UDC 621.3
DOI https://doi.org/10.32782/2663-5941/2025.3.2/20

Holod I.V.
Kharkiv National University of Radio Electronics

DEVELOPMENT OF A PARAMETRIC MODEL AND FORMALIZATION OF PARAMETERS FOR MICROCLIMATE CONTROL IN INDUSTRIAL PREMISES BASED ON CYBER-PHYSICAL SYSTEMS

The rapid development of various industries, its digitalization, the comprehensive spread of the Internet, its availability has led to the increasing application of the principles of the Concept of Industry 4.0 and the emergence of cyber-physical systems. Such systems, based on these sensors, are capable of making decisions and performing actions in the physical world.

The article is devoted to the development of a parametric model for microclimate control in industrial premises based on cyber-physical systems. With the automation advancement and increased demands for energy efficiency, stability of technological processes, and workplace safety, there is a need to create adaptive control systems capable of self-learning and real-time operation. The aim of the study is to enhance the effectiveness of microclimate parameter regulation through formalization of a parametric model, which considers both external influences and internal technological disturbances.

Within the scope of the research, a parametric model has been developed describing the dynamics of temperature, humidity, gas composition, and air exchange in industrial areas. The model incorporates the operational logic of actuators such as heating, ventilation, and cooling systems, and includes a decomposition graph that visually represents the cause-and-effect relationships among system parameters. Special attention is given to the model's adaptability to changing external conditions through the implementation of self-learning algorithms and the utilization of historical data.

The results of the study demonstrate that the proposed approach allows for the creation of a flexible and scalable parametric microclimate model, easily adaptable to the specifics of different industrial processes. Integration with cyber-physical systems opens up possibilities for building autonomous and intelligent solutions for industrial automation. The formalized parameter model presented serves as a universal platform for implementing advanced microclimate control strategies in industrial enterprises.

Key words: *microclimate, cyber-physical systems, adaptive model, industrial automation, actuators, energy efficiency.*

Formulation of the problem. In modern production conditions, the requirements for the quality, stability of technological processes, energy efficiency and safety of staff are increasing. One of the key factors affecting these parameters is the microclimate in production facilities. The fluctuations in temperature, humidity and concentration of harmful gases can not only adversely affect the health of workers, but also reduce the accuracy and durability of technological equipment. In view of this, the automation of microclimate control systems is becoming more relevant, especially in the context of the introduction of cyber-physical systems and Industry 4.0 and 5.0 concepts.

Despite the availability of numerous solutions aimed at controlling individual microclimate parameters, most modern systems do not provide sufficient adaptability to rapidly changing environmental conditions. Often there are no integrated models that can take into account the relationships between different parameters and manage actuators on the basis of comprehensive analysis of input data. This leads to poor use of resources, energy overruns and reducing production efficiency.

Thus, the relevance of the research lies in the need to develop a universal parametric model of intelligent microclimate control, combining physical modeling, actuator logic, and self-learning capabilities. Such a model should be capable of flexible real-time adaptation and easily scaled for various industrial environments, which is particularly important within the context of industrial digital transformation.

Analysis of recent research and publications. Research [1] examined approaches to building an automated system for measuring microclimate parameters in industrial premises. The authors emphasize the development of a reliable, cost-effective, and flexible platform for collecting temperature and humidity data, which serves as the basis for further automation of regulatory processes. Holinko, I.M. and Halytska, I.Ye. in [2] proposed methods for integrating microclimate subsystems into a unified enterprise automation management system. This approach synchronizes environmental parameters with technological processes, enhancing resource management efficiency. Antoniuk V.S. and Merezhanyi Yu.G. in their paper [3] investigated the impact of microclimate parameters on the reliability and lifespan of precision mechanisms. It was demonstrated that even minor deviations in temperature and humidity could significantly reduce the lifetime of precision equipment, highlighting the importance of continuous monitoring and adaptive control. In [4], Aliinyk Yu.V. and Skidan V.V. focused on issues of energy efficiency in climate control systems. They suggested methods for optimizing the operation of ventilation and heating equipment to reduce electricity consumption without compromising the stability of environmental parameters. In article [5], Altayeva A.B. et al. presented an IoT-oriented intelligent microclimate control system employing fuzzy logic. This approach enables remote monitoring and decision-making based on multiparametric analysis of sensor data in real-time conditions. Kostarev S.N. and Sereda T.G. in [6] developed a basic microclimate control model that accounts for interactions of temperature, humidity, and ventilation through an integrated feedback platform. In subsequent work [7], the same authors, together with Novikova (Kochetova) O.V. and Ivanova A.S., adapted their system for poultry farm conditions, achieving practical regulation of environmental conditions for optimal quail growth, thus confirming the versatility of their model. Makarenko A. and Brajon J. in [8] investigated the use of cellular automata with internal boundaries for solving intelligent control problems. This approach enables decentralized systems with local data processing, offering potential for zone-based microclimate control. In [9], Moholivets Yu.I. and Yaremchuk N.A. proposed a method using fuzzy linguistic variables to derive conclusions on microclimate parameters based on fuzzy scales. This approach allows operation with data characterized by low precision, typical in industrial conditions.

Thus, the analysis of recent studies shows significant progress both in hardware solutions for measuring microclimate parameters and in intelligent algorithms for their regulation. The integration of IoT, fuzzy logic, physical models, and adaptive strategies enables the creation of a new generation of microclimate systems capable of real-time operation with high accuracy and energy efficiency.

Task statement. In this scientific research it is necessary to develop and formalize a parametric model for microclimate control in industrial premises based on cyber-physical systems, enabling improved efficiency of temperature, humidity, air gas composition, and air exchange regulation, ensuring adaptive, energy-efficient, and reliable operation of actuators under changing industrial conditions.

Outline of the main material of the study. Modern production requires effective approaches to maintaining optimal microclimate parameters in industrial premises. This necessity is driven not only by the need to provide comfortable conditions for employees but also to comply with technological parameters, critically important for the process's stability and the final product quality. The application of intelligent microclimate control systems based on cyber-physical systems allows achieving high accuracy in control and adaptability to changes in external and internal environmental conditions. The mathematical model developed in this research takes into account fundamental physical parameters such as temperature, humidity, air gas composition, and actuators that regulate these parameters in real-time.

The mathematical model for intelligent microclimate control is based on a parametric approach, allowing the formalization of dynamic changes in microclimate parameters under the influence of both external and internal factors. The core dependency of the model is described by the equation:

$$MicroClimate = < T_{in}, T_{out}, H_{in}, H_{out}, GasMix, N_{piople}, Actuators, Disturbances > \quad (1)$$

Where T_{in} – indoor air temperature;

T_{out} – outdoor air temperature;

H_{in} – indoor air humidity;

H_{out} – outdoor air humidity;

$GasMix$ – total concentration of other gases;

N_{piople} – number of people present in the premises;

$Actuators$ – mechanisms regulating the microclimate;

$Disturbances$ – disturbances affecting the microclimate, such as heat emissions from equipment, opening of doors, and solar radiation.

The indoor air temperature (T_{in}) directly affects comfortable working conditions and the effectiveness of technological processes:

$$T_{in} = \frac{\sum_{i=1}^{Nz} T_{zonei} * Area_{zonei}}{\sum_{i=1}^{Nz} Area_{zonei}} \quad (2)$$

Where T_{zonei} – temperature in the i-th zone of the premises;

$Area_{zonei}$ – area of the i-th zone (defines the size of a specific zone where microclimate control is implemented);

N_z – total number of zones in the premises.

The temperature in a zone (T_{zone}) can vary depending on these factors:

$$T_{zone} =< T_{set}, RangeFactore, H_{in}, T_{out}, Actuators, HeatSources, Disturbances > \quad (3)$$

Where T_{set} – a setpoint temperature for the respective zone. It defines the desired temperature depending on the specifics of the technological process. For example, in areas with high technological requirements, temperature can be set at a certain level for optimal equipment operation or worker comfort.

$RangeFactore$ – a coefficient accounting for different temperature ranges, used to adjust temperature according to specified temperature modes, such as low, normal, or high temperatures:

$$RangeFactor = \begin{cases} -1, if\ -30°C \le T_{zone} < +10°C (low\, mode) \\ 0, if\ +10°C \le T_{zone} < +25°C (normal\, mode) \\ 1, if\ +25°C \le T_{zone} \le +60°C (high\, mode) \end{cases} \quad (4)$$

$HeatSources$ – additional heat sources (technological equipment, radiation, heat from personnel):

$$HeatSources = \sum_{i=1}^{Nh} P_{heat,i} \quad (5)$$

Where $P_{heat,i}$ – power of the i-th heat source, i=1,2,...,N;

Nh – total number of heat sources in the zone.

$Disturbances$ – disturbances influencing temperature changes in a zone (e.g., door openings, ventilation speed variations, personnel movements):

$$Disturbances = \begin{cases} 1, if\ active\, disturbance \\ 0, if\ no\, disturbance \end{cases} \quad (6)$$

The outdoor air temperature (T_{out}) is a significant parameter influencing the microclimate inside industrial premises. Its formulation may be as follows:

$$T_{out} = f\left(T_{atm}, Solar_{rad}, Wind_{speed}, RangeFactor\right) \quad (7)$$

Where T_{atm} – ambient air temperature (meteorological data);

$Solar_{rad}$ – intensity of solar radiation impacting the heating of external constructions:

$$Solar_{rad} = \begin{cases} 0,\ if\ 18 \le Time < 6 (night / evening) \\ \alpha \cdot (Time - 6), if\ 6 \le Time < 12 (morning) \\ \beta \cdot (18 - Time), if\ 12 \le Time < 18 (daytime) \end{cases} \quad (8)$$

Where – morning growth coefficient of solar radiation (6:00–12:00). Defines the rate of increase of solar radiation after sunrise. Depends on geographical latitude (larger closer to the equator), season (lower in winter than in summer), cloudiness (reduced on cloudy days). For example, in mid-latitudes, a typical summer day has $\alpha \approx 50-100$ W/m²·hr, and in winter – 10−30 W/m²·hr.

β – coefficient of solar radiation decrease after noon (12:00–18:00). Defines how quickly the intensity of radiation decreases after peak intensity. Also dependent on geographical latitude and season; generally, β is slightly lower than α in mid-latitudes because heated surfaces continue emitting heat longer. For example, a typical summer day has $\beta \approx 40-90$ W/m²·hr, and in winter – 5–25 W/m²·hr.

These coefficients can be calibrated based on actual meteorological data from a specific region to achieve greater accuracy.

$Wind_{speed}$ – wind speed affecting premises cooling. This factor is not considered since industrial premises are typically insulated from direct wind exposure, and its influence on the overall heat balance is insignificant compared to other factors;

$Time$ – time of day determining the level of solar radiation and possible temperature variations.

Indoor air humidity (H_{in}) is also a key parameter of the microclimate, affecting technological process efficiency, equipment conditions, and personnel comfort:

$$H_{in} = f\left(H_{out}, T_{in}, \text{Actuators}, RangeFactor\right) \quad (9)$$

The external humidity level (H_{out}) can be described as a function of external factors:

$$H_{out} = f\left(T_{out}, Weather, RangeFactor\right) \quad (10)$$

Where $Weather$ – current weather conditions (rain, snow, wind, etc.):

$$Weather = \begin{cases} 1, if\ precipitation (rain, snow, fog, etc.) \\ 0, if\ no\ precipitation (clear\, or\, cloudy\, without\ precipitation) \end{cases} \quad (11)$$

Air gas composition (GasMix) is a critically important microclimate parameter defining the air quality in industrial premises:

$$GasMix = \\ = f(O_2, CO_2, NH_3, NO_x, SO_2, CH_4, Actuators, RangeFactor) \quad (12)$$

Where O_2, CO_2, NH_3, NO_x , SO_2 , CH_4 – concentrations of main gases;

$Actuators$ – executive mechanisms regulating the temperature in the zone (heating systems, cooling systems, on/off fans, variable-speed fans, and air volume control mechanisms).

Activation (13) and deactivation (14) of heating are based on the logic related to the setpoint temperature (T_{set}) and hysteresis values ($Hyst_{on}, Hyst_{off}$) to prevent fluctuations:

$$Heat_{on} = True, \ if \ T_{zone} < \left(T_{set} - Hyst_{on}\right) \quad (13)$$

$$Heat_{off} = True, if \ T_{zone} \geq \left(T_{set} + Hyst_{off}\right) \quad (14)$$

Cooling systems are responsible for reducing the zone temperature when it exceeds the defined threshold:

$$Cool_{on} = True, if \ T_{zone} > \left(T_{set} + Hyst_{on}\right) \quad (15)$$

$$Cool_{off} = True, if \ T_{zone} \leq \left(T_{set} - Hyst_{off}\right) \quad (16)$$

$Fans_{on/off}$ – fans operating in on/off mode:

$$Fans_{on} = True \ , if \ T_{zone} > \left(T_{set} + Hyst_{on}\right) \quad (17)$$

$$Fans_{off} = True, if \ T_{zone} \leq \left(T_{set} - Hyst_{off}\right) \quad (18)$$

Fans can also be activated in the event of insufficient air exchange in the zone:

$$Fans_{on} = True \ if \ AirV < AirV_{reg} \quad (19)$$

Where $AirV$ – actual volume of air processed by the ventilation system;

$AirV_{reg}$ – required air volume for the specific technological process, determining minimal ventilation requirements.

Fans are additionally activated when harmful gas concentrations exceed permissible limits in the zone:

$$Fans_{on} = True \ if \ GasMix > GasMix_{max} \quad (20)$$

Where $GasMix$ – total concentration of harmful gases (expression 12);

$GasMix_{max}$ – permissible threshold value of gas concentration in the zone.

Variable-speed fans allow precise adjustment of airflow intensity for accurate temperature regulation within the zone. They operate based on the defined temperature regime, helping achieve optimal indoor microclimate conditions:

$$Fans_{reg} = f\left(T_{zone}, T_{set}, T_{out}, H_{in}, H_{out}, GasMix, N_{piople}, AirV\right) \quad (21)$$

The air volume ($AirV$) processed by ventilation systems ensures necessary circulation and microclimate maintenance in the industrial premises. This parameter defines the total airflow through the system, balancing exhaust and intake air:

$$AirV = f\left(Fans_{\frac{on}{off}}, Fans_{reg}, T_{zone}, T_{out}, N_{piople}, AirV_{reg}, FAir_{reg}\right) \quad (22)$$

Where $FAir_{reg}$ – parameter defining the degree of opening of automated fresh air dampers used for supplying fresh air to the production zone. The $FAir_{reg}$ value is based on the controlled pressure indicator in the production zone (ΔP_{zone}), indicating vacuum or excess pressure. Depending on this parameter, dampers open or close to the required level, adjusting the fresh air inflow speed and influencing the microclimate:

$$FAir_{reg} = f(T_{zone},, T_{out}, H_{in}, H_{out}, GasMix, N_{piople}, AirV, \\ Disturbances, \Delta P_{zone}) \quad (23)$$

$Alarm$ – is a component of the control system providing prompt notification of hazardous or unstable conditions potentially leading to technological disruptions or personnel safety threats.

Unlike other actuators, the $Alarm$ does not directly influence the microclimate but serves as a monitoring tool, drawing operator attention to situations requiring intervention or special monitoring:

$$Alarm = f\left(GasMix_{cls}, T_{in}, T_{set}, \Delta T, Time, H_{in}, T_{zone}\right) \quad (24)$$

To ensure efficient microclimate management in industrial environments, having not only a mathematical model but also its visual representation is crucial. Visualization of the parametric microclimate model in the form of a decomposition graph allows for clear representation of the relationships between input parameters, intermediate calculations, and actuators.

The model's decomposition graph provides a structured depiction of each parameter's influence on the final microclimate state. Input parameters (temperature, humidity, gas concentration) form initial conditions processed by intermediate mechanisms: heating, ventilation, and cooling.

This enables real-time monitoring of the system state and forecasting necessary adjustments.

Additionally, visual representation facilitates faster diagnosis of deviations and response to critical situations, enhancing control efficiency and maintaining microclimate stability in the premises.

The first level includes all input parameters that are directly measured or externally set.

The second level involves categorization of these parameters according to defined criteria and boundary conditions, forming an intermediate layer utilized for decision-making within the model.

The third level comprises the logic for activating or deactivating actuators, which directly influence microclimate conditions within the zone.

The Alarm system is placed on a separate level and activates exclusively under critical microclimate conditions.

The implementation of the developed parametric microclimate model into industrial processes provides new opportunities for enhancing environmental management efficiency through cyber-physical systems (CPS). The integration of this model with CPS enables linking physical production processes with virtual models, thus ensuring continuous monitoring, analysis, and adaptive real-time control.

This approach allows continuous updating of microclimate sensor data, automatically adjusting temperature, humidity, ventilation, and air purification parameters. Thanks to self-learning algorithms, the model can incorporate historical data, improving forecasting accuracy and optimizing energy consumption.

Scaling this model for large industrial facilities is achievable due to the modular structure of the decomposition graph. This structure allows easy integration of new actuators or additional control zones, adapting the model to specific requirements of various enterprises.

Therefore, the parametric microclimate model integrated with cyber-physical systems not only ensures high flexibility and adaptability but also enhances overall production efficiency through effective energy resource management and technological process stability.

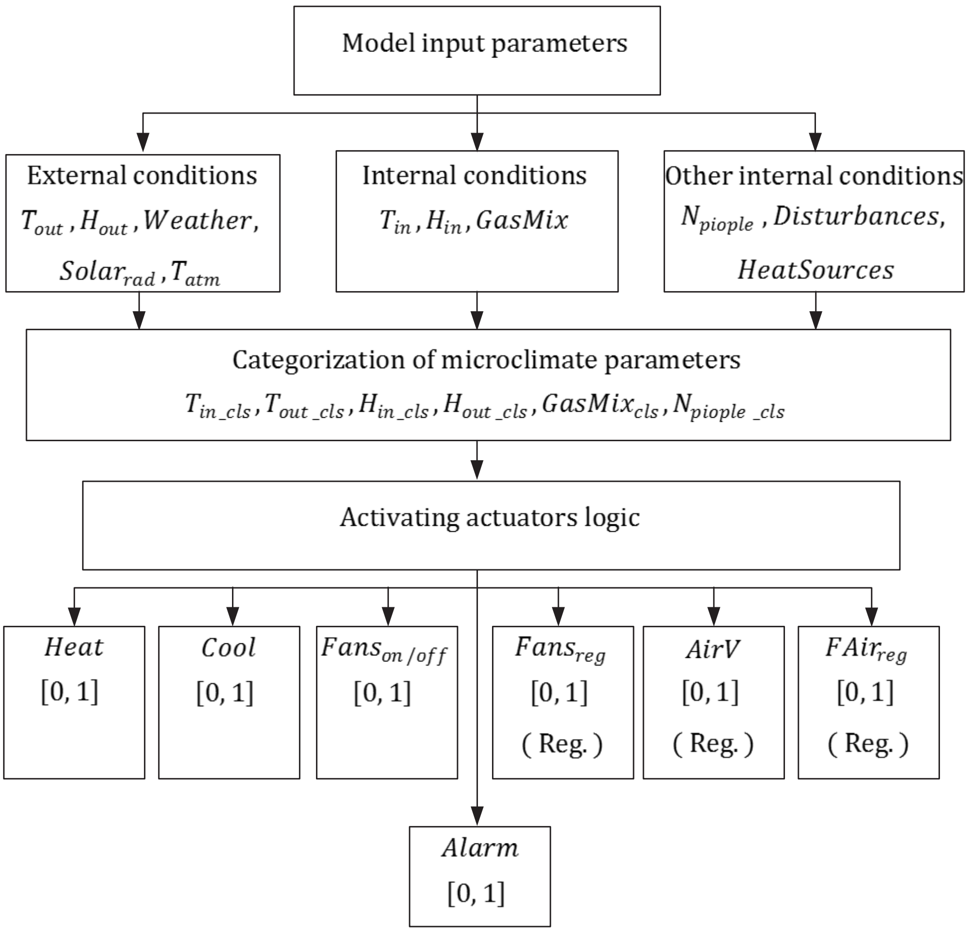

Fig. 1. General decomposition graph of the parametric microclimate model

Conclusions. The developed parametric model for microclimate control in industrial premises based on cyber-physical systems provides efficient control of environmental parameters by formalizing the relationships between input parameters, technological disturbances, and actuator logic. The model considers fundamental physical parameters – temperature, humidity, air gas composition, and air exchange – ensuring structured and adaptive real-time control. Through a decomposition graph, formalized parameters provide a clear representation of causal relationships and facilitate prompt managerial decision-making.

The proposed formalization of model parameters offers several advantages in real industrial conditions. Firstly, it provides a high degree of adaptability through self-learning algorithms. Secondly, optimal energy consumption is achieved due to clearly defined actuator control logic. Thirdly, stability of technological processes is enhanced by the precision of formalized parameters and their interdependencies.

Further research can focus on improving formalization mechanisms for adaptation, expanding self-learning capabilities, and integrating with other cyber-physical system components to develop fully autonomous microclimate management systems. Additionally, scaling the developed parametric model for large industrial complexes with heterogeneous microclimate conditions appears to be a promising research direction.

Bibliography:

1. Ігнатенко Д. В., Боцман І. В. Розробка автоматизованої системи вимірювання параметрів мікроклімату у виробничих приміщеннях. Автоматизація та комп'ютерно-інтегровані технології: матеріали міжнар. наук.-практ. конф. (ACS-2020, Харків, 26 листопада 2020 р.). Харків: ХНУРЕ, 2020. С. 93–95.

2. Голінко І. М., Галицька І. Є. Інтегрування систем керування мікрокліматом в автоматизовану систему керування підприємством. Інформаційні системи, механіка та керування. 2020. № 19–20. С. 78–87. DOI: https://doi.org/10.20535/2219-3804202019194413.

3. Антонюк В. С., Мережаний Ю. Г. Вплив параметрів мікроклімату виробничих приміщень на ресурс прецизійних механізмів приладів. Вісник двигателебудування. 2012. № 1. С. 98–102.

4. Алійник Ю. В., Скідан В. В. Методи підвищення ефективності системи автоматизованого керування клімат-контролю виробничих приміщень. Мехатронні системи: інновації та інжиніринг: матеріали VI міжнар. наук.-практ. конф. (Київ, 2022). 2022. С. 141–142.

5. Altayeva A. B., Omarov B. S., Cho Y. I. Intelligent microclimate control system based on IoT. International Journal of Fuzzy Logic and Intelligent Systems. 2016. Vol. 16, No. 4. P. 254–261. DOI: https://doi.org/10.5391/IJFIS.2016.16.4.254.

6. Kostarev S. N., Sereda T. G. Microclimate control system development. IOP Conference Series: Materials Science and Engineering. 2018. Vol. 450. P. 062013. DOI: https://doi.org/10.1088/1757-899X/450/6/062013.

7. Kostarev S. N., Sereda T. G., Novikova (Kochetova) O. V., Ivanova A. S. Development of a microclimate control system for a quail farm. IOP Conference Series: Earth and Environmental Science. 2022. Vol. 1043. P. 012004. DOI: https://doi.org/10.1088/1755-1315/1043/1/012004.

8. Makarenko A., Brajon J. New possibilities of using cellular automata in space with internal boundaries for computational intelligence problems. Computational Intelligence: Proc. of the 5th Int. Sci.-Pract. Conf. (Uzhhorod, Ukraine, 15–20 April 2019). 2019. P. 17–20.

9. Моголівець Ю. І., Яремчук Н. А. Способи отримання результату вимірювання параметрів мікроклімату промислових приміщень за шкалою з нечіткою лінгвістичною змінною. Обчислювальний інтелект. 2019. № 1 (51). С. 257–259.

Голод І.В. РОЗРОБКА ПАРАМЕТРИЧНОЇ МОДЕЛІ ТА ФОРМАЛІЗАЦІЯ ПАРАМЕТРІВ КЕРУВАННЯ МІКРОКЛІМАТОМ У ВИРОБНИЧИХ ПРИМІЩЕННЯХ НА ОСНОВІ КІБЕРФІЗИЧНИХ СИСТЕМ

Стрімкий розвиток різних галузей виробництва, його цифровізації, всеохоплюючого розповсюдження Інтернету, його доступності призвів до все більшого застосування принципів концепції Індустрія 4.0 та виникнення кіберфізичних систем. Такі системи на основі даних сенсорів здатні самостійно ухвалювати рішення та виконувати дії в фізичному світі.

Статтю присвячено розробці параметричної моделі керування мікрокліматом у виробничих приміщеннях на основі кіберфізичних систем. З розвитком автоматизації та зростанням вимог до енергоефективності, стабільності технологічних процесів і безпеки працівників виникає потреба *у створенні адаптивних систем керування, здатних до самонавчання та роботи в реальному часі. Метою дослідження є підвищення ефективності регулювання параметрів мікроклімату шляхом формалізації параметричної моделі, яка враховує як зовнішні впливи, так і внутрішні технологічні збурення.*

У рамках роботи побудовано параметричну модель, що описує динаміку зміни температури, вологості, газового складу повітря та повітрообміну у виробничих зонах. До моделі включено логіку роботи виконавчих механізмів, таких як обігрів, вентиляція та охолодження, а також сформовано граф декомпозиції, що дозволяє візуалізувати причинно-наслідкові зв'язки між параметрами системи. Особливу увагу приділено адаптивності моделі до зміни зовнішніх умов завдяки реалізації алгоритмів самонавчання та використанню історичних даних.

Результати дослідження демонструють, що запропонований підхід дозволяє створити гнучку та масштабовану параметричну модель мікроклімату, яка легко адаптується до специфіки різних виробничих процесів. Інтеграція з кіберфізичними системами відкриває перспективи побудови автономних і розумних рішень для промислової автоматизації. Запропонована формалізована модель параметрів є універсальною платформою для впровадження сучасних стратегій керування мікрокліматом на підприємствах.

Ключові слова: *мікроклімат, кіберфізичні системи, адаптивна модель, промислова автоматизація, виконавчі механізми, енергоефективність.*