ABSTRACT

of the doctoral thesis (PhD): **"Development of hardware and software-methodical complex for automated energy audit of buildings based on wireless sensor systems"**

submitted for the degree of Ph.D in specialty 6D071700 – "Heat Power Engineering"

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Relevance of work. Sustainable development of the economy of Kazakhstan is impossible without addressing the problems of increasing energy efficiency and energy saving. Activities in this area will contribute to the modernization of industry, electrical power engineering, housing and public utilities and transport sectors, by stimulating the use of modern technologies and innovations. In this regard, the leadership of Kazakhstan, despite significant reserves of energy resources and developed energy infrastructure in the country, has chosen a course for energy saving and energy efficiency as the main priorities of the country's energy policy. With the adoption of the "Strategy of Kazakhstan 2050" and the Concept of the transition to a "green" economy, the country has chosen a fundamentally new way of development of the society. According to the Concept, a key role will be played by the direction of state policy to reduce the impact on the environment, energy saving and the achievement of a high level of the quality of life of the population[1].

Since 2012, a number of legislative acts have been adopted in Kazakhstan [2,3], defining the basic requirements in the field of energy efficiency. The main document is currently the Law "On Energy Saving and Energy Efficiency Improvement", according to which all subjects of the state energy register must pass mandatory energy audit at least once every five years. The government of the Republic of Kazakhstan also set a goal to reduce the energy intensity of GDP by at least 40% by 2020 from the level of 2008 [1].

On average, residential buildings in Kazakhstan consume three times more energy per unit area than in the Northern Europe countries. Energy audit of buildings conducted within the framework of the UNDP project showed that the energy consumption of residential buildings in Kazakhstan averages 273 kWh per m^2 per year, which is several times higher than consumption in developed countries [1]. A comparison of the individual heat consumption of buildings in different countries is presented in accordance with figure 1.

The housing sector consumes about 11-13% of electricity and 40% of the generated heat energy. According to experts, thermo-technical characteristics of 70% of buildings (especially those built in the 1950s-1980s) do not meet modern requirements. The housing stock of the Republic of Kazakhstan is more than 270.9 million square meters of the total area, of which 50.1 million square meters or 32% of the housing stock belonging to multi-apartment houses needs various types of repair and thermal upgrading [4]. The duration of the heating season in different regions of the Republic of Kazakhstan ranges from 3,500 to 5,000 hours per year.

From the total heat energy consumption in the amount of 175.2 million GCal, about 74.8 million GCal is accounted for by heating and hot water supply of housing stock. In 2012, final energy consumption in the housing sector amounted to 9.96 million tons of oil equivalent or 18% of total primary energy consumption. The above listed facts testify to the huge potential for energy saving in the country's housing stock, for the precise determination of which it is necessary to use an effective and qualitative method for conducting an energy audit and take appropriate energy-saving measures.

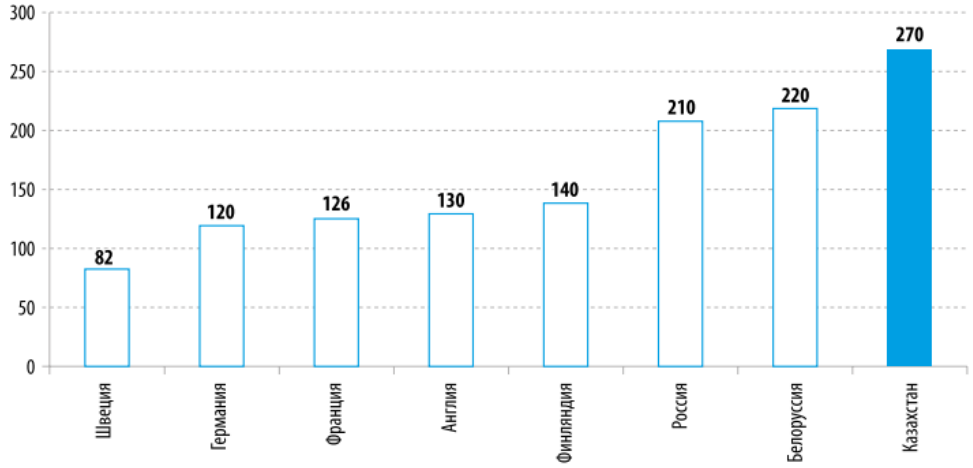

Figure 1 - Comparison of individual heat consumption in buildings, kWh / m^2 per year

After the adoption of the Law "On Energy Saving and Energy Efficiency Improvement" from 2012, there is a sharp increase in the number of energy audit companies. At the moment in Kazakhstan, energy audit services are provided by 110 companies, 26 of which are members of the Kazakhstan Association of Energy Auditors.

Attention should also be paid to the rapid pace of development of the energy service market in Kazakhstan, the basis of which is the drafting of an energy service contract using the mechanism of public-private partnership, on the fundamental importance of which the President of the country stressed in his message to the people of January 31, 2017. This is also mentioned in Step 59 of the Plan of the Nation - 100 specific steps of the Head of State: "Involvement of strategic investors in the sphere of energy saving through the internationally recognized mechanism of energy service agreements; it’s main task is to stimulate the development of private energy service companies to provide a range of energy saving services with reimbursement of their own expenses and to receive financial profit from the actually achieved energy savings ".

Conducting energy audit is a laborious and expensive service. According to the company "Energy partner" the cost of energy audit of the building varies from 200 tenge per m2, i.e. to conduct an energy audit of a building with a total area of 5,000 m2, the customer must pay 1 million tenge. The deadline for an energy audit depends on the area of the building and the number of energy auditors involved, and can range from one month to one year. Taking into account the tasks set by the state in the field of energy saving, the volume and condition of the housing stock

of the Republic of Kazakhstan, the total cost of energy audit of the housing stock, according to preliminary calculations, may amount to more than 54 billion tenge and will require large time costs.

At present, the following main problems of energy audit of buildings and implementation of tasks of energy service companies in Kazakhstan can be singled out:

1) Insufficient reliability of the results of energy audit - during the measurements it is not taken into account that the conditions under which the measurements are performed may differ from the actual operation modes in different periods of operation;

2) When compiling the energy balances of objects, their actual state and modes of use are not taken into account, which does not allow to reliably estimate the reliability, technical feasibility and economic validity of recommendations for the entire life cycle;

3) There is no major stage - "input control" of the quality and completeness of the source information, unreliability and distortions in which lead to deliberately erroneous conclusions and recommendations;

4) Systemic interference of recommended measures is not taken into account, as a result, as a rule, an unjustifiably overestimated energy-saving potential is formed;

5) The rules for conducting energy audits developed by the Government of the Republic of Kazakhstan do not contain information on the required volume of measurements at the enterprise, the depth of research, which indicates an independent choice by energy audit companies of the required volume of instrumental research and the depth of study, and as a rule to minimize costs, companies seek to reduce the amount of research that affects the quality of research results;

6) High cost of technical means;

7) Low labor productivity of auditors and, accordingly, high cost and duration of work, which also affects the quality of the data.

To solve the above-mentioned problems, a new solution is proposed - the creation of a hardware and software-methodical complex (HSMC) for automated and centralized energy audit of residential and public buildings, which has a set of new qualities that allows to multiply the productivity of auditors, the objectivity and reliability of audit results, significantly reduce the cost and duration work, and also to reach the final result - real energy saving with increasing energy efficiency, reliability and safety of buildings, power plants and utility systems.

The purpose of the thesis is the development of a hardware software-methodical complex that has new qualities, which allows to multiply the productivity of the auditors' work, the objectivity and reliability of the audit results, and significantly reduce the cost and duration of work. In addition, the results of energy research using HSMC will help determine effective measures to achieve real energy savings with increasing energy efficiency, reliability and safety of buildings, power plants and engineering systems.

The main tasks of the work:

1. Analysis of modern technologies, technical means, methods and software products used in energy audits of buildings.

2. Drawing up the concept of simulation of energy balance of buildings, based on continuous observations of internal and external factors and models of heat and mass transfer processes of the objects under study.

3. Development of a simulation model for the energy balance of buildings, taking into account the dynamics of the complex influence of internal and external parameters of the building and the environment.

4. Development and implementation of software products (SP) required for the hardware software-methodical complex (HSMC), functioning on the basis of the proposed methodology for calculating the energy balance of the room.

5. Development of algorithms for the automation of the formation, adjustment and calibration of the simulation model based on the results of instrumental observations in real time, allowing to create a digital counterpart of the object under study.

6. Development of the concept of energy research of buildings on the basis of the digital counterpart of the object under study.

7. Designing, collecting and implementing the wireless sensor system and ensuring its full integration with the developed SP.

8. Conducting experimental studies of the energy balance of the room using the developed HSMC.

9. Processing and analysis of the results of experimental studies, and its comparison with the results of calculations of the simulation model in order to verify the adequacy of the model, as well as to evaluate the effectiveness of the proposed techniques, software products and HSMC's hardware.

The scientific novelty of the research is:

1. A new concept of simulation modeling of the energy balance of buildings based on continuous observations of internal and external factors and models of processes of heat and mass transfer of the investigated objects is proposed.

2. A new method for determining the heat losses of buildings associated with natural and/or forced ventilation based on continuous measurements of temperature, humidity and the concentration of carbon dioxide in the air is proposed.

3. A new method for indirect measurements of heat input from people in the room is proposed.

4. The structure and composition of the system for energy research of buildings and structures based on a wireless sensor network has been developed.

5. Software products for automated energy audit of buildings and structures with the function of automatic calibration of individual parameters have been developed.

6. A method for modeling heat exchange through opaque enclosing structures is proposed.

7. The concept of energy research of buildings based on a digital counterpart is proposed.

8. A fully functional system for automated energy research has been created. Long-term tests and experimental energy studies using the developed HSMC were carried out.

Reliability of work. The obtained results have the necessary degree of reliability, for the following reasons:

– when performing a comparative analysis of existing and developed methods for solving heat transfer problems through enclosing structures, the most accurate mathematically-oriented high-level modeling tools, such as Matlab, Labview have been used;

– the results of experimental studies and dynamic numerical simulation coincide, with a small error.

The reliability of the work is also supported by a systematic approach to conducting experiments, a high degree of accuracy of measurement systems.

The following provisions are made for protection:

– developed analog models of typical opaque enclosing structures, represented in the form of transfer functions, for a simplified and rapid calculation of the heat transfer of enclosures;

– the method and subroutine for automatic calculation of heat losses of buildings associated with natural and/or forced ventilation;

– the method and subroutine for automatic calculation of heat input from people;

– the concept of energy research of buildings based on a digital counterpart;

– developed software products and hardware as new tools for automated energy research of buildings and structures.

The practical value of the work is:

– development of a new methodology for determining the actual value of the specific heat consumption for heating and ventilation of a particular building, taking into account its heat engineering, design features and operating conditions;

– application of the developed HSMC as a tool for energy research and interpretation of its results;

– possibility of HSMC’s application for creation of automated embedded systems for optimal control of energy supply of buildings;

– the development of the HSMC, which allows to significantly reduce the financial costs and timing of energy research projects.

Approbation of the thesis results. The main results of the dissertation work were tested at international scientific and practical conferences and forums:

– International conference "Environmental and climate technologies" CONECT 2015, with international participation (Riga, 2015);

– International conference on cogeneration, small-scale power plants and centralized power supply (Bangkok, 2016);

– VI-th international scientific and technical conference " Kazakhstan-cold 2016 "(Almaty, 2016);

– VI-th international conference on thermal equipment, renewable energy and rural development, "TE-RE-RD 2017" (Romania, 2017).

Publications. The main provisions of the work are presented in 10 publications, including 5 editions recommended by Committee for Control in the Sphere of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan, in the journal "Journal of Engineering and Applied Sciences", "Medwell Journals" included in the Scopus database, and in 4 international scientific conferences and forums .

Personal contribution of the author is:

- in conducting comparative analysis and generalization of the literature data;
- in the development of a dynamic simulation model of the energy balance of the room;
- in the development of software and hardware products of HSMC;
- in planning, organizing and conducting experimental research, processing and generalization of the results obtained;
- in the development of new technical solutions.

Volume and structure. The thesis contains an introduction, 4 sections, conclusion, list of used literature, appendixes. The thesis is set out on 143 pages of a computer typing, including 86 pictures and 17 tables, 68 formulas, a list of literature from 131 titles.

The introduction substantiates the urgency of the research problem, presents a general description of the field of research, sets out the purpose and objectives of the study, describes the scientific novelty, the practical significance of the thesis, articulates the provisions to be defended, describes the validity and reliability of the results obtained in the work.

The first section reviews and analyzes existing technologies and methods for conducting energy research of buildings and structures. The software complexes used for processing the results of energy audit are considered and analyzed. For each software package, technical features, functional characteristics and disadvantages are revealed. The chapter presents standard and extended lists of the composition of information-measuring complexes and technical means for conducting energy audit of buildings. In accordance with the goal, research objectives are formulated.

The second part of the thesis describes a new concept of dynamic simulation and calculation of energy balance of buildings based on continuous observations and the complex influence of internal and external climatic factors. A new method for determining the heat losses of buildings associated with natural and/or forced ventilation based on continuous measurements of temperature, humidity and carbon dioxide concentration in the air is developed, making up an alternative to the costly method of assessing the air permeability of fences using blower door. A new method of indirect measurements of heat input from people in the room under study was developed. This method consists in determining the current value of the number of people, due to the measured rate of growth of CO_2 concentration in the room. Also, a method for simulating heat transfer through opaque enveloping structures was proposed and justified, and the possibility of using the proposed

method was proved by replacing laborious solutions of differential equations with simple and accessible transfer functions. The concept of a digital counterpart of the room is developed, possessing a number of new qualities and advantages.

The third section contains a complex of software products for HSMC with a full description of the algorithms of work developed in the LabView programming environment. The developed software products function on the basis of the methodology for calculating the energy balance of buildings proposed in this thesis. Also created a wireless sensor system, which includes the designed and assembled four main types of sensor blocks.

The fourth section presents the results of experimental studies of the energy balance of the room, obtained with the help of the developed HSMC's WSS. The evaluation of the microclimate of the room under investigation was made, the comparative analysis of the calculated and actual specific characteristics of the heat energy consumption for the heating and ventilation system of the building is given. Based on the continuous measurements of the energy parameters of the room, savings were made for heating if natural heat input into the room was taken into account. The results of the analysis of the dynamics of daily indicators of the energy balance of the room are presented. Also, based on the results of experimental studies and the method of frequency analysis of objects, the coefficients of transfer functions of the digital counterpart of the room were determined. The adequacy and accuracy of the developed dynamic model was evaluated from the results of experimental studies.

In conclusion, the main results of the work and conclusions on the thesis work are formulated.