

COMPREHENSIVE ON SITE THERMAL DIAGNOSTICS OF BUILDINGS – POLISH PRACTICAL EXPERIENCE

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Abstract

The Polish National Centre for Research and Development has been coordinating the implementation of a strategic research project “Integrated System for Reducing Energy Consumption in the Maintenance of Buildings”. The main goal of the project is to support Poland's efforts to reduce energy consumption in buildings, which is a strategic goal of the European Union. Within the scope of the aforementioned project, Task 4, “Development of thermal diagnostics of buildings”, was realized. Silesian University of Technology in Gliwice was a leader of the scientific-industrial consortium implementing the task. The main objectives of Task 4 and achieved relevant results are presented in the paper. A new method for the rapid on-site thermal diagnosis of a building envelope and systems of heating, ventilation, air conditioning and domestic hot water preparation and the diagnosis of indoor environment quality, as well as a method for drawing up energy performance certificates based on the measurements were developed.

Streszczenie

Narodowe Centrum Badań i Rozwoju koordynowało realizację strategicznego projektu badawczego „Zintegrowany System Zmniejszenia Eksploatacyjnej Energochłonności Budynków”. Głównym celem projektu było wsparcie działań Polski w zakresie zmniejszenia zużycia energii w budynkach, co jest strategicznym celem Unii Europejskiej. W ramach ww. Projektu zrealizowano Zadanie 4, „Rozwój diagnostyki cieplnej budynków”. Politechnika Śląska w Gliwicach była liderem konsorcjum naukowo-przemysłowego realizującego to zadanie. W artykule przedstawione zostały główne cele zadania 4 i osiągnięte wyniki. W ramach tego zadania badawczego opracowana została nowa metoda szybkiej diagnostyki izolacyjności cieplnej budynku, systemów ogrzewania, wentylacji, klimatyzacji i przygotowywania ciepłej wody użytkowej oraz jakości środowiska w pomieszczeniach. Opracowano także metodę sporządzania świadectw charakterystyki energetycznej budynków na podstawie pomiarów.

Keywords: Thermal diagnostics; Building; Heating; Ventilation; Air conditioning; Domestic hot water; Indoor environment quality; Energy performance certificate.

1. INTRODUCTION

Savings of energy in buildings is a priority in many countries. The EU Member States took on the obligation to reach highly energy efficient building stock by 2050. Poland, as a member country of the EU, makes efforts to reduce energy consumption in the building sector. The Polish National Centre for Research and

Development is an agency of the Minister of Science and Higher Education. It is the entity created as the platform for dialogue between the business and scientific communities. The Board of the National Centre for Research and Development prepares and announces competitions for strategic research and development programmes. A strategic programme

comprises projects in scientific, technical, and social areas. The project applicants must meet the criteria defined in the announcements of competitions.

The National Centre for Research and Development has been coordinating the implementation of two strategic research and development programmes: “Advanced Technologies for Energy Generation” and “Interdisciplinary System for Interactive Scientific and Scientific Technical Information”. The Centre has been also coordinating the implementation of three strategic research projects: “Integrated System for Reducing Energy Consumption in the Maintenance of Buildings”, “Work Safety Optimization in Mines”, and “Safe Nuclear Power Engineering Development Technologies”.

The Strategic Research Project “Integrated System for Reducing Energy Consumption in the Maintenance of Buildings” has been carried out since 2010. The Centre has spent PLN 26.6 million in total on the project. The following research tasks, lasting from one to three years, have been realized within the project:

- Task 1. “Study of socioeconomic possibilities and effects of raise in energy efficiency in civil engineering” (contractor – University of Zielona Góra);
- Task 2. “Structure/materials and installations energetically optimal for buildings” (consortium leader – Building Research Institute in Warsaw);
- Task 3. “Increase in the use of renewable energy in civil engineering” (consortium leader – Silesian University of Technology in Gliwice);
- Task 4. “Development of thermal diagnostics of buildings” (consortium leader – Silesian University of Technology in Gliwice);
- Task 5. “Optimization of energy consumption in buildings” (consortium leader – Academy of Mining and Metallurgy in Cracow);
- Task 6. “Analysis of technical and operational constraints for buildings supplied with power from centralized energy sources” (contractor – University of Zielona Góra); and,
- Task 7. “Energy saving conditions and possibilities created by municipal policy instruments” (contractor – University of Zielona Góra).

The purpose of the aforementioned strategic research project was to find technical and organizational solutions regarding designing, construction, and the utilisation of residential and public utility buildings, aimed at reducing their energy consumption and increasing the consumption of renewable energy sources. It was expected that the project will

contribute to the increase of energy efficiency and to the significant decrease in coal consumption and the release of carbon dioxide and other pollutants.

The Silesian University of Technology, after the submission of its proposal, won the competition and, having signed a contract with the National Centre for Research and Development and a consortium agreement, became the leader in the implementation of Task 4 “Development of thermal diagnostics of buildings”. The first author of the paper, Popiolek Z., was the Task 4 manager, while the co-author of the paper, Kateusz P., was a member of the research team and the Task 4 Coordination Office.

In order to carry out the Task, a scientific-industrial consortium was established, which consisted of the following institutions:

LEADER:

Silesian University of Technology, Faculty of Energy and Environmental Engineering, Department of Heating, Ventilation and Dust Removal Technology, Gliwice;

PARTNER 1:

Silesian University of Technology, Faculty of Civil Engineering, Department of Building Engineering and Building Physics, Gliwice;

PARTNER 2:

Silesian University of Technology, Faculty of Electrical Engineering, Institute of Measurement Science, Electronics and Control, Gliwice; and,

PARTNER 3:

Industrial Park of Upper Silesia Ltd. (Górnośląski Park Przemysłowy Sp. z o.o.), Katowice.

The purpose of this task was to develop and disseminate a new tool for the thermal diagnosis of various kinds of buildings, which consists of a simplified procedure for on site measurements and specialized equipment and software for the acquisition and interpretation of measurement data. It was assumed that the following goals should be reached:

- a) The development of a new, rapid method for (1) the on site thermal diagnosis of a building envelope and systems of heating, ventilation, air conditioning, and domestic hot water preparation, and (2) the diagnosis of indoor environment quality, and the development of a method for the measurement based drawing up of energy performance certificates;
- b) The development and construction of (1) a wireless measurement system assisting the rapid on site thermal diagnostics of a building, and (2) a soft-

were supportive of the interpretation of the obtained results;

- c) The preparation of the developed methods and tools for implementation in the community of people involved in energy performance certificates or energy audits, as well as the preparation of training materials and methods for the scientific and engineering staff in the field of thermal diagnostics of buildings.

2. SCOPE OF TASK 4

Thermal diagnostics of a building includes the identification and assessment of key elements affecting the consumption of heat in the building, such as the building envelope, heating, ventilation, air conditioning and domestic hot water systems, the indoor environment, and building exploitation. The partial diagnoses must be properly integrated and, thus, lead to the determination of the heat consumption of the building as a whole. The result should provide clear information on the building thermal insulation and on the efficiency of systems of heating, ventilation, air conditioning, and domestic hot water. The specified thermal characteristics of the building should provide data for any action of the thermal upgrading of the building.

Rating the energy performance of the building envelope is often difficult due to the lack of documentation for existing buildings on Polish territory. The documentation of older buildings either generally does not contain the information necessary to properly calculate the heat loss through the building envelope or provides information inconsistent with the actuality. Therefore, it was a need to develop practical methods and measurement tools to determine the insulation characteristics of walls.

In Poland, there has been no implemented method for rapid, comprehensive diagnosis of the individual heat source and heating systems. In assessing the heat sources, different types of sources should be taken into account: gas, oil and solid fuel boilers, electric compressor heat pumps, solar collectors, and heat exchangers used for receiving heat from the district heating network. The method of diagnosis should allow one to interfere in the efficiency of the heat source and to establish roads leading to the following:

- a) Improving energy efficiency, safety and reliability of the source;
- b) The reduction of emissions; and,
- c) The minimization of the total cost per unit of heat produced.

With regard to the ventilation and air conditioning systems, it was expected to develop methods for determining the energy consumption appropriate for rapid on-site diagnosis. It was assumed that diagnosis should include the following:

- a) The collection of the data based on the technical documentation;
- b) A description of the system divided into subsystems that are subject to separate diagnoses;
- c) The performance assessment and verification of the compliance by all subsystems of ventilation and air conditioning systems with the design data and the real demand for air, heat and cold;
- d) The determination of the actual energy consumption by the subsystems;
- e) The assessment of ventilation and air conditioning systems in terms of the modernity of the solutions and the technical condition of the installation;
- f) The evaluation of building envelope leakage (air tightness); and,
- g) The combinations of different techniques to be used, namely, measurement, computation (simulation), observation, and questionnaire.

While assessing energy consumption, attention should be paid to indoor environment quality (i.e., thermal comfort and air quality). Energy savings must not be done together with the deterioration of the indoor environment quality. In order to conduct thorough and objective assessment of energy consumption in buildings, it is also necessary to know all influencing quantities, including the system operation mode (such as lowering the temperature during a night or turning off the ventilation in the absence of occupants), and the behaviour of the users themselves (such as opening windows, the choice of a thermostat setting, etc.).

Diagnostics based on measurements can be a valuable source of knowledge about the actual energy needs of the building. It may provide useful data for the assessment of compliance with design goals. This assessment is comparative in nature by reference to the standard, so it is necessary to standardize the process parameters and develop suitable methods for converting the results to standard conditions. Because the energy consumption measured in a short term of the heating season is not representative and comparative in size, it was important to develop a method of determining seasonal heat consumption based on short-term, fragmentary measurements in the building. It is important to select a suitable measuring period used to convert, with required accuracy.

cy, the measured energy consumption into the consumption of a whole season or year.

3. RESULTS

On-site diagnostics of building thermal insulation

In the frame of Task 4, a method was developed for the rapid diagnostics of the thermal insulating power of outer walls that applies the measuring instrument for overall heat transfer coefficient that has not been used earlier. The method was tested in laboratory and field conditions. The laboratory tests consisted in the calibration of both the thermographic method and the rapid-measurement method using an instrument under testing and the thermovision technique. The results of laboratory tests were verified on real existing buildings. Different outer walls in over a dozen selected buildings were put through an examination, and successful results were obtained. At the same time, strenuous work was being performed that comprised the identification of the outer walls in the building objects that have been raised in Poland for the last hundred years. Several hundred specialist publications, including the ITB (the Polish Building Technology Institute) Guidelines, manuals and catalogues, were analysed. Surveys of several hundred different buildings in Poland from the point of view of the structure of vertical and horizontal walls were made. The end effect of the completed investigations is the development of a handbook entitled "On-site diagnostics of building thermal insulation" [1] (in Polish; see Fig. 1). The handbook contains an electronic catalogue of building walls as well as a catalogue of the thermograms of walls, also those with typical thermal defects. The digital catalogues are put on a CD accompanying the handbook. These catalogues are the first ones in Poland to assist the work in the thermal diagnostics of buildings.

On-site diagnostics of heat sources and heating and domestic hot water installations

The aim of the developed diagnostic method is to establish the technical state of the heating installations and the heat source in respect of energy efficiency and the reliability in obtaining the required conditions in the building under consideration, and the operational safety of the heating system as well. The method under discussion results from uniting different techniques: measurement, computational, observation and questionnaire ones, with the suitable effectiveness of the resultant method of rapid diag-

nostics being the goal. The above mentioned sequence of the techniques that can be applied simultaneously represents the recommended preference for using them, whereby the feasibility and expected accuracy should be treated as the basic criteria for the selection of a particular technique. In the instance of the on site diagnostics of a heat source, the diagnostic activities refer to heat sources containing a heating boiler or an electric compressor heat pump, or solar plant, and heat sources in the shape of heating stations. In addition to those procedures, which regard the heat sources, methods were presented for the determination of heat power demand for heating that embody both known and new, original proposals. Within the diagnostic procedure that pertains to the method in question, two stages have been distinguished, namely, survey and diagnostic measurements. The task of the survey is to establish the following: (a) the general operating state of the central heating and hot water supply systems and the heat source, including its departure from an assumed (design, required) one, (b) low cost actions for restoring the required state, and (c) general recommendations for corrective and improving actions for the operation of the systems. The execution of the actions as indicated in the framework of the survey, aimed to remove undesirable, temporary features (due to exploitation defects) in favour of ensuring the persistent normal features, is also treated as the preparation of the heating system for possible diagnostic measurements. The formulation of the general recommendations concerning corrective and improving actions for the operation of the central heating and hot water supply systems and the heat source is of particular significance when the thermal diagnostics ends at the survey stage. The purpose of the diagnostic measurements is to identify the persistent features of the heating system (i.e. to identify the state pertaining to the post survey period), which cannot be ascertained without specialized methods and measuring apparatus. Based on the diagnostic measurement results, one can specify detailed activities serving to improve the operation of the central heating and hot water supply systems and the heat source, and also establish the thermal performance of the building. While the method was being developed, tests of the devices, including the checks on their functional attributes, were conducted both at laboratory stands and in selected buildings. Certain trials of diagnostics were realized in several buildings with the object of verifying the designed procedures, measuring apparatus, measurement sheets, and questionnaires. The procedures, measurement sheets, and questionnaires were

drawn up separately for heating boilers, heat sources with electric compressor heat pumps, source systems with solar collectors, heat exchanger stations, central heating installations, and hot water systems. The methodology of comprehensive inspection and diagnostics of heating and domestic hot water systems was presented in the paper [2]. The scope of basic activities that should be performed were outlined and the practical application of such diagnostics in several buildings was also presented.

The end effect of the completed investigations was the production of a handbook entitled “On-site diagnostics of heat sources and heating and domestic hot water installations” [3] (in Polish; see Fig. 1).

On-site diagnostics of sources of cold and ventilation and air conditioning systems

An analysis of literature reports such as standards, EU directives, documents on existing diagnostics methods and surveys of ventilation/air conditioning systems and sources of cold, and the related recommendations was made. It gave a foundation for developing and verifying original methods and procedures concerning the survey and diagnostic measurements within this part of the Task. Methods of diagnostic measurements and the survey of sources of cold and mechanical ventilation and air conditioning systems were worked out. Moreover, methods of the diagnostic measurements and survey for natural ventilation systems were developed. The prepared diagnostic methods were tested on selected units and systems of ventilation and air conditioning. Results of diagnostics of cooling sources and mechanical ventilation systems in two office buildings are presented in [4,5]. The end effect of the completed investigations was the production of a handbook entitled “On-site diagnostics of cooling sources ventilation and air conditioning systems” [6] (in Polish; see Fig. 1).

On-site diagnostics of indoor environment in buildings

As a result of the research that was carried out, a method was developed for the assessment of indoor environment quality, while taking into account the thermal environment and air quality. The method contains the procedures that are used in the case of buildings with natural ventilation as well as buildings equipped with mechanical cooling. Guidelines were presented here for the selection of measuring instruments and the procedures for conducting measurements with a division of diagnostic measurements into basic and detailed ones. A description was also provided of how to run questionnaire tests. A selection of proper assessment criteria was given together with the

means of the handling and presentation of the results. Practical directions for applying the method and examples of conducting the diagnostics are to be found in the handbook “On-site diagnostics of indoor environment in buildings” [7] (in Polish; see Fig. 1).

Measurement system for thermal diagnostics of buildings

A system was constructed serving for measurements resulting in the determination of thermal state of buildings being operated. This is a portable system, which may be mounted in different sorts of buildings for a period enabling the representative data sets on the state of the building object to be obtained. The solutions used allow thermal measurement apparatus that is available on the market to be integrated into the system. Additionally, in the system, one can use different types of sensors, namely using voltage or current, or resistance output, being connected by means of a constructed universal microprocessor unit called an analogue module. The measuring devices, arranged into nodes, use wire transmission in the RS232 and RS485 standards, while the communication between the nodes and the local computer that supervises the measurements is realized as a wireless transmission in the ZigBee standard. This computer can be connected, via the Internet, with computers that permit remote measurement control; however, in the absence of accessible direct connection with the computer network, it is possible to make use of the mobile network. The system is characterized by large structural flexibility, which allows the system to be relatively simply adapted for executing thermal measurements in different kinds of building objects, including multi storey ones or those consisting of many buildings. The measurements can be carried out continuously through many days, and due to the possibility of the remote control of them via the Internet, the operator is relieved of the duty of a permanent presence in the object under test. In the version of the system that has been constructed, it is possible to use more than 100 instruments and analogue modules.

Comprehensive on-site thermal diagnostics of buildings in practice

The developed method of complex thermal diagnostics of a building was exemplified by eight different buildings. Two single family houses, two multi family residential blocks, one school, one museum, and two office buildings were selected for tests. The performed

diagnostic tests consisted in (a) making an inventory of the buildings in terms of construction and equipment, (b) performing the complex thermal diagnostics of the buildings, and (c) drawing up the energy performance certificates for the buildings based on the measurements and calculations according to the currently binding method. The complex thermal diagnostics included the diagnostics of the thermal insulating power of the building, the survey of the heat source, the survey of the central heating and hot water supply systems, the measurement of the heat source efficiency, the measurement of energy consumption for central heating and hot water supply purposes, the measurement of tightness of the building envelope, the measurement of total ventilation air flow rate and distribution, the measurement of temperature in the air conditioning handling unit and installation, the measurement of heat/cold supply for ventilation air, the measurement of heating/cooling capacity of the handling unit, the measurement of electric energy consumption of the fans, the measurement of energy consumption and efficiency of the cold producing devices, and full indoor environmental diagnostics (see Table 1). The end effect of the completed investigations was the production of a handbook entitled "Comprehensive on-site thermal diagnostics of buildings in practice" [8] (in Polish; see Fig. 1).

Building energy performance certificates based on measurements

A method was developed to determine the energy performance of buildings based on the on site measurements carried out in buildings that are in use in the course of performing these measurements. The energy consumption that is determined for a standard season using the measurement results coming from the actual season constitutes a predicted value of energy consumption under standard climate conditions and, at the same time, for real, average operational conditions of a building object. The method of the determination of measurement based energy performance of buildings was developed by making resources out of the analysis of the results of the measurements that were made in eight different buildings and also the analysis of simulation calculation results. An energy signature method using linear regression was suggested for buildings with natural ventilation to calculate heat consumption in a standard heating season as described in Polish standard EN 15603:2008.

The impact of building thermal insulation, airtightness, and the value of internal gains on the accuracy of seasonal heat demand determination based on the

measured heat consumption in the short term is presented in papers [9-11]. In order to extend the scope of analysis they were conducted based on actual measurements and the results of the simulation. For the purpose of the determination of heat consumption based on measurement periods lasting less than one month, as well as in the case of buildings with mechanical supply or supply-exhaust ventilation, a balance method was suggested using the heat flow rate balance in a building with the assumption of the steadiness of the processes described in the balance.

The balance approach was verified in the occupied multifamily building. The building heat consumption in the standard heating season based on measurements carried out in the real building in a short time period of the actual heating season was forecasted. The 14-day measurement period was examined as a shortest possible in view of the accuracy of results [12]. As for the determination of cold consumption over a standard cooling season for buildings equipped with a cooling installation, two methods were suggested: the $H-m$ method and the balance method. $H-m$ method is based on linear regression between H - which is the ratio of the average power delivered to the building in a given day to the difference of internal and external temperature, and the value of m which is a "meteorological" variable defined as the ratio of the solar irradiance to the difference of internal and external temperature, according to EN 15603:2008). In the paper [13] the possibility of using the $H-m$ method in the office building was analyzed. It has been shown that the determination of energy consumption for cooling in the cooling season is possible only based on the cooling power measurements in the building in the entire cooling season. Determining this value based on short on-site measurements is not possible due to the high uncertainty.

For establishing remaining components of energy performance of a building, i.e. energy consumed for preparing hot water, built in lighting and auxiliary purposes, it was proposed to apply calculation formulas from the regulation on the methodology of drawing up building energy performance certificates, whereas the input data should originate from the measurements and the diagnostics concerning the building and the installations. A handbook entitled "Method for drawing up a building energy performance certificate based on the measurements" [14] (in Polish) was produced; see Fig. 1.

Table 1.

Diagnostic activities realized in the frame of the sample comprehensive on-site thermal diagnostics performed for selected eight existing buildings

| Diagnostic activities | Type of the building | | | | | |
|--|-----------------------|------------------------|--|--------|--------|------------------------|
| | Single family house I | Single family house II | Five and eleven storey multi-family houses | School | Museum | Office building I & II |
| Diagnosis of the building thermal insulation | + | + | + | + | + | + |
| Survey of heat source and heating and domestic hot water installations | + | + | + | + | + | + |
| Measurement of heat source efficiency | + | + | + | + | + | + |
| Measurement of energy consumption for heating and domestic hot water preparation | + | + | + | + | + | + |
| Measurement of the building envelope air tightness | + | + | + | + | + | + |
| Measurement of the supply and exhaust ventilation air flow rates | + | + | | | | + |
| Measurement of air flow in the ventilation exhaust grilles | | | + | | + | |
| Air change rate measurement based on the changes of concentration of metabolically generated CO ₂ | | | | + | + | |
| Efficiency measurement of the ground heat exchanger | | + | | | | |
| Efficiency measurement of the recuperator and its electric power consumption | + | + | | | | |
| Temperature measurement in the AHU and in the air conditioning installation | | | | | | + |
| Measurement of energy consumed for the heating and cooling of the air | | | | | | + |
| Measurement of the heating and cooling capacity of the AHU | | | | | | + |
| Measurement of electric energy consumed by the fans | | | | | | + |
| Measurement of the energy consumption and the efficiency of the source of cold | | | | | | + |
| Complete diagnostics of the indoor environment quality | + | + | + | + | + | + |
| Issuing the energy performance certificate based on measured energy consumption | + | + | + | + | + | + |
| Issuing the energy performance certificate using the calculation method | + | + | + | + | + | + |
| Inventory of built-in lighting and auxiliary equipment | | | | + | + | + |

**Figure 1.**

A six volume handbook on thermal diagnostics of buildings as being a result of Task 4. “Development of thermal diagnostics of buildings” in the Strategic Research Project “Integrated System for Reducing Energy Consumption in the Maintenance of Buildings”

4. SUMMARY

Methods for (1) the rapid on-site thermal diagnosis of a building envelope and systems of heating, ventilation, air conditioning and domestic hot water preparation, (2) the diagnosis of indoor environment quality, and (3) preparing energy performance certificates based on the measurements were developed. Task 4. "Development of thermal diagnostics of buildings" of the Strategic Research Project "Integrated System for Reducing Energy Consumption in the Maintenance of Buildings" was accomplished according to the contract; all the planned results were obtained and assumed objectives reached.

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