



## Intelligent Thermal Insulation Systems with Built-in Means of Remote Monitoring of Heat Transfer Parameters

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### ABSTRACT

Modern construction faces the challenge of increasing the energy efficiency of buildings by improving thermal insulation and reducing heat loss. Intelligent thermal insulation systems with built-in IoT solutions offer a new approach to controlling and optimizing heat transfer. This article considers the problem of the inefficiency of traditional insulation materials without monitoring. The purpose of the study is to analyze current technologies for remote monitoring of thermal parameters of building envelopes. The introduction substantiates the relevance of the topic, gives the share of buildings in global energy consumption and the need for smart insulation solutions. The state of development of IoT technologies in the field of thermal insulation is reviewed: from wireless sensor networks for tracking the impact of weather conditions to adaptive "smart" insulation materials with variable thermal conductivity. The main approaches and methods of monitoring heat transfer are described – the use of temperature sensors, hygrometers, heat fluxes and infrared control – using the example of several implemented systems. The results show the effectiveness of implementing IoT monitoring: high-frequency temperature control allows detecting thermal losses in real time and reducing energy consumption. The discussion focuses on practical aspects of application, comparing the obtained data with literary sources and Petrukha's research on innovations in the construction industry. The conclusions summarize that the implementation of intelligent thermal insulation systems with remote monitoring increases the energy efficiency of buildings and contributes to sustainable development, while requiring consideration of cybersecurity and standardization for mass application.

### KEYWORDS

*intelligent thermal insulation, remote monitoring, Internet of Things, heat transfer, energy efficiency, building enclosures.*

## Introduction

Residential and commercial buildings are among the largest energy consumers, accounting for about 34% of global final energy consumption and 37% of CO<sub>2</sub> emissions (Bruno et al., 2021). Heat loss through building envelopes directly affects all of these indicators, so improving thermal insulation is critical for energy conservation and environmental safety. There is also growing interest in building intelligent thermal insulation systems - systems that combine effective insulation materials with built-in sensors and automated control. The construction industry is considered a critical area for reducing its carbon footprint, which is driving the adoption of Internet of Things (IoT) technologies and smart solutions in building infrastructure (Mobaraki et al., 2025).

## Literature Review

Today, there is an active development of IoT solutions aimed at improving the thermal insulation efficiency of buildings. According to recent studies, the implementation of sensor networks allows real-time monitoring of the state of thermal insulation and the influence of external factors. In particular, Abdalgader et al. (2020) proposed an IoT system for measuring the efficiency of wall insulation, which monitors the influence of weather conditions on thermal insulation. This system uses temperature and relative humidity sensors that were connected to an Arduino microcontroller, which sends the collected data to a cloud-based analytical platform (e.g., the ThingSpeak service) for further processing (Abdalgader et al., 2020). This approach is low-cost and provides the ability to aggregate, analyze, and visualize temperature and humidity data online, which is confirmed by experimental tests of the system in various climatic conditions (Abdalgader et al., 2020). The results showed that the use of an IoT sensor network allows for the prompt detection of the influence of weather on heat transfer and provide end users with information to minimize these negative effects.

Another promising direction is adaptive thermal insulation with variable properties controlled by electronic systems. Bruno et al. (2021) developed an innovative wall panel with variable thermal conductivity that can switch between insulating and thermally conductive states depending on the conditions (Bruno et al., 2021). Such a "thermal switch" is built on the basis of internal moving elements that, upon command from an IoT controller, change the structure of the panel (for example, rotate or shift), allowing the level of thermal insulation of the wall to be adjusted dynamically. Modeling and experiments have shown that the thermal resistance of the panel can be changed tenfold in a matter of minutes, moving from a well-insulated state in cold weather to a more thermally conductive state for heat accumulation in winter (Baldinelli et al., 2026). Integration of such a panel with an IoT-based control system allows you to automatically optimize the energy consumption of a building depending on the season: in summer, the panel increases the resistance to reduce heat gain, and in winter, it decreases the resistance for passive heating from the sun (Bruno et al., 2021). This has resulted in a 15-40% reduction in cooling demand compared to conventional static insulation in hot climates (Bruno et al., 2021). This demonstrates the significant potential of intelligent building envelopes that can adapt to external conditions.

At the same time, developers are also implementing modern telecommunication and algorithmic solutions to improve indoor climate control. For example, Woźniak et al. (2020) proposed the concept of using sixth-generation (6G) networks together with IoT to optimize the microclimate of a house based on fuzzy logic (Woźniak et al., 2020). In such a system, high-speed 6G wireless communication provides instant collection of a large amount of data from sensors, and fuzzy control algorithms (type 2) allow for a more flexible response to changing conditions than traditional automation systems. An intelligent controller, using fuzzy logic rules, analyzes temperature, humidity, etc. and provides optimal solutions for heating and air conditioning systems in real time. Thus, the combination of IoT with next-generation technologies opens the way to fully autonomous, self-learning heat conservation control systems in buildings.

In general, there is a clear trend that Industry 4.0 technologies (AI, IoT, digital twins, blockchain) are increasingly penetrating the field of building thermal engineering, increasing its efficiency. A review by Atofarati and Enweremadu (2025) showed that the use of IoT sensors for continuous collection of thermal engineering data, together with artificial intelligence for their processing, allows for predictive heat management and maintenance of heating/cooling systems (Atofarati & Enweremadu, 2025).

For example, digital twins of building systems allow for virtual simulation of heat transfer and optimization of operating modes virtually, and blockchain ensures the security of sensor network data (Atofarati & Enweremadu, 2025). However, the authors also note challenges: large data sets require significant computing resources, the issue of cybersecurity arises, and the need to develop device compatibility standards (Atofarati & Enweremadu, 2025).

In parallel with the implementation of IoT, research is also ongoing into the creation of new materials and composite insulation systems. In particular, Jia et al. (2025) proposed a multilayer facade insulation that combines foam concrete with nanodispersed SiO<sub>2</sub> and vacuum insulation panels (VIP) (Jia et al., 2025). The goal was to create a lightweight panel for external wall insulation with increased heat transfer resistance. This study showed that adding an optimal amount of SiO<sub>2</sub> nanoparticles to the foam concrete structure improves the thermal stability of the material, and the combination of layers “foam concrete - VIP - foam concrete” ensures minimal heat loss (Jia et al., 2025). Heat flow modeling using COMSOL confirmed that this three-layer arrangement demonstrates the best insulation properties among the considered options, surpassing traditional solutions. Although this development does not directly relate to remote monitoring, it complements the overall picture of progress in the field of thermal insulation: both passive (materials) and active (digital) energy saving means are being improved simultaneously.

### Problem Statement

The problem is that traditional thermal insulation materials can lose their properties over time or work less optimally under different conditions, and continuous monitoring of heat transfer in real conditions has so far been almost never carried out. The research direction of this work is the development of “smart” thermal insulation systems with remote monitoring of heat transfer parameters. The purpose of the work is to study the current state of IoT solutions for monitoring the effectiveness of insulation, analyze available methods and assess their impact on increasing energy efficiency. **To achieve the goal**, it is necessary to investigate a number of issues, namely:

- analyze the latest scientific developments in the field of using IoT for thermal insulation of buildings;
- summarize approaches to heat transfer monitoring (sensors, methods, platforms) and their accuracy;
- evaluate the results of the implementation of intelligent systems for monitoring thermal parameters and their effectiveness;
- consider the prospects and challenges (data security, standards, cost) of implementing such systems.

Thus, the study has scientific novelty: a comprehensive overview of IoT in thermal insulation; and practical significance, as intelligent insulation systems can provide energy savings and improve comfort, which meets the goals of energy security and climate protection.

### Methods and Materials

To implement intelligent thermal insulation systems, it is necessary to combine data from various sensors and apply adequate methods for assessing heat transfer. The input data for monitoring are temperature (internal and external), air humidity, heat flow through the wall, and sometimes thermal images. These parameters are collected using a network of sensors integrated into the building structure or installed on its surface. Compared to traditional single measurements, the IoT approach provides distributed multi-point measurement and data transmission in real time.

Heat transfer monitoring methods are divided into direct and indirect. The direct method is a classic measurement of the heat transfer coefficient  $U$  by establishing the heat flux (heat sensor on the inner surface) and the temperature difference on both sides of the enclosure. This approach (heat flux method) is quite accurate, but requires expensive heat flux sensors and a long-term stabilized mode. In modern IoT systems, an indirect method based on temperature measurements, called the Temperature-Based Method (TBM), is gaining popularity, when the  $U$ -value is estimated by calculation from the readings of several thermometers. For example, Mobaraki et al. (2025)

integrated this method into their IoT HEAT system: three groups of sensors continuously measure the temperature of the internal air, on the inner surface of the wall and the external air for different sections of the facade (Mobaraki et al., 2025). The obtained data is fed to a microcontroller, which calculates the current heat transfer coefficient of the enclosure using heat transfer formulas, actually simulating the U-value measurement without using a heat flow meter. This approach significantly reduces the cost of the system (compact, inexpensive sensors are used) and allows for continuous monitoring of U in dynamic conditions (changing temperature, wind, solar radiation, etc.), which is difficult to achieve using traditional methods (Mobaraki et al., 2025).

As an example of a hardware implementation, we can cite a smart device for monitoring window insulation, developed by Mach et al. (2025). This device is a compact module on a printed circuit board with built-in contact temperature sensors (for measuring the glass surface) and a contactless IR sensor for measuring the temperature of the air layer (Mach et al., 2025). The module is equipped with a Wi-Fi transmitter, thanks to which it is easily integrated into smart home systems or BMS (building management systems) (Mach et al., 2025). The principle of operation is to constantly monitor the thermal characteristics of the glass unit - if the efficiency of the glazing deteriorates over time (for example, due to inert gas leakage or a leak), the system records this as an abnormal change in the temperature profile on the window. The collected data is transmitted to a cloud server or a local gateway for further analysis and can be used for adaptive HVAC (heating, ventilation, air conditioning) control (Mach et al., 2025). Experimental tests have confirmed the high accuracy and reliability of this approach, demonstrating the potential of IoT devices for monitoring enclosing structures even in specific cases, such as glazing, where heat losses are traditionally the greatest (Mach et al., 2025).

When building IoT systems for thermal insulation, a modular architecture is usually used: sensors are connected to built-in microcontrollers (Arduino, Raspberry Pi, etc.), which provide data collection and pre-processing (Mach et al., 2025). Arduino most often acts as a central node that polls sensors (via analog/digital inputs or communication buses), and then transmits information to a server via a communication module (ESP8266, GSM, LoRa). There, the data is aggregated in a database, and specialized software performs analytics - calculating U-factors, detecting trends, and notifying about deviations. Thanks to this, the user or the building management system can receive key parameters of the building's thermal behavior in real time and make decisions - for example, turn on the heating if the insulation fails, or plan insulation repairs when materials degrade.

Therefore, the monitoring methodology is based on a combination of environmental sensors, computing modules and network infrastructure, which together form a cyber-physical system. The input data are measured physical quantities, the methods are algorithms for calculating heat transfer and data analysis (including using AI for prediction or noise filtering), and the output is information about the actual efficiency of thermal insulation, accessible remotely via the Internet.

## Results and Discussion

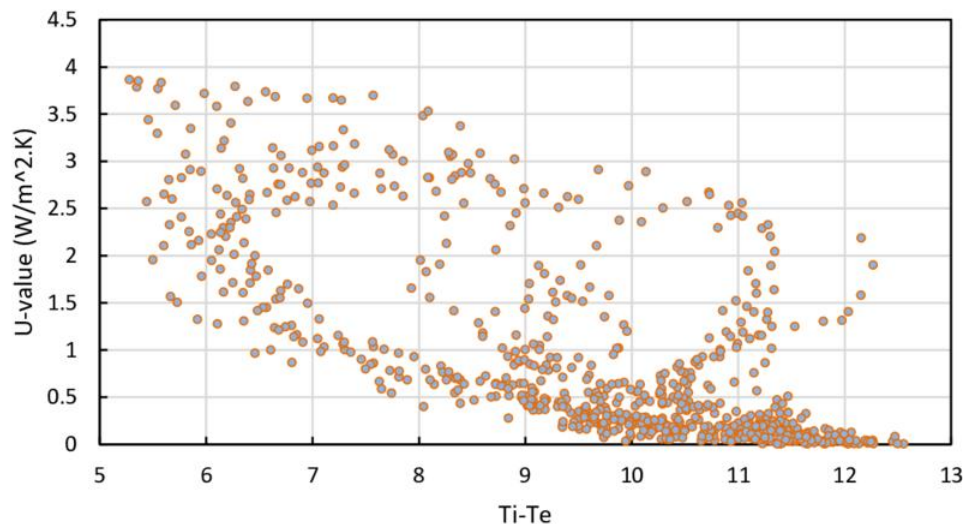
The practical implementation of the described approaches has demonstrated a significant increase in the efficiency of thermal insulation and optimization of energy consumption of buildings. In particular, the results of using IoT monitoring indicate its ability to timely detect heat losses and provide a quantitative assessment of the state of insulation. The already mentioned Abdalgader system (2020) after deployment in real buildings showed that data from temperature and humidity sensors, compared with a weather station, allow us to quantitatively assess the impact of weather (solar radiation, air humidity, wind) on the deterioration of the thermal insulation properties of walls (Abdalgader et al., 2020). This allowed users to make decisions on additional measures: for example, in case of high humidity and wetting of the insulation, reduce ventilation or turn on dehumidifiers to restore its efficiency.

An important indicator of efficiency is the reduction in energy consumption for heating and air conditioning after the implementation of intelligent systems. For example, the use of the adaptive insulation panel Bruno et al. (2021) in a simulation for the Mediterranean climate allowed to reduce annual energy costs for air conditioning by 6-23 kWh/m<sup>2</sup> (which is 15-40% of the baseline scenario) (Bruno et al., 2021). This was achieved due to the fact that the panel automatically switched to "cooling mode" during hot periods, reflecting excess heat, and returned to "accumulation mode"

during cold periods, allowing more solar energy for heating. Thus, it was confirmed that active management of thermal insulation can give a tangible energy saving effect.

Another example is the IoT facade monitoring system by Mobaraki et al. (2025). Its innovation lies in the fact that it allows determining the actual heat transfer coefficient of the building walls based on simple temperature measurements, without expensive devices. The results published by the authors confirm that the IoT HEAT system successfully detects even minor insulation inefficiencies and provides data for making decisions on the modernization of enclosing structures (Mobaraki et al., 2025). In particular, in one of the studied buildings, sensors recorded higher U values on the sections of the walls facing north (compared to the calculated ones), which indicated possible insulation defects or the influence of high humidity. This allowed for targeted repairs and reduction of heat loss through these walls. In general, according to the authors, the implementation of such a system can significantly reduce the operational energy losses of the building due to the timely detection and elimination of insulation problems (Mobaraki et al., 2025).

Fig. 1 shows the dependence of the calculated heat transfer coefficient  $U$  on the temperature difference between the internal and external environment ( $T_i - T_e$ ), formed on the basis of the data flow of the IoT system for monitoring enclosing structures. At small values of the temperature gradient (approximately 5-7 °C), the results have an increased scatter and may give overestimated  $U$  estimates, which is associated with an increase in the relative error of the indirect temperature method with insufficient  $\Delta T$ . As the temperature difference increases to about 10 °C and more, the  $U$  values stabilize and group in the range characteristic of a properly insulated wall, which indicates the achievement of a regime suitable for correct identification of thermal parameters. Therefore, to increase the reliability of remote heat transfer estimation, it is advisable to either select time windows with sufficient  $\Delta T$  for analysis, or apply filtering/weighted averaging, reducing the influence of measurements at small gradients. Also, the graph can be used as an indicator of insulation degradation: a long-term shift of the "plateau" of stabilized  $U$  values towards larger values signals a deterioration in thermal insulation properties (wetting of the material, the appearance of thermal bridges, violation of the tightness of the layers), which creates the basis for preventive maintenance and targeted repair work (Abdalgader et al., 2020).



**Fig. 1. Calculated heat transfer coefficient  $U$  of the enclosing structure ( $W/m^2 \cdot K$ ) depending on the temperature difference between the room and the external environment ( $T_i - T_e$ ), obtained based on data from the IoT HEAT system**

Source: (Mobaraki et al., 2025)

The use of intelligent monitoring systems also contributes to improving comfort conditions in premises. IoT sensors allow to detect thermal imbalances: for example, "cold zones" on internal walls or drafts near windows. Having received this data, the climate control system can more precisely regulate the supply of heat or air to specific zones, eliminating discomfort. In addition, the very presence of feedback from the building (via sensors) allows to implement predictive control: for

example, if a sharp cooling is predicted and according to the current state of insulation it is clear that the building lacks thermal inertia, the system can raise the temperature of the internal air in advance or reduce ventilation to prevent excessive heat loss. Thus, the results of the implementation of intelligent insulation systems are measured not only in the percentage of energy saved, but also in increasing the adaptability and reliability of the operation of building thermal protection systems.

The analyzed results confirm that the integration of IoT technologies into thermal insulation is an effective tool for increasing energy efficiency. The data obtained in various studies are consistent with each other: automated monitoring ensures timely detection of problems (insulation degradation, increased humidity, thermal bridges, etc.) and provides a quantitative basis for making decisions to eliminate them. This means a transition from passive insulation to actively managed thermal protection systems. Such interdisciplinary solutions fit into the general trend of digital transformation in the construction industry. In particular, Ryzhakova et al. (2020) emphasize the need for structural and methodological innovations in construction, emphasizing the role of introducing new technologies to increase the efficiency of enterprises developing construction projects (Ryzhakova et al., 2020). Therefore, the successful application of IoT for thermal insulation monitoring requires not only technical solutions, but also new management approaches, process standardization and specialist training. Intelligent insulation systems should be considered as a component of a smart home and a smart city, requiring coordination between technologists, builders and operational services.

When assessing the impact of implementing IoT monitoring, it is important to also consider possible barriers and risks. First, there is the issue of data security and cybersecurity of building sensor networks. As noted in the review by Atofarati and Enweremadu (2025), the deployment of large-scale IoT systems poses challenges in ensuring information security and privacy, especially if data is transmitted over the open Internet (Atofarati & Enweremadu, 2025). The implementation of blockchain technologies or other encryption tools can partially solve this problem, but this increases the cost and complexity of the system. Second, there is the issue of compatibility and standardization: today there are many IoT platforms (data transfer protocols, cloud services), and the lack of a single standard can complicate the integration of heterogeneous devices. Therefore, in the future, work is needed to develop unified standards for “smart” heat engineering systems, as well as the use of hybrid control models that combine physical heat transfer models with artificial intelligence algorithms for greater reliability (Atofarati & Enweremadu, 2025).

Another aspect is economic feasibility. It is necessary to assess how much the costs of installing and supporting IoT systems are offset by energy savings. It is obvious that for new buildings, the implementation of such technologies is most justified, especially within the framework of the concept of zero energy consumption. For existing buildings, the decision should be made on the basis of an audit: if the building already has significant heat loss, an investment in a monitoring system and further insulation can quickly pay off by reducing energy bills. In addition, it is worth considering indirect benefits: increased comfort, extended service life of building structures (due to moisture control and temperature deformations), etc.

In the context of sustainable development, intelligent thermal insulation systems with remote monitoring are part of a broader paradigm of decentralized energy management. They can interact with other components of a “smart” building – for example, with solar panels, energy storage systems, ventilation with recuperation – and jointly optimize the energy balance. Given the goals of decarbonization and resource conservation, such systems receive support at the state level in the form of incentive programs for energy efficiency. Therefore, it can be predicted that further research and implementation will only intensify, and intelligent insulation will become a standard element of buildings in the coming decades.

## Conclusions

This paper examines in detail modern approaches to creating intelligent thermal insulation systems with remote monitoring of thermal parameters. The literature analysis showed that the combination of highly efficient insulation materials with smart sensors and IoT platforms can significantly increase the energy efficiency of buildings. The review identified a number of key areas: from temperature and humidity data collection systems that allow monitoring the state of insulation

in real time to adaptive structures with variable thermal conductivity that adapt to climatic conditions. Examples of implementation of monitoring methods were considered, in particular, inexpensive IoT devices based on Arduino and Raspberry Pi, which continuously measure temperature and calculate the heat transfer coefficient of enclosing structures.

Intelligent thermal insulation systems with remote monitoring are a promising direction for the development of the construction industry. They allow to move from a passive energy-saving building envelope to an actively managed, "living" system that responds to changes in the environment and user needs. This approach contributes to achieving sustainable development goals, reducing emissions and more rational use of energy in the buildings of the future.

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