3
2021

Valeriy DESHKO, Inna BILOUS, Dmytro BIRIUKOV

National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine

Corresponding author: biloys_inna@ukr.net

DOI: 10.53412/jntes-2021-3-1

MODELING OF UNSTEADY TEMPERATURE REGIMES OF AUTONOMOUS HEATING SYSTEMS

Abstract: *The paper analyzes the energy consumption for heating a two-room apartment based on dynamic modeling of energy processes in Matlab software environment and quasi-stationary model EN ISO 13790, which is the basis of the national standard of Ukraine DSTU B A.2.2-12:2015. A comparison of the results of modeling, taking into account the thermal interaction between the zones of the building, using a dynamic model was carried out. A comparative analysis of the installation of air temperature sensors in rooms, the signal from which is used to operate the On-Off controller, is presented. Recommendations on the installation of room temperature sensors and their number are provided.*

Keywords: *energy need for heating, controller, internal air temperature, Matlab Simulink.*

Introduction

Buildings are one of the main consumers of primary energy resources in the world. The climate conditions of Ukraine are characterized by a long heating period, which causes more than 85% of energy consumption for heating needs, a similar situation is typical for Western and Central European countries. Reducing energy consumption for heating of buildings can be achieved in various ways. One way is the use of modern insulation materials and technologies at the stages of both design and operation. The second direction is the use of renewable and alternative energy sources in distributed generation systems. The third direction is the use of automatic control of heating systems of buildings (local control of heat consumption). The fourth is the influence on the social factor, operating conditions, management of user behavior.

For qualitative evaluation and prediction of energy consumption in short time intervals, it is necessary to use dynamic calculation models [1]. There is a large number of dynamic software products, which allow estimating energy consumption of buildings, such as EnergyPlus, TRNSYS, eQuest, Matlab/Simulink, and others [1-5].

Poor regulation of indoor temperature is the most common indoor heating issue for centrally heated households in China [3]. The article [3] deals with the development of approaches for dynamic regulation of indoor temperature. The system developed in the article [3] makes it possible to provide DHS heat to a group of buildings with the same temperature demand being controlled by a single control system. However, for residents of apartment buildings with an autonomous heating system (usually a gas or electric boiler), the adjustment of automation of the heating system is carried out without taking into account several influential factors. Building Energy Management Systems (BEMS) are constantly attracting attention as an effective building control system [6, 4, 7], which 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 precisely controlled by classical control methods [6]. Thus, advanced control systems that can handle multiple inputs and multiple outputs are the best approach to control the thermal condition of buildings [6-8].

In the article [9] a comparative analysis of On-Off controllers and PID-controllers used to control heat supply systems in terms of comfort conditions and energy efficiency of buildings was carried out. The research [9] 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 [9] 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.

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

Purpose and research objectives

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

According to the set goals, the following tasks should be solved:

1. Creation of dynamic models of the apartment with a division into zones in Matlab software environment.
2. Creation of quasi-stationary models of the apartment based on the standard DSTU B A.2.2-12:2015 [4].
3. Analysis of energy characteristics of the apartment.
4. Comparison of the calculation results in case of installation of air temperature sensors in the room, on which the controller is being operated.

Material and research results

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, built in 2016. The total area of the apartment is 49.44 m^2, 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 metal-plastic 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 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 conditions [10]. 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. Figure 1 shows hourly climate data.

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 an 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 on/off controller has no intermediate states, either fully on or fully off. The heat output of the gas boiler is 3.5 kW, efficiency – 80%. The flow rate of the heating medium in the heating system is 0.0835 kg/s. The simulation was performed under the condition of maintaining a constant air temperature of 20°C.

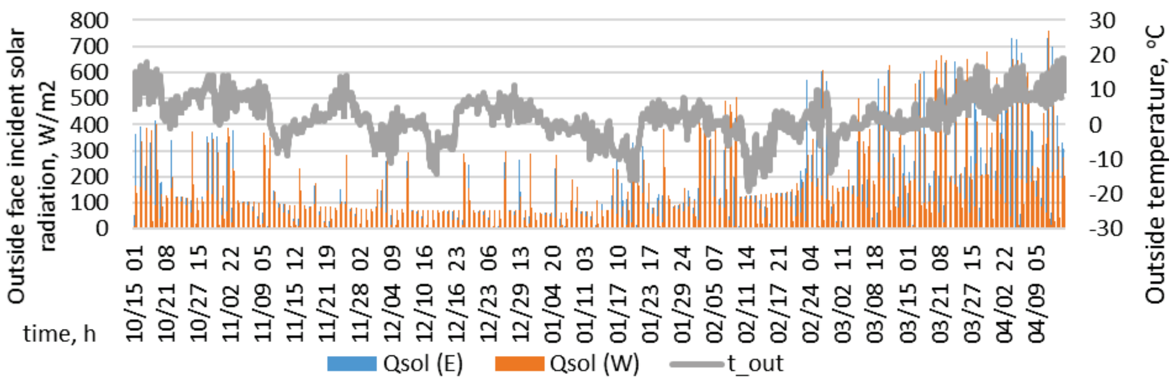
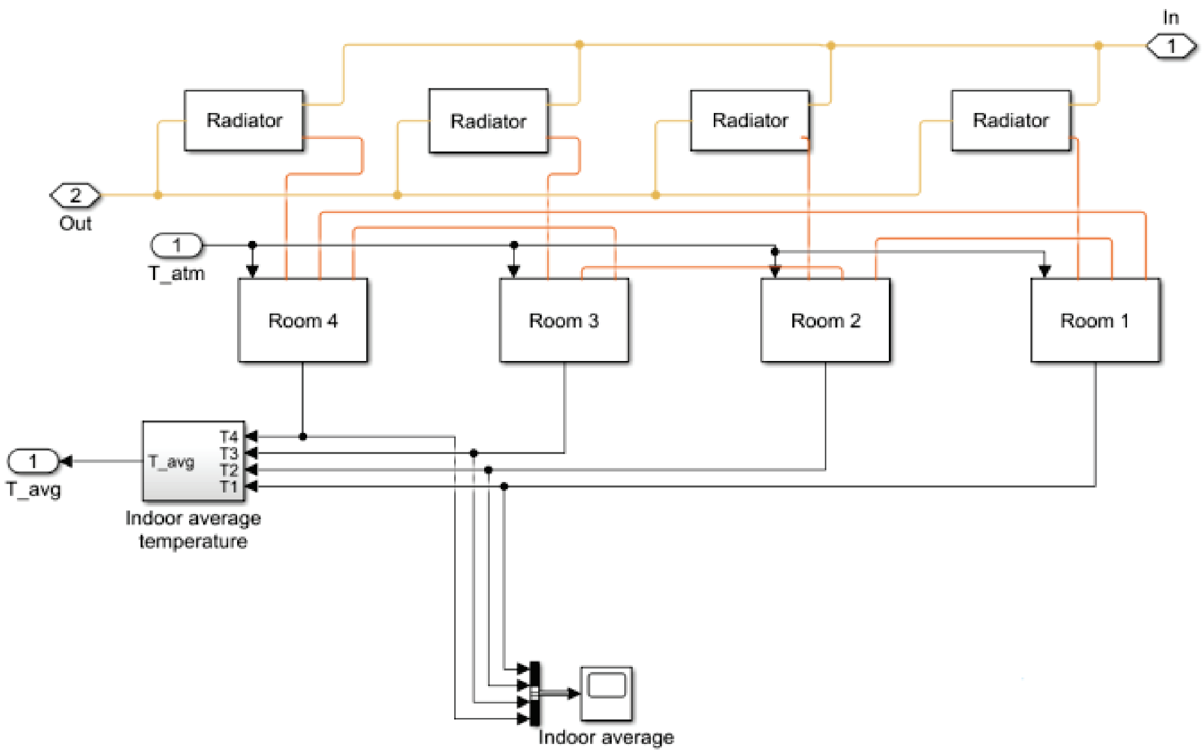
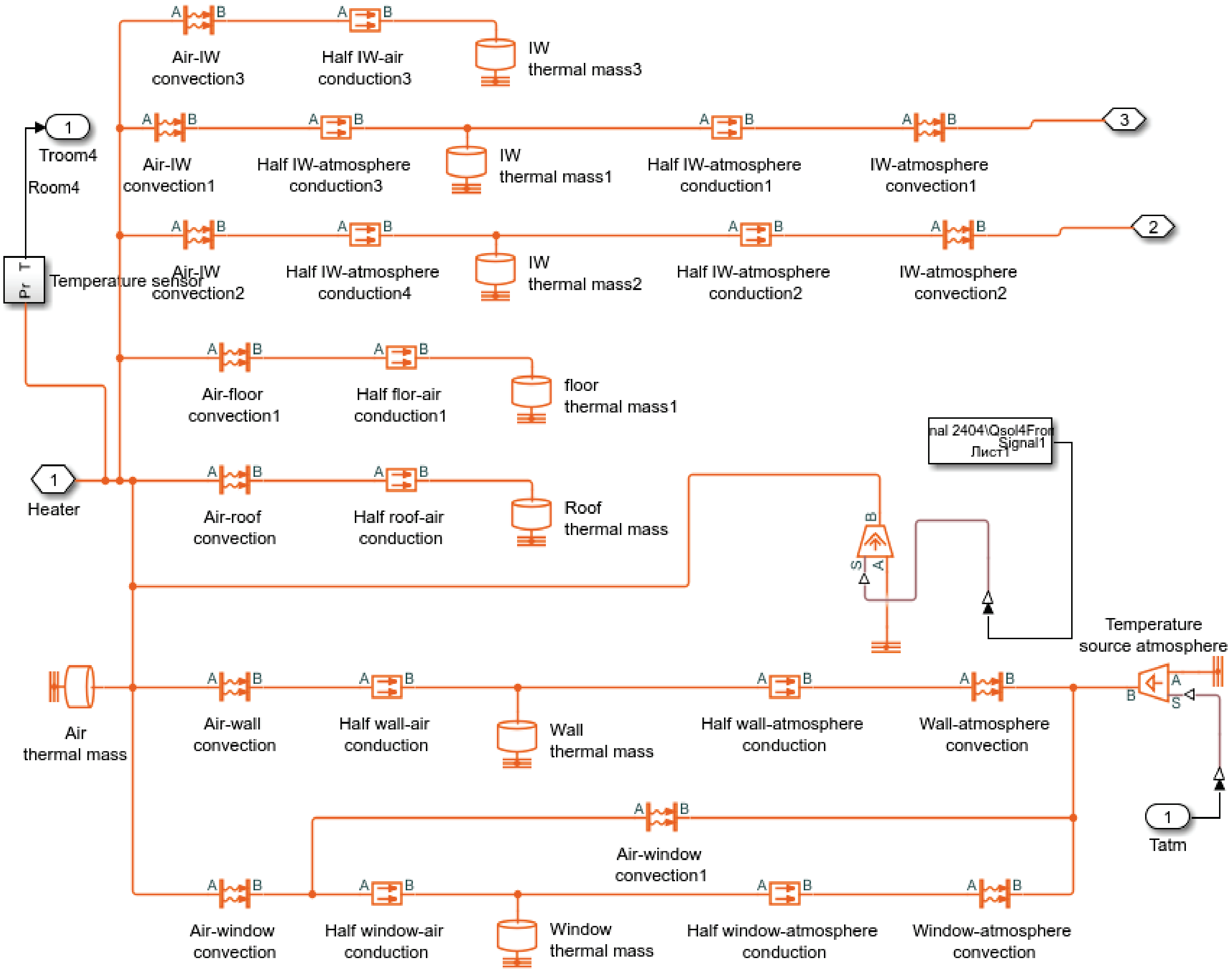


FIGURE 1. *Hourly climate data from IWEC file for Kyiv; where: t_out – outside temperature, °C; Q_{sol} – heat gain on vertical surfaces of east (E) and west (W) orientation, W/m²*

Figure 2a shows the thermal energy model of the apartment, figure 2b illustrates the thermal inertia units of one of the rooms. 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.



(a)



(b)

FIGURE 2. *The thermal energy model of the apartment (a) and the grid model of one of the rooms (b)*

Model testing and tuning. 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 are taken into account. Under design conditions, following the standard [11], 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 standard [11], is 20°C. It is determined that the capacity of heating appliances in the apartment rooms are the following: bedroom 1/room 4 – 500 W, bedroom 2/room 3 – 1200 W, kitchen/room 2 – 880 W, common areas (corridor, bath)/room 1 – 320 W.

To verify the mathematical model of the apartment created in the Matlab software environment, a comparison of the results with the quasi-stationary method according to DSTU B A.2.2-12:2015 [11]. The mathematical model based on the quasi-stationary method according to DSTU B A.2.2-12:2015 considers the apartment as a single zone and takes into account the thermal inertia properties of the external envelope only, in contrast to the mathematical model created in Matlab, which takes into account the heat storage properties of each indoor and outdoor envelope separately. The basic formulas for calculations according to the standard DSTU B A.2.2-12:2015 are given below [11].

The annual energy consumption of the house in heating and/or cooling is determined by the methodology [7]:

$$Q_o^{year} = \sum_{i=1}^{n} Q_{HC.nd.i} \tag{1}$$

where:

i – index number of the heating month;

n – number of heating months;

$Q_{HC.nd}$ – monthly energy consumption for heating or air conditioning, W·h.

$$Q_{HC.nd} = Q_{HC.tr} + \eta_{HC.gn} Q_{HC.gn} \tag{2}$$

where:

$Q_{HC.tr}$ – monthly total heat transfer by transmission and ventilation, W·h;

$Q_{HC.gn}$ – monthly total heat gains in heating mode, W·h;

$\eta_{HC.gn}$ – dimensionless monthly coefficient of utilization of gains.

$$Q_{HC.hr} = Q_{tr} + Q_{ve} \tag{3}$$

where:

Q_{tr} – heat transfer by transmission by month, W·h;

Q_{ve} – heat transfer by ventilation, kW·h.

$$Q_{HC.gn} = Q_{int} + Q_{sol} \tag{4}$$

where:

Q_{int} – sum of internal heat gains over a given period, W·h;

Q_{sol} – sum of solar heat gains over a given period, W·h.

$$Q_{tr} = H_{hr}\left(\theta_{int} - \theta_{e}\right)t \tag{5}$$

where:

H_{hr} – transmission conductivity of the zone, W/K;

θ_{int} – given building zone temperature for heating, °C;

θ_{e} – average monthly outdoor temperature, °C;

t – duration of the month for which the calculation is performed, h.

$$Q_{ve} = H_{ve}\left(\theta_{int} - \theta_{e}\right)t \tag{6}$$

where:

H_{ve} – conductivity by ventilation, W/K.

The calculation to DSTU B A.2.2-12:2015 is performed for monthly intervals, i.e., only seasonal weather fluctuations are taken into account, and daily fluctuations are not taken into account. To compare the results of mathematical modeling based on the two models, weather data of a typical IWEC year [10] was used. The given values of climatic data for the monthly intervals of calculation of the heating season (October 15 – April 15) for DSTU B A.2.2-12:2015 are shown in figure 3.

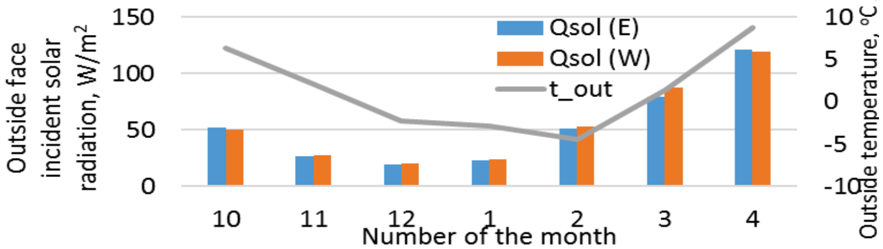


FIGURE 3. *Monthly climate data from IWEC file for Kyiv*

Analysis of the study results. Figure 4 shows the results of the simulation of heat energy consumption for heating needs. In the annual section, the difference of simulation results at constant air temperature in the apartment by the two considered models is 13%, the dynamic model created in the Matlab software environment was selected for the reference model. A smaller difference in the results is observed for the off-season period (October, April) – about 30 kWh, for other colder months it is 80 kWh, ..., 140 kWh.

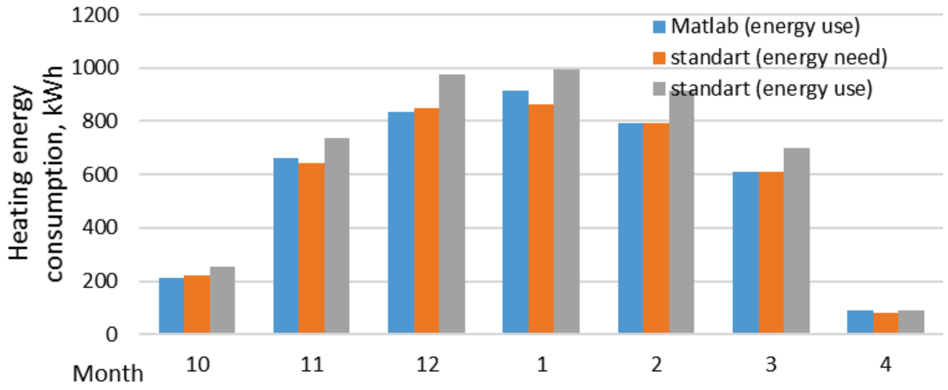


FIGURE 4. *Heating energy consumption*

From the mathematical modeling in Matlab software environment it follows that the total heat consumption of the apartment is distributed: bedroom 1/room 4 – 17%, bedroom 2/room 3 – 40%, kitchen/room 2 – 31%, common areas (corridor, bath)/room 1 – 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 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°C to 24°C, while maintaining the average air temperature at 20°C ±0.5°C (fig. 5).

In real-world practice, the control of maintaining the specified air temperature in the apartment is carried out by the air temperature values in the representative rooms, for small-sized typical housing, there are usually 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 staying most of the time, i.e. in bedrooms or a living room. Three different options for installing temperature sensors are considered, as follows: 1) two sensors in bedroom 1 and bedroom 2; 2) in bedroom 1; and 3) in bedroom 2. The results of the model calculation show that the average air temperature in the rooms at which the controller is set up is: sensors in all the rooms – 19.9°C; sensors in bedroom 1 and 2 – 20°C; bedroom 2 – 19.9°C; bedroom 1 – 20.1°C. Under these control conditions, the average load on the gas boiler is: the sensors in all rooms – 954 watts; in bedroom 1 and 2 – 945 watts; in bedroom 2 – 976 watts; in bedroom 1 – 902 watts. Figure 5 shows the air temperature that the controller is outputting for the various temperature sensor installation points.

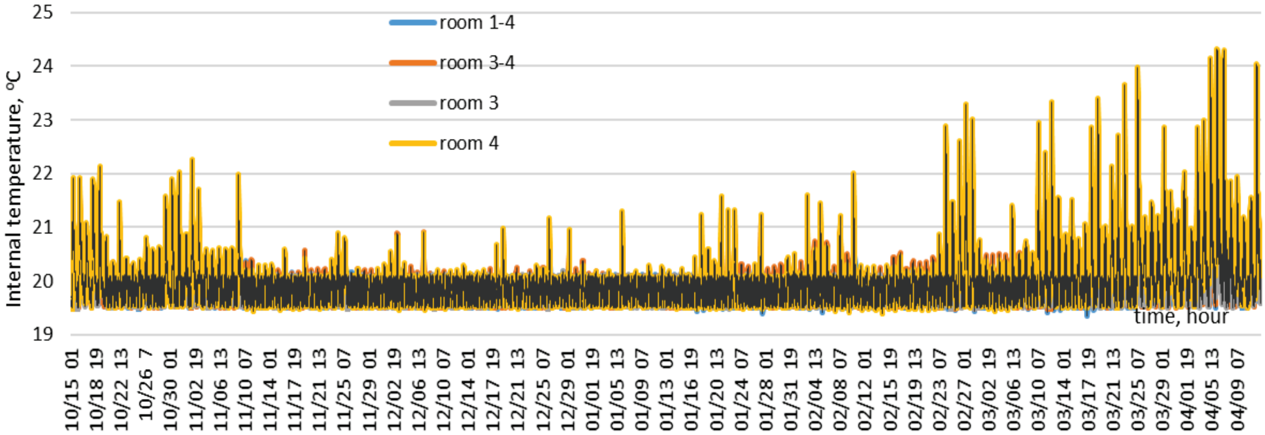


FIGURE 5. *The average air temperature in the apartment, where temperature control sensors are installed; where: room 1-4 – temperature control is based on the average temperature of all rooms; room 3-4 – based on the average temperature of bedroom 1 and bedroom 2; room 3 – based on the temperature of bedroom 2; room 4 – based on the temperature of bedroom 1*

During March-April the solar activity is high, which explains that during this period, the average air temperature in the representative rooms/groups of rooms, where sensors are installed, exceeds the value of the internal temperature change 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 leads to an increase in indoor air temperature.

Table 1 shows deviations of the air temperature in the rooms (zones) from the average air temperature in the apartment for different locations of installation of temperature control sensors, transmitting the signal to the controller. The obtained results of the modeling show that the average air temperature in the apartment is: 1) sensors installed in all rooms (room 1-4) – 19.9°C; sensors installed in two bedrooms (room 3-4) – 19.7°C; sensor installed in room 3 – 20.2°C; sensor installed in room 4 – 19.2°C.

TABLE 1. *Deviation of air temperature in the room from the average*

Sensor installation location	Room number	Deviation from the average value, °C		
		average	max	min
room 1-4	room 1	0.3	0.9	–0.3
	room 2	–0.2	0.6	–3.5
	room 3	0.2	1.3	–1.4
	room 4	–1.1	0.1	–6.1
room 3-4	room 1	0.5	1.3	–0.2
	room 2	–0.1	1.1	–3.6
	room 3	0.4	1.7	–1.2
	room 4	–0.9	0.1	–5.7
room 3	room 1	0.0	0.4	–0.3
	room 2	–0.6	0.1	–4.2
	room 3	–0.2	0.2	–2.1
	room 4	–1.4	0.1	–6.6
room 4	room 1	1.0	2.4	–0.2
	room 2	0.5	2.5	–2.1
	room 3	0.9	3.1	–1.0
	room 4	–0.3	0.3	–4.6

The maximum fluctuations of air temperature in the rooms from the average value for the apartment as a whole are observed for the interseasonal period (March-April). The largest range of temperature fluctuations for all cases of model experiments is typical for room 4 (bedroom 1), which is caused by solar activity in the daytime hours and its absence in the dark time of the day. The rather close range of temperature deviations from the average apartment level is observed in room 3 (kitchen), which is quite close to room 4 by dimensions, amount of solar gains. Less variation in air temperature during the heating year is characteristic of room 1 (corridor and bathroom), which is explained by the absence of solar heat gain in this zone.

Figure 6 shows the energy consumption of the apartment rooms at different installation locations of the air temperature sensors, according to which the controller operates. From figure 6 it follows that with the installation of two indoor air temperature sensors in bedroom 1 and bedroom 2, the difference in energy consumption is –1.2%, in bedroom 1: –5.8%, in bedroom 2: +1.9%, as compared to the base case of calculating the installation of temperature sensors in all the rooms. The largest deviation of energy consumption for heating is obtained when the air temperature sensor is installed in room 4 (bedroom 1), which is explained by the smaller size of the room, one external wall with a large glazing factor (0.4), compared to other rooms.

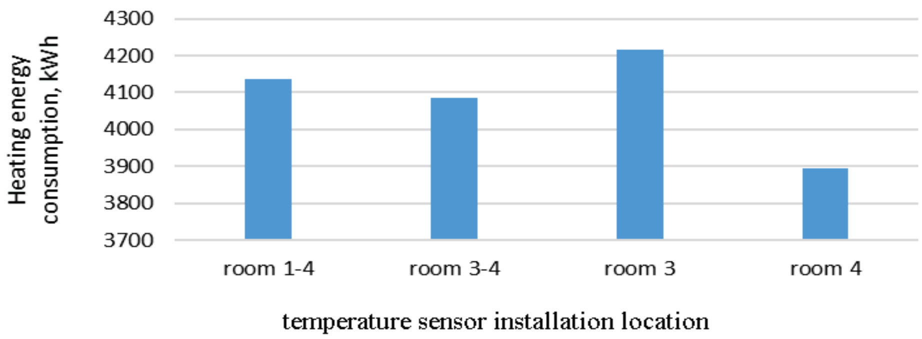


FIGURE 6. *Heat energy consumption for heating in the apartment rooms*

Conclusions

In the study, dynamic modeling of energy consumption of a two-room apartment was carried out, based on the model, created in Matlab software environment A comparative analysis of simulation results between the dynamic and quasi-stationary model has been performed. In annual terms, the discrepancy between the simulation results with the dynamic simulation created in the Matlab software environment and quasi-stationary according to DSTU B A.2.2-12:2015 is 13%. A smaller difference in the results is observed for the off-season period (October, April) – about 30 kWh, for other colder months it is 80 kWh, ..., 140 kWh. From the analysis of using different quantities and different locations of installation of air temperature sensors in the rooms, it follows that the installation of two indoor air temperature sensors in bedroom 1 and bedroom 2, the difference in energy consumption is –1.2%, in bedroom 1: –5.8%, in bedroom 2: +1.9%, as compared with the base case of installation of temperature sensors in all the rooms.

In the future, it is planned to study different types of heating system regulation settings for intermittent and continuous heating modes and to give recommendations for the installation of indoor air temperature sensors, which transmit it to the controller.

References

[1] Deshko V.I., Bilous I.Yu., Sukhodub I.O., *Mathematical models for determination of specific energy need for heating used in Ukraine*, Journal of New Technologies in Environmental Science (JNTES), 2018, No. 1. pp. 13-25.

[2] Alibabaei A., Fung A.S., Raahemifar K., *Development of Matlab-TRNSYS co-simulation for applying predictive strategy planning models on residential house HVAC system*, Energy and Buildings, 2016, No. 128. pp. 81-98.

[3] Lu G., Zhou X., Yan J., Yan G., *A temperature and time-sharing dynamic control approach for space heating of buildings in district heating system*, Energy, 2021. Vol. 221.

[4] Perera D.W.U., Winkler D., Skeie N.-O., *Multi-floor building heating in MATLAB and Modelica environments*, Applied Energy, 2016, Vol. 171, pp. 4-57.

[5] Deshko V., Buyak N., Bilous I., Voloshchuk V., *Reference state and exergy based dynamics analysis of energy performance of the "heat source – human – building envelope"*, Energy, 2020, Vol. 200.

[6] Perera D.W.U., Halstensen M., Skeie N.O., *Prediction of space heating energy consumption in cabins based on multivariate regression modelling*, International Journal of Modeling and Optimization, 2015. Vol. 5, No. 6, pp. 385-392.

[7] Perera W., Pfeiffer C.F., Skeie N.O., *Modeling and simulation of multi-zone buildings for better control*, 55th Conference on Simulation and Modelling, 2014, Aalborg, Denmark, Linköping University Electronic Press.

[8] Perera D.W.U., Pfeiffer C., Skeie N.O., *Control of temperature and energy consumption in buildings*, International Journal of Energy and Environment, 2014, Vol. 5, No. 4, pp. 471-484.

[9] Saleh A., Mosa M., *Analysis of control strategies and simulation of heating systems using Simulink/Matlab potential*, Journal of Thermal Engineering, 1 October 2016, Vol. 2, Issue 5, pp. 921-927.

[10] International Weather for Energy Calculations, https://energyplus.net/weather-location/europe_wmo_region_6/UKR.

[11] Enerhetychna efectyvnist budivel. Metod rozrahunku enerhospozhyvannia pry opalenni, okholodzhenni, ventyliatsii, osvitlenni ta hariachomu vodopostachanni/DSTU B A.2.2-12:2015 (Natsionalnyi standart Ukrainy), K.: Minrehion Ukrainy, 2015, p. 203.