils and non-condensing gases. The output products differ in composition due to the type, shape of the reactor, etc. Basically, the pyrolysis process allows getting more energy compared to the method of solid waste incineration. This is explained by the substances formed in an inert atmosphere – nitrogen oxide (NO_x) and sulphur oxide (SO_x) (Shah *et al.*, 2021). The decomposition temperature is usually in the range of 300 to 850°C. Basically, this method of processing is used conditioned upon high efficiency in the production of biofuels. There are also varieties of pyrolysis – conventional, fast and flash pyrolysis. Advantageous combinations with pyrolysis are also offered, for example, the use of solar energy. In this case, the reactor receives heat from the sun, but for 2024 there is little research in this area (Mukherjee *et al.*, 2021). Thus, pyrolysis technology is good because it is possible to produce raw materials, but, however, the cost of such a procedure is high.

Solid household waste can be quite suitable sources of energy. Studies show that MSW contains about 20.72% of organic waste, 37.86% of combustible materials, 20.95% of commercial materials and 20.46% of various waste (Gurunathan & Sahadevan, 2022). As a result, it can be concluded that they can be a substitute for coal. A number of studies have been devoted to a new recycling technology – microbial fuel cell (MFC). This method is environmentally friendly for generating electricity from liquid waste due to bacteria and oxygen. Through the process of anaerobic digestion, wastewater is treated, which reduces the number of pathogenic microorganisms and also allows the conversion of biogas into electricity. Thus, the provided MFC technology is known for the production of energy from waste, without the use of any external or additional energy, however, MFC appears as a technology for the production of ethanol, hydrogen, biogas, enzymes and bioremediation of wastewater. Therefore, MFC has the potential to work in various fields and in various applications (Vyas *et al.*, 2022). Thus, this new method is environmentally beneficial, it is expected to contribute zero to greenhouse gas emissions during production from waste, and also an important advantage is that with this technology no unpleasant odours come from, but on the contrary it is eliminated.

Effective waste management will contribute to mitigation with global challenges, affecting even energy recovery. New technologies for processing solid household waste include biological ones, with the help of which it is possible to extract and develop hydrogen (H_2) production. An example is biochemical leaching at extremely high temperatures using concentrated sulfuric acid or NaOH followed by acid treatment or heating $CaCO_3$ and $CaCl_2$ and HCl at temperatures above ⩾975°C followed by leaching with 3% HCl solution (Sharma & Kumar, 2021). There is also a microbial electrolysis cell (MEC) technology, which uses microorganisms with which it is possible to convert solid household waste into H_2, acetate, formic acid, ethanol, etc. This technology has similarities with the above MFC method, the difference is only in the cathodes. MEC can convert any biodegradable waste into H_2 and biofuels, i.e., into high-value energy carriers and bio-products. The only downside is the high cost of this method.

There are also technologies for producing fuel from waste. To do this, the sorted waste is delivered to factories, where it is deformed using a drum machine. Then the compostable fraction mixed with inert materials is passed through the holes. The remaining waste, which is a fraction suitable for combustion, is processed into solid secondary fuel RDF. However, this will require sorting solid waste – removing food waste, metals, glasses, etc. from the total mass. The result should be an inorganic composition with the lowest possible moisture content. Large-sized fractions and recyclable plastics and metals are sorted manually, and the remaining combustible waste is transferred to a mechanical separation unit. Incombustible and inert materials are separated from light combustible fractions when air is supplied. At the end, the combustible material is crushed, and then crushed manually into a fine fluffy fraction called RDF fluff (Kaur *et al.*, 2021).

C.-H. Liu & C. Hung (2023) investigated the utilisation of thermochemical processes, including gasification and pyrolysis, for the generation of energy from municipal solid waste (MSW). The findings indicate that pyrolysis, in particular, produces a high-quality solid fuel and significantly reduces the environmental footprint in comparison to traditional incineration methods. Furthermore, the study emphasises the potential of co-pyrolysis with other waste materials to optimise energy recovery and minimise harmful emissions. This approach could provide a more sustainable method of waste disposal by integrating with other sectors, such as agriculture, where waste from organic farming could be co-processed for energy recovery.

Another innovative approach is the utilisation of hydrothermal carbonisation, as discussed in a study (Li *et al.*, 2024). Hydrothermal carbonisation has the potential to convert organic waste materials into carbon-rich solids, commonly known as hydrochar, which have a high calorific value and can be used as a renewable energy source. This technology is particularly well-suited to the processing of high-moisture content waste, such as food waste, which presents a significant challenge in terms of incineration. Furthermore, the study underscores the significance of hydrothermal carbonisation in reducing the volume of waste and producing value-added materials, such as activated carbon for industrial applications.

Furthermore, R. Shi *et al.* (2024) conducted an economic analysis of the viability of RDF production in developing countries, with a particular focus on the integration of RDF production within existing municipal waste management systems. The results of the study indicate that RDF has the potential to serve as a substitute for conventional fuels in industries such as cement manufacturing. Nevertheless, the success of such initiatives is contingent upon the implementation of governmental policies that facilitate waste sorting at the source and investments in infrastructure. Furthermore, it was discovered that the calorific value of RDF could be augmented by combining it with agricultural waste, which is prevalent in numerous regions.

In the study by B. Wei *et al*. (2023) assessed the utilisation of MEC for the processing of organic waste with the objective of hydrogen production. This approach offers two distinct advantages: the recovery of energy in the form of hydrogen and the reduction of greenhouse gas emissions. Although still in its infancy, this technology shows great promise in addressing both waste management and renewable energy needs, particularly in regions where other waste-to-energy technologies may be uneconomical. Further research is required to optimise the cost-effectiveness and scalability of this method for its widespread adoption.

For 2024, the commercial application of RDF for energy production is mainly used in the cement industry for heating cement furnaces, but is also used for combined heat and electricity production in incinerators. It was also found that during incineration, joint operation with biomass, coal and bird droppings is possible at conventional waste-to-energy processing plants. Studies show that active pyrolysis occurs in the temperature range of 300-550°C, and the interaction of various RDF components has a great influence on the kinetic parameters. A comparative assessment of the life cycle of rapid thermochemical processing of solid waste with burial, incineration and anaerobic digestion shows that the pyrolysis process is one of the most environmentally friendly technologies for solid waste valorisation (Bhatt *et al.*, 2021).

A. Veses *et al*. (2020) carried out the pyrolysis process in conjunction with the stage of thermal catalytic cracking of solid waste at the installation, which includes a reactor with a fixed layer and a tubular cracking reactor. The results showed that with the help of this technique, it is eventually possible to obtain synthesis gas, including mainly solid fuel. Such a process tactic can be considered cost-effective and profitable conditioned upon the potential of using the resulting charcoal as a fuel obtained from waste to meet the energy needs of the process. The paper by P. Rajca *et al*. (2020) presents the results of a study showing that RDF consists mainly of 2 types of materials: biomass and thermoplastic polymers. Further, the authors carried out pyrolysis of samples at a temperature of 900°C in a nitrogen atmosphere in the form of a periodic process using a technological furnace. The results of the analyses showed a high calorific value. Thus, the great potentials of the above techniques and processes have been demonstrated, which can be effectively operated with the production of solid fuel materials of good quality. RDF can become an interesting alternative to traditional fuels, while at the same time contributing to limiting the role of waste storage and increasing the level of environmental protection.

Conclusions

The government needs to introduce programmes and develop a system for the disposal of municipal solid waste, and find innovative ways to integrate informal waste collection contractors into the formal system, as they seek to fill the gaps created by the formal waste collection contractor. It is important for authorities, researchers, formal and informal businesses, global communities and organisations to be interested in conducting a feasibility study in the field of waste management. Waste sorting helps to improve waste volume control. It is necessary to increase the level of knowledge and training at all levels of the population, because there is a lack of awareness of people and the availability of trained specialists in the field of waste recycling. Technological improvements in recycling methods can help reduce environmental protection costs. The waste recycling system in energy is not only a useful way of obtaining energy, but also a comprehensive solution to a number of problems. The latest technologies allow significantly expanding the production of energy from waste. The current, innovative and safest technologies for processing solid household waste into electricity, and into fuel cells are the microbial fuel cell and microbial electrolysis cell technology. Municipal solid waste can be converted into solid fuel materials such as RFD, i.e., it is possible to use it to obtain useful energy vectors, thereby solving problems such as excessive consumption of fossil fuels and the exponential growth of landfills. Prospects for subsequent scientific research in the direction of studying the prospects for the processing of municipal solid waste for the purpose of their use as solid fuel materials lie in the possibility of finding optimal solutions to this problem and creating the appropriate conditions for high-quality energy supply of modern industrial and household enterprises. This will be expressed in the possibility of obtaining additional energy sources for the needs of these areas, which will contribute to the effective solution of energy supply issues in the short and long term.

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None.

Conflict of Interest

None.

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Огляд перспективних досліджень у галузі переробки твердих побутових відходів для подальшого використання як твердопаливних матеріалів

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Анотація. Актуальність заявленої теми даного наукового дослідження полягає в глобальному зростанні екологічних проблем, включаючи виснаження ресурсів і забруднення, що призвело до нагальної потреби у розробці рішень щодо сталого управління відходами. Це дослідження стосується переробки твердих побутових відходів, з особливим акцентом на перетворення відходів у тверді паливні матеріали. Було проведено порівняльний аналіз літературних джерел за період по 2024 рік з метою виявлення найбільш ефективних технологій перетворення відходів на енергію. Отримані результати підкреслюють дві ключові суспільні проблеми: погіршення стану довкілля внаслідок неадекватних практик поводження з відходами та дефіцит ресурсів, спричинений урбанізацією та індустріалізацією. Серед помітних результатів – визначення спалювання та піролізу відходів як перспективних технологій для відновлення енергії, зменшення кількості сміттєзвалищ та пом'якшення впливу на довкілля. Зокрема, було показано, що піроліз дає більше енергії і призводить до менших викидів, ніж традиційне спалювання. Крім того, аналіз показав потенціал палива з відходів та мікробних паливних елементів як інноваційних підходів до сталого виробництва енергії з відходів. Ці технології можуть забезпечити додаткові джерела енергії для побутових і промислових потреб, одночасно зменшуючи вплив на навколишнє середовище, пов'язаний з утилізацією відходів. Практична цінність цього дослідження полягає в його потенціалі для розробки передових технологій переробки твердих побутових відходів з метою отримання енергії, що може підвищити ефективність використання ресурсів та енергетичну стійкість

Ключові слова: енергетичні ресурси; сортування відходів; глобальне потепління; промислова переробка

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Assessment of the quality of the microclimate in the EKG-12K excavator cab

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Abstract. This research addresses critical issues within the construction and mining sectors, encompassing operator health and safety, productivity, equipment durability, and regulatory compliance. In addition, the research focuses on microclimate management, ergonomics, and technology, and can improve the safety, comfort, productivity, and sustainability of the industry. The objective of this study was to evaluate the quality of the microclimate within the EKG-12K excavator cab, specifically examining airflow, temperature, operator comfort, and safety. Using ANSYS Fluent, the microclimate was modelled under warm and cold conditions in accordance with international standards. The findings revealed deficiencies in ventilation and air conditioning. During warmer periods, the positioning of fans fails to facilitate adequate circulation of cooled air within the domain of the operator. Under colder conditions, the interaction between fans and heat curtains generates air circulation around the axle at the level of the driver's seat. Temperature analyses demonstrated that during warm periods, the temperature ranges between 23-25°C, necessitating substantial effort from the air conditioning system. During cold periods, certain areas experience temperatures as low as 5°C, posing the risk of condensation and mould growth. Additionally, there are concerns regarding dust circulation and the potential for glass breakage owing to temperature variations. The conclusions underscore the necessity of optimising the microclimate within a cab to ensure operator comfort,

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safety, and excavator efficiency. The practical importance of this work lies in offering solutions to enhance the safety, comfort, productivity, and longevity of the equipment

Keywords: cabin airflow dynamics; thermal comfort optimisation; dust particle suspension; computational fluid dynamics simulation; ventilation system efficiency; temperature gradient analysis; condensation risk assessment

Introduction

Improving the health and safety of heavy mining and construction equipment operators through improved microclimate management is an important task. It is inextricably linked to labour productivity and overall production efficiency. I. Mehmood *et al.* (2022) show that working with construction equipment for long periods can lead to mental fatigue and, as a result, an increased risk of accidents related to human error, as well as health problems for operators. E.C. Kayar & H. Özcan (2024) emphasised that the ambient temperature is one of the main factors that negatively affects the working conditions of excavator operators. The authors emphasise that it is difficult to provide comfortable air conditioning in excavator cabs because the weather conditions are unpredictable. Therefore, before installing an air-conditioning system, it is necessary to calculate the efficiency of airflow distribution in the cab. The authors Yu. Voichyshyn *et al.* (2023) emphasise that the microenvironment in the excavator cab consists of a number of physical parameters, including temperature, humidity, air velocity and thermal radiation, which affect the operator's well-being. These parameters depend on several external and internal factors. External determinants that affect the cab microenvironment include meteorological conditions, geographical location of the work site, seasonal periods of work, and daily cycles.

As cabs have become an integral component of modern excavators, the need to maintain thermal comfort has significantly increased. The main challenge associated with this is the regulation of ambient temperature, which is crucial for providing a favourable working environment for excavator operators. Maintaining a proper level of air conditioning in excavator cabs is particularly challenging because of the unpredictability of weather conditions. F. Lan *et al.* (2023) and V. Aulin & M. Mahopets (2024) noted that evaluating the efficiency of airflow distribution in an excavator cab before installing an air conditioning system facilitates further optimisation. These system optimisation studies have several benefits. Developing systems that maintain optimal conditions accelerates project completion, thereby saving financial resources and time. In addition, these studies aimed to improve air conditioning by assessing the specific cooling needs of the excavator based on the expected workload.

The reviewed studies highlight the importance of providing a favourable working environment for excavator operators and other mining and construction equipment. One of the ways to solve this problem is to create an optimal microclimate in the cab. These studies emphasise the need to model the distribution of airflow at the design stage of microclimate systems. At the same time, the above studies do not sufficiently cover the issues of temperature and air velocity distribution in different areas of the cabin. In addition, no studies have modelled the air distribution in machines used in quarries and construction sites. Standards of Ukraine do not regulate the distribution of air flows, but only their temperature and speed. Manufacturers ensure compliance with the operating conditions of the operators of these machines by supplying the calculated amount of air at the calculated temperature. In this regard, the aim of this study was to analyse the microclimate of a mine excavator cab, paying particular attention to air flow, temperature conditions, operator comfort, and safety.

Materials and Methods

An EKG-12-K open-pit excavator was chosen for this study. This type of excavator is widely used in the Kryvyi Rih basin mining sector. The excavator is operated under challenging conditions. In quarries, there are often significant temperature fluctuations throughout the day and seasons. There can be extreme heat in summer and frost and snow in winter. Strong winds kick dust and small particles that enter the cab and can lead to respiratory illnesses. Numerical simulations were developed utilising ANSYS Fluent software (Ansys fluent theory guide, 2021) (Fig. 1). The analysis was executed in transient mode. The realisable k-epsilon model (Shaheed *et al.*, 2019) was chosen to simulate turbulence, and the energy option was enabled.

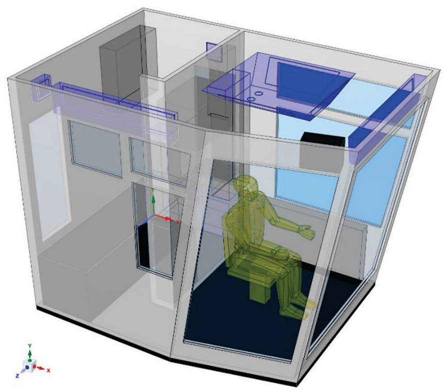

Figure 1. A mathematical representation of the operator's compartment of the EKG-12K excavator
Source: compiled by the authors

The simulations adhered to ISO No. 10263-4 (2009), which delineates the minimum performance thresholds for air conditioning systems within earthmoving equipment. This standard elaborates a methodology for evaluating the influence of a heating system on the ambient temperature within the operator's cabin and explicates the fundamental heating criteria. Figure 2 illustrates the positioning of the measurement points relative to the cabin floor. The simulation was executed utilising the finite element method (Hou *et al.*, 2021), incorporating a mathematical model of the cabin airspace, which comprised 364,666 nodes and 1,865,048 finite elements (Fig. 3).

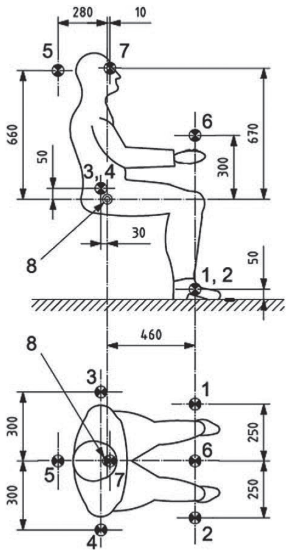

Figure 2. The parameters of the excavator operator model that were utilised within the study
Source: ISO No. 10263-4 (2009)

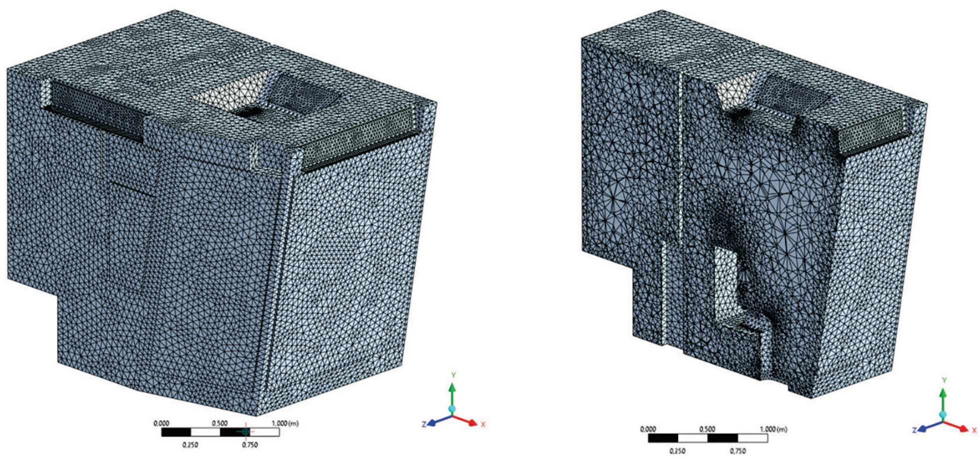

Figure 3. A mathematical representation of the airspace within the operator's cabin of the EKG-12K excavator, encompassing both a general overview and sectional analysis
Source: compiled by the authors

The simulation process accounted for the turbulent characteristics of the airflows, as well as the heat exchange occurring within the airflows themselves and between the air, the cabin walls, and the glazing. The analysis excluded radiation heat transfer effects during calculations. The parameters of the model, as obtained for both warm and cold seasons, were thoroughly examined. This simulation enabled the estimation of the velocity, orientation, and temperature of the airflows within the excavator cabin. Calculations have been conducted considering the optimal functionality of heat-generating equipment, neglecting the intermittent automatic deactivation of the heating system.

Results

The EKG-12K excavator is engineered for the excavation and loading of rocks classified under categories I-II, based on the level of excavation difficulty without requiring loosening, category III with partial loosening, and categories IV-V with full loosening. The driver's cab of the EKG-12K excavator possesses dimensions of 2×2.8×2.2 metres. The front facade of the cab is constructed with a 15° inclination to enhance visibility. The cab is systematically divided into two distinct zones: the excavator control zone and the rest zone. A stationary partition delineates these zones. The excavator control zone is equipped with video surveillance apparatus and devices for monitoring the status of the primary excavator components, in addition to mechanisms for controlling the excavator's rotation, boom, and bucket positions. Conversely, the rest zone is furnished with a sofa, a dining table, a microwave oven, and an electric kettle. Furthermore, both zones are furnished with communication devices and electrical apparatus. The working zone features comprehensive glazing, while the rest zone is outfitted with two blind light openings.

The cabin features a mechanically assisted ventilation system comprising both supply and exhaust components. The air is introduced into the cabin via a WildWind fan, which possesses a capacity of 185 cubic metres per hour. Before entering the cabin, the air is subjected to filtration. In conditions of cold weather, there is provision for heating the incoming air. The supply fan is installed on the rear wall of the cabin, directing airflow along the right wall towards the occupational zone. Air extraction is conducted through a VENTS Ukraine fan situated in the recreation area, located at the upper section of the left wall. The operational capacities of both the supply and exhaust fans are equivalent.

During periods of elevated temperatures, the cabin's air is regulated by a Coleman-Mach air conditioning unit. This unit employs a split system configuration, with the external component positioned atop the cabin's roof and the internal component affixed to the ceiling. The air conditioning system possesses a maximum air capacity of 118 litres per second. Air intake within the internal unit is facilitated via lateral air intakes, which are fitted with mesh dust filters. The conditioned air is distributed through the front outlet channel and two lower rotary deflectors. During colder periods, the air within the cabin is warmed by two air curtains and an electric convector. Both air curtains are manufactured by OLEFINI. Specifically, the L/REN-13S model air curtain is positioned above the front glass, while the MINI 700 model air curtain is installed above the entrance door. Additionally, the cabin's recreation area is equipped with a "Thermiya" electric convector produced by the "Vinnytsia Mayak Plant".

An examination of the direction and velocity of airflows during the warm and cold seasons revealed deficiencies in the arrangement of ventilation and air conditioning systems. These deficiencies become particularly pronounced during the hot season when there is a necessity to activate the air conditioning unit. The issue lies in the placement of both the supply and exhaust fans, which are situated at the rear of the cabin and positioned at an identical height from the floor (Fig. 4).

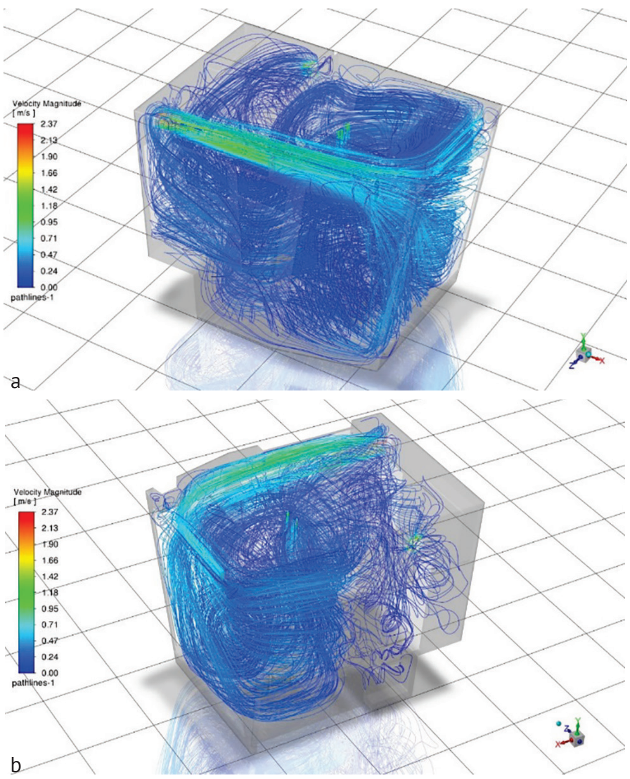

Figure 4. The orientation and velocity of air currents within the operator's cabin of the EKG-12K excavator under conditions of elevated temperatures

Notes: a – perspective from the anterior right corner of the cabin; b – perspective from the front-left corner of the cabin

Source: compiled by the authors

The supply fan generates a confined airstream with a velocity range of 2.37 to 1.2 metres per second. This airstream progresses along the upper right quadrant of the cabin and converges at the windscreen, at which point it diverges into multiple branches. One specific branch extends along the upper section of the windscreen and, upon integration with the airflow from the air conditioning unit, facilitates a circular air circulation within the operational area of the cabin. An alternate branch descends and proceeds along the anterior right corner of the cabin, reaching the cabin floor, where it bifurcates and integrates with additional airflows. Another segment of the airflow traverses from the upper to the lower section and from right to left along the diagonal of the cabin's front window. Upon arriving at the front left corner of the cabin, this airflow alters its trajectory towards the rear and, in conjunction with the initial branch, contributes to the establishment of a circular airflow pattern within the operational section of the cabin. During this rotational movement, the air gradually descends to the cabin's lower area, where it redirects towards the cabin's rear. In the rear section, a portion of the air ascends within the cabin, becomes engulfed by the primary airflow generated by the supply fan, and subsequently re-engages in the recirculation within the cabin's operational zone. The remainder of the air gradually advances to the exhaust fan and is expelled from the cabin. The velocity of the circulating air ranges from 0.2 to 0.6 m/s. During winter, the nature of air movement is slightly altered, attributed to the lack of airflow from the air conditioner and the introduction of airflow from air curtains and an electric convector (Fig. 5).

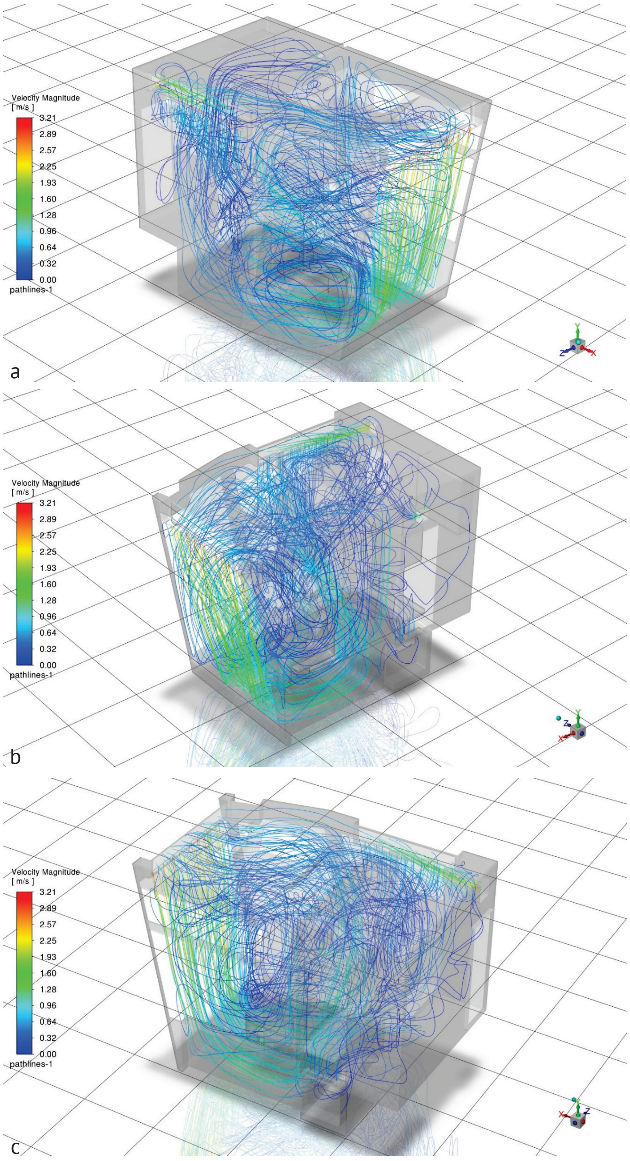

Figure 5. An analysis of the direction and velocity of air currents within the operator's cabin of the EKG-12K excavator under cold climatic conditions

Notes: a – perspective from the front right corner of the cabin; b – perspective from the anterior left section of the cabin; c – perspective from the rear left corner of the cabin

Source: compiled by the authors

The airflow originating from the supply fan intersects with the airflow from the heat curtain located above the entrance door, subsequently dividing into two principal branches. One branch progresses along the cabin's ceiling into the working area, where it is intercepted by the heat curtain above the front glazing and directed towards the lower section of the cabin. The alternative branch, merging with the air from the heat curtain above the entrance door, advances towards the floor of the working area within the cabin, where it further combines with the air from the heat curtain above the front glazing. This process culminates in air circulation. Notably, during warmer periods, air circulation is oriented around a vertical axis that traverses the centre of the cabin's working area, whereas in colder periods, circulation predominantly orients around a horizontal axis extending from the left to the right wall of the working area, corresponding to the excavator driver's seat level. The frequency of air circulation within the working area is significantly reduced during colder periods compared to warmer ones; however, the air velocity is substantially increased, ranging between 0.5 and 1.8 metres per second.

The current ventilation system facilitates extensive air circulation within the confines of the cabin's workspace. Concurrently, a substantial proportion of the circulating air interacts with the floor surface. Considering that the velocity of air flows is documented to be within the range of 0.2-0.6 m/s during summer and 0.5-1.8 m/s in winter, it is unavoidable that dust particles are dislodged from the cabin floor and subsequently transported to the respiratory zone of the excavator operator. Analogous to assessing velocity, the air temperature within the cabin was examined for both hot and cold periods. The computed external temperature for summer was 30°C, whereas for winter it was -15°C. The thermal conductivity values of the walls, inclusive of the thermal insulation, were considered to be 0.033 W/(m·°K). Meanwhile, the thermal conductivity of the cabin windows was assumed to be 1.22 W/(m·°K). The analysis excluded radiation heat transfer effects during calculations. The temperatures of both the airflow and the internal surfaces of the cabin, including the glazing, were systematically evaluated. Figure 6 illustrates the temperature of air flows observed during the hot period.

Figure 7 illustrates that the active air circulation within the cabin inhibits the distribution of air cooled by the air conditioning system from reaching the area occupied by the excavator operator. The primary concentration of the cooled air, maintaining a temperature range of 22-23°C, is situated in the vicinity of the cabin's front window. Air at a colder temperature, ranging from 19-21°C, extends along the upper portion of the cabin, approaching the partition that separates the work and rest areas. The temperature of the air within the operator's area remains between 23-25°C.

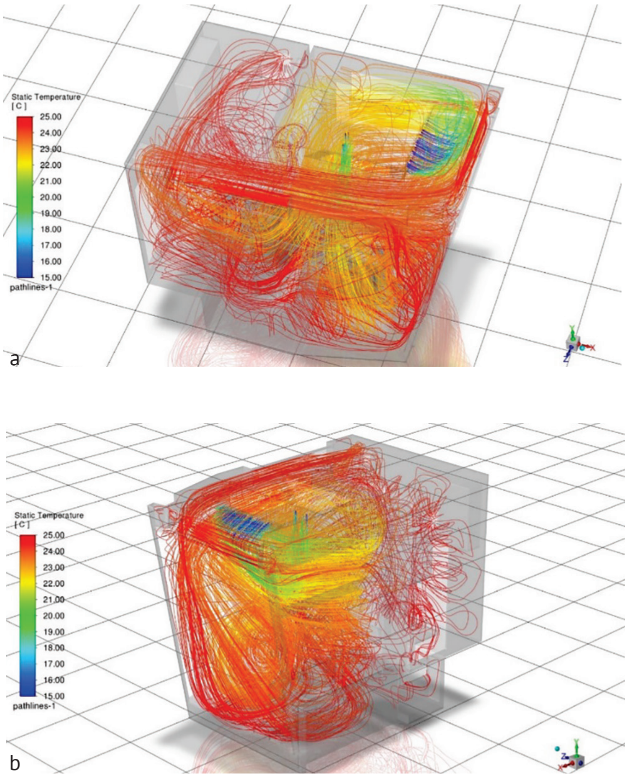

Figure 6. The orientation and thermal characteristics of air currents within the operator's cabin of the EKG-12K excavator during elevated ambient temperatures

Notes: a – perspective from the front right corner of the cabin; b – perspective from the anterior left section of the cabin

Source: compiled by the authors

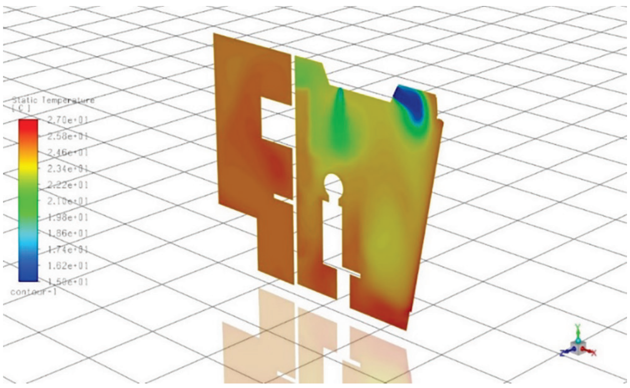

Figure 7. Ambient temperature inside the operator's cabin of the EKG-12K excavator under conditions of elevated external temperatures

Notes: measurement conducted along the central axis of the cabin

Source: compiled by the authors

The temperature distribution across the cabin walls within the working area exhibits variability, ranging from 26°C at the floor level to 20°C at the ceiling level, as illustrated in Figure 8. Typically, due to its higher density, the cooler air is situated in the lower regions of the premises. However, as the air circulates and descends, it undergoes heating by the warm surfaces of the cabin glazing, as depicted in Figure 9. A differential of 6°C in wall temperature, when considering the effect of active air circulation, may result in moisture condensation in cooler regions, consequently facilitating the proliferation of mould and fungal organisms.

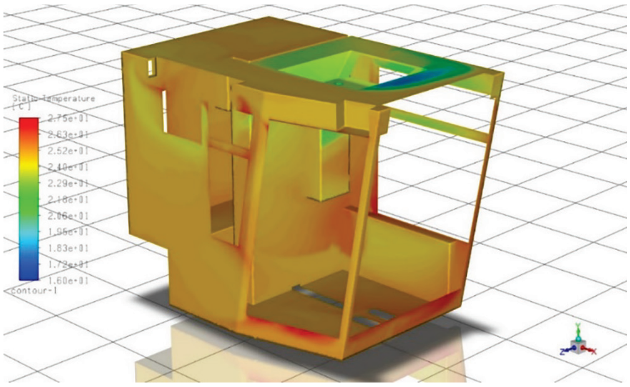

Figure 8. Thermal conditions of the interior surface of the walls within the driver's cabin of the EKG-12K excavator during periods of elevated ambient temperature

Source: compiled by the authors

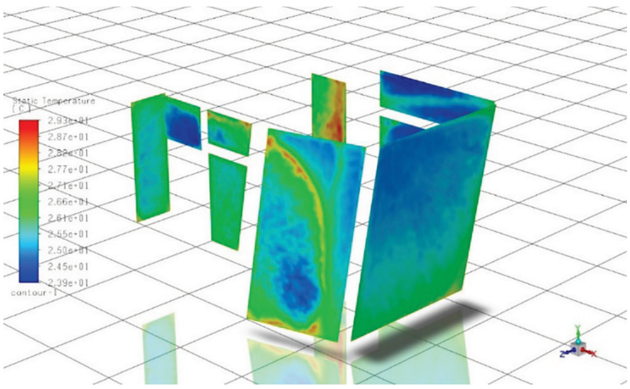

Figure 9. The thermal characteristics of the internal surface of the glazing within the driver's cabin of the EKG-12K excavator during elevated temperature conditions

Source: compiled by the authors

During cooler periods, the cabin microclimate proves to be more conducive to the driver's operational efficiency. Figures 10-11 demonstrate that, under maximal heat curtain performance, the air temperature surpasses the minimum acceptable thresholds. Nevertheless, the driver maintains the ability to adjust the temperature as needed.

The thermal condition of the walls within the working area surpasses the dew point temperature for moisture condensation (Fig. 12). Nonetheless, within the recreational zone located in the lower left quadrant, there exist regions where the temperature falls to 5°C, consequently facilitating potential moisture condensation and the associated risk of mould and fungal proliferation.

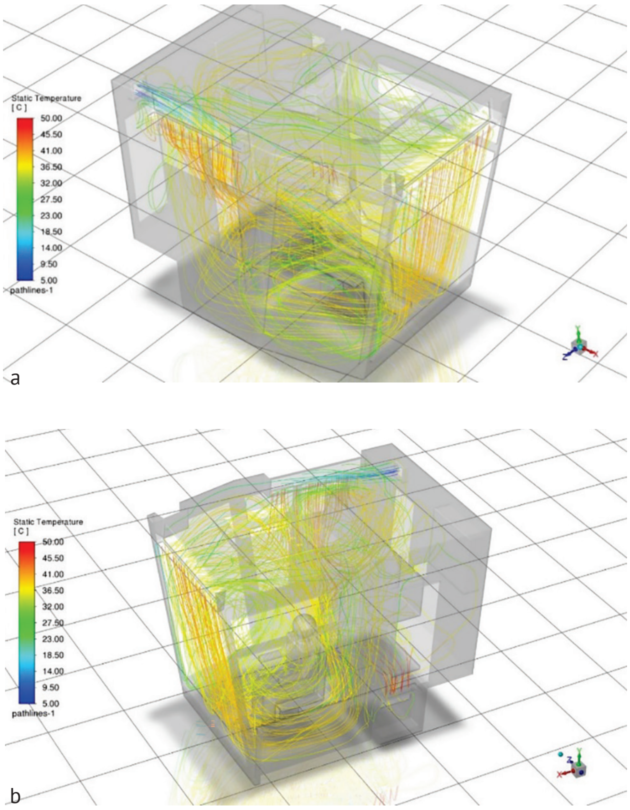

Figure 10. Orientation and thermal characteristics of airflow within the operator's compartment of the EKG-12K excavator under cold climate conditions

Notes: a – perspective from the front right corner of the compartment; b – perspective from the anterior left corner of the cabin

Source: compiled by the authors

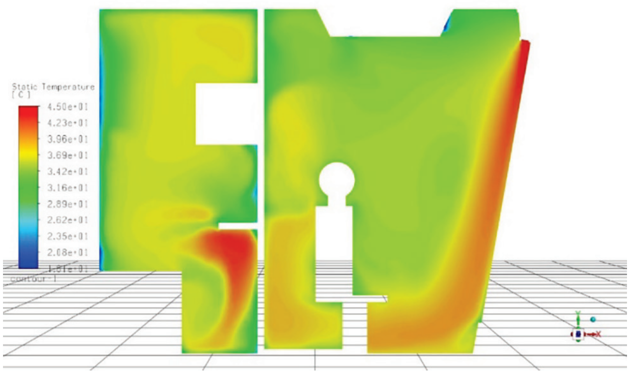

Figure 11. The air temperature within the driver's cabin of the EKG-12K excavator during cold conditions

Notes: measured along the axis of the cabin

Source: compiled by the authors

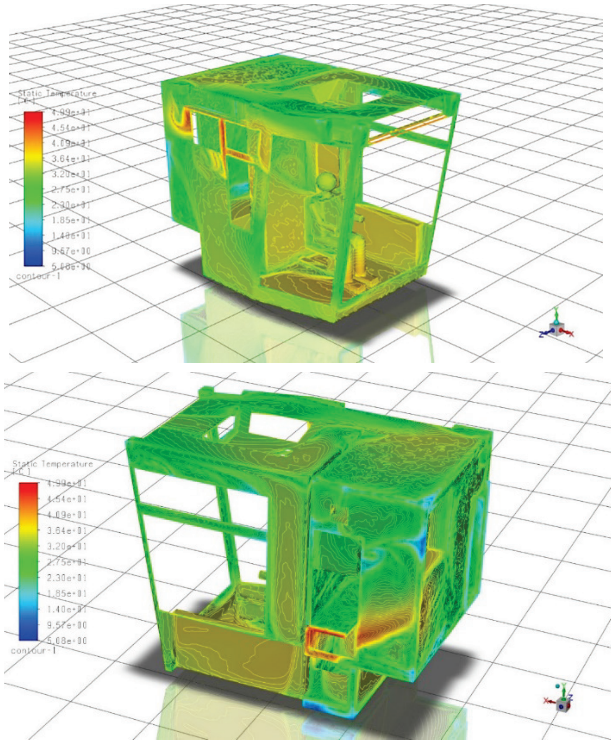

Figure 12. Temperature measurements of the internal surface of the operator's cab walls of the EKG-12K excavator during the colder season

Notes: a – perspective from the front right corner of the cab; b – perspective from the rear left corner of the cab

Source: compiled by the authors

The temperature of the cabin glass ranges from 7 to 46°C (Fig. 13). The maximum temperatures are observed in the area of thermal curtain operation, with the temperature variation within a single glass panel reaching 22°C. Under conditions of cyclic activation and deactivation of the heating system, these disparities can contribute to the potential failure of the glass.

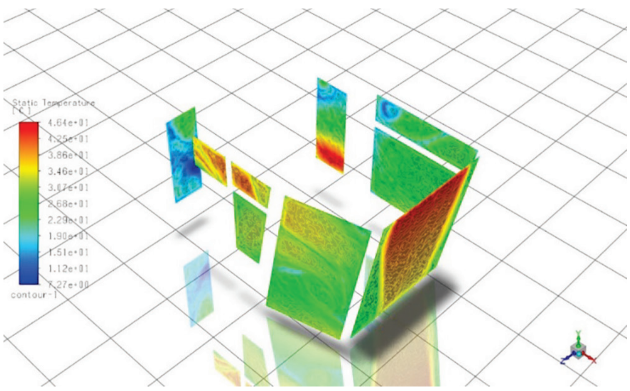

Figure 13. Thermal characterisation of the interior surface of the glazing within the driver's cabin of the EKG-12K excavator during periods of low ambient temperature

Source: compiled by the authors

Thus, the analysis of the microclimate in the cab of the EKG-12K excavator has revealed several key issues that affect the operator's comfort, safety and potential productivity. The study provides valuable information on air circulation patterns, temperature distribution, and potential health hazards in both warm and cold conditions.

Discussion

The current design of the ventilation system, featuring supply and exhaust fans located at the rear of the cab, results in problematic circular air circulation patterns under both warm and cold conditions. This design flaw aligns with the findings of F. Lan *et al*. (2023), demonstrating that improper placement of air intakes and exhausts can lead to undesirable air circulation in vehicle cabs. Furthermore, the system generates high air velocities ranging from 0.5 to 1.8 m/s in cold weather, which exceeds the recommended velocity range of 0.1 to 0.3 m/s for optimal thermal comfort in vehicle cabins, as suggested by I. Mehmood *et al*. (2022). This inefficiency prompts consideration of alternative designs. J.H. Hwang *et al*. (2013) propose a system where air exchange is achieved exclusively through exhaust ventilation, which may offer improved air distribution and comfort. Such redesign strategies could mitigate the identified circulation issues and align the system with recommended air velocity guidelines for enhanced thermal comfort. In the study by B. Pirouz *et al*. (2021), the focus was on airflow rates with respect to infection prevention, but it did not address how airflows affect cabin elements or the constraints related to comfortable air velocity. F. Arpino *et al*. (2021) expanded on these ideas by employing the Euler-Lagrange model to explore the transient non-isothermal dispersion of aerosols in air, also from the perspective of infection prevention. Their findings, related to air and heat exchange, are applicable mainly to small cabins like those of passenger cars. It is noteworthy that such findings may not be directly applicable to larger or more complex environments, such as excavator cabs, which have significantly larger volumes, larger glazing areas, and are composed of two separate rooms. These differences highlight the need for further research to understand airflow dynamics and infection prevention measures specific to larger and more complex cab environments like excavators.

In environments with high temperatures, the interaction between the air supplied by the fan and the power of the air conditioning unit is inadequate for effective cooling in the operator's area, maintaining temperatures at around 23-25°C. This results in temperature gradients as large as 6°C on the cab surfaces. These observations align with U. Arora *et al*. (2022), who identified difficulties in ensuring consistent temperatures within excavator cabs. In contrast, research by K. Koushik Balaji & M.S. Alphin (2016) suggests that optimising vent locations through computer modelling can lead to more even cooling distribution. Further experimentation by Y. Mao *et al*. (2018) measured air and surface temperatures in an electric vehicle's cabin during both heating and cooling phases, establishing high correlation between simulated and experimental data. Notably, these analyses are pertinent only to single-volume cabins. Current research extends this framework by examining a two-volume cabin characterised by extensive glazing, providing new insights into the complex dynamics of air distribution and temperature regulation within such environments.

A significant concern during both seasons is the potential respiratory hazard posed to operators by the high-speed, circular airflows that pick-up dust particles from the floor. This issue aligns with the findings of M. Palega & D. Rydz (2018), who highlighted the crucial role of adequate filtration in excavator cabs to minimise dust exposure. B. Xu *et al*. (2018) identified the primary air pollutants within vehicle interiors, which include ultrafine particles, aromatic hydrocarbons, carbonyls, semi-volatile organic compounds, and microbes. These pollutants stem from various sources, such as emissions from interior materials and exhaust gases entering through the ventilation system. Consequently, there is a call to enhance filtration and air distribution systems to tackle these health concerns. Furthermore, improved air filtration systems are proposed to reduce health risks, as emphasised by B. Xu *et al*. (2018). However, this proposal does not fully consider the potential for secondary pollution caused by unorganised high-speed air flows at the floor level. Therefore, addressing this issue requires a comprehensive approach that includes optimising air distribution to prevent such secondary pollution. Significant temperature fluctuations were observed on the interior surfaces, especially on the glass, with measurements showing up to a 22°C difference. These findings align with observations by J.H. Hwang *et al*. (2013) and I. Yakymenko *et al*. (2022), who also reported notable temperature variations on vehicle interior surfaces and their implications for thermal comfort. Such fluctuations can induce thermal stress and potentially cause failure of interior components, particularly as the heating system cycles.

The study identified regions susceptible to condensation and mould proliferation due to temperature gradients, particularly in recreational areas during the colder seasons. Mold growth is predominantly determined by humidity, temperature, and the availability of appropriate substrates (Lai *et al.*, 2024). In confined environments, such as operator cabins, condensation may occur when warm, moist air interfaces with cooler surfaces, thereby facilitating conditions conducive to mould growth (Bastien & Winther-Gaasvig, 2018). The propensity of mould development escalates in environments with elevated relative humidity, generally exceeding 75% RH at 25°C (Qiao *et al.*, 2024). This aligns with the issues articulated by M. Perišić *et al*. (2024)

regarding the management of humidity in enclosed operator cabins. To mitigate these risks, it is imperative to ensure effective ventilation and temperature regulation. The adoption of dehumidification systems and the maintenance of uniform temperatures throughout the area can aid in preventing condensation and diminishing the probability of mould proliferation. Moreover, systematic inspections and maintenance of potential problem zones, such as corners, joints, and inadequately insulated surfaces, are essential for identifying and rectifying issues prior to their escalation. The utilisation of mould-resistant materials and coatings in areas at elevated risk may offer supplementary protection (Doroshenko *et al.*, 2022). By addressing these factors, operators can cultivate a healthier and more comfortable environment, thereby mitigating the risk of mould-associated health complications and potential damage to equipment and structures. Consequently, the study underscores the essential requirement for practical design enhancements and environmental controls to ameliorate these risks in vehicular and cabin environments.

In cold weather conditions, maintaining a favourable cab microclimate is crucial for driver performance, as it often requires the temperature to exceed minimum thresholds for comfort and effectiveness. This finding presents a contrast to the previous study by J. Bonehill (2010), which highlighted issues with sustaining a comfortable temperature within excavator cabs during extreme cold conditions. However, the current study points out that ensuring optimal comfort may necessitate the operator adjusting cab settings. This flexibility in temperature control within the cab environment can enhance driver performance and safety by accommodating individual comfort needs and maintaining a suitable working atmosphere.

Conclusions

Based on the study findings, the current ventilation system design in the EKG-12K excavator cab generates suboptimal circular air circulation patterns in both warm and cold conditions, resulting in inefficient temperature distribution and potential health risks. Air velocities within the cab exceed recommended ranges for optimal thermal comfort, particularly in cold weather conditions (0.5-1.8 m/s compared to the recommended 0.1-0.3 m/s). The interaction between the supply fan and air conditioner is insufficient for effective cooling in the operator's area during hot conditions, resulting in temperatures of 23-25°C and temperature gradients up to 6°C on cab surfaces. High-velocity circular airflows present a potential respiratory hazard by suspending dust particles from the floor, emphasising the necessity for improved air distribution and filtration. Significant temperature fluctuations were observed on interior surfaces, particularly on the glass (up to 22°C difference), which may result in thermal stress and potential component failure. Areas susceptible to condensation and mould growth were identified, especially in the recreational area during colder seasons, due to temperature gradients. In cold weather, the cab microclimate can exceed minimum temperature thresholds, allowing for operator adjustment to maintain comfort and performance. These conclusions underscore the necessity for design enhancements in ventilation, air distribution, and temperature control systems to improve operator comfort and safety. While this study provides valuable information on the specific microclimate issues in the EKG-12K excavator cab, it confirms the findings of other researchers on the challenges of maintaining an optimal microclimate in heavy equipment cabs. The results of the study emphasise the need for further research and development in the design and optimisation of HVAC systems for these special conditions to ensure operator comfort, safety, and productivity.

Acknowledgements

None.

Conflict of Interest

None.

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Оцінка якості мікроклімату в кабіні екскаватора ЕКГ-12К

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Анотація. Дослідження вирішує ключові питання будівельної та гірничодобувної галузей, зокрема здоров'я і безпеку операторів, продуктивність, довговічність обладнання, і відповідність нормативним вимогам. Крім того, дослідження зосереджене на управлінні мікрокліматом, ергономіці і технологіях, і може поліпшити безпеку, комфорт, продуктивність і стійкість галузі. Мета – оцінка якості мікроклімату кабіни екскаватора ЕКГ-12К, з акцентом на потоки повітря, температури, комфорт і безпеку оператора. Використовуючи ANSYS Fluent, проведено моделювання мікроклімату в теплих і холодних умовах згідно з міжнародними стандартами. Результати вказують на недоліки вентиляції і кондиціонування. У теплий період розміщення вентиляторів не забезпечує належної циркуляції охолодженого повітря в зоні оператора. У холодних умовах взаємодія вентиляторів з тепловими завісами створює циркуляцію повітря навколо осі на рівні сидіння водія. Температурний аналіз показав, що в теплі періоди температура становить 23-25 °C, хоч це і вимагає значних зусиль системи кондиціонування. У холодні періоди існують зони з температурою до 5 °C, що викликає ризики конденсації і плісняви. Крім того, є занепокоєння щодо циркуляції пилу і ризику руйнування скла через температурні коливання. Висновки підкреслюють необхідність оптимізації мікроклімату в кабіні для захисту комфорту оператора, безпеки і ефективності екскаватора. Практична значимість роботи полягає у наданні рішень для поліпшення безпеки, комфорту, продуктивності і терміну служби обладнання

Ключові слова: динаміка повітряного потоку в салоні; оптимізація теплового комфорту; зваженість частинок пилу; моделювання обчислювальної гідродинаміки; ефективність системи вентиляції; аналіз градієнта температури; оцінка ризику утворення конденсату

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Optimisation of process parameters for improved desulphurisation in propane-propylene processing

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Abstract. The purpose of the study was to optimise the parameters of the propane-propylene desulphurisation process to increase its efficiency. The study analysed the influence of temperature, pressure, and adsorbent type on the effectiveness of the propane-propylene desulphurisation process. It was found that an increase in temperature contributes to an increase in the rate of adsorption of sulphur compounds, but this effect persists only up to a certain temperature value. After reaching a certain limit, the temperature begins to have a negative effect on the adsorbent, causing its degradation. Based on the data obtained, the optimal temperature for maximum efficiency of the desulphurisation process was determined to be in the range of 250-300°C. The effect of pressure on the desulphurisation process turned out to be significant: increasing the pressure improves the results, as it increases the density of the gas phase, which, in turn, contributes to better capture of sulphur compounds. However, if the pressures are too high, there is no additional improvement in the results, and the energy costs of the process increase. In addition, aluminium oxide proved to be the most effective of all the adsorbents considered. It has demonstrated the best results compared to activated carbon and silica gel under optimal temperature and pressure conditions, providing the greatest degree of sulphur removal from the gas mixture. Ultimately, the mathematical models developed during the study confirmed that optimising the temperature and pressure parameters can significantly increase the efficiency of the desulphurisation process. This allows not only increasing the degree of sulphur removal, but also reducing energy costs and extending the service life of the equipment, which is important for its practical application. The practical value of the research lies in the fact that an integrated approach that considers the relationship between temperature, pressure, and adsorbent type significantly improves the desulphurisation process on an industrial scale, providing higher efficiency and cost-effectiveness

Keywords: temperature; pressure; adsorbent; aluminium oxide; energy costs

Introduction

The propane-propylene desulphurisation process is an important step in the processing of hydrocarbon gases, as it allows the removal of sulphur compounds that can significantly degrade product quality and negatively affect equipment. The effectiveness of this process depends on many factors, among which the main ones are

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temperature, pressure, and the choice of adsorbent. The correct selection and optimisation of these parameters can significantly improve the quality of desulphurisation, reduce operating costs, and improve the overall efficiency of the process. In this regard, research aimed at optimising these factors represents an important step in improving the productivity and durability of equipment in the petrochemical industry.

The problem of effective propane-propylene desulphurisation remains relevant in the petrochemical industry, since the removal of sulphur from hydrocarbon gases is necessary to improve product quality and protect equipment. Y. Lei *et al*. (2022) investigated the effect of temperature on the process of propane-propylene desulphurisation, noting that an increase in temperature to a certain level accelerated the adsorption of sulphur compounds. However, they also warned that excessive temperature rise could lead to degradation of the adsorbent, which reduced the efficiency of the process. M. Mehri *et al*. (2021) studied the role of pressure in the desulphurisation process, revealing that an increase in pressure contributed to an improvement in the interaction of gases with the adsorbent. However, they stressed that the overpressure did not significantly improve results and increased operating costs. M. Andrade *et al*. (2021) concluded that the optimal temperature for effective desulphurisation of propane-propylene was 200-350°C. This value contributed to the maximum rate of adsorption, without leading to overheating and degradation of the adsorbent used. R. Kancherla *et al*. (2021) emphasised that an increase in pressure contributed to an increase in the density of gases, which improved the interaction of molecules with the adsorbent. However, they also noted that high pressures did not always lead to significant process improvements and could cause additional equipment costs. A.G. Georgiadis *et al*. (2021) noted that increasing the pressure to a certain level enhanced the efficiency of the process, but its further increase had no noticeable effect on the result, which made such optimisation economically impractical. They also emphasised the importance of balancing pressure and other parameters to achieve optimal conditions.

X. Li *et al*. (2023) studied various types of adsorbents, revealing that aluminium oxide demonstrated the greatest efficiency in removing sulphur compounds. They also noted that the correct choice of adsorbent depended on the composition of the gas mixture and the operating conditions, which required additional analysis. P.S. Castro *et al*. (2023) confirmed that adsorbents based on metal oxides, such as aluminium oxide, are significantly more effective than other materials, such as activated carbon or silica gel. They also investigated how various parameters, including temperature and pressure, affected the effectiveness of these adsorbents. P. Kumar & V.C. Srivastava (2023) developed mathematical models for the analysis of the desulphurisation process, which considered the influence of temperature, pressure, and type of adsorbent. These models allowed predicting the efficiency of the process under different conditions and became the basis for further optimisation research. C.-T. Wang *et al*. (2025) created models that helped fine-tune desulphurisation parameters in real-world industrial conditions, minimising energy costs and increasing productivity. They emphasised the importance of using such models to increase the sustainability and long-term effectiveness of processes. X. Li *et al*. (2022) emphasised that the composition of the initial mixture influenced the choice of adsorbent, which had to be taken in consideration to achieve maximum sulphur removal efficiency. Their studies examined various combinations of gas mixtures and adsorbents to optimise desulphurisation.

Despite these achievements, there are still gaps in understanding the exact interaction between the process parameters, which requires additional study. For example, the effect of the composition of the gas mixture on the choice of adsorbent, the specifics of using mathematical models to optimise the operating conditions of the installation, and the durability of various types of adsorbents on an industrial scale remain poorly understood.

The purpose of the study was to determine the optimal values of temperature, pressure, and adsorbent type for the propane-propylene desulphurisation process aimed at improving its performance in energy and engineering systems. Research objectives:

1. To consider various methods for optimising these parameters to improve the removal of sulphur compounds.

2. To assess the effectiveness of using different types of adsorbents depending on the composition of the gas mixture and operating conditions.

3. To evaluate energy costs under various temperature and pressure conditions.

Materials and Methods

As part of this study, the key parameters of the propane-propylene desulphurisation process were studied in detail, with an emphasis on their impact on sulphur removal efficiency and optimisation of operating costs. The study focused on parameters such as temperature, pressure, and adsorbent selection to optimise these factors to improve process efficiency and minimise energy costs. Temperature is an important factor because it directly affects the reactivity of the adsorbent and the rate of adsorption of sulphur compounds. The study examined how an increase in temperature affects the reaction rate between the gas mixture and the adsorbent, which, in turn, promotes faster removal of sulphur from the gas. However, the potential negative effects of excessively high temperature, such as adsorbent degradation, reduced adsorbent efficiency and increased operating costs, were also investigated. The study of temperature conditions was aimed at finding the optimal temperature at which the desulphurisation process proceeds with maximum efficiency without damaging the adsorbent. This would not only improve the purification speed, but also extend the service life of the equipment. Different temperature regimes were selected for each group of adsorbents based on their thermal stability and ability to effectively remove sulphur under various conditions.

Pressure also played a key role in the desulphurisation process. The study examined how an increase in pressure affects the density of the gas phase, which improves the interaction of the gas with the adsorbent. The problem of excessive energy costs arising from too high pressure, which can reduce the economic viability of the process, was also investigated. To assess the effect of pressure on the process, experiments were conducted during the study aimed at identifying optimal pressure values at which the desulphurisation process would be most effective and energy costs would be minimal. The pressure increase factor was also considered to improve the density of gases, which had a positive effect on the interaction with the adsorbent, but only up to a certain limit.

One of the key aspects of the study was the choice of adsorbent. For this purpose, materials with high adsorption capacity, selectivity, resistance to high temperatures and mechanical influences, and efficiency in removing sulphur from the gas mixture, were considered. Various types of adsorbents, such as metal oxides, activated carbon, and metal-organic framework (MOF) structures, were analysed. These materials have different physicochemical characteristics and can exhibit different properties under different temperature and pressure conditions.

In addition, an important part of the research was the development of mathematical models that took into consideration the influence of temperature, pressure, and adsorbent type on the effectiveness of the desulphurisation process. The models were used to predict the optimal operating conditions of the plant, which made it possible to accurately select the parameters that ensure the best result in real production conditions. Mathematical modelling also allowed evaluating the economic efficiency of the process, which was important for choosing optimal operating modes, minimising energy costs and improving the overall production economy. The models not only increased the efficiency of sulphur removal, but also provided prediction of the long-term characteristics of the plant, which played a key role in optimising the process. The study presented graphs based on calculations of mathematical models, such as the change in sulphur concentration over time and the effect of plant parameters on the total cost of operation. The data on the initial concentration, adsorption coefficient, adsorbent cost, and energy consumption were used, which helped to confirm the theoretical conclusions and give practical recommendations.

Results

Desulphurisation is a critical process in the processing of gas mixtures such as propane-propylene. The main task of this stage is the removal of sulphur compounds present in the raw materials. Sulphur and its compounds pose a serious threat to production systems. When they accumulate, the risk of corrosion of the equipment increases, which reduces its service life and increases the cost of repair and replacement. In addition, sulphur compounds degrade the quality of the final product, making it less competitive on the market. From an ecological standpoint, sulphur removal reduces emissions of toxic compounds into the environment, preventing air pollution and minimising harm to ecosystems. With increasing demands on the quality of hydrocarbon products and industrial safety standards, desulphurisation is becoming even more important. Modern processing technologies require a high degree of purity of the raw materials, which directly affects the productivity and reliability of the processes (Chen *et al.*, 2022).

Temperature is a key factor determining the efficiency of the desulphurisation process of hydrocarbon gases, including propane-propylene mixture. It directly affects the reactivity of the adsorbent and its ability to remove sulphur compounds. Optimisation of the temperature regime helps to accelerate adsorption, while avoiding undesirable effects such as thermal degradation of the adsorbent or the development of secondary pollutants (Wang *et al.*, 2023).

An increase in temperature promotes the activation of gas molecules, which increases the rate of their interaction with the active surface of the adsorbent. For example, for aluminium oxide-based adsorbents, an increase in temperature to 250-300°C leads to a noticeable improvement in their sorption capacity. However, an excessive increase in temperature can cause thermal destruction of the active components, reducing sorption properties and shortening the service life of the material. This, in turn, increases the cost of operation and maintenance of the installation.

At low temperatures, the activity of the molecules and adsorbent decreases, which slows down the desulphurisation process. As a result, the purification efficiency decreases, and the plant's performance may not be sufficient for industry standards. To achieve optimal results, it is necessary to find a balance between these extremes. The optimal temperature range for most industrial desulphurisation processes is 250-300°C, which achieves high sulphur removal efficiency and minimises the risks of adsorbent degradation.

In practice, temperature selection requires consideration of many factors, such as the composition of the gas mixture, the type of adsorbent used, and the operating conditions. For example, mixtures with a high concentration of sulphur compounds may require a higher temperature to ensure sufficient reactivity of the adsorbent. At the same time, temperature limits can be set for adsorbents with low thermal stability to avoid their destruction.

An integrated approach to the choice of temperature regime includes the use of experimental data and mathematical modelling. Such models allow predicting the behaviour of the system at different temperatures and selecting optimal parameters, considering technical and economic feasibility. This makes the temperature regime an important element for the successful implementation of desulphurisation processes in industry.

Pressure plays a crucial role in the efficiency of hydrocarbon gas desulphurisation processes, including propane-propylene mixtures. It determines the density of the gas mixture and the intensity of the interaction of gas molecules with the active surface of the adsorbent, which directly affects the removal of sulphur compounds. However, pressure management requires finding the optimal balance between technical efficiency and economic feasibility, since excessive pressure can significantly increase operating costs (Huang *et al.*, 2023).

An increase in pressure leads to a convergence of gas molecules, which increases the likelihood of their contact with the adsorbent. This contributes to a more intensive adsorption of sulphur compounds and, as a result, improved purification results. For example, M.A. Pordsari *et al.* (2024) have shown that when using aluminium oxide-based adsorbents, pressure in the range of 10-20 atmospheres provides optimal results. Nevertheless, the effect of increasing pressure has its limits: after reaching a certain level, its further increase ceases to have a significant effect on the effectiveness of desulphurisation.

Too high pressure is accompanied by increased gas compression costs and increased equipment loads. This requires the use of more expensive materials and structures to ensure reliable and safe operation of the system. For example, increasing the pressure above 20 atmospheres may require the installation of specialised compressors, which increases capital costs. In addition, energy consumption associated with maintaining high pressure is increasing, which reduces the overall economic efficiency of the process.

To determine the optimal pressure, it is necessary to consider the composition of the gas mixture and the characteristics of the adsorbent used. For example, mixtures with a high content of sulphur compounds require a higher pressure to achieve a given degree of purification. When using adsorbents with low mechanical strength, pressure limitations become critical to prevent material damage.

Pressure optimisation is an important step in the design and operation of desulphurisation systems. The range of 10-20 atmospheres is considered to be the most balanced in terms of technical and economic performance. This approach helps to achieve a high degree of purification of hydrocarbon gases at minimal cost of equipment and energy resources.

Rational pressure management helps to increase the stability of the process, improve the quality of the final product, and reduce the negative impact on the environment. This is especially important in modern conditions, when the requirements for environmental safety and economic efficiency of production are constantly being tightened. The type of adsorbent is a crucial factor in the effectiveness of desulphurisation processes, since its physicochemical properties directly affect the ability to remove sulphur compounds from hydrocarbon mixtures. Modern technologies offer a wide range of materials, among which metal oxides, activated carbon, and silica gels occupy a special place, including the latest developments such as MOF (Table 1).

Table 1. Efficiency of different types of adsorbents depending on gas mixture composition and operating conditions

Adsorbent type	Composition of the gas mixture	Operating temperature (°C)	Operating pressure (atm)	Adsorption coefficient (*Ka*) (mg/g)
Aluminium oxide	Propane-propylene, hydrogen sulphide 0.5%	200-300	10-15	85
Activated carbon	Propane-butane, mercaptans 0.2%	50-150	1-5	70
Silica gel	Propane-propylene, sulphur dioxide	100-250	5-15	60
MOF	Propane-propylene, hydrogen sulphide 0.1%	150-250	5-20	95

Source: compiled by the authors based on J.Y. Lai *et al.* (2021)

Metal oxides, for example, aluminium oxide, are characterised by high chemical stability and the ability to bind molecules of sulphur compounds. This material has proven to be an effective and affordable option, especially at temperatures of 250-300°C (Ikram *et al.*, 2021). In addition, it has a good regenerative ability, which makes it economically beneficial. However, the effectiveness of aluminium oxide may decrease in the presence of complex impurities such as carbon dioxide or organic pollutants, which requires additional pretreatment steps.

Activated carbon is valued for its high specific surface area and versatility, allowing it to adsorb a wide range of compounds. However, its properties may deteriorate at high humidity, which makes it less effective for working with gas mixtures containing water vapour.

Silica gels demonstrate high efficiency in low-temperature processes and can adsorb moisture, improving the quality of purification. However, their chemical resistance is limited, which makes them less suitable for handling aggressive components such as hydrogen sulphide or organic sulphur compounds.

MOFs are the latest generation of adsorbents that have a unique porous structure and high selectivity. They can be modified to work with certain sulphur compounds, ensuring maximum efficiency with minimal material consumption. For example, MOFs successfully operate at low temperatures, which makes them promising for use in installations with limited energy consumption. However, their widespread industrial use is limited by the high cost and complexity of production.

Thus, the choice of adsorbent should be based on a comprehensive analysis of the characteristics of the initial mixture, operating conditions and economic feasibility. Modern research in the field of developing new materials and modifying existing adsorbents continues to expand the possibilities of optimising the desulphurisation process, which makes it more efficient and sustainable (Omar & Verma, 2022).

The process of propane-propylene desulphurisation is an important step in the industrial processing of hydrocarbon mixtures aimed at removing sulphur compounds. In order to achieve high efficiency in this process, kinetic and dynamic parameters must be considered, which directly affect the choice of optimal operating conditions for the installation. Studying these factors helps not only to improve the process, but also to significantly reduce operating costs, while increasing production and environmental performance.

The kinetics of desulphurisation determines how quickly and efficiently the adsorption of sulphur compounds occurs on the surface of the adsorbent (Al-Khodor & Albayati, 2023). This aspect is key to optimising the operating cycle of the installation. Important parameters to consider are the duration of contact of the gas mixture with the adsorbent and the rate of gas flow through the reactor. The longer the contact of the gas with the adsorbent, the higher the probability that sulphur compounds will be effectively removed from the gas stream. However, it is important to balance this parameter with the energy costs and throughput of the installation.

In parallel with the duration of contact, the gas flow rate through the installation is also important. A high flow rate can speed up the process, but the degree of adsorption will decrease, since the gas will not be in contact with the adsorbent for a long time. On the contrary, too low a flow rate can lead to insufficient equipment efficiency and excessive costs for maintaining the necessary conditions.

The dynamics of the process, in contrast to kinetics, considers the behaviour of a gas mixture over time and its interaction with an adsorbent (Karimi *et al.*, 2021). An important aspect of the dynamics is to ensure an even distribution of gas throughout the reactor volume. If the gas passes through the adsorbent unevenly, this can lead to the development of "dead zones" – areas where the gas does not come into contact with the adsorbent properly, which significantly reduces the effectiveness of desulphurisation. Thus, it is important to adjust the gas flow parameters to prevent the occurrence of such zones and ensure an even distribution of the mixture components. One solution to increase dynamic efficiency is to use flow distributors or technologies with improved gas-adsorbent contact. These technologies allow minimising the loss of working material and significantly improving the degree of gas purification from sulphur.

In order to accurately determine the optimal parameters of the kinetics and dynamics of the process, it is necessary to conduct experimental studies to collect data for building models. Such data may include information on the rate of adsorption of sulphur compounds at various temperatures, pressures, and gas mixture compositions. The use of mathematical modelling allows predicting the behaviour of the system and optimise the parameters in real production conditions.

Several approaches can be used to develop mathematical models of the desulphurisation process during propane-propylene processing. The main elements to be considered include the adsorption coefficient, the dynamics of changes in the concentration of sulphur compounds, energy costs, and operating costs (Naderi *et al.*, 2024). Basic mathematical models have been proposed that can be used to analyse and optimise this process.

The adsorption model can be based on the classical theory of adsorption, where the concentration of sulphur compounds in the gas phase decreases over time, depending on the process parameters. The basic model for this process is the adsorption rate equation, which can be written as (1):

$$\frac{dC}{dt} = K_a \cdot C, \tag{1}$$

where C – concentration of sulphur compounds in the gas mixture (mg/m^3); t – time (h); K_a – adsorption coefficient (m^3/mg·h), which depends on the type of adsorbent and temperature.

The solution of this equation gives the dependence of the sulphur concentration on time (2):

$$C(t) = C_0 \cdot e^{-K_a \cdot t}, \tag{2}$$

where C_0 – initial concentration of sulphur compounds (mg/m^3); $C(t)$ – concentration of sulphur at time t.

The duration of the desulphurisation cycle depends on the capacity of the adsorbent and the volume of gas to be treated. The model for the cycle duration has a form (3):

$$t_c = \frac{m \cdot q_{max}}{F \cdot C}, \tag{3}$$

where t_c – duration of the desulphurisation cycle (h); m – weight of the adsorbent (g); q_{max} – maximum capacity of the adsorbent (mg/g); F – volume flow rate of gas (m^3/h); C – concentration of sulphur compounds in the gas mixture (mg/m^3).

This model allows estimating the operating time of the installation before the adsorbent needs to be replaced or regenerated. The energy costs of maintaining temperature and pressure can be expressed in terms of equipment capacity and operating time (4):

$$E = P \cdot t, \tag{4}$$

where E – energy cost (kWh); P – power of the equipment (kW); t – operating time of the installation (h).

This model will help to calculate energy consumption for different operating modes of the installation, which is important for optimising processes. The total cost of operating the plant consists of several components: the cost of adsorbent, energy costs, and maintenance costs. The model for the total cost of operation is as follows (5):

$$C_{total} = C_{ads} + C_{energy} + C_{maint}, \tag{5}$$

where C_{total} – total cost of operation (USD); C_{ads} – adsorbent cost (USD); C_{energy} – energy cost (USD); C_{maint} – equipment maintenance and replacement costs (USD).

Here, the adsorbent cost may depend on the amount of material used, energy consumption on the installation capacity and operating time, and maintenance costs on the frequency of equipment replacement and maintenance. Graph of changes in the concentration of sulphur compounds over time: based on the equation for adsorption (2), a graph can be constructed that shows a decrease in sulphur concentration depending on time at different values of the adsorption coefficient K_a (Fig. 1). The initial concentration values of C_0 = 100 mg/m^3 and adsorption coefficients K_a = 0.1, 0.2, 0.3 mg/m^3 were used in the calculations. Such data help to estimate how fast the desulphurisation process takes place at the specified parameters.

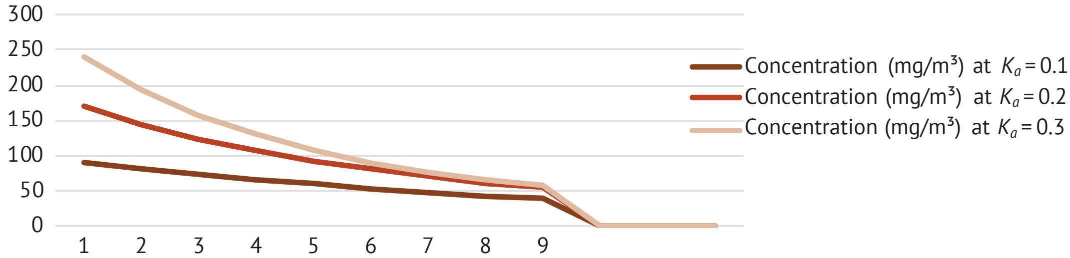

Figure 1. Graph of changes in the concentration of sulphur compounds as a function of time at different values of the adsorption coefficient

Source: compiled by the authors

Graph of the dependence of the total cost of operation on the parameters of the installation: a graph can be constructed that shows the variation of total cost of operation as a function of plant capacity, operating time, adsorbent cost, and energy consumption (Fig. 2). The total cost was calculated using the equation (5). For calculations, the values of equipment power P = 50, 75, 100 kW, operating time t = 100, 200 h, and electricity price 0.1 USD/kWh, and the cost of adsorbent in the range from USD 1,500 to 4,000 were used. These data allow visually showing how the installation parameters affect the economics of the process.

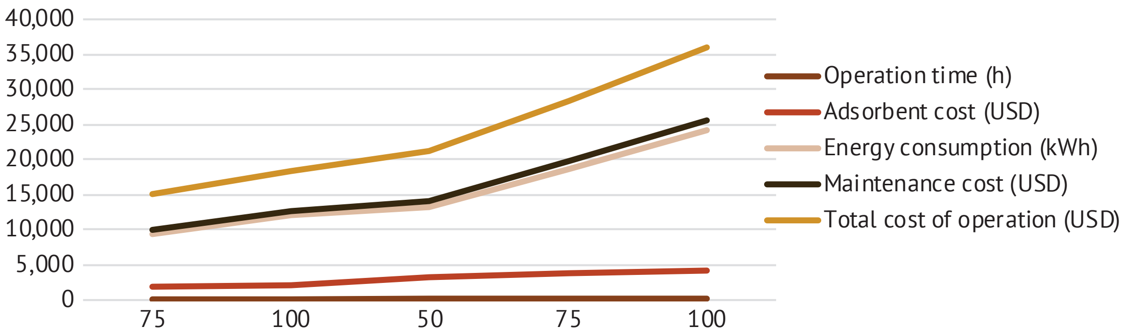

Figure 2. Graph of the dependence of the total cost of operation of the installation on the capacity of the equipment and the operating time

Source: compiled by the authors

In engineering applications, the importance of optimisation lies in ensuring the reliability and accuracy of data for system design. For example, when designing desulphurisation plants, dynamic parameter changes such as temperature or pressure fluctuations must be considered to minimise the risks of equipment failure. Accurate mathematical models allow predicting possible deviations and developing compensating mechanisms, which increases the overall safety of the installation (Ahn *et al.*, 2023). Energy aspects are also central to the process. Efficient energy management, for example by choosing a low-energy adsorbent or optimising pressure, reduces the load on the company's energy systems. This is especially important in the context of modern requirements for reducing carbon dioxide emissions and energy conservation (Table 2).

Table 2. Energy costs under different temperature and pressure conditions

Temperature (°C)	Pressure (atm)	Equipment power (*P*) (kW)	Operation time (*t*) (h)	Energy costs (*E*) (kWh)	Notes
150	5	50	10	500	Optimal mode for adsorbents with low temperature resistance
200	10	70	10	700	Requires stable temperature control, suitable for aluminium oxide
250	15	90	10	900	High sulphur removal efficiency, increased equipment cooling costs
300	20	120	10	1,200	Energy consumption increases significantly, the use of heat-resistant adsorbents is required

Source: compiled by the authors based on P.R. Chauhan *et al.* (2022)

Optimisation also significantly reduces operating costs. For example, a more durable adsorbent reduces the frequency of its replacement, which minimises maintenance costs. In addition, reducing energy consumption helps to reduce energy costs, which makes the process more economically attractive for enterprises. Engineering applications include the use of such models to select optimal materials, design equipment, and predict system performance. The integration of these models into automated control systems makes the process more stable and adaptive to changing conditions.

Optimisation of desulphurisation parameters is an integral part of engineering and energy applications. It not only increases the efficiency of the installation, but also ensures safety, reduces environmental risks and improves the economic performance of the enterprise, which makes the process more promising and sustainable in the long term. Thus, successful optimisation of these parameters using appropriate models can significantly improve the desulphurisation process, increasing its economic and energy efficiency, and reducing operating costs.

Discussion

In the course of the study, the key parameters influencing the process of propane-propylene desulphurisation were analysed: temperature, pressure, and type of adsorbent. The results showed that temperature significantly affects the rate of adsorption of sulphur compounds. The optimal temperature range established during the experiments ensured high efficiency of adsorbents, whereas a slowdown in adsorption was observed at lower temperatures, and degradation of the adsorbent structure at high temperatures.

This problem was also analysed by S.H. Shafeianpour *et al.* (2024), and their findings confirmed that the process of propane-propylene desulphurisation depends on temperature, since a change in temperature regime affects the activity of catalytic processes. At high temperatures, the reaction accelerates, which can lead to faster desulphurisation, but also increases the risk of adsorbent degradation. Determining the optimal temperature range is critical to maximise the efficiency of the process without loss of adsorbent quality. A.K. Singh *et al.* (2024) demonstrated that it is important to establish a temperature regime that ensures a balance between high reactivity and maintaining the stability of the material to prevent adsorbent degradation. The choice of a suitable temperature range also affects the service life of the equipment and the cost-effectiveness of the process. Careful analysis of the thermodynamic characteristics of the adsorbent helps to avoid its destruction when operating at high temperatures.

It should be emphasised that optimising the temperature conditions for propane-propylene desulphurisation is of key importance not only for increasing the speed of the process, but also for extending the service life of adsorbents. Despite the obvious advantages of high temperatures in accelerating chemical reactions, it is important to consider their impact on the stability and durability of materials. Gas pressure also proved to be a significant factor. Experimental data have shown that an increase in pressure increases the density of the gas flow and, as a result, improves the contact of gas molecules with the adsorbent. However, with a further increase in pressure, the adsorption efficiency stopped increasing, which can be explained by the saturation of the active centres of the adsorbent. This indicates the need to fine-tune the operating parameters to prevent an unjustified increase in energy costs.

J. Sun *et al.* (2022) concluded that increasing the pressure during desulphurisation can significantly improve the contact of the gas mixture with the adsorbent, which contributes to a more efficient capture of sulphur compounds. Higher pressure increases the density of gas molecules, which increases the likelihood of collisions with the active centres of the adsorbent. This can lead to faster and more complete removal of sulphur from the gas mixture. The study by Q. Dong *et al*. (2021) found that it is important to consider that increasing the pressure has its limitations, since too high pressure can lead to an overabundance of molecules, which makes it difficult for them to interact with the adsorbent. Determining the optimal pressure for desulphurisation is critical, as it must ensure maximum process efficiency without unnecessary energy costs and threats to system stability. This requires careful analysis and experiments aimed at identifying the maximum pressure for optimal operation of the adsorber.

These results confirm the previously presented study, as they demonstrate a significant improvement in desulphurisation efficiency when optimising temperature and pressure conditions, which corresponds to the conclusions of previous studies. It is confirmed that the correct balance between temperature, pressure, and reaction time can significantly increase the productivity of the process, while maintaining the durability of the adsorbent. Such data also confirm the importance of an integrated approach to the development and improvement of desulphurisation technologies to achieve maximum efficiency and cost-effectiveness. The type of adsorbent used showed the greatest variability in the results. The most effective material was aluminium oxide, which provided a high degree of removal of sulphur compounds. Organometallic skeletal structures have shown promising results, but their high cost and limitations in operating conditions have so far reduced their competitiveness.

It is important to note the study by F. Ahmadijokani *et al*. (2021), in which it was also found that adsorbents based on aluminium oxides and organometallic skeleton structures have various advantages in the desulphurisation process. Aluminium oxides are known for their high stability and good adsorption properties under various temperature conditions, but their effectiveness is limited compared to more specialised materials. Whereas organometallic adsorbent framework structures offer improved selectivity and greater porosity, which can significantly increase their efficiency in removing sulphur from gas mixtures. In turn, A.T. Kadhum & T.M. Albayati (2022) concluded that the prospects for using modified adsorbents in industrial desulphurisation look promising, as they can combine the advantages of both types of materials. Modification of organometallic skeleton structures and aluminium oxides can significantly improve their resistance to high temperatures and aggressive environments, and expand their range of applications. These improvements open up new possibilities for more efficient and cost-effective desulphurisation, which can lead to significant improvements in industrial gas purification processes.

The data obtained are consistent with the statements outlined in the previous section, confirming that optimisation of parameters such as temperature and pressure plays a key role in improving desulphurisation efficiency. The results of the study demonstrate that the correct combination of these factors can significantly improve the contact of the gas mixture with the adsorbent, which contributes to a more complete removal of sulphur compounds. Thus, observations confirm the importance of an integrated approach that considers the relationship between temperature and pressure conditions, and the need to fine-tune them to achieve maximum process performance.

The study of the kinetics of the process deserves special attention. The results showed that the duration of contact of the gas mixture with the adsorbent directly affects the effectiveness of desulphurisation. The optimal contact time ensured a balance between energy consumption and the required purification levels, while the insufficient duration did not allow achieving the desired process quality. S. Li *et al*. (2021) also conducted a study, and their results confirmed that optimising the gas-adsorbent contact time is an important aspect for reducing energy consumption during desulphurisation. Too short a contact time can lead to insufficient gas purification, while excessively long contact leads to unjustified energy costs. Therefore, it is important to determine the optimal duration of contact, which will ensure effective purification with minimal energy costs. S. Abbasi *et al*. (2023) also found that the effect of the duration of contact on the degree of purification of propane-propylene shows that there is a certain time at which the purification process reaches maximum efficiency. Increasing the contact time usually improves the degree of purification, but after reaching the optimal point, efficiency begins to decrease due to overheating and increased energy consumption. This highlights the need to fine-tune the contact duration to achieve the best balance between purification efficiency and cost-effectiveness of the process.

Comparing the data obtained during the research, it can be concluded that optimising the contact time with the adsorbent has a significant impact on the effectiveness of the desulphurisation process. While increasing the duration of contact improves the degree of purification, it must be borne in mind that after a certain threshold, a further increase in time does not significantly improve results, but increases energy consumption. These results highlight the importance of precise control of contact time, which will optimise the process, taking into account both purification efficiency and energy savings. The dynamic properties of the process also revealed the need for uniform gas distribution in the reactor. It was observed that the uneven gas flow led to the development of "dead zones" where adsorption was practically absent. The use of flow distributors and preliminary calculations of gas dynamics made it possible to significantly reduce these zones and improve the overall productivity of the process.

K. Kaczmarski & M.K. Szukiewicz (2021) concluded that the time of gas contact with the adsorbent is indeed a key factor in the desulphurisation process, affecting the degree of purification. The results showed that at the initial stages, an increase in contact time leads to a significant improvement in efficiency, since the gas has time to interact with the active centres of the adsorbent. However, after a certain point, the efficiency of the process stabilises, which confirms the need to find the optimal time to minimise energy consumption. X. Zhang *et al.* (2021) found that an excessive increase in contact time leads not only to a slight improvement in the degree of purification, but also to an increase in energy consumption, which is impractical from an economic standpoint. This approach requires careful process control to reduce unnecessary energy costs while maintaining the required purification quality. It is important that this study provides a basis for further optimisation of the conditions under which it will be possible to achieve the best results in terms of both savings and efficiency.

An analysis of the findings shows that optimising the contact time with the adsorbent has a noticeable effect on the effectiveness of desulphurisation, allowing for better purification performance with minimal energy consumption. While increasing the contact time improves the degree of purification, it has been found that further increasing it after a certain limit does not lead to significant improvements. This highlights the importance of precise time control, which helps to save energy without compromising process quality. Thus, the analysis of the obtained results confirms that optimisation of the parameters of the desulphurisation process requires an integrated approach. The established relationships between temperature, pressure, adsorbent type, and gas flow characteristics can become the basis for further design and configuration of industrial installations. This will increase the efficiency of the process and reduce its operating costs.

Conclusions

As a result of the conducted research, the key parameters influencing the efficiency of the propane-propylene desulphurisation process were identified. It has been established that temperature plays one of the leading roles in ensuring optimal operation of adsorbents. The use of a temperature range at which adsorbents retain their activity helps to achieve a high degree of purification of the gas mixture without loss of the working properties of the materials. The analysis of the pressure effect revealed its critical importance for process optimisation. A moderate increase in pressure contributes to a more intense contact of gas molecules with the active centres of the adsorbent, which increases the efficiency of purification. However, an excessive increase in pressure does not provide significant advantages and may lead to unnecessary energy costs. The type of adsorbent proved to be a key factor influencing the results of desulphurisation. Aluminium oxides proved to be the most effective materials. Despite the promise of organometallic skeleton structures, their cost and limitations in operating conditions limit their widespread use.

The kinetics of the process demonstrated that the duration of gas contact with the adsorbent plays a significant role. Optimal time parameters allowed achieving a high degree of purification without excessive expenditure of resources. The dynamic characteristics of the process have shown that the uniformity of gas distribution in the reactor is crucial. The use of special switchgear helped to minimise the development of "dead zones". Thus, an integrated approach to optimising the temperature, kinetic, and dynamic parameters of the process ensure high productivity and reduced operating costs. The results obtained can be applied in the design and modernisation of industrial desulphurisation plants. The main limitation of this study is that the experiments were conducted in a laboratory setting, which may not fully reflect the complexity of industrial processes. Further research is needed to investigate the long-term stability of adsorbents under actual operating conditions, including the effects of impurities and temperature fluctuations.

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Conflict of Interest

None.

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Оптимізація технологічних параметрів для покращення десульфурації в процесі переробки пропан-пропілену

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Анотація. Метою роботи була оптимізація параметрів процесу сіркоочищення пропан-пропілену для підвищення його ефективності. В роботі проаналізовано вплив температури, тиску та типу адсорбенту на ефективність процесу десульфурації пропан-пропілену. Встановлено, що підвищення температури сприяє збільшенню швидкості адсорбції сполук сірки, але цей ефект зберігається лише до певного значення температури. Після досягнення певної межі температура починає негативно впливати на адсорбент, викликаючи його деградацію. На основі отриманих даних було визначено, що оптимальна температура для максимальної ефективності процесу сіркоочищення знаходиться в діапазоні 250-300 °C. Вплив тиску на процес сіркоочищення виявився значним: підвищення тиску покращує результати, оскільки збільшує щільність газової фази, що, в свою чергу, сприяє кращому вловлюванню сполук сірки. Однак, якщо тиск є занадто високим, додаткового покращення результатів не відбувається, а енергетичні витрати на процес зростають. Крім того, оксид алюмінію виявився найефективнішим з усіх розглянутих адсорбентів. Він продемонстрував найкращі результати порівняно з активованим вугіллям і силікагелем за оптимальних температурних і тискових умов, забезпечивши найбільший ступінь видалення сірки з газової суміші. Розроблені в ході дослідження математичні моделі підтвердили, що оптимізація параметрів температури і тиску дозволяє значно підвищити ефективність процесу сіркоочищення. Це дозволяє не тільки підвищити ступінь видалення сірки, але й знизити енерговитрати та продовжити термін служби обладнання, що є важливим для його практичного застосування. Практична цінність роботи полягає в тому, що комплексний підхід, який враховує взаємозв'язок між температурою, тиском і типом адсорбенту, значно покращує процес сіркоочищення в промислових масштабах, забезпечуючи вищу ефективність та економічність

Ключові слова: температура; тиск; адсорбент; оксид алюмінію; енергетичні витрати

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Optimisation of air exchange in thermally modernised buildings by means of natural ventilation

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Abstract. The aim of the study was to compare the efficiency of the supply devices of passive ventilation systems (wind catcher of the original design and window ventilator with the options of location "above the window" and "under the window"). As a result, an assessment of the nature of air distribution and features of air flow circulation in the room with different options for supply air supply was provided. To collect and systematise information on passive ventilation, its effectiveness in thermally modernised buildings and to assess the possibility of ensuring standardised air exchange in the premises, methods of generalising the results of previous studies, as well as comprehensive and logical-structural analysis were used. Scientific and analytical analysis was used to process and evaluate the data obtained. Computer modelling made it possible to compare the results and evaluate the distribution of air flows, temperature gradients and air exchange efficiency in the room. A comprehensive analysis of the efficiency of passive ventilation in a thermally modernised building using different types of air inlets was carried out. Their influence on indoor air exchange under different climatic conditions (warm and cold seasons) is investigated, taking into account the distribution of temperature and air flow velocity. Optimal solutions for passive ventilation have been identified that reduce energy consumption while creating a standard air exchange in thermally modernised buildings, which is a key aspect for ensuring energy efficiency and comfortable living conditions. As a result of the modelling, data on the distribution of temperature and air flow velocity in the room for a window ventilator and a wind catcher were obtained. The data obtained were analysed in the frontal and horizontal planes, which allowed to assess the peculiarities of air distribution in the room volume. Particular attention was paid to the analysis of the area directly near the air inlet, which made it possible to study in detail the behaviour of the air flow at the initial stages of its distribution in the room and to assess changes in temperature and flow rate depending on air flow and distance from the air inlet. The results obtained allow for a detailed assessment of the air exchange in the room, taking into account the influence of the design features of the air inlets on the efficiency of air distribution and circulation

Keywords: passive ventilation; wind catcher; microclimate; energy efficiency

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Introduction

Insulation of the exterior walls of buildings remains a key measure to improve the energy efficiency of buildings, which suffer from freezing walls and humidity in winter and overheating in summer. External thermal insulation can significantly improve the microclimate in apartments by protecting walls from the negative effects of moisture, wind and ultraviolet radiation. Replacing outdated windows and balcony blocks with sealed profiles with double-glazed windows also helps to create a stable indoor climate, which in turn helps to significantly reduce energy consumption.

In the context of modern requirements for energy efficiency in buildings, it is important to find alternative ventilation methods that will reduce or even avoid dependence on mechanical systems. Ensuring efficient ventilation in thermally modernised buildings should take into account not only the standard air exchange, but also the minimum energy consumption. Ensuring effective ventilation in thermally modernised buildings should take into account not only the standard air exchange, but also the minimum energy consumption. The study by N. Fu *et al.* (2021) analyses and justifies the effectiveness of several mechanical ventilation strategies in high-rise buildings in terms of air quality and energy efficiency. A significant amount of research and development has been devoted to mechanical ventilation systems and improving their efficiency, among which the work of H.Y. Bai *et al.* (2022). But they all have one drawback in common: the need for significant energy consumption for operation. That is why it is promising to study passive ventilation, which makes it possible to reduce the energy consumption of mechanical ventilation systems by using wind power and buoyancy. The study by T. Ahmed *et al.* (2021) reveals the potential of natural ventilation in solving problems related to the quality of the indoor environment and confirms the viability of natural ventilation to ensure thermal comfort in the building.

One of the most well-known elements of a passive ventilation system used to improve indoor air quality is a wind catcher. As noted by V. Savin & V. Zhelykh (2023a), this element provides efficient ventilation due to its ability to direct wind flows towards the interior of the building. G. Allesina *et al.* (2019) and M. Alwetaishi & M. Gadi (2021) add that the wind catcher is a traditional architectural solution typical of the Middle East, where it is used to optimise ventilation using natural air flows. Authors P. Nejat & F. Jomehzadeh (2018) and A.H. Chohan & J. Awad (2022) note that wind catchers demonstrate high efficiency in providing natural air exchange, while A. Bekleyen & Y. Meli̇koğlu (2021) emphasise their importance in the cultural context and architectural design. In modern architecture, this device is also gaining popularity due to its versatility and ability to provide the required level of ventilation (Wahab *et al.*, 2019; Sangdeh & Nasrollahi, 2022). A study by A.H. Chohan *et al.* (2024) confirms that wind turbines contribute to improving the energy efficiency of buildings and addressing current environmental challenges, while also being key elements in modern environmental design.

Another element of passive ventilation that uses buoyancy and does not compromise the airtightness and thermal insulation properties of a thermally modernised building is a window ventilator (Hoffmann *et al.*, 2021). A window ventilator is a device that is mounted in the window frame and works on the principle of using buoyancy to ensure natural air exchange, but it does not have the ability to control the flow of incoming air. The greater the temperature difference between the outside and inside air, the more efficient the air exchange.

Despite a considerable amount of research on mechanical and passive ventilation systems, aspects of optimising natural air exchange in thermally modernised buildings remain poorly understood. This article was aimed at studying the influence of the design characteristics of air handling units on the uniformity of air distribution in the premises, as well as their ability to provide a standard level of air exchange in different climatic conditions.

Materials and Methods

The study analyses the results of modelling the impact of natural ventilation on the air exchange of a thermally modernised building on the example of a separate room, which is a key aspect for ensuring energy efficiency and comfortable living conditions. A thermally modernised one-storey residential building located in Kryvyi Rih was chosen for the study. The geometric dimensions of the room for which the modelling was carried out and the layout of the supply and exhaust elements are shown in Figure 1.

The supply air temperature, taking into account the climatic conditions of Kryvyi Rih, is -21°C in the cold season. The internal air temperature is assumed to be +20°C. The modelling of the impact of natural ventilation on the air exchange of the thermally modernised building was carried out using the licensed software Solidworks Flow Simulation.

To simulate the supply air flow, the air inlets were located as follows: the inlet of the wind catcher at a height of 2,700 mm; window ventilator, depending on the modelling conditions: "above the window" or "under the window". The maximum capacity of the window ventilator is 20 m^3/h (Mucha *et al.*, 2024), which was taken as a threshold value for modelling with flow rates from 5 to 20 m^3/h. The wind catcher was studied with a wider range of flow rates: from 5 to 100 m^3/h to identify the optimal conditions for efficient air exchange.

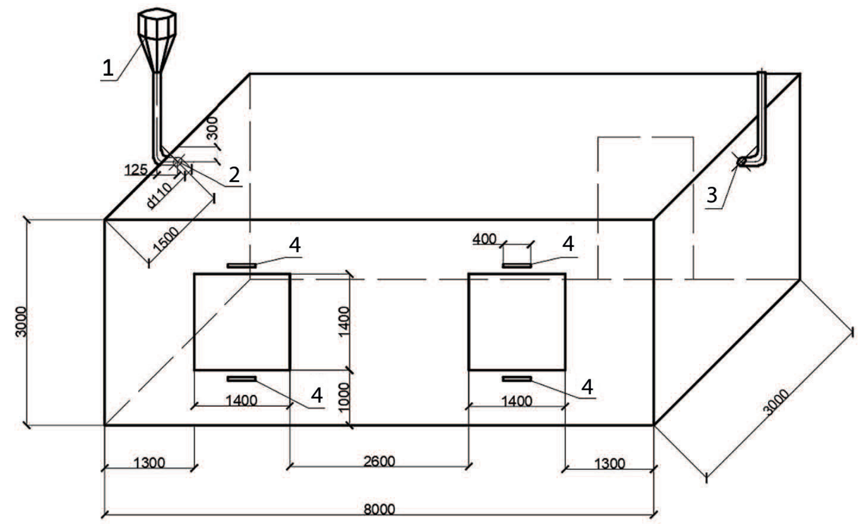

Figure 1. Layout of supply and exhaust elements in a room of a thermally modernised house
Notes: 1 – wind catcher; 2 – inlet of the wind catcher; 3 – exhaust opening; 4 – window ventilators
Source: developed by the authors

The study of passive ventilation efficiency analysis and assessment of air exchange in the room was carried out in several stages: 1. computer modelling of the operation of a wind catcher and a window ventilator under different conditions of supply air supply; 2. special conditions of air distribution and circulation in the room when using each type of supply equipment and different options for its location; 3. the influence of air flow rate on the efficiency of air distribution and features of air flow circulation in the room is analysed; 4. recommendations on the choice and installation location of supply devices of passive ventilation to ensure.

Results

The modelling results showed that at the minimum flow rate (5 m³/h) in each of the two variants of the window ventilator location ("above the window" and "under the window"), the air flow develops slowly, which ensures gradual mixing of the supply air with the internal air, although circulation is limited to areas close to the window ventilators. The flow remains in the lower layers of the room when supplied through the lower window ventilators or in the upper layers – through the upper window ventilators, which does not ensure full coverage of the room volume.

As the flow rate increases, the air flow penetrates deeper into the room, reaching the middle layers, which ensures more efficient mixing with the indoor air. Regardless of the location of the window ventilator, the air flow covers a large part of the room, distributing evenly. With a maximum flow rate of 20 m³/h in both the upper and lower outlets (Fig. 2), the airflow demonstrates high speed, actively circulating throughout the room. The air flow is evenly distributed in both horizontal and vertical planes, with complete mixing of supply and internal air, providing full coverage of the room volume and intensive air exchange.

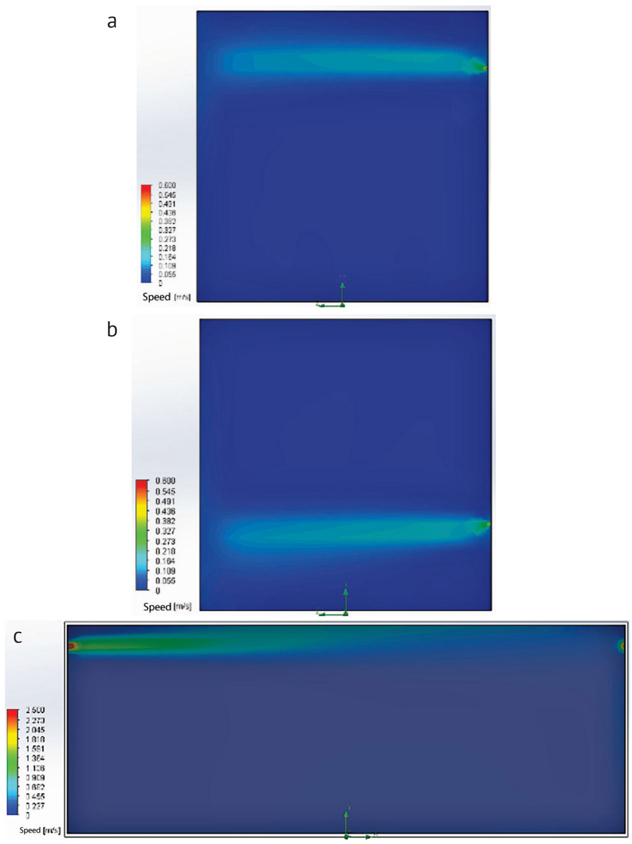

Figure 2. Modelling the inflow velocity in the frontal plane
Notes: a – through a window ventilator located "above the window"; b – through a window ventilator located "under the window"; c – through a wind catcher
Source: developed by the authors

The combination of the modelling results for the upper and lower air supply is possible due to the identical temperature conditions of the supply and internal environments (+20°C). Under such conditions, both air supply options, although they have different directions of distribution at the initial stages, demonstrate similar patterns in air distribution at the same flow rates. The main differences in the flow behaviour are smoothed out at the mixing stage, when the air is evenly distributed throughout the room, indicating a similar effect on the microclimate.

Modelling of the intake air flow through the wind catcher showed that at minimum flow rates, the intake air flow is uniform, without sudden changes in direction. Due to the low velocity, the flow does not penetrate far from the wind catcher outlet and quickly dissipates in the room. As the flow rate increases, the ability of the air flow to distribute evenly throughout the room gradually increases. At flow rates in the range of 15-40 m^3/h, the air flow circulates well without significant turbulence, and at high flow rates (from 60-80 m^3/h) turbulent zones begin to appear, which can cause discomfort. At a maximum flow rate of 100 m^3/h, the most intense air flow is provided (Fig. 2). The turbulence becomes significant, and the air movement can create unpleasant sensations for the occupants due to excessive speed and uneven distribution of air flows throughout the room.

According to the modelling data, at low flow rates (5 m^3/h), and thus low velocities, the cold supply air is slowly mixed with the warm indoor air. The air flow remains close to the window ventilator, with a gradual decrease in speed as it moves away. The cold air settles, causing cold zones to form in the lower layers of the room. The slow spread of air with a temperature of -21°C has a slight effect on the temperature of the room. Low temperatures remain in the area close to the window ventilator.

With increased flow rates, the mixing of cold and warm air is more efficient. The cold air is more actively distributed throughout the room, but there are still significant temperature gradients between the area near the window ventilator and the farther parts of the room. The temperature in the room begins to drop, especially closer to the floor. At the maximum capacity of the window ventilator (20 m^3/h), the air flow has a high velocity, which ensures uniform mixing of the cold supply air with the warm internal air (Fig. 3). The flow extends over the entire area of the room, covering all its nooks and crannies. The simulation results illustrate that the air no longer settles in the lower layers, but is evenly distributed throughout the room.

The room temperature remains more stable, although the cold air still has an impact on the temperature drop near the window ventilator (Fig. 4). However, at the maximum flow rate, the air exchange becomes intense enough to avoid the formation of excessively cold zones.

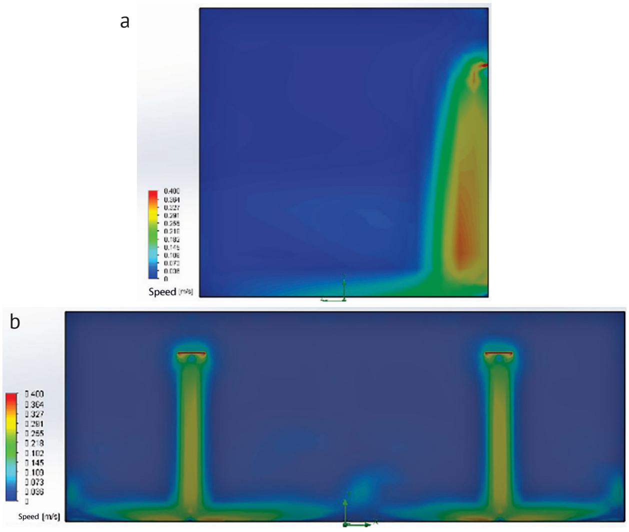

Figure 3. Simulation of the inflow velocity through the window ventilator with the location "above the window" in the frontal plane

Notes: a – along the axis of the window ventilator; b – along the wall

Source: developed by the authors

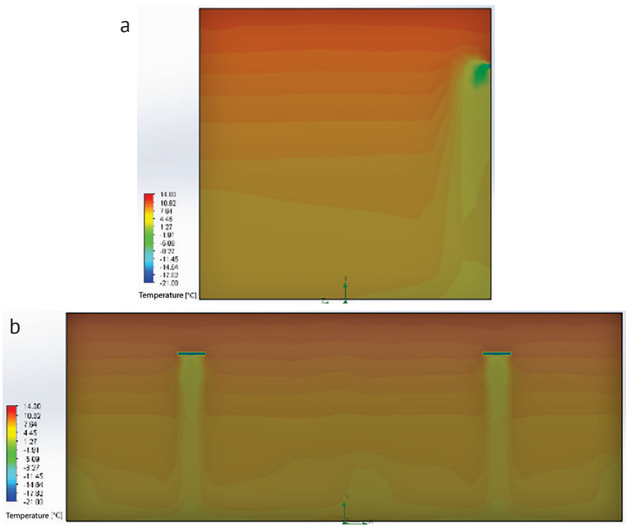

Figure 4. Simulation of the supply air velocity through a window ventilator with the location "above the window" in the frontal plane

Notes: a – along the axis of the window ventilator; b – along the wall

Source: developed by the authors

The simulation results show that at a cold supply air flow rate of 5 m^3/h, the cold air slowly rises and gradually mixes with the warm room air. The air velocity remains low, and the cold zone near the floor is maintained over a large area. Cold air settles in the lower layers of the room, creating temperature gradients. The temperature patterns show that a large proportion of the air remains cold near the floor and heating is slow due to limited mixing with the warm room air.

As the flow rate increases, the cold air starts to spread upwards more quickly. This results in a more even distribution of cold air, but there is still some zonal cooling near the floor, which affects the temperature comfort in the room. At a flow rate of 20 m^3/h, the cold air actively rises upwards, providing better mixing with the warm air (Fig. 5). The modelling results show that the air reaches the upper layers of the room, ensuring uniform air exchange. The air flow rate avoids the formation of cold stagnation zones near the floor. The results of the simulation of temperature changes in the room demonstrate a more even temperature distribution throughout the room (Fig. 6). Cold zones become less pronounced, and temperature gradients are reduced.

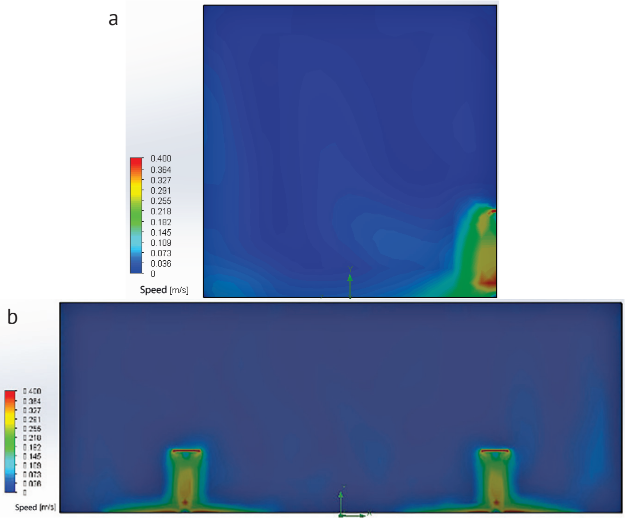

Figure 5. Simulation of the inflow velocity through the window ventilator with the location "under the window" in the frontal plane

Notes: a – along the axis of the window ventilator; b – along the wall

Source: developed by the authors

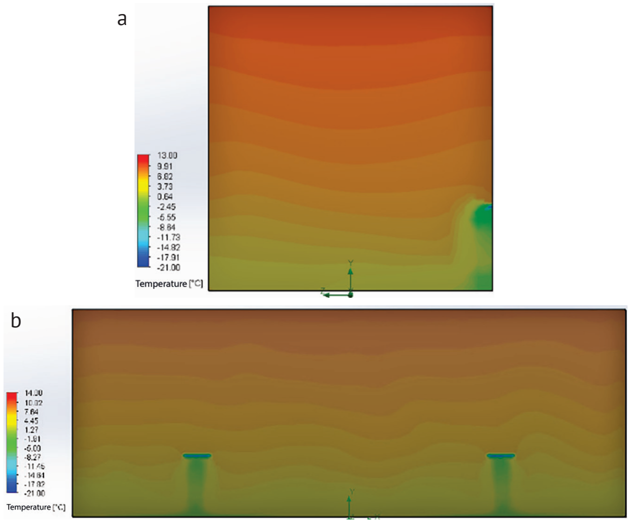

Figure 6. Simulation of the supply air velocity through a window ventilator with the location "under the window" in the frontal plane

Notes: a – along the axis of the window ventilator; b – along the wall

Source: developed by the authors

As the cold supply air flow rate increases, the likelihood of localised cooling zones is reduced due to more efficient mixing of the cold supply air and warm indoor air. However, the increased air flow rate associated with the increase in air velocity may cause some discomfort to the occupants.

Discussion

Due to the high level of airtightness and thermal insulation, thermally modernised buildings significantly reduce heat loss. M.S. Ünlütürk & T.G. Özbalta (2024) note that such measures contribute to a significant increase in energy efficiency, but at the same time create new challenges in ensuring adequate ventilation. In turn, M. Bhandari *et al.* (2018) and C. Banister *et al.* (2022) point out that the increased airtightness of structures significantly limits natural air exchange, which affects the quality of the indoor environment. Z.-Y. Chen *et al.* (2024) analyse the impact of external sources of pollution on indoor air, pointing out the particular importance of ventilation systems in such conditions. M. Mannan & S.G. Al-Ghamdi (2021) and S. Fujiyoshi *et al.* (2022) add that a significant source of air pollution is internal factors such as furniture, finishing materials, and occupants' household activities. Mechanical ventilation systems are commonly used to address this problem. As noted by V. Savin & V. Zhelykh (2023b) note that such systems allow controlling air exchange and microclimate parameters, however, according to Y. Tang *et al.* (2022), they are characterised by high energy consumption. This contradicts the main goal of thermo-modernisation, which is to reduce energy consumption by the building.

The authors of M. Carlsson *et al.* (2019) conducted a study of different methods of sealing the building envelope using heat recovery ventilation in multi-room buildings. Based on the results of the study, they concluded that proper modernisation reduces the overall energy demand for heating by 78% and greenhouse gas emissions by 83%. The work of N. Bianco *et al.* (2023) focused on analysing the impact of building insulation on ventilation systems with heat recovery technologies. The authors of the study emphasise that building insulation significantly reduces heat loss due to the low thermal conductivity of the building envelope, limiting natural air exchange, which in turn negatively affects indoor air quality and requires the introduction of additional ventilation solutions. The use of heat recovery systems can reduce energy consumption for heating and cooling and ensure efficient ventilation. The results of the study show that regenerative and recuperative systems technologies effectively maintain microclimate parameters, but are dependent on additional electricity use.

The authors H.Y. Bai *et al.* (2022) point out the possibility of increasing the efficiency of traditional air handling units by modernising them or integrating them with other ventilation systems. The paper emphasises that the combination of air handling units with mechanical components or the use of adaptive solutions helps to eliminate air stagnation zones and improve the uniformity of air exchange even in difficult climatic conditions. Unlike traditional mechanical ventilation systems described in H.Y. Bai *et al.* (2022), the proposed solution is aimed at reducing energy consumption and ensuring high indoor air quality. This approach emphasises the potential of passive ventilation as an effective alternative to mechanical systems.

The results of the study demonstrated the high efficiency of the wind catcher in creating a standard air exchange in thermally modernised buildings, while ensuring an even distribution of the supply air throughout the entire volume of the room, which meets modern requirements for energy efficiency and a comfortable microclimate. Similar conclusions were reached by the authors of T. Ahmed *et al.* (2021) and P.K. Sangdeh & N. Nasrollahi (2022), who note that due to their design features, wind catchers are able to provide efficient air circulation regardless of external climatic conditions. The results of modelling the operation of window ventilators show that their use is not able to ensure proper air exchange, in particular in the cold season, when there are significant temperature gradients and the formation of cold air stagnation zones, which negatively affects the indoor climate.

It is also important to compare the results obtained with the studies of M. Alwetaishi & M. Gadi (2021) and A.H. Chohan & J. Awad (2022), which analysed wind catchers of various designs and the possibility of their integration into modern architectural solutions. The modelling results showed that wind turbines can become a key component of the natural ventilation system, functioning effectively in different climatic conditions without the need for additional energy consumption.

The authors of the study by Z. Liu *et al.* (2019) emphasise the need to introduce modern approaches to fresh air treatment to improve the energy efficiency of buildings. The use of innovative technologies helps to reduce energy consumption and carbon emissions, which is important in the context of global sustainable development goals. The results emphasise the feasibility of using energy-saving solutions in the ventilation systems of thermally modernised buildings, especially in cases where it is necessary to ensure high air quality with minimal energy consumption. In general, the results obtained indicate that the wind catcher is an effective solution for ensuring regulatory air exchange in thermally modernised buildings, which is confirmed by the data of many scientists mentioned in the article.

Conclusions

The analysis of the modelling results showed that the use of ventilators in the warm season, regardless of their location ("above the window" or "under the window"), can partially distribute the air in the room, but even with the maximum performance of the ventilators, the standard air exchange is not ensured. During the cold season, there are significant temperature gradients in the vicinity of the air handlers, especially when supplying through the lower air handler. This creates cold zones in the lower layers of the room, which leads to a decrease in thermal comfort in the room and an increase in energy consumption required for additional heating of the room.

Due to its design features, the wind catcher ensures standard air exchange in the room regardless of the temperature difference between the internal and external environment, promotes efficient circulation of the supply air and prevents the formation of stagnant zones, which is confirmed by the modelling results. Thus, the results of the study prove the high efficiency of the wind catcher as a passive ventilation element capable of providing standard air exchange in the room regardless of the season, which makes it a universal passive ventilation solution for use in different climatic conditions.

The modelling of the impact of natural ventilation on the air exchange of a thermally modernised building was carried out on the example of a single room, which limited the study, since the specifics of air exchange in multi-room premises were not taken into account. The study also adopted modelling conditions without taking into account possible changes in external factors (wind speed, etc.). Further research should be aimed at analysing the behaviour of air handling units in multi-room buildings, determining the optimal design parameters of wind catchers for different types of buildings and expanding research to take into account climatic features. This will provide more accurate recommendations for the effective use of passive ventilation to improve the energy efficiency of buildings.

Acknowledgements

None.

Conflict of Interest

None.

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Оптимізація повітрообміну в термомодернізованих будівлях за допомогою природної вентиляції

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Анотація. Метою дослідження було порівняння ефективності роботи припливних пристроїв пасивних систем вентиляції (вітровловлювача оригінальної конструкції та віконного провітрювача з варіантами розташування «над вікном» і «під вікном»). В результаті надано оцінку характеру повітророзподілу та особливостей циркуляції повітряних потоків в приміщенні при різних варіантах подачі припливного повітря. Для збору та систематизації інформації про пасивну вентиляцію, її ефективність застосування у термомодернізованих будинках та оцінки можливості забезпечення нормативного повітрообміну в приміщеннях було використано методи узагальнення результатів попередніх досліджень, а також комплексний та логіко-структурний аналіз. Для обробки та оцінки отриманих даних було застосовано науково-аналітичний аналіз. Комп'ютерне моделювання дозволило порівняти результати та оцінити розподіл повітряних потоків, температурні градієнти та ефективність повітрообміну в приміщенні. Проведено комплексний аналіз ефективності пасивної вентиляції в термомодернізованому будинку із використанням різних типів припливних пристроїв. Досліджено їхній вплив на повітрообмін у приміщенні за різних кліматичних умов (теплий та холодний періоди року) з урахуванням розподілу температури та швидкості повітряного потоку. Визначені оптимальні рішення для пасивної вентиляції, які дозволяють знизити енерговитрати при створенні нормативного повітрообміну в термомодернізованих будинках, що є ключовим аспектом для забезпечення енергоефективності та комфортних умов проживання. В результаті моделювання отримано дані про розподіл температури та швидкості повітряного потоку в приміщенні для віконного провітрювача та вітровловлювача. Проведено аналіз отриманих даних у фронтальній та горизонтальній площинах, що дозволило оцінити особливості розповсюдження повітря в об'ємі приміщення. Особлива увага приділена аналізу зони безпосередньо біля припливного пристрою, що дозволило детально вивчити поведінку повітряного потоку на початкових етапах його розподілу в приміщенні та оцінити зміни температури й швидкості потоку залежно від витрати повітря і відстані від припливного пристрою. Отримані результати дозволяють детально оцінити повітрообмін у приміщенні, враховуючи вплив конструктивних особливостей припливних пристроїв на ефективність розподілу та циркуляції повітря

Ключові слова: пасивна вентиляція; вітровловлювач; мікроклімат; енергоефективність

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Solar panels' energy efficiency optimisation using mathematical methods with computerisation of calculations

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Abstract. Solar energy development in Ukraine is reaching peak values and will increase in the coming decades. For this reason, it is important to use various methods of optimising panel's operation to increase their energy efficiency. Given the fact that the angle of the sun's rays incidence has the greatest influence on the efficiency of photovoltaic cells on the working surface, it is important to find the stationary (non-rotating) system's optimal angle of inclination and forecast the generated power. The purpose of the work was to determine the dependency between the power generated by the photovoltaic element and the angle of the sun's rays incidence and to develop a universal document that would allow automatic calculation of the optimal solar panels' inclination angle relative to the horizon and the maximum daily generated power. Calculations were performed analytically using functions and digital tools of mathematical software, elements of the mathematical theory of optimisation. As a result of the study, a digital file was created that automatically calculates the optimal solar panel inclination angle and the maximum generated power depending on the change in this angle. An algorithm was developed that allows to automate calculations based on the mathematical theory of optimisation and the means of specialised mathematical software. The research work carried out will allow to increase the solar modules efficiency in the simplest way without material costs for additional equipment and time costs for mathematical calculations of the technical parameters of the system. Implementation of research results in practice will increase the profitability of solar panels

Keywords: solar energy; automation of calculations; profitability; ecology; search for the optimum; solar panel inclination angle

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Introduction

The development of alternative energy becomes a priority for Ukraine and many countries around the world. The percentage of energy sources that will be produced from alternative types will grow from 1 (as of 2015) to 13% (forecast for 2035) (Pavlov *et al.*, 2022) This is due to the constant reduction and increase in the price of reserves of natural resources (oil, coal, gas, etc.), the significant negative impact on the environment of traditional energy processes, emissions of carbon dioxide, nitrogen oxides and sulphur into the atmosphere, pollution by dust and radioactive particles. In Ukraine, as noted by Yu. Kolontaievsky *et al.* (2019), the technically achievable annual solar energy potential allows for saving about 5 billion m^3 of natural gas.

The operational principle of the solar cell is based on the photo effect phenomenon – the knocking out of free electrons from the material atoms by the sunlight photons flow. The efficiency of the solar module photovoltaic cells is affected by several main factors. In the work of A. Khotian *et al.* (2019) considered the influence of the angle of incidence of the light flux on the photovoltaic cell efficiency. Research by D. Zibalov (2022) identifies photocell quality as one of the important factors. The work of D. Ostrenko & O. Kollarov (2020) considered such aspects as the influence of temperature, contamination of the module and atmosphere (dust, smoke), uniformity and intensity of lighting, which depend on weather conditions.

The search for ways to improve the efficiency of solar modules is carried out in many directions. In the work of H.S. Majdi *et al.* (2021), the authors suggested using systems of active cooling of the solar panels surface. The efficiency of energy generation decreases by 10% or more due to the heating of the working surface. Studies have shown that active heat dissipation systems can increase the life of a photovoltaic panel from 30 to 50 years. Active air cooling increases the efficiency coefficient by 11.2%, passive – by 1.41%, and water – by 5.36%.

The analysed studies showed that the angle of sunlight falling on the working surface has the greatest influence on the photovoltaic cells efficiency, but using the special rotary devices that maintain the optimal angle of 90° is limited by their high cost. Therefore, the goal of this work was to find the optimal angle of inclination of a stationary (non-rotating) system and predict the generated power.

Materials and Methods

The highest efficiency of the solar installation is achieved when the sun's rays fall normal to the receiving surface. But constant maintenance of an optimal angle of 90° is impossible due to physical processes (rotation of the Earth around its own axis, change of seasons). A schematic representation of the change in the optimal angle of panel inclination relative to the horizon during the year is shown in Figure 1.

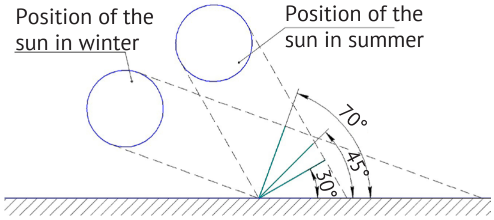

Figure 1. Schematic representation of the change in the optimal angle of inclination of the solar panel depending on the year season

Source: developed by the authors

The design of the installation (Fig. 2) was developed for calculating the optimal tilt angle of the panel during the year, which consists of two solar modules, oriented to the East and the West respectively.

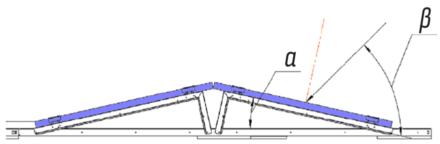

Figure 2. Design of the solar module system

Source: developed by the authors

To simplify calculations, the total generation per day of only half of the system was found. The dependence on the latitude of the area, the day of the year, the hour and length of the day, the level of insolation, the coefficient of light reflection, and the scattering of solar radiation were not taken into account. The reference power of the solar flux was taken as the average annual value on the territory of Ukraine W_i = 1,200 W/m^2. The dependence of the power of the sun's rays on the angle of incidence β is:

$$W(\beta) = W_i sin\beta. \quad (1)$$

In the projected model, the solar flux is a vector. One of the components of this vector was singled out for calculating and taking into account the power generated by the panel:

$$W_y(\alpha, \beta) = W_i sin(\alpha + \beta), \quad (2)$$

where α – the angle of inclination of the panel relative to the horizon, which must be found.

The function of the energy generation power is obtained. To obtain the objective function of daily energy generation, depending on the angle of inclination of the panel to the horizon, the integral of this function was found in the range from 0 to 90°:

$$\int_0^{90} W_y(\alpha, \beta) d\beta = W_y(\alpha). \quad (3)$$

The maximum value of the function, which corresponds to the optimal value of the angle of inclination, was found by finding the critical points of this function. MathCAD software for mathematical calculations was used to computerise the calculations.

Results and Discussion

The need for electrical energy rapidly increases due to the rapid development of technologies, energy-intensive industries, and urbanisation processes. The economic aspect plays an important role – the cost of renewable energy sources is significantly lower than the cost of fossil fuels, while the cost of such energy is higher. Focusing on alternative energy is the key to the energy independence of all countries. In Ukraine, the development of renewable energy is one of the five priorities of post-war recovery and further building up of the country's energy capacity, because the energy sector of Ukraine has suffered from huge losses. In 2024, targeted and large-scale attacks on facilities that ensure the production, transmission, and distribution of electricity continue. In the conditions of attacks on the country's energy infrastructure, the consequences of which are partial or complete planned and emergency power outages, the transition to alternative decentralised energy sources is the only means to meet the energy needs of the population.

It is necessary to choose the most effective natural energy resources available in this region for the productive development of renewable energy. The most promising is solar energy in connection with the favourable geographical location of Ukraine and the degree of availability of one or another type of alternative energy for an individual consumer. The process of converting solar energy into electrical energy is environmentally safe and is especially relevant in wartime conditions, as it is the only way to obtain electrical energy in some regions.

The length of daylight hours in Ukraine allows the efficient use of solar modules for 7-9 months a year, as reported by the State Agency for Energy Efficiency and Energy Saving of Ukraine (Energy of the sun, n.d.). The annual flow of sunlight per 1 m^2 of horizontal surface in the southern regions of Ukraine is 1,250-1,350 kW/m^2, and its duration is approximately 2,000 hours. As of 2024, there are no devices capable of working directly on pure solar energy, so science has invented methods of converting solar energy into electrical energy. The most common devices for transforming solar energy into electrical energy are solar panels. One of the advantages of such energy sources is the possibility of continued operation after the disconnection of destroyed modules due to air attacks.

Installing solar panels is a promising capital investment, particularly, in the engineering industry. In the process of work, plants and factories consume a significant amount of energy, which increases the cost of finished products and, as a result, expensive electricity reduces the profitability and competitiveness of manufacturing and repair factories. The large territory of manufacturing enterprises allows for the installation of a significant number of solar panels, and relatively small initial capital investments have an economically beneficial payback period at the scale of the enterprise. The generated clean energy can be used for production purposes or as an additional source of income. The problem lies in the relatively low efficiency of devices (18-25%), which requires finding ways to increase it. For this, it is important to conduct scientific research in the field of solar energy with practical testing of the proposed hypotheses and created structures.

The stages of calculating the optimal inclination angle by the method of differential calculation of the function of two variables implemented in the MathCAD software are given below in MathCAD terms and symbols. Let the initial value of the maximum power be W_i = 1,200. Function (3) of two variables is integrated from 0 to 90°:

$$f(\alpha) = \int_0^{90} W_y(\alpha, \beta) d\beta \rightarrow 1{,}200 \cdot cos(\alpha) - 1{,}200 \cdot cos(\alpha + 90). \quad (4)$$

The first derivative of the objective function is found:

$$f(\alpha) := \frac{d}{d\alpha} f(\alpha) \rightarrow 1{,}200 \cdot sin(\alpha + 90) - 1{,}200 \cdot sin(\alpha). \quad (5)$$

Figure 3 shows finding the critical points of the objective function.

Given
$f_1(\alpha) = 0$
$\alpha > 0$
M: = Find(α) → 0.55309

Figure 3. Finding the critical points of the objective function in the MathCAD software
Source: developed by the authors

Optimal tilt angle of the panel is:

$$deg(\alpha) := \frac{M \cdot 180}{\pi} \longrightarrow 31.69. \quad (6)$$

The second derivative of the objective function is found:

$$f_2(\alpha) := \frac{d}{d\alpha} f_1(\alpha) \rightarrow 1{,}200 \cdot cos(\alpha + 90) - 1{,}200 \cdot cos(\alpha);$$
$$f_2(M) = -2{,}042.2. \quad (7)$$

The value of the objective function at the maximum was calculated. The maximum generated power in W/m^2 is $f(M)$ = 2,042.2. Thus, the optimal angle of inclination of the solar panel in the proposed model is α = 31.69°. This value of the angle will allow to reach the maximum value of the generated power of 2,042.2 W/m^2.

A significant number of various methods of increasing the energy efficiency of solar systems have been proposed by other scientists. For example, systems for cleaning panel surfaces have been developed (Sinchuk *et al.*, 2020). Studies have shown an increase in generated power from 2,000 to 2,300 kW (15%) using a magnetic cleaning system. In the article Ye. Korniienko *et al.* (2023) the authors proposed a method of controlling the power generation system using wireless technologies. If the generated electricity covers the needs of consuming objects, then its surplus is directed to charging batteries. When they are fully charged, the energy is sent to the network at the "green" tariff. If the amount of generated energy is insufficient for the needs of the consumer, the batteries are switched on. If they are discharged, power comes from the mains, additionally charging the batteries. When there is no voltage in the network, a diesel or gasoline generator is switched on.

One of the most successful ways to increase the energy efficiency of solar panels is the use of trackers, which are mechanisms capable of automatically changing the angle of inclination of the working surface. The greatest efficiency is achieved when the sun's rays fall normal to the panel. The moving part of the tracker can change its position, track the position of the Sun, and orient the panel as needed. The tracking system designed in the work Ye. Korniienko *et al*. (2023) demonstrates an increase in the energy efficiency of solar panels by 25%. Basically, their high cost limits the wide use of trackers.

The authors I. Vashchyshak & V. Tsykh (2020) conducted comparative studies of the solar panels' energy efficiency with systems of directing mirrors, Fresnel lenses to create additional optical flow on the surface of solar panels. Measurements of electric power showed that additional mirrors can increase the initial energy by 35-60%. But at the same time, the temperature on the working surface increases significantly. In addition, the use of the mirror system requires additional areas for their placement, which is not always possible and expedient. The work M. Myroshnichenko & K. Klen (2022) considers increasing the accuracy of forecasting the amount of produced energy due to the use of mathematical predictive models.

Therefore, most of the feasible ways and methods of improving energy efficiency are expensive, which increases the cost of generated electricity. This work presents a successful and inexpensive method of installing solar systems at an optimal angle of 31.69° to the horizon, which does not require additional costs and maintenance, but provides maximum generation in a stationary state compared to other methods of stationary installation. However, the panel turned to the East will generate more in the morning and afternoon, and will generate significantly less in the evening and will actually be idle. The panel turned to the West will work vice versa.

Conclusions

The article analyses and briefly describes various approaches to increasing the energy efficiency of solar systems. All approaches have a rational point and a good proposition to increase the generated power, but also have significant disadvantages. For example, there is a high cost of manufacturing, installation and maintenance, low reliability in operation, the need for power supply, etc. It has been proven that the installation of solar systems according to the proposed scheme at an angle of 31.69° to the horizon can achieve the maximum energy generation capacity compared to installation at any other angle without motion. The advantages are small costs for a special design of the support, no need for maintenance, and energy independence of the method. The disadvantage is the fact that the two panels in the system work during the day alternately, which leads to a partial idle time of the solar panel.

In further studies, it is planned to supplement the calculations with additional variables, such as the latitude of the area, the day of the year, the hour and length of the day, the level of insolation, the coefficient of light reflection, and the scattering of solar rays. The goal is to find new solutions for increasing the energy efficiency of stationary installed solar systems.

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Conflict of Interest

None.

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Оптимізація енергоефективності сонячних панелей математичними методами з комп'ютеризацією розрахунків

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Анотація. Розвиток сонячної енергетики в Україні сягає пікових значень і буде у наступні десятиліття тільки посилюватися, тому для підвищення енергоефективності роботи панелей важливо застосовувати різноманітні способи і методи оптимізації їх роботи. З огляду на те, що найбільший вплив на ефективність фотоелементів чинить кут падіння сонячного проміння на робочу поверхню, актуальним є питання знаходження оптимального кута нахилу стаціонарної (неповоротної) системи та прогнозування згенерованої потужності. Мета роботи полягала у визначенні зв'язку потужності, згенерованої фотоелектричним елементом, від кута падіння сонячних променів та розробці універсального документу, який дозволить автоматично розраховувати оптимальний кут нахилу сонячних панелей відносно горизонту та максимальну добову генеровану потужність. Виконано обчислення аналітичним методом зі застосуванням функцій та цифрових інструментів математичного програмного забезпечення. Крім того, використано елементи математичної теорії оптимізації. У результаті дослідження було створено документ, який автоматично обчислює оптимальний кут нахилу сонячної панелі та максимальну генеровану потужність у залежності від зміни цього кута. Розроблено алгоритм, який дозволяє максимально автоматизувати процес розрахунків і побудови графіків функцій за рахунок використання елементів математичної теорії оптимізації та засобів спеціалізованого математичного програмного забезпечення. Проведена дослідницька робота дозволить підвищити коефіцієнт корисної дії сонячних модулів у найбільш простий у реалізації спосіб без матеріальних затрат на додаткове обладнання і часових затрат на проведення математичних обчислень технічних параметрів системи, а впровадження результатів дослідження на практиці дозволить збільшити прибутковість сонячних панелей

Ключові слова: сонячна енергетика; автоматизація розрахунків; прибутковість; екологія; пошук оптимуму; кут нахилу панелі

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Analysis of the relationship of forces acting on the material in the centrifugal air separator

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Abstract. The relevance of the study derives from the need to increase efficiency of dry beneficiation of minerals, in particular through improving methods of separation of finely dispersed materials. The research aimed to analyse the regularities of the relationship of forces acting on a material particle in the vortex airflow in the centrifugal separator. The paper uses the analytical research method and generalisation of existing studies dealing with determining the balance of forces acting on a material particle in a vortex airflow. The main results of the research consist in determining the dependencies between the most influential forces acting on a particle of a mineral with a relatively high density in a centrifugal air separator. The balance of the airflow resistance, gravity and centrifugal forces was established, which is a key aspect for improving designs and optimising operating modes of centrifugal separators. The dependencies determining positions of resultants of the main forces were established and allowed determining parameters of the rational operating mode of air separators and substantiating recommendations for improving efficiency of their operation. The obtained equations of the resultants are universal and do not depend on the specific design of the air separator, which allows them to be used to analyse and optimise operation of various models of centrifugal air separators as well as other classes of separators considering relevant adjustments. The practical value of the work consists in obtaining equations that determine positions of the resultants of the three main forces acting on a particle in the vortex airflow. This, in turn, enables determining parameters of the required mode of operation

Keywords: mineral beneficiation; centrifugal force; gravity force; airflow resistance force; balance of forces

Introduction

The problem of efficient sorting of fine-grade materials is becoming increasingly relevant in modern environment, when mineral beneficiation technologies require high process precision and optimality. Improvement of material separation methods is of crucial significance for increasing productivity and economic efficiency of mining and beneficiation enterprises. Employment of centrifugal air separators is of particular importance as they provide high efficiency of dry separation of finely dispersed materials, replacing inefficient screening.

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This equipment is becoming indispensable in conditions of increased application of dry mineral processing technologies instead of wet processing to reduce energy costs.

Sorting by centrifugal separators is an important operation, especially for materials with a high content of less than 0.1-0.5 mm fractions. However, efficiency of this equipment depends on understanding and considering the complex of forces acting on the material particles, in particular the centrifugal force, the airflow resistance force and weight. Improvement of these technologies requires detailed mathematical modelling to optimise separation processes. In current studies of centrifugal separators, much attention is paid to the analysis of forces that act on material particles. In particular, most researchers (Adamchuk *et al.*, 2021; Esmaeilpoura *et al.*, 2024) distinguish three main forces: particle weight, the airflow resistance force, and the centrifugal force. M. Madaliev (2020) presents differential equations that describe the motion of particles in vortex flows. The author notes that the centrifugal force and the airflow resistance force are the main forces that determine the trajectory of particles. S. Stepanenko (2019) provides formulas for determining these forces, but their application is complicated due to the need to determine additional coefficients. The above authors point out that mathematical modelling of such processes is critical for optimising operation of separators. S. Stepanenko & B. Kotov (2020) further highlight the lifting force generated by the Magnus-Zhukovsky effect, which acts in the direction opposite to the force of gravity. Thus, a comprehensive approach to modelling and consideration of all forces acting on particles is necessary to improve efficiency of the process.

The present work aimed to build mathematical models to determine prevailing forces influencing efficiency of material separation and to substantiate recommendations for improving process performance.

Materials and Methods

Specific features of the research object condition application of the analytical method when the research focuses not on a specific design, but only on the model of the separation process and its parameters. When considering movement of a single material particle in the vortex airflow, the following assumptions are made: the particle is a solid undeformed ball-shaped body, its density is $\rho_p = 3{,}500$ kg/m^3 (that corresponds to the density of iron-containing concentrates), the radius of the circle of the particle movement is accepted $r = 0.5$ m, the airflow has a uniform velocity field.

The following factors act on a single particle in the spiral flow vortex (Fig. 1):

- the particle weight (the vector is in the downward direction):

$$G = g \cdot m_p, \tag{1}$$

where m_p – the particle mass, kg; g – the free fall acceleration, m/s^2.

- the airflow resistance force, N (the vector is directed collinearly with the air velocity vector):

$$P_a = c_r \cdot k_s \cdot \rho_a \cdot \upsilon_\tau^2 \cdot \pi \cdot \frac{d_p^2}{8}, \tag{2}$$

where c_r – the coefficient of the airflow resistance of the particle; k_s – the coefficient that depends on the particle shape ($k_s = 1$ – for ball-shaped; $k_s = 1.1$ – for oval; $k_s = 1.5$ – for pyramidal; $k_s = 1.76$ – for longitudinal; $k_s = 3.8$ – for acicular ones); d_p – the equivalent diameter of the particle, m; ρ_a – air density, kg/m^3; υ_τ – the tangential air velocity component.

- the centrifugal force, N (the vector is in the radial direction from the centre):

$$P_c = \frac{\pi \cdot \rho_p \cdot \upsilon_\tau^2 \cdot d_p^3}{6 \cdot r}, \tag{3}$$

where ρ_p – the density of the particle material, kg/m^3; r – the radius of the particle location, m.

- the medium resistance force during the radial movement of the particle from the vortex centre, N:

$$P_r = \frac{C \cdot F_p \cdot \rho_p \cdot \upsilon_p^2}{2 \cdot g}, \tag{4}$$

where C – the factor depending on Reynolds number ($C = 0.48$ for $Re = 1000...200000$) of the airflow resistance of the particle; F_p – the particle cross-section area, m^2; υ_p – the speed of the particle's radial movement from the vortex centre.

υ_p is determined as:

$$\upsilon_p = \frac{d_p^2 \cdot \rho_p \cdot \upsilon_r^2}{18 \cdot \nu \cdot \rho_a \cdot r}, \tag{5}$$

where υ_r – the radial component of the air velocity, m/s; ν – the kinematic viscosity of air ($\nu = 1.5 \cdot 10 - 5$), m^2/s.

- the kinematic lifting force, N (the vector is in the opposite direction to gravity):

$$P_{kl} = \frac{m_p \cdot g \cdot \rho_a}{\rho_p}. \tag{6}$$

- the friction force of particles on the curvilinear surface of the separator housing, N (the vector is in the opposite direction to the airflow resistance force vector):

$$P_{fr} = k \cdot P_c, \tag{7}$$

where k – the coefficient of friction of the particle on the separator housing wall.

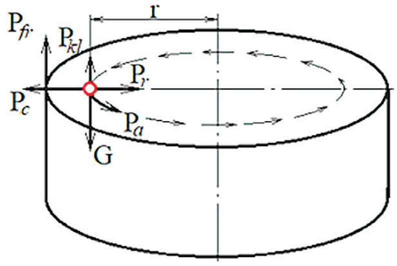

Figure 1. Forces acting on a material particle in the vortex airflow

Source: developed by the authors

Results and Discussion

The values of the forces acting on the particle under the same conditions are compared using the dependencies presented in the above methodology (Fig. 2).

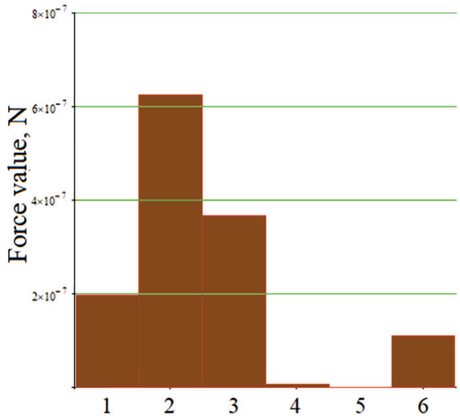

Figure 2. Comparison of the forces acting on the particle in the centrifugal separator under the same conditions

Notes: 1 – the particle weight G; 2 – the airflow resistance force P_a; 3 – the centrifugal force P_c; 4 – the medium resistance force during the radial movement of the particle from the vortex centre P_r; 5 – the hydrodynamic force P_{kl}; 6 – the friction force P_{fr}

Source: developed by the authors

Figure 2 demonstrates that the hydrodynamic force and the medium resistance force during the radial movement of the particle from the vortex centre are the smallest in comparison with the others. It should be noted that the relationship of the most influential forces of gravity, airflow resistance and the centrifugal force can vary significantly because they depend on the size and mass of the particles, the radius of their location inside the separator and the air velocity.

In the further force analysis, the hydrodynamic force and the medium resistance force during the radial movement of the particle from the vortex centre are not considered due to their relatively small values. In addition, the force of particle friction on the curvilinear surface of the separator housing is not considered either because the present work deals with movement of the particles in the airflow before their contact with the walls of the separator housing.

Analysing the three most influential forces acting on a particle in a centrifugal separator, it should be noted that their values depend on the size, weight (density) of the particle, the air velocity and the current radius of the particle's location inside the centrifugal separator. Therefore, this dependency cannot be plotted in its entirety because it is a hypersurface. The relationship of the three most influential forces acting on a particle is shown in Figure 3.

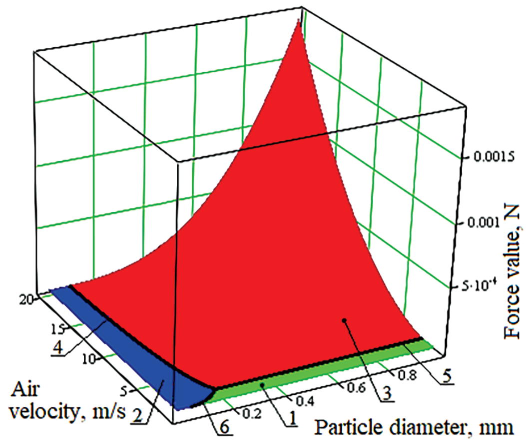

Figure 3. Relationship of the forces acting on a particle depending on its diameter and speed at the location radius of 0.5 m

Notes: 1 – the particle weight G; 2 – the airflow resistance force P_a; 3 – the centrifugal force P_c; 4 – the resultant of the airflow resistance P_a and centrifugal P_c forces; 5 – the resultant of the centrifugal force P_c and the particle weight G; 6 – the resultant of the airflow resistance force P_a and the particle weight G

Source: developed by the authors

Figure 3 shows that as the size and, accordingly, the weight of the particle and the air velocity increase, the centrifugal force becomes dominant. At low air velocities, the force of gravity is dominant. Finally, at small particle sizes and, accordingly, their weight, it is the airflow resistance force that dominates.

Special attention should be paid to the position of the resultants. The position of the resultant of the air resistance force and the centrifugal force determines the boundary of the material separation by size in centrifugal separators. Positions of the resultant of the airflow resistance force and the particle weight determine the boundary of the material separation by size in gravity separators. Based on (1) and (3), the equation of the projection of the resultant of the centrifugal force and the particle weight (Fig. 4) looks like:

$$\upsilon_\tau{}^{GPc}(d_p) = 3.13 \cdot \sqrt{r}. \quad (8)$$

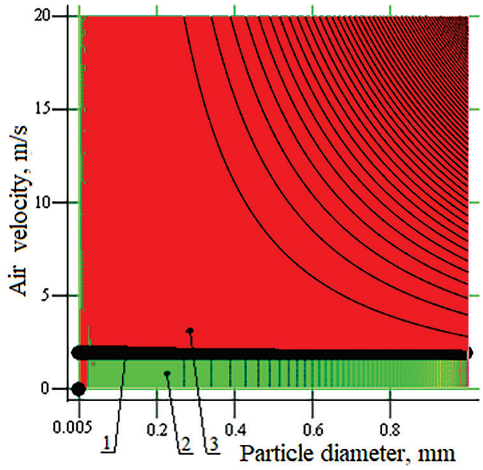

Figure 4. Projection of the resultant of the centrifugal force and the particle weight

Notes: 1 – the resultant; 2 – the particle weight *G*; 3 – the centrifugal force P_c

Source: developed by the authors

Then the condition of the centrifugal force exceeding the weight of the material particle looks like:

$$P_c > G, \text{ if } \upsilon_\tau > 3.13 \cdot \sqrt{r}. \quad (9)$$

It should be noted that the position of the resultant does not depend on the air velocity and is determined only by the radius of the particle location. Based on (1) and (2), the equation of the projection of the resultant of the airflow resistance force and the particle weight (Fig. 5) looks like:

$$\upsilon_\tau{}^{GPa}(d_p) = 1.003 \cdot d_p \cdot \sqrt[3]{\frac{\rho_p^2}{\nu \cdot k_s^2 \cdot \rho_a^2}}. \quad (10)$$

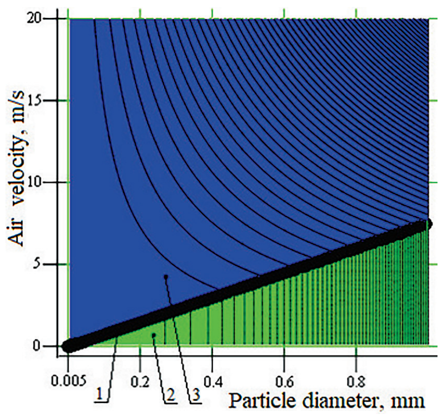

Figure 5. Projection of the resultant of the airflow resistance force and the particle weight

Notes: 1 – the resultant; 2 – the particle weight *G*; 3 – the airflow resistance force P_a

Source: developed by the authors

Then the condition of the airflow resistance force exceeding the material particle weight looks like:

$$P_a > G, \text{ if } \upsilon_\tau > 1.003 \cdot d_p \cdot \sqrt[3]{\frac{\rho_p^2}{\nu \cdot k_s^2 \cdot \rho_a^2}}. \quad (11)$$

The position of the resultant of the airflow resistance force and the particle weight is determined by the linear dependency and additionally depends on the density of material particles. Based on (2) and (3), the equation of the projection of the resultant of the airflow resistance force and the centrifugal force (Fig. 6) looks like:

$$\upsilon_\tau{}^{P_cP_a}(d_p) = \frac{95.0625 \cdot r^2 \cdot \nu \cdot k_s^2 \cdot \rho_a^2}{d_p^3 \cdot \rho_p^2}. \quad (12)$$

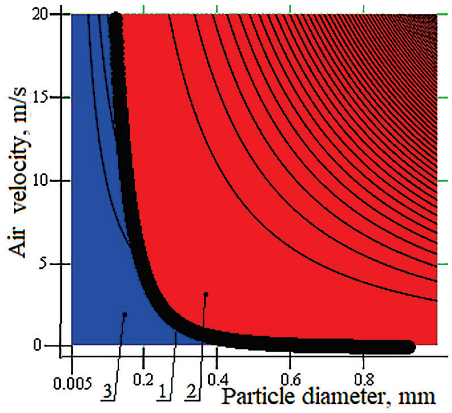

Figure 6. Projection of the resultant of the airflow resistance force and the centrifugal force

Notes: 1 – the resultant; 2 – the centrifugal force P_c; 3 – the airflow resistance P_a

Source: developed by the authors

Then the condition of the centrifugal force exceeding the airflow resistance force looks like:

$$P_c > P_a, \text{ if } \upsilon_\tau > \frac{95.0625 \cdot r^2 \cdot \nu \cdot k_s^2 \cdot \rho_a^2}{d_p^3 \cdot \rho_p^2}. \quad (13)$$

The performed analysis of the relationship of the acting forces confirms the conclusion made by K.W. Chu *et al.* (2011) that the centrifugal, gravity and airflow resistance forces are the predominant ones acting on a particle. The obtained conditions of positioning the resultant of the main forces acting on material particles in centrifugal separators enable quick determination of the required air velocity depending on the size of the separator and parameters of the processed material. The fact that the obtained equations do not depend on the specific design of the separator allows using them for analysing the entire class of centrifugal air separators, and, with some adjustments, other classes of air separators.

N.X. Ho *et al.* (2024) consider the influence of the additional medium resistance force which acts on the particle during its movement in the curvilinear flow.

This aspect differs from previous studies, in which this force was not taken into account. Interestingly, at low particle density and relatively large sizes, which are characteristic of agricultural but not mineral materials, the kinematic lifting force becomes more influential, as shown in the work by B. Kotov *et al*. (2019). Y. Zeng *et al*. (2020) and R. Shen *et al*. (2022) additionally mention the force of particle friction on the separator wall, which appears when the material comes into contact with the equipment housing. The work by N. Morkun *et al*. (2022), that dealt with the modelling and control of magnetic separator parameters, should also be considered in this connection.

Moreover, the airflow resistance force value depends more on the air velocity and particle size, and the centrifugal force value depends on the particle weight and location. Thus, closer to the axis of the separator, the centrifugal force prevails for heavy particles and pushes them outward to the housing wall; the airflow resistance force predominates for smaller particles with low mass and pick them up and carries them out for discharge. At that, as can be seen from the above graphs, to provide normal operation of centrifugal air separators with particles of large mass and size, the airflow velocity should be relatively high. This again confirms that centrifugal air separators operate more efficiently with small-sized particles of up to 0.1…0.5 mm.

Conclusions

The analysis performed has resulted in identifying regularities of the relationship of forces acting on particles of dense materials, such as mineral raw materials, and determining their trajectories and behaviour in the vortex airflow of the centrifugal separator. It has been established that the most influential forces are gravity, airflow resistance and centrifugal ones. The balance between them is determined by the particle size and mass (density), the air velocity and the current radius of the particle location in the separator. Thus, for heavy particles located closer to the separator axis, the centrifugal force prevails and pushes them outward to the housing wall; for smaller particles with low mass, the airflow resistance force predominates and picks them up and carries out for discharge. So, to provide normal operation of centrifugal air separators with particles of large mass and size, the airflow velocity should be relatively high.

The dependencies have been established that identify positions of the resultants of the main forces and allow determining parameters of the rational mode of operation of air separators and substantiating the recommendations for improving their efficiency. The obtained equations of the resultants are universal and do not depend on the specific design of the air separator, which allows them to be used to analyse and optimise operation of various models of centrifugal air separators, as well as other classes of separators considering relevant adjustment. Prospects for further research consist in determining designs of centrifugal air separators with the best balance of the three mentioned forces, which will contribute to increased efficiency of separation of finely dispersed mineral raw materials, as well as determination of possible ways to improve the separator design.

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None.

Conflict of Interest

None.

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Аналіз співвідношення сил, що діють на матеріал у повітряному відцентровому сепараторі

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Анотація. Актуальність дослідження зумовлена необхідністю підвищення ефективності процесів сухого збагачення корисних копалин, зокрема через вдосконалення методів поділу тонкодисперсних матеріалів. Метою дослідження був аналіз закономірностей співвідношення сил, що діють на частинку матеріалу у вихровому повітряному потоці у відцентровому сепараторі. У роботі використано аналітичний метод дослідження та узагальнення існуючих досліджень, орієнтованих на визначення балансу сил, що діють на частинку матеріалу в вихровому потоці повітря. Основні результати дослідження полягають у визначені залежностей між найвпливовішими силами, що діють на частинку мінеральної сировини, що відрізняється порівняно високою щільністю, у відцентровому повітряному сепараторі. Встановлений баланс між силою аеродинамічного опору, силою тяжіння і відцентровою силою, який є ключовим аспектом для вдосконалення конструкцій та оптимізації режимів роботи відцентрових сепараторів. Встановлено залежності, що визначають положення рівнодіючих між основними силами, та дозволяють визначати параметри раціонального режиму роботи повітряних сепараторів та обґрунтувати рекомендації щодо підвищення продуктивності процесу їх роботи. Отримані рівняння положення рівнодіючих є універсальними та не прив'язані до конкретної конструкції повітряного сепаратора, що дозволяє застосовувати їх для аналізу та оптимізації роботи різноманітних моделей відцентрових повітряних сепараторів, а також інших класів сепараторів з урахуванням відповідних уточнень. Практична цінність роботи полягає в отриманні рівняннь, які визначають положення рівнодіючих між трьома основними силами, що діють на частинку у вихровому повітряному потоці. Це, в свою чергу, дозволяє визначати параметри необхідного режиму роботи

Ключові слова: збагачення корисних копалин; відцентрова сила; сила тяжіння; сила аеродинамічного опору; баланс сил

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