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Transient Energy Models of Housing Facilities Operation

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Abstract: Buildings are the main consumer of energy resources in the total energy balance of the countries in Central and Eastern Europe, the main energy consumption is allocated for heating. Efficient use of energy resources for heating needs to a large extent depends on the efficiency of regulation of heating systems. In the article, dynamic mathematical models of a two-room typical apartment in Ukraine, built in 2016, were developed in Matlab and EnergyPlus software environment. The simulations were carried out using IWEC hourly climate data for the city of Kyiv. The results of simulations of thermal energy consumption in Matlab are characterized by a larger range of fluctuations of the heating system load, which is typical for the real operating conditions of the system with the controller of ON/OFF type. In EnergyPlus it is assumed that the gas boiler operates continuously in the ON mode. In the research, the change of load on the apartment heating system was studied at different numbers and locations of air temperature control sensors installation, according to which the controller of the autonomous gas boiler operates.

Keywords: dynamic modeling, simulation, temperature, heating system load, controller, Matlab, Simscape, Simulink, EnergyPlus

1. Introduction

Buildings are one of the main consumers of primary energy resources in the world. For countries with continental and sharply continental climates, heating costs account for more than 85% of energy costs.

Poor indoor temperature control is the most common indoor heating issue for centrally heated households in China (Lu et al. 2021). The article (Lu et al. 2021) focuses on the development of dynamic indoor temperature control approaches. The system developed in the article (Lu et al. 2021) allows DHS to provide heat to a group of buildings with the same temperature demand, while assuring control with a single control system. However, for residents of apartment buildings with an autonomous heating system (usually a gas or electric boiler), the adjustment of the heating system automation is carried out without taking into account a number of influential factors. The energy saving potential for elementary schools with resident-centered controls was assessed in a paper (Ye et al. 2021) for 96 schools in different climate zones; finding out that the energy saving potential ranged from 10.2% to 12.41% depending on the climate zone in the U.S. Building Energy Management Systems (BEMS) have consistently received attention as an effective building control system (Perera et al. 2016, Perera et al. 2015) that requires the use of building energy modeling (BEM). These systems currently work with classical control methods such as ON/OFF, PID control (proportional-integral-derivative controller), and optimal start-stop procedures. The thermal interaction between the different areas of the building and HVAC (Heating, Ventilation and Air-Conditioning) leads to different behaviors that cannot be accurately controlled by classical control methods (Perera et al. 2014). Thus, advanced control systems that can handle multiple inputs and multiple outputs are the best approach to control the thermal condition of buildings and thermal comfort (Deshko et al. 2020b). In addition, with the efficient use of energy resources in the direction of achieving NZEBs in HVAC systems, the study of ventilation systems requires special attention (Bilous et al. 2020, Deshko et al. 2020a).

In the article (Saleh et al. 2016) a comparative analysis of ON/OFF type controllers and PID controllers used to control heating systems in terms of comfort conditions and energy efficiency of buildings. The study (Saleh et al. 2016) showed that the use of Simulink / Matlab has a very high potential for the analysis of control strategies and for taking into account the thermal and other characteristics of the building. ON/OFF controllers are most commonly used because of their constructive simplicity, although great savings in energy-saving modes of operation and providing comfort conditions are better realized by PID controllers. Simulation results (Saleh et al. 2016) showed that buildings with high thermal mass can significantly reduce the air temperature fluctuations in the rooms, which leads to a decrease in energy consumption. Buildings of Ukraine belong to buildings with high thermal mass.

A paper (Kull et al. 2020) analyzed energy consumption for a room with underfloor heating, where local ON/OFF controllers typically regulate the air temperature with poor accuracy. Proportional-integral (PI) controllers are known to be able to accurately regulate most processes (Kull et al. 2020). For NZEBs homes, water heating systems have greater inertia and thus will require more precise adjustment. When the air temperature deviates ±0.5 K from the setpoint, the energy consumption for heating is reduced by 9...5% when using PI controllers compared to an ON/OFF controller, the analysis was done in the Matlab software environment (Kull et al. 2020). In (Võs et al. 2019), energy use for radiator and underfloor heating systems coupled with ON/OFF and PI controls was investigated using the IDA ICE software package. The results of experimental measurements in early 2018 at the nZEB test facility (representative room) near Tallinn University of Technology are used to calibrate radiator models and controllers. In a paper (Võs et al. 2019), the calibrated models are used to estimate the energy performance of systems in simulations. For older buildings, the PI controller, as opposed to ON/OFF, saves 6% energy for heating, for nZEB it saves 12% (Võs et al. 2019).

It should be noted that the article (Kaymaz 1995) compared the use of PI/PID controllers with the ON/OFF controller in terms of accuracy as well as power consumption for the hospital. It is noted that PI/PID controllers are superior to ON/OFF controllers, but are also less reliable. ON/OFF controllers are much less sensitive to changes in system parameters, resulting in greater reliability (Kaymaz 1995).

Integration of BEM mathematical models that can describe building physics can help in successfully controlling energy-efficient energy consumption in buildings while ensuring comfortable conditions.

The purpose of the work is to analyze the energy consumption of heat energy for heating an ON/OFF controlled two-room apartment using dynamic modeling, taking into account characteristics of thermal interaction between zones (rooms).

Tasks:

1) creation of dynamic models of the apartment with division into zones in Matlab software environment,
2) creation of dynamic models of the apartment with division into zones in EnergyPlus software environment,
3) comparative analysis of energy modeling of energy consumption of apartment heating,
4) analysis of the specific features of the heating system configuration and the source of the autonomous heating system of the apartment.

2. Materials and methods

In order to study the energy performance of the building, energy models of a typical two-room apartment of a modern economy class building were created based on the software product EnergyPlus and Matlab. The dynamic EnergyPlus software product uses the DOE-2 and BLAST functions, which are close to the European standards. 3D model of the building geometry was created in the graphic editor Design Builder; thermal properties of the multi-layer enclosure, window structures with optical features of glazing, engineering systems, operation schedule, and temperature regimes, and so on were specified. The software product takes into account the inertial characteristics of the building envelope and systems, the dynamics of climatic data variability. At the output, the software product allows obtaining air temperature, surface radiation temperature, heating/cooling and ventilation system (HVAC-system) load, and others (Deshko et al. 2020). The dynamic model in the Matlab software environment is created using Simulink tool subsystems, which in turn uses Simscape. With Simscape, which allows you to quickly create models of physical systems in the Simulink environment, a model of physical components based on physical relationships, directly integrated into the simulation flowcharts, is created. Matlab software environment allows designing control systems, taking into account the physical system in Simulink. Fig. 1 shows a schematic of the apartment and the interconnection of the rooms/zones of the apartment in Simulink. The heating system of the apartment is regulated by switching the autonomous gas boiler ON/OFF, maintaining a constant flow rate of coolant, the coolant temperature can reach 90°C in the coldest period of the year. The principle of qualitative regulation of heating by the coolant temperature is realized. The ON/OFF controller has no intermediate states, either fully ON or fully OFF. This control scheme is quite typical for the autonomous heating of apartment buildings in Ukraine. The heat output of the gas boiler is 3.5 kW, the efficiency is 79.

The grid model of the thermal-physical characteristics of the room envelope and the relationship between the rooms of the apartment are shown in Fig. 2 (on the example of bedroom 1 / room4).

The energy model of the apartment created in the EnergyPlus software environment reproduces an idealized version of the heating systems operation, i.e. the heating system is inertia-free, and the air temperature in the apartment rooms is maintained at the set level without fluctuations. The energy model of the apartment created in the EnergyPlus software provides that the gas boiler operates continuously (in ON mode) with a constant coolant flow rate of 0.1 kg/s. The supply temperature is constant at 60°C. Regulation takes place at the heater to maintain the set temperature in the rooms, that is, the principle of quantitative regulation is implemented.

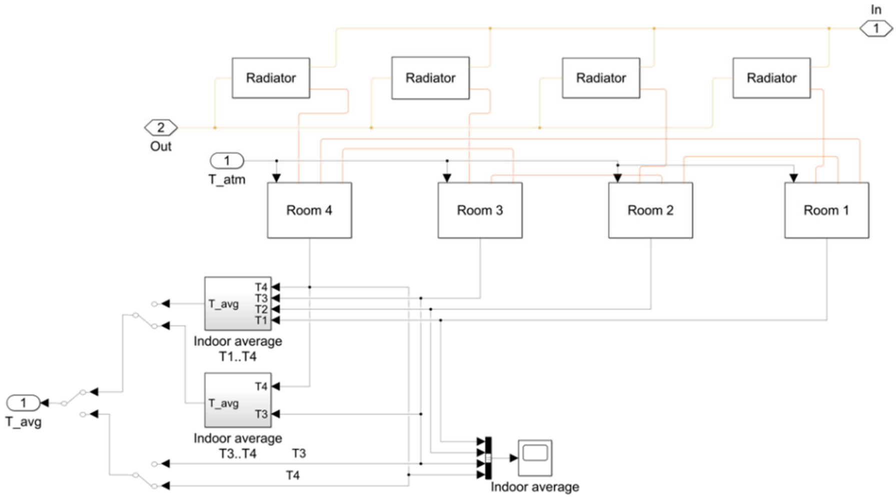


Fig. 1. The thermal energy model of the apartment

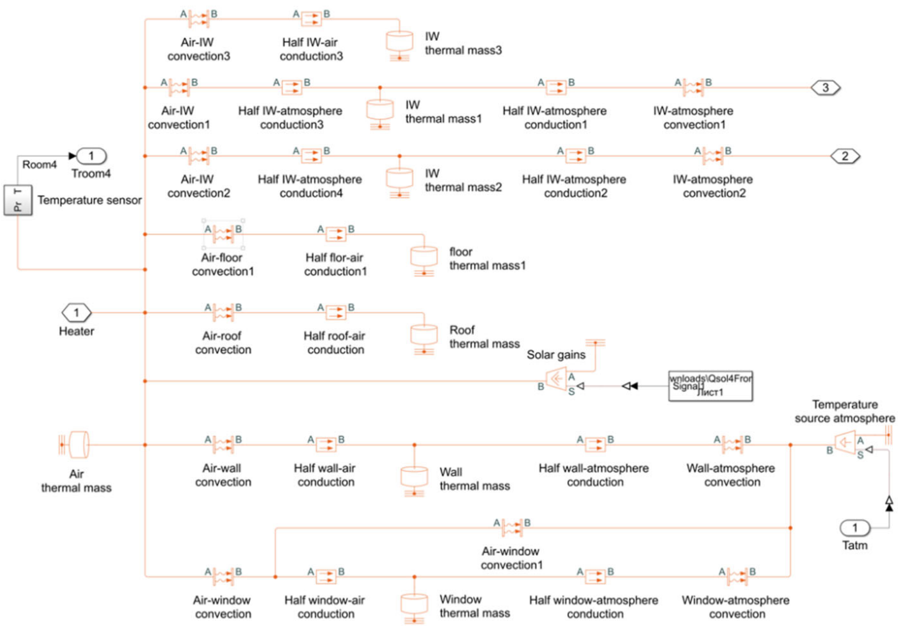


Fig. 2. The thermal grid model of one of the rooms

3. Results and discussion

Initial data

Existing residential housing was chosen for the study. It is a two-room apartment, located on the fourth floor of a five-story apartment building in Kyiv (Ukraine), built in 2016. The total area of the apartment is 49.44 m^2 (Fig. 3, all dimensions are given in meters), the height of the walls is 2.7 m. The apartment has a window orientation to the east (E) and west (W) sides, as well as a blank outer wall oriented to the north (N). Translucent elements of the enclosures are made of metalplastic two-chamber energy-saving double-glazed windows with argon filling of the chambers. The load-bearing part of the external wall is made of 0.4 m red hollow brick, and insulated with 0.05 m layer of mineral wool. Ventilation is natural with a multiplicity of air exchange of 0.6 $hours^{-1}$. The study used hourly climate data of a typical year of the IWEC international weather file for the Kyiv city (Ukraine) conditions. Solar heat inputs in the IWEC weather file are presented as global horizontal, diffuse horizontal, and direct normal. To recalculate the solar heat gains, which come into the area of the room, EnergyPlus software product was used, which allows taking into account the reflections of solar radiation from the surfaces of fences and soil, and take into account the optical transmittance of solar radiation, which is equal to 0.55. Fig. 4 shows hourly climate data.

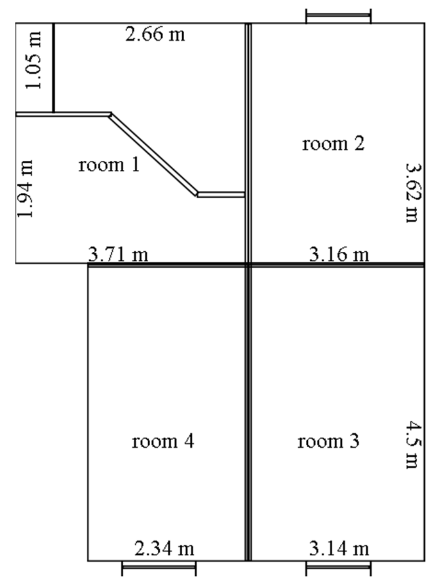
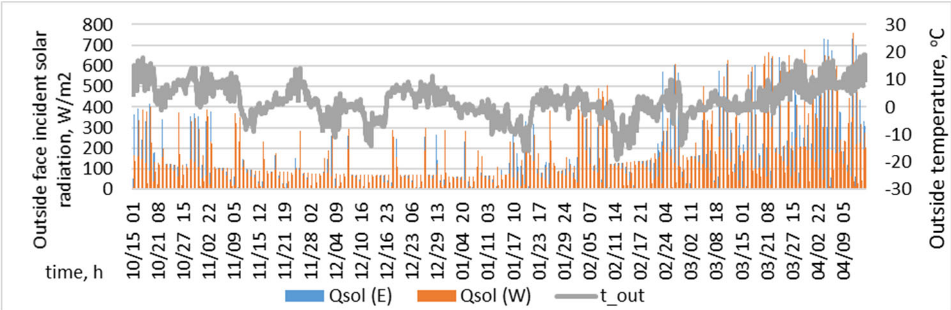


Fig. 3. The studied apartment plan



t_out – outside temperature, ºC; Q_{sol} – heat gain on vertical surfaces of east (E) and west (W) orientation, W/m^2

Fig. 4. Hourly climate data from IWEC file for Kyiv (Ukraine)

Model description

The apartment room was created in Matlab software environment by specifying the enclosure area and thermal resistance, which was introduced through blocks describing the convective and thermal conductivity components, as well as the heat storage properties of the internal and external envelopes, and the air in the room. Rooms are interconnected by thermal interaction. In addition, the hourly amount of heat inputs from the sun to the area of each room and the hourly external air temperature were set. The heat source was a gas boiler in which the mass flow rate was controlled by a valve using ON/OFF controller, which turned on when the air temperature in the rooms fell below the specified limits and turned off when it rose above. The simulation was performed under the condition of maintaining a constant air temperature of 20°C. The step of calculating the energy demand varied automatically depending on the magnitude of changes of external and internal fluctuations of the input parameters and was in the range of 1...200 sec.

Model testing and setup

For the design conditions, the selection of heating devices was carried out based on a mathematical model created in Matlab software environment, where the type of heating devices, area, mass, thermal inertial characteristics of the device were taken into account. Under design conditions, following the DSTU-N B V.1.1-27:2010 standard, for the city of Kyiv, the outside air temperature is assumed to be -22°C and with no solar heat gain. The indoor air temperature, following the DSTU B A.2.2-12:2015 standard, is 20°C. It is determined that the capacity of heating appliances in the apartment rooms are the following: bedroom 1 / room4 – 500 W, bedroom 2 / room3 – 1200 W, kitchen / room2 – 880 W, common areas (corridor, bath) / room1 – 320 W.

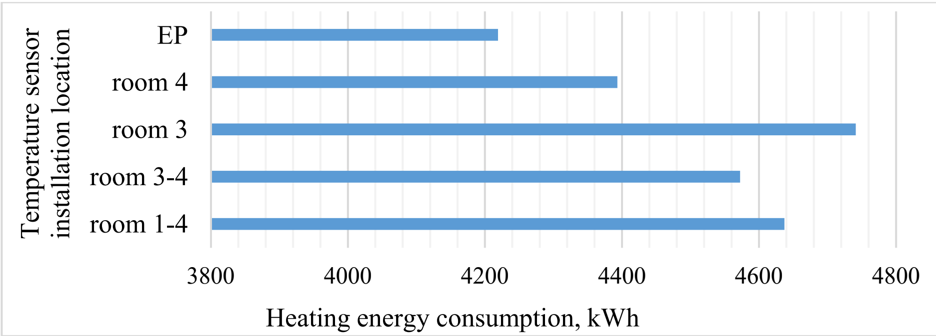
To verify the mathematical model of the apartment created in the Matlab software environment, the results are compared with the data of modeling in the EnergyPlus software environment. Considered grid dynamic models take into account the thermal inertia properties of each fence separately. From the mathematical modeling in Matlab software environment it follows that the total heat consumption of the apartment is distributed: bedroom 1 / room4 – 17%, bedroom 2 / room3 – 40%, kitchen / room2 – 31%, common areas (corridor, bath) / room1 – 12%. In bedroom 1, bedroom 2 steel radiators are installed, in the kitchen – steel radiator and water heated floor, in common areas – water heated floor and a heated towel rail.

It should be noted that the boiler is controlled by the average air temperature in the rooms of the apartment, i.e. the boiler operates at a constant flow rate, and depending on the conditions, it changes the temperature of the water supply, thereby leading to a situation where the hourly air temperature in different rooms under the influence of, primarily, different heat gains varies from 18 to 24°C, while maintaining the average air temperature at 20 ±0.5°C in Matlab software environment.

In real practice, the control of maintaining the specified air temperature in the apartment can be carried out by the values of the air temperature in representative rooms; for a compact typical housing, it is 1-2 points of installation of air temperature control sensors, according to the readings of which the controller sends a signal to the boiler to turn it ON/OFF. Typically, the sensors are installed in the rooms where the residents are spending most of their time, i.e. in the bedrooms or living room. This study looks at four different options for installing temperature sensors, specifically: 1) average reading from two sensors in room4 and room 3, respectively; 2) in room 4; 3) in room 3; 4) average reading from four sensors in each room, respectively. The results of the model calculation are shown in Fig. 5.

From Fig. 5 it follows that with the quantitative regulation of heating and the absence of inertia in the heating devices according to the mathematical model created in EnergyPlus software environment, we have the lowest result of heat consumption for heating needs of the building. For the conditions of Ukraine, it is typical to use ON/OFF controllers for autonomous heating systems, so depending on the number and location of temperature control sensors, the temperature in the premises may vary ±3%. The simulation results in Matlab differ by 4...10% from the simulation results in EnergyPlus.

Under these control conditions, the average load on the gas boiler is: sensors in all rooms – 1073 W; in rooms 3 and 4 – 1058 W; in room 3 – 1100 W; in room 4 – 1010 W; in EnergyPlus – 965 W.



room 1-4 – air temperature control sensor installed in rooms 1-4; room 3-4 – sensor in rooms 3-4; room 3 – sensor in room 3; room 4 – sensor in room 3-4; EP – simulation in EnergyPlus software

Fig. 5. Heat energy consumption for apartment space heating

Fig. 6 shows the hourly simulation results for the heating season in the software environments Matlab and EnergyPlus. The results of modeling the energy consumption of thermal energy in Matlab are characterized by a larger range of fluctuations of the heating system load, which is typical for the real operating conditions of the system. The trend of load variation for the apartment heating system according to the results of modeling in Matlab and EnergyPlus is the same. The maximum deviation of the simulation results of the two dynamic mathematical models is up to 0.5 kW, and the average deviation is 0.1 kW.

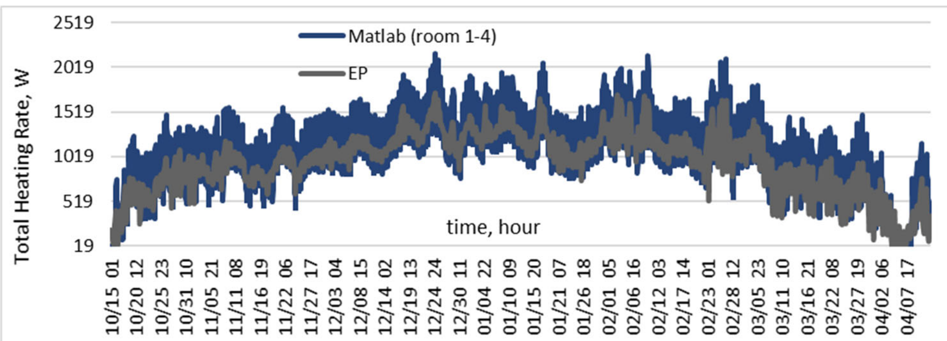


Fig. 6. The load on the heating system of the apartment for the heating season

There is a high solar activity in April, which explains that for this period the average air temperature in the representative rooms/groups of rooms, where sensors are installed, exceeds the value of the internal temperature range set in the controller, that is, at the time of complete short-term heating shutdown (at times of peak solar activity) due to the excess of solar heat gain, the internal air temperature in the apartment rooms increases.

Fig. 7 shows the loads on the autonomous apartment heating system for the period of January 10-14, which is characterized by low solar activity and external temperature in the range of -10...-2°C. A decrease in the graph of daily load variation is characteristic for the periods of solar heat gain. Simulations in EnergyPlus result in a smooth change in the load on the heating system with a decrease in the load during peak load hours, and then with a smooth increase. Four series of simulations were performed in Matlab for different locations of the temperature control sensor installation. For the considered apartment, room 3 is the largest, which in turn, when installing an air temperature sensor only in this room, leads to less load fluctuations compared to the similar situation of installing a control sensor in room 4 (which has dimensions up to 10 m^2, Fig. 3), which is half as large and with a higher glazing factor. For other combinations of installation of air temperature control sensors in the apartment, the load variation graphs will fluctuate within the range of load variation in the case of installation of one sensor in room 4 and 3.

During the period of solar activity, there is a decrease in the load on the heating system for different control options. With quality regulation and operation of the gas boiler with the controller of ON/OFF type, and taking into account the thermal inertia of engineering networks, there are significant fluctuations in the load on the heating system, which lasts from 3 to 10 hours during daylight hours. When installing the temperature control sensor in room 4, which is characterized by having a large area of glazing (which leads to significant solar heat gain in the room during daylight hours), and having most of the perimeter walls being internal, leading to long shutdowns of the autonomous gas boiler, which causes the nature of the load decreasing in Fig. 7. The scenario where the temperature control sensors are installed in large rooms of the apartment with two outer walls/larger area of outer walls leads to significantly shorter boiler shutdown intervals.

Fig. 8 shows the variation of the average air temperature in the apartment for different variants of the location of the temperature control sensors, according to the results of simulation in the Matlab software environment.

The indoor temperature is maintained at 20°C in the deviation range of 0.5...+0.1°C from the reference level. The upper control limit is slightly lower than the lower control limit. This control range is due to the inertia of the heating system; in order to ensure comfortable conditions (avoiding overheating) and energy-efficient use of thermal energy, the above range of maintaining the internal temperature was set. In the EnergyPlus software environment, the heating system is inertia-free and the room temperature is maintained according to a setpoint value of 20°C utilizing a thermostat on the heater.

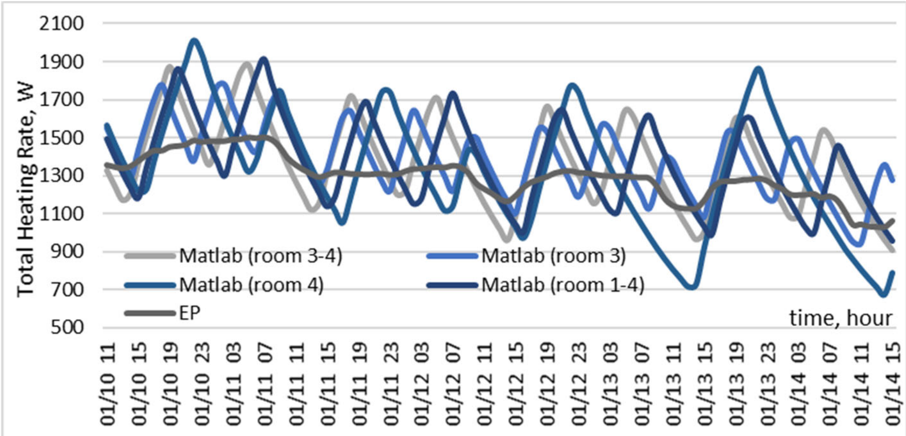


Fig. 7. Heating system load of the apartment for different variants of heating system control

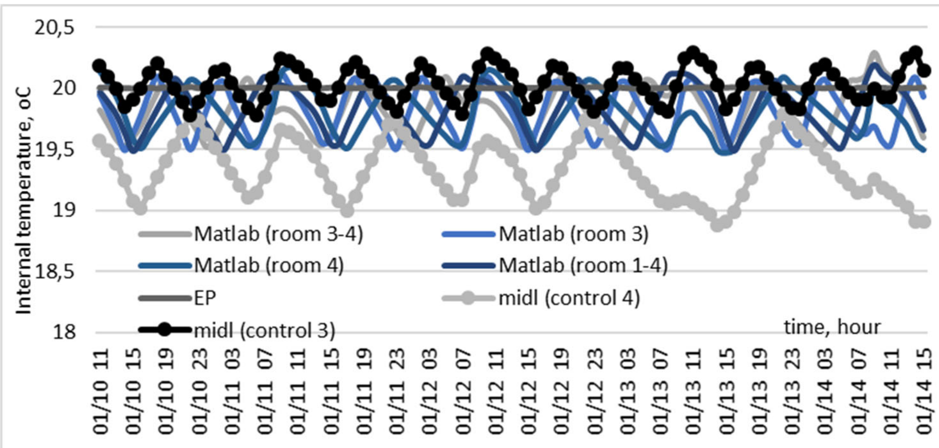


Fig. 8. Average air temperature in the rooms of the apartment, where sensors are installed, and in the apartment as a whole at different variants of heating system regulation

Fig. 8 shows the average air temperature in the apartment according to the results of modeling in the EnergyPlus software environment, which is at 20°C. The average air temperature in the apartment (the average of the four rooms) according to the results of modeling in the Matlab software environment when installing the temperature sensor in room 4 is 19.1°C – the lowest compared to other variants of modelling, when installing the sensor in room 3 (the largest room of the apartment with 2 external walls) – 20.2°C (the highest value).

4. Conclusions

The paper analyzes the transient heating modes when controlling the heating systems of a two-room apartment with an autonomous heating system. In the work, dynamic models of the apartment were created in EnergyPlus and Matlab software environments. The heating system has been configured; the following heating devices have been selected: bedroom 1 / room 4 – 500 W, bedroom 2 / room 3 – 1200 W, kitchen / room 2 – 880 W, common areas (corridor, bath) / room1 – 320 W.

Regulation of the apartment heating system in Matlab is performed by switching ON/OFF the autonomous gas boiler, maintaining a constant flow rate of the medium, the heating medium supply temperature can reach 90°C in the coldest period of the year, i.e. there is a qualitative regulation of the heating medium temperature. In EnergyPlus it is provided that the gas boiler operates continuously in ON mode with a constant supply temperature of 60°C, which is an idealized version of the heating system operation with quantitative regulation of the flow rate of the heating medium at the heaters.

The results of the simulation of the energy consumption of thermal energy in Matlab are characterized by a larger range of fluctuations of the heating system load, which is typical for real system operating conditions. The trend of the load variation of the apartment heating system according to the simulation results in Matlab and EnergyPlus is the same. A decrease in the graph of daily load variation is characteristic for the periods of solar heat gain in the apartment area. The simulation in EnergyPlus results in a smooth change in the load on the heating system with a decrease in the load during the peak hours of the load, and then with a smooth increase in the load. Four series of simulations were performed in Matlab for different numbers of temperature control sensors and their installation locations.

The different period of variation of the load on the heating system depends on the interconnection between the place of installation of the sensor in the apartment rooms and their heat load relative to the total load of the apartment. For the considered apartment, room 3 is the largest, which leads to less load fluctuations when installing the air temperature sensor only in this room compared to the similar situation of installing the control sensor in room 4, which is half the area and with a large glazing factor. The average temperature in the apartment, when the temperature sensor is installed in room 4, is 19.1°C, in room 3 – 20.2°C. Regardless of the controller type, the number and place of installation of temperature control sensors is important, which not only determine the operation of the apartment heating system but also the general assurance of comfort in the entire apartment.

In future research, it is planned to investigate the use of more complex/detailed PI controllers.

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