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HARDWARE-SOFTWARE MODULE FOR INTELLIGENT MICROCLIMATE CONTROL IN INDUSTRIAL FACILITIES

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ABSTRACT

The article addresses the problem of automated and intelligent microclimate control in industrial premises, where the stability of the temperature and humidity regime directly affects the efficiency of technological processes, energy efficiency, and equipment reliability. It is shown that traditional control systems based on simplified linear models do not provide the required accuracy under conditions of multifactor disturbances and dynamic changes in environmental parameters. The purpose of the study is to develop a hardware–software module capable of providing adaptive, stable, and energy-efficient control of microclimate parameters based on the coordinated operation of sensor, computational, and executive subsystems.

The research methodology involves the development of a structural architecture of the hardware–software module, integration of a sensor system, a controller with embedded HMI, and executive mechanisms, as well as the formation of algorithmic logic for regulating temperature, humidity, air exchange, and internal pressure. The study applies methods of analysis and synthesis, mathematical modeling, and experimental testing under real industrial conditions. The module operation was verified through continuous data acquisition, real-time parameter logging, and evaluation of the response of executive mechanisms to changes in external and internal factors.

The test results confirmed the module’s ability to maintain stable microclimate parameters within specified setpoints, ensuring smooth switching between heating, cooling, and ventilation modes. The recorded temperature dynamics demonstrate the absence of sharp fluctuations, effective operation of hysteresis mechanisms, and rapid system response to load changes. The practical applicability of the module is confirmed by its stable operation under daily variations in outdoor temperature, the presence of thermal disturbances, and variations in air exchange. The selected combination of equipment (KSP-08.L controller, data acquisition modules, and sensor devices) provided the required performance, accuracy, and flexibility.

Prospects for further research include expanding the functionality of the hardware–software module through the integration of predictive models, in particular neural network structures of the NNARX type, which will increase the accuracy of microclimate dynamics assessment and optimize control logic in complex industrial scenarios. The obtained results form a basis for improving intelligent control systems in industrial cyber-physical complexes and for their implementation in various industrial sectors.

Keywords: *intelligent control; microclimate; hardware-software module; cyber-physical systems; sensor subsystem; actuators; control algorithms; parameter forecasting.*

Task statement

Maintaining a stable microclimate in industrial premises determines the reliability of technological processes and the level of energy consumption; therefore, the accuracy of the control system operation directly affects product quality and equipment lifetime. Real-world operation is associated with nonlinear heat and moisture exchange processes, the presence of unpredictable disturbances, and changes in internal conditions, which complicate the performance of traditional controllers. Their response is delayed, and environmental parameters

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change inertially, causing deviations from technologically permissible values.

The industrial environment requires a solution capable of continuously registering parameters, correctly interpreting changes in thermal load, and coordinating the operation of executive mechanisms under conditions of incomplete information and disturbances. The system must ensure the generation of control actions in real time and remain robust to noise and time delays that affect control accuracy.

Against this background, there is a need to develop a hardware–software module that integrates a sensor subsystem, data acquisition tools, a computational platform, and executive mechanisms into a unified control loop. Such a solution should demonstrate microclimate stabilization under real industrial disturbances and form a basis for further system development through the implementation of predictive models capable of increasing control accuracy and adaptability to changing technological scenarios.

Analysis of recent research and publications

In study [1], modern approaches to the use of artificial intelligence in climate research and energy systems are summarized, highlighting the growing role of intelligent methods in modeling and optimizing microclimate processes. Study [2] demonstrates the significance of digital twins and smart manufacturing in the context of sustainable development, emphasizing the close integration of sensor systems, communication tools, and real-time analytics. Paper [3] presents a comprehensive vision of the architecture and practices of cyber-physical systems for Industry 4.0, where computational resources, communications, and physical processes are integrated. Study [4] complements this approach by focusing on cybersecurity and resilience aspects of cyber-physical systems, which are crucial for the implementation of intelligent control modules in industrial environments.

The methodological foundations for the construction and formal description of cyber-physical production systems are considered in studies [5–7]. In [5], a method for synthesizing CPS operation algorithms oriented toward subsystem coordination and ensuring consistency of their operation is proposed, which is important for building an integrated microclimate control loop. In [6], a declarative modeling language for CPS is developed, enabling the formalization of the structure and behavior of production systems, which directly correlates with the tasks of designing hardware–software modules. Study [7] is devoted to the organization of secure access to HMI/SCADA systems over unsecured networks and emphasizes the importance of reliable user authentication in the context of distributed cyber-physical systems. Review [8] systematizes possible applications of edge computing in industry, demonstrating the feasibility of transferring part of data processing to the local device level, which corresponds to the concept of a hardware–software module with embedded intelligent functions.

A separate group of studies focuses on sensor systems and hardware. In [9], a sensor-based navigation system for a mobile robot using ultrasonic sensors is developed, highlighting the role of multichannel real-time data acquisition and its relevance for building a microclimate sensor subsystem. Report [10] analyzes modern sensors and control systems for commercial buildings, outlining barriers and drivers for the implementation of intelligent sensors and controllers in HVAC practice. Review [11] summarizes data-driven approaches to fault diagnosis in HVAC systems, indicating the importance of high-quality data acquisition and processing to ensure the reliability of microclimate control systems.

Considerable attention in contemporary research is given to control algorithms that use neural network and fuzzy approaches. In [12], the application of a nonlinear autoregressive NARX model for temperature prediction in a solar adsorption cooling system is demonstrated, confirming the effectiveness of autoregressive neural network structures for thermodynamic modeling tasks. Paper [13] examines guaranteed control in interval type-2 fuzzy systems, emphasizing operation under uncertainty, which is relevant for industrial facilities with variable environmental parameters. In [14], context-dependent HVAC control based on fuzzy logic is proposed, oriented toward adaptive mode changes depending on building state and external conditions. Study [15] demonstrates the capabilities of artificial neural networks for short-term indoor temperature forecasting, which directly relates to predictive microclimate control tasks. Review [16] systematizes neuro-fuzzy architectures in the context of interpretable AI, highlighting their potential for building transparent and adaptive control systems.

Issues of energy efficiency and comparison of classical and intelligent control methods are considered in studies [17–20]. In [17], a comparative modeling of HVAC control systems based on PID controllers and reinforcement learning methods is performed, demonstrating the advantages of intelligent approaches in tasks of simultaneous optimization of comfort and energy consumption. Paper [18] describes the integration of machine learning with model predictive control to improve the energy efficiency of HVAC systems, confirming the feasibility of combining predictive models with flexible control logic. Study [19] analyzes the potential of AI-oriented smart energy grids for reducing the carbon footprint, aligning with trends toward decarbonization of industrial processes. Review [20] systematizes the application of artificial intelligence to improve energy efficiency and indoor environmental quality in buildings, confirming

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the general trend of transitioning from traditional controllers to hybrid, data-driven control systems.

In summary, the analyzed studies demonstrate the intensive development of cyber-physical systems, intelligent sensor and computational platforms, as well as hybrid control algorithms based on artificial neural networks and fuzzy logic. At the same time, existing works mainly address either general CPS concepts and energy-efficient control or individual aspects of software and algorithmic solutions for HVAC systems. The issue of creating an integrated hardware–software module for intelligent microclimate control in industrial premises–combining hardware platform selection, sensor infrastructure, executive mechanisms, and control logic, and validated through full-scale testing under real operating conditions–remains insufficiently explored, which determines the relevance of this study.

Separation of previously unresolved parts of the overall problem

Despite the active development of automated microclimate control systems, most existing solutions focus on partial aspects of their operation and do not provide full integration of hardware and software components into a unified industrial platform. Current studies present isolated descriptions of sensor devices, principles of executive mechanism operation, or control algorithms; however, a holistic architectural vision in which all these subsystems operate in a coordinated manner is lacking.

Issues related to the development of a modular computational structure capable of operating in an open software environment while simultaneously ensuring industrial reliability, resistance to external influences, and compliance with real-time requirements remain insufficiently explored. The literature lacks descriptions of solutions capable of maintaining parameter stability under variable industrial conditions, where the system must respond to dynamic thermal loads, spatial heterogeneity of the environment, and significant fluctuations in airflow.

Another unresolved problem is the lack of practical studies in which the hardware platform is combined with the possibility of further implementation of predictive data analysis methods. Scientific works predominantly address simulation-based or laboratory models, whereas real industrial scenarios are scarcely described. This complicates the assessment of how theoretically proposed approaches can operate in the complex environment of industrial premises.

Thus, the problem of creating an integrated hardware–software module that unifies sensor infrastructure, data acquisition tools, a computational platform, and an executive subsystem into a single solution–validated under real operating conditions and prepared for expansion through intelligent and predictive algorithms–remains unresolved. This gap defines both the direction and the necessity of the present study.

Purpose of the study

The purpose of the study is to improve the efficiency of microclimate control and the stability of technological processes in industrial premises by developing and experimentally validating a hardware–software module for intelligent control that ensures coordinated interaction of sensor, computational, and executive subsystems within a unified cyber-physical loop. The implementation of the module is aimed at minimizing the impact of industrial disturbances, reducing the system response time to parameter deviations, and creating a basis for the integration of predictive neural network models.

Methods, object, subject and methods of research

Methods. Observation, analysis and synthesis, mathematical modeling, artificial neural network and fuzzy logic methods, and experimental modeling in the Python environment using the Keras library.

Object of the study. Microclimate control processes in industrial premises under conditions of variable external and internal factors.

Subject of the study. The structure, principles of design, and operation of a hardware–software module for intelligent microclimate control in industrial premises, which ensures coordinated operation of sensor, computational, and executive subsystems.

The main material

The stability of the microclimate in industrial premises is a key condition for the efficiency of technological processes, energy efficiency, and reliable equipment operation, since the temperature and humidity regime directly affects product quality and equipment durability. Traditional threshold-based control systems that use a limited set of sensors do not provide the required accuracy or timely response to changes in external conditions, which leads to fluctuations in environmental parameters and increased energy consumption.

The development of modern automation systems creates opportunities for more accurate and adaptive operation through coordinated interaction of sensor devices, executive mechanisms, and controllers capable of processing data in real time. In this context, the development of a hardware–software module that provides integrated microclimate control with scalability and potential for further development is particularly relevant.

This study presents a hardware–software module for intelligent microclimate control, the operability of which has been confirmed through full-scale testing under real industrial conditions, making it possible to ensure stable

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environmental parameters and improve the efficiency of technological processes.

Structure of the hardware–software module. The architecture of the hardware–software module forms an integrated system for collecting, processing, and utilizing technological information to stabilize the microclimate in industrial premises. The module integrates a sensor subsystem, primary data processing tools, a controller with embedded HMI, and a set of executive mechanisms that provide regulation of temperature, humidity, air exchange, and pressure. All components operate in real time, enabling prompt response to external and internal disturbances.

The structural diagram (Fig. 1) illustrates the interaction between sensor channels, the data acquisition module, the central controller, communication interfaces, and executive mechanisms. The sensor subsystem provides measurements of temperature, humidity, air gas composition, and internal pressure, with the possibility of adapting sensor types to the requirements of a specific facility. Primary data undergo filtering, linearization, and normalization within the data acquisition module.

Communication interfaces, including RS-485 and Ethernet, enable data exchange between subsystems, ensuring module scalability and resistance to electromagnetic interference, which is critical for industrial environments. The controller with embedded HMI performs microclimate parameter analysis and generates control actions, supporting coordinated operation of heaters, fans, and valves. The operator is able to monitor the system status and adjust settings in real time.

Actuators implement physical effects on the environment through smooth or discrete regulation of heating and ventilation. The coordination of their operation is based on feedback principles, which ensures microclimate stabilization under dynamic external factors. Measurement and control signal flows form a closed loop that determines control accuracy and system reliability.

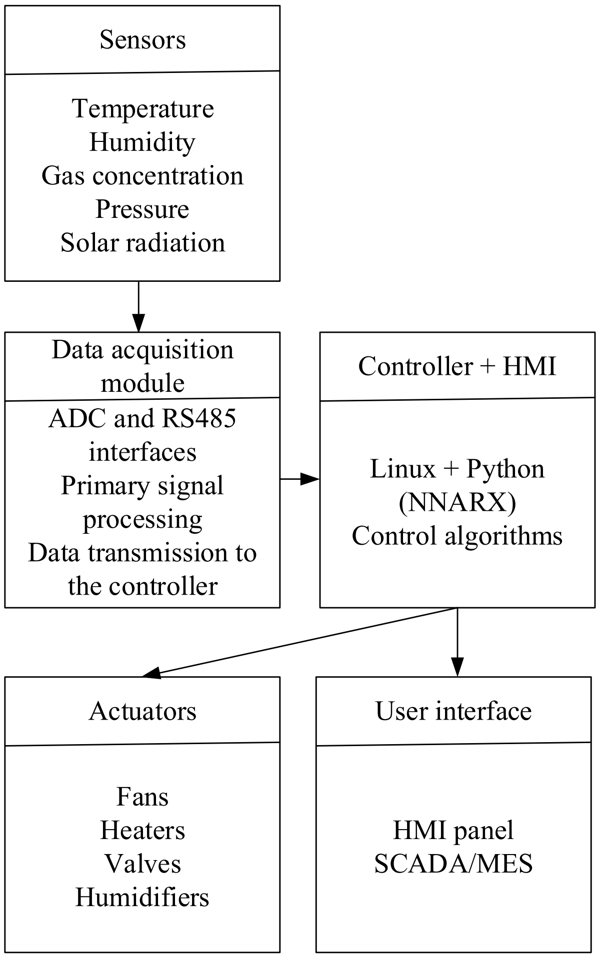

Fig. 1. Structural diagram of the hardware–software module

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Selection of hardware components

The development of a hardware–software module for intelligent microclimate control requires the selection of a computational platform that provides sufficient performance, support for modern algorithms, and a user-friendly operator interface. In this context, a key component is a controller with an embedded HMI that combines data acquisition, control logic, and local visualization functions.

The presented comparison covers the key parameters that determine the suitability of controllers for operation in intelligent microclimate control systems. Closed platforms with fixed functionality limit flexibility and complicate the integration of modern data processing methods, whereas open systems based on Linux create conditions for scalability, network interaction, and the implementation of complex algorithms.

In this context, the KSP-08.L controller is distinguished by its open architecture, Python support, and the ability to implement web-oriented and SCADA solutions without additional hardware modules. The availability of Ethernet and RS-485 interfaces simplifies integration into industrial infrastructure and ensures interaction with data acquisition modules, sensors, and executive mechanisms. The embedded HMI enables local monitoring, parameter configuration, and real-time observation of system response.

Considering the combination of functionality, openness of the software platform, and cost, the KSP-08.L is an optimal basis for implementing a hardware–software module for intelligent microclimate control under industrial conditions.

Data acquisition tools are a key element of the hardware–software module, as they determine measurement accuracy, system response speed, and data quality for control algorithms. For comparison, several typical data acquisition modules from different manufacturers were selected.

The comparison shows that commercial modules are often characterized either by excessive orientation toward discrete channels with limited analog capabilities or, conversely, by support for several analog inputs with a lack of discrete signals. This complicates the connection of temperature, humidity, pressure, and gas composition sensors, which require the simultaneous operation of different types of channels. In addition, many modules provide only basic filtering functions, which creates an additional load on the controller and affects system performance.

The MP100-24.02.2 module is distinguished by a balanced configuration that includes integrated discrete and analog inputs and outputs with support for standard signal ranges. The presence of built-in digital filtering mechanisms ensures measurement stability under electromagnetic interference conditions. Support for industrial interfaces enables synchronized data exchange with the controller and minimizes information transmission delays, which is critical for real-time systems.

Due to the combination of functionality, performance, and the possibility of direct integration with sensor and executive devices, the MP100-24.02.2 module is an effective solution for intelligent microclimate control systems in industrial environments.

The sensor subsystem provides measurement of the main microclimate parameters and forms streams of primary data for further processing. Its quality determines the system's ability to respond promptly to disturbances, maintain a stable operating mode, and ensure correct operation of control algorithms. The subsystem is based on sensors of temperature, humidity, gas composition,

Table 1. Comparison of technical characteristics of controllers with HMI

Characteristics	AKYTEC KSP-08.L	Siemens KP700 Comfort	Schneider HMIGTO4310
Display	8", 1024×768	7", 800×480	7.5", 640×480
Processor	up to 1.8 GHz	500 MHz	333 MHz
Memory	2-4GB RAM, 64GB SSD	12 MB, SD card	96MB Flash, SD 4GB
OS / Software	Linux (Python, SCADA)	WinCC	Vijeo Designer
Interfaces	Ethernet, RS-485, USB	PROFINET, Ethernet	Ethernet, Modbus
Price (UAH)	28 300	48 900	49 749

Table 2. Comparison of data acquisition modules from different manufacturers

Signal type / Modules	AKYTEC MP100-24.02.2	Siemens SM modules	Schneider TM3
Discrete inputs	built-in	SM1223 (8DI+8DO)	TM3DI
Discrete outputs	built-in	–	TM3DQ
Analog inputs	built-in	SM1231	TM3AI
Analog outputs	built-in	SM1234	TM3AQ
Rated price	12 960 UAH	high range	medium range

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and pressure, which must provide high accuracy, fast response, and resistance to industrial conditions, including vibration, dust, and humidity fluctuations.

Temperature sensors must ensure a linear characteristic and stability over a wide operating range, while combined temperature and humidity sensors should have minimal response time and protection against contamination. Gas composition sensors impose increased requirements on calibration stability and resistance to electromagnetic interference, which is critical for systems in which air exchange is regulated according to air quality characteristics. Pressure sensors provide differential pressure control and enable stabilization of airflow.

For compatibility with the data acquisition module, sensors must operate within standardized ranges of 4–20 mA or 0–10 V, and their design must meet IP protection requirements. In the case of digital sensors, response speed and compliance with data exchange protocols are important. The combination of these characteristics defines the requirements for the sensor subsystem, which must ensure accurate and reliable measurements under dynamic industrial conditions.

The executive subsystem forms the physical level of influence on environmental parameters and ensures the implementation of control actions generated by the controller. It includes fans, air damper actuators, and heating elements, each of which has its own dynamic characteristics and requirements for control algorithms.

Supply air dampers are equipped with servo actuators that provide precise damper positioning and stable air exchange. They can operate in discrete or continuous modes, allowing adaptation to rapidly changing conditions. Ventilation equipment is represented by fans with discrete switching and units with smooth speed control driven by variable frequency drives. Smooth regulation of fan performance ensures stable airflow, reduces microclimate parameter fluctuations, and improves energy efficiency.

Heating elements ensure temperature maintenance under heat loss conditions or seasonal variations of the external environment. They can operate in discrete or proportional modes, which helps prevent overheating and reduces energy consumption.

Coordinated interaction of all executive mechanisms, supported by feedback, forms a closed control loop that ensures microclimate stability and creates a foundation for further implementation of intelligent algorithms.

Algorithmic logic of module operation. The algorithmic part of the hardware–software module ensures the generation of control actions in accordance with the current microclimate parameters and specified technological requirements. The system is based on feedback principles, through which the controller evaluates deviations of parameters from setpoints and initiates appropriate actions of the executive mechanisms. The control logic is aimed at smooth regulation, avoidance of excessive cycling, and reduction of energy consumption while maintaining stable conditions in the industrial premises.

The central element of the system is the temperature control loop. Heating control is performed based on the temperature error: when the temperature falls below the allowable range, heating elements are activated to provide a gradual increase in temperature. A hysteresis mechanism defines the range between heater switching on and off points, preventing frequent switching and reducing equipment wear. After reaching the upper setpoint limit, the system switches off heating and enters a standby mode, minimizing intervention under stable conditions.

The cooling logic is based on a comprehensive assessment of temperature, humidity, and the influence of the external environment. When the temperature exceeds the set threshold, the system activates ventilation or other cooling mechanisms, gradually reducing the temperature to the operating range. Consideration of humidity helps avoid undesirable fluctuations of this parameter, while responsiveness to outdoor temperature ensures adaptation to changing environmental conditions. In cases of simultaneous increases in temperature and humidity, the system transitions to a more intensive air exchange mode.

The operation of the ventilation subsystem is based on a combination of temperature, humidity, and pressure criteria. The system can employ both discrete fan on/off control and smooth speed regulation using variable frequency drives. Smooth regulation enables more precise adaptation of air exchange intensity to changing conditions, reduces microclimate parameter fluctuations, and improves energy efficiency.

The control logic for supply air dampers is based on evaluating the pressure difference between the indoor and outdoor environments. When internal pressure increases, the dampers open to provide air inflow, whereas when it decreases, they partially close. Control can be implemented in either discrete or continuous modes, allowing precise dosing of the supply air volume and maintaining coordinated operation with the ventilation equipment.

The system includes emergency state control mechanisms that ensure timely detection of critical deviations and faults. In the event of a sharp temperature rise, pressure drop, loss of sensor signals, or failure of executive mechanisms, the system transitions to a safe operating mode, generates an alarm signal, and limits the action of regulating elements. This prevents equipment overload, overheating, and undesirable pressure differentials, thereby ensuring the stability of the technological process.

The coordinated interaction of all control loops – heating, cooling, ventilation, and pressure control–forms

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a closed regulation cycle that ensures microclimate stability and creates prerequisites for the further implementation of intelligent control algorithms.

FULL-SCALE TESTING OF THE HARDWARE–SOFTWARE MODULE. Full-scale testing was conducted to evaluate the practical effectiveness of the hardware–software module and to determine its ability to maintain stable microclimate parameters under real industrial operating conditions. The tests were carried out at an operating facility with a large internal volume and significant thermal and airflow loads, which ensured representative operating conditions. The premises were equipped with fans, supply air ducts with servo actuators, and electric heaters, while their structural features imposed increased requirements on the control system due to potential heat losses and variable technological influences.

During the tests, the module operated in a fully automatic mode, analyzing signals from temperature, humidity, pressure, and gas sensors and generating control actions in accordance with the implemented logic. The operation included both periods of steady-state conditions and abrupt changes in external factors, such as fluctuations in outdoor air temperature, variations in air exchange, and changes in thermal load. This made it possible to evaluate the accuracy, response speed, and adaptability of the system under conditions close to real operating scenarios.

To analyze the module operation, continuous real-time data acquisition was organized. The controller generated time series of measurements with a predefined sampling rate and synchronized them with the states of the executive mechanisms. Temperature, humidity, internal pressure, air gas composition, as well as control commands for heaters, fans, and servo actuators were recorded. This approach provided a comprehensive view of the interaction between subsystems and enabled assessment of time delays between parameter changes and equipment response.

The sampling period was selected to ensure sufficient temporal resolution of measurements without overloading computational resources. The recording interval was several seconds, which allowed capturing both gradual microclimate changes and rapid transient processes associated with changes in the operating modes of executive mechanisms. The collected data formed the basis for further analysis of system stability, accuracy, and reliability under industrial conditions.

Structured real-time logging of parameters enabled the construction of graphical dependencies reflecting system behavior during operation. Figure 2 presents a key fragment of temperature dynamics obtained over a daily period in the autumn season, when external conditions are characterized by moderate fluctuations.

The graph demonstrates a typical daily temperature variation: during daytime, a natural increase is observed due to solar heat gains, which causes a partial exceedance of the upper hysteresis limit and activation of the cooling subsystem. The temperature decrease occurs smoothly, without abrupt changes, indicating stable regulation. In the evening and at night, the outdoor air temperature decreases, leading to cooling of the indoor environment and activation of the heating mode after crossing the lower hysteresis threshold. Heating is performed uniformly, without inertial spikes,

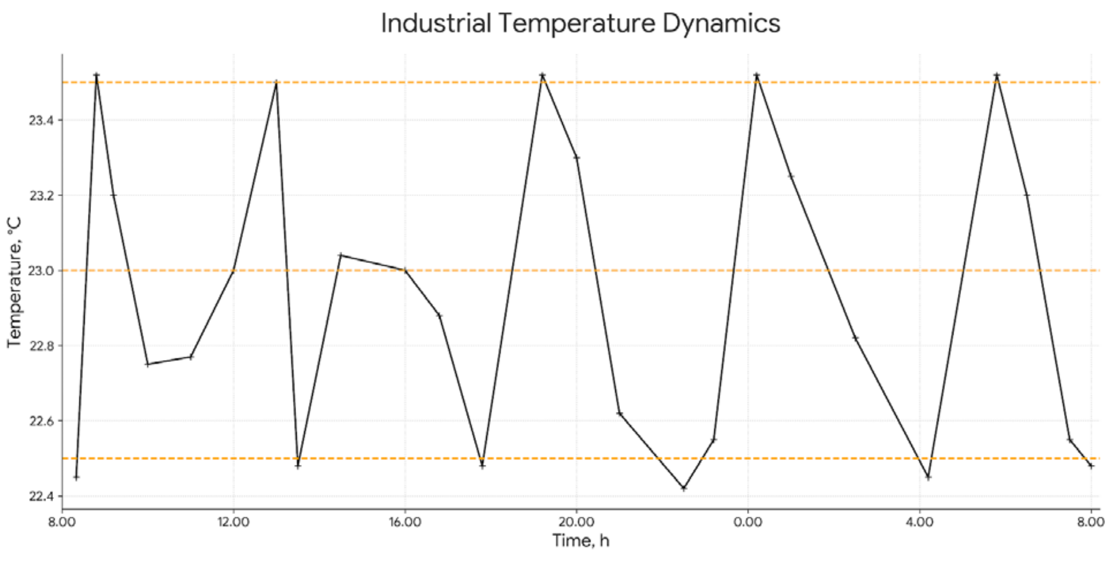

Fig. 2. Temperature dynamics in the industrial premises during full-scale testing

which confirms the correct operation of the temperature control loop.

The observed behavior corresponds to the algorithmic logic implemented in the system: cooling is activated only when the temperature actually exceeds the setpoint range, while heating is activated when it drops below the lower threshold. The absence of sharp peaks or dips in the graph indicates accurate interaction between the sensor and executive subsystems and an appropriate selection of hysteresis width. Analysis of the system response during periods of rapid changes in thermal load shows that the module promptly compensates for deviations, returning the temperature to the operating range without overshoot or excessive equipment activity.

The obtained results confirm the system’s ability to maintain stable microclimate parameters and adapt to dynamic technological conditions. The smooth operation of the heaters and the reduced number of switching events indicate the potential energy efficiency of the solution and reduced load on executive devices. This demonstrates the practical applicability of the module and its compliance with the requirements of industrial applications with variable thermal and airflow loads.

In the future, it is planned to expand the functionality of the hardware–software module by integrating predictive models, in particular neural network structures of the NNARX type, which will increase the accuracy of microclimate dynamics assessment and optimize control algorithms.

Discussion of the results obtained

The conducted full-scale tests showed that the hardware–software module provides stable temperature maintenance within the specified setpoint under real industrial disturbances, demonstrating coordinated operation of the sensor subsystem, executive mechanisms, and algorithmic control logic. The obtained parameter dynamics confirm the absence of abrupt fluctuations, the correct system response to changes in external conditions, and sufficient control accuracy for the use of the module in an industrial environment, which indicates the practical effectiveness of the proposed solution.

Conclusions

The conducted study confirmed the operability and effectiveness of the hardware–software module for intelligent microclimate control in industrial premises, which ensures temperature stability and coordinated operation of the sensor, computational, and executive subsystems under real operating conditions. The obtained results demonstrate the reliability of the proposed solution and create a foundation for further system improvement through the expansion of functional capabilities and enhancement of control accuracy.

Conflict of Interest

The authors declare that they have no conflicts of interest related to this study, including financial, personal, authorship, or any other interests that could have influenced the research or the results presented in this article.

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Data Availability

The data will be provided upon reasonable request.

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АПАРАТНО-ПРОГРАМНИЙ МОДУЛЬ ІНТЕЛЕКТУАЛЬНОГО КЕРУВАННЯ МІКРОКЛІМАТОМ У ВИРОБНИЧИХ ПРИМІЩЕННЯХ

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У статті розглянуто проблему автоматизованого й інтелектуального керування мікрокліматом у виробничих приміщеннях, де стабільність температурно-вологісного режиму безпосередньо впливає на ефективність технологічних процесів, енергоощадність та надійність обладнання. Визначено, що традиційні системи регулювання, які базуються на спрощених лінійних моделях, не забезпечують необхідної точності в умовах багатофакторних збурень і динамічної зміни параметрів середовища. Метою дослідження є розробка апаратно-програмного модуля, здатного забезпечувати адаптивне, стійке й енергоефективне керування параметрами мікроклімату на основі узгодженої роботи сенсорних, обчислювальних та виконавчих підсистем.

Методика дослідження передбачає побудову структурної архітектури апаратно-програмного модуля, інтеграцію сенсорної системи, контролера з вбудованим HMI та виконавчих механізмів, а також формування алгоритмічної логіки регулювання температури, вологості, повітрообміну та внутрішнього тиску. У роботі застосовано методи аналізу та синтезу, математичне моделювання, а також експериментальні випробування у реальних виробничих умовах. Функціонування модуля перевірено завдяки безперервному збору даних, логуванню параметрів у реальному часі й оцінюванню реакції виконавчих механізмів на зміну зовнішніх і внутрішніх факторів.

Результати випробувань підтвердили здатність модуля підтримувати стабільні параметри мікроклімату в межах заданих уставок, забезпечуючи плавне перемикання між режимами нагріву, охолодження та вентиляції. Зареєстрована динаміка температури демонструє відсутність різких коливань, ефективну роботу гістерезисних механізмів та швидку реакцію системи на зміни навантаження. Практична придатність модуля підтверджена його стабільною роботою за умов добових коливань зовнішньої температури, наявності теплових збурень і варіацій повітрообміну. Вибрана комбінація обладнання (контролер КСП-08.L, модулі збору даних та сенсорні пристрої) забезпечила необхідну продуктивність, точність та гнучкість.

Перспективи подальших досліджень полягають у розширенні функціональності апаратно-програмного модуля шляхом інтеграції прогнозних

моделей, зокрема нейромережевих структур типу NNARX, що дасть можливість підвищити точність оцінювання динаміки мікроклімату й оптимізувати логіку керування у складних виробничих сценаріях. Отримані результати створюють основу для вдосконалення систем інтелектуального керування в промислових кіберфізичних комплексах та їх упровадження у різних галузях виробництва.

Ключові слова: *інтелектуальне керування, мікроклімат, апаратно-програмний модуль, кіберфізичні системи, сенсорна підсистема, виконавчі механізми, алгоритмічне регулювання, прогнозування параметрів.*

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