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Research paper

Influence of Subjective and Objective Thermal Comfort Parameters on Building Primary Fuel Energy Consumption

***V.I. Deshko*[1], *N.A. Buyak*[1]*, *I.O. Sukhodub*[1]**

[1]*National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"*
**Corresponding author E-mail:* korovaj.te@gmail.com

Abstract

The building is considered together with a heating source in the analysis, it is also proposed to include a human thermal comfort model in this complex system. Regression equations for determining the comfortable room air temperature according to energy and exergy approaches are presented. Human thermal comfort model is included for the first time in the complex building energy system, by determining the comfortable room air temperature, which corresponds to PMV (predicted mean vote), not lower than value for the corresponding building category. The effect of enclosing structures thermal resistance changes on space average radiant temperature and on building category in terms of providing comfortable conditions is estimated. The influence of thermal comfort subjective parameters on primary fuel exergy consumption by the centralized heating system is estimated on the basis of developed model for the Ukrainian conditions.

Keywords*: energy efficiency indicators, energy efficiency, exergy, heating, heat losses, human body exergy model, thermal comfort, primary fuel.*

1. Introduction

Providing an adequate level of human thermal comfort and simultaneous reduction of energy consumption is a complicated and controversial task, that can be solved by using renewable energy sources and by extending the knowledge on human thermal comfort. The assessment of human-related factors impact on building energy use is a new direction in research of building energy efficiency improvement. In this context, there are six factors that influence the building energy consumption, namely: climate, building envelope, building services and energy systems, building operation and maintenance, occupants' activities and behavior, and indoor environmental quality [1]. On the basis of the relevant occupants' behavior driving factors related to energy consumption for office buildings, it is possible to classify the occupants' behavior on three different levels: individual inhabitants, zones and buildings. Recent research presents analytical and modelling techniques as well as software programs that assess the potential of energy saving in terms of occupants' behavior. Major programs that allow taking into account occupants' behavior during the building energy modeling include EnergyPlus, DeST, DOE-2, TRNSYS, IDA-ICE, ESP-r [3].

In Ukraine, an energy approach is used for building energy performance assessment, which is based on determination of annual energy need for heating, cooling and hot water supply and its comparison with the maximum allowable values [4], this approach does not give an opportunity to estimate efficiency of primary fuel use. Energy flows of different quality can be used to provide thermal comfort in buildings; therefore, the exergy approach is also used to analyze the quality of energy flows in the building [5].

Today, the concept moves to low exergy buildings, the main focus during the design of which are devoted to technologies that allow using energy of the environment for a comfortable conditions provision [5]. Particular attention is paid to the comfort parameters in such buildings. The authors S. Gopisetty and J. Pfafferot conducted an optimization of the operational control strategy in a low-exergy building constructed in Germany [6].

With the current trends in the use of different quality heat sources in the building and the development of low temperature heating concepts, the use of exergy and energy analysis provides a more complete understanding when optimizing the "building - heating source" system. The use of the exergy approach allows taking into account the interconnections between the energy flows of different physical nature and dissipative energy losses. The use of exergy approaches for the analysis of buildings energy efficiency in the Ukrainian conditions needs further development. The combination of whole building exergy analysis and human body exergy analysis [7] will reduce the exergy consumption by the system and provide a microclimate in a building that corresponds to the human best functioning in terms of the second law of thermodynamics.

The questions of thermal comfort are defined by the following standards, which are based on the Fanger's energy model of the thermal comfort [8, 9] and on the basis of the adaptive approach [10]. The exergy model of human thermal comfort, which is based on the first and second law of thermodynamics, also allows taking into account the thermoregulation mechanism. The features of this model are outlined in the papers [11-15]. In the context of approach development to analyzing the exergy flows from the heating source to the building envelope [16-19], the exergy model of human thermal comfort is necessary to be used, that is highlighted in the paper [20]. The study of M. Shukuya [14] presents the introduction to the exergy concept and the human body exergy balance for typical and transitional conditions. The further development of this approach is reflected in comparison of the human body exergy consumption model under steady and transitional conditions [21]. The analysis of building envelope thermal protection effect on human body exergy consumption [12] for various climatic conditions has shown that human body exergy consumption is reduced by 0.6%, 6.4%, 10.1% and 35.9% for the warm/humid, moderate, warm/dry and cold types of climate respectively, subject to increased thermal protection of building envelope. The structure of the energy and exergy balance for the human body during the summer period is reflected in the H. Caliskan’s study [22]. The process of human thermoregulation is analyzed in different types of climate with the use of an exergy human body model [23]. The exergy analysis method is used to find the optimal relationship between the room air temperature and the average radiant temperature for Finnish office workers in the summer, because according to the research the exergy approach to thermal comfort provides the highest productivity [23]. Using the human body exergy analysis, it is proposed to evaluate exergy value that is destroyed and the exergy entering the environment, since the minimal values of exergy destruction do not always correspond to comfortable conditions [24]. The stationary model of thermal comfort and the value of human body exergy consumption are described using the program developed for Excel spreadsheets by Hideo Asada [25]. Input data in the program are the parameters of the new environment and the human body, and the output results are represented by the ratio between the components of the incoming and outflow exergy for human body, the value of PMV (predicted mean vote). The following tables allow us to estimate the human body exergy consumption for the given parameters, but the room air temperature, which corresponds to the minimum of human body exergy consumption, is very important for choosing and designing a heat source. The estimation of the influence of human and building-related factors on the comfortable room air temperature will allow it to be reduced as much as possible, and, consequently, to reduce buildings energy consumption. The influence of the parameters depending on the human and the building enclosing structures on primary fuel consumption for the system "heating source – human – building envelope" has not yet been investigated and needs further study.

2. Simulation Model Description

The research model is the system "heating source – human – building envelope", shown in Fig. 1. The model basic parameters are presented in Table 1. The parameters of the environment correspond to the average value for the heating period in Kyiv, Ukraine [26]. The geometric parameters of the room virtual model are shown in Fig. 2.

To calculate the room air temperature that meets the comfort conditions in accordance with the energy approach, the regression equation [14] is applied:

$$t_{comf} = -0.774 \cdot t_r + 6.4 \cdot PMV - 0.253 \cdot M - 64 \cdot I_{cl} - \\ -0{,}048 \cdot \varphi + 70.934 \qquad (1)$$

where t_r – mean radiant temperature, °C; PMV – predicted mean vote; M – metabolic heat gains from people, W / m^2; I_{cl} – thermal resistance of human clothing m^2·K/W; φ – relative humidity, %.

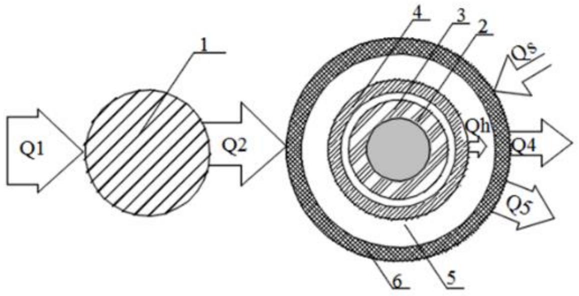
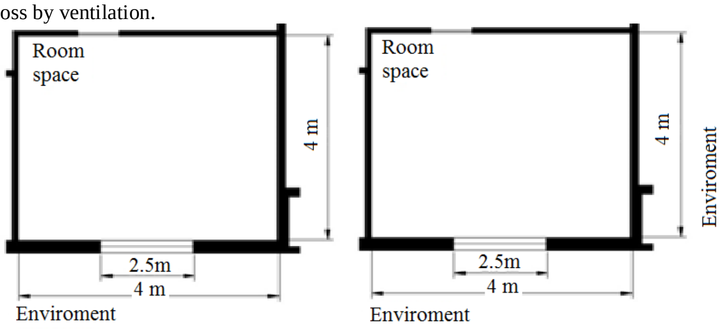


Fig. 1: Research model of complex system “heat source - human - building envelope”:

1 – generation; 2 – core; 3 – shell; 4 – clothing; 5 – room space; 6 – building envelope; Q1 – primary fuel consumption; Q2 – energy need for heating, Qh – heat gains from people, Qs – solar radiation heat gains; Q3 – other heat gains; Q4 – heat loss through the building envelope; Q5 – heat loss by ventilation.



a) b)

Fig. 2: Virtual room model: a) one exterior wall; b) two exterior walls

And for the calculation of the room air temperature that meets the comfort conditions in accordance with the exergy approach, the following equation [14] is applied:

$$t_{comf} = -0.61 \cdot t_r - 0.057 \cdot T_0 - 0.443 \cdot M - 76.38 \cdot I_{cl} - \\ -0.0397 \cdot \varphi + 92.978 \qquad (2)$$

where T_0 – ambient temperature, K.

Table 1: The basic parameters of the research model

Virtual room model	a)	b
Exterior wall area Fz, m2	6.25	16.25
Window area Fv, m2	3.75	
The area of internal enclosing structures, m2	62	52
Thermal resistance of the exterior wall Rz, m2·K/W	3.3	
Thermal resistance of the window Rv, m2·K/W	0.75	
Air exchange rate n, hour-1	1	
Parameters of the internal and external environment		
The ambient air temperature To, K	273	
Relative humidity of the environment φ0, %	60	
Relative humidity of the room air, φv, %	50	
Atmospheric pressure, Pa	101325	
Average solar heat gains on the vertical surface W/m2	30	

Therefore, based on the relations (1) and (2), average radiation temperature has significant influence on the room air temperature, which corresponds to the comfort conditions. The average radiant temperature is calculated using the temperature of the enclosing structures:

$$t_r = \frac{\sum_{i=1}^{n} F_i t_i}{\sum_{i=1}^{n} F_i}; \qquad (3)$$

where F_i – area of enclosing structure; t_i – temperature of the enclosing structure, $^\circ C$; n – number of enclosing structures.

To take into account the solar radiation coming through the window, the temperature t_i is taken as:

$$t_v = \sqrt[4]{\frac{P_s + P_v}{\sigma}} - 273, \qquad (4)$$

where t_v – window inner surface temperature, $^\circ C$; P_s – average heat gains from solar radiation W/m^2; P_v – the radiation power from the inner surface of the window W/m^2; σ– Boltzmann constant.

3. Results and Discussion

On the basis of exergy approach to comfortable conditions and the regression equation (2), a change in room air temperature which corresponds to the comfort conditions is determined after thermo-modernization for different geometric characteristics of the virtual room (with one and two exterior walls).

For the analysis of thermo-modernization effect on thermal comfort level, as well as on the average radiant temperature for the room virtual model (Fig. 2), the change in the average radiant temperature *tr* and the temperature on the inner surface of the exterior wall *tzs* is determined for different values of the ambient air temperature, namely the minimum and average value for the heating period (Fig. 3). It is shown that changing the enclosing structures thermal resistance for the room virtual model from the standards established in the 1980s to the modern requirements [4], the room average radiant temperature increases by 0.5°C (for outside air temperature t_0 = -1°C) and 1.2°C (for outside air temperature t_0 = -21°C), the internal air temperature is assumed to be 20°C. This is due to the increase in temperature on exterior wall inner surface by 1 and 3.7 ° C respectively. The change of PMV and PPD values during thermo-modernization was estimated for given human-related parameters: M = 70 W/m2 and Icl = 1 clo. It has been established that for t_0 = -1°C the PMV varies from -0.26 to -0.19 and PPD varies from 6.4 to 5.8%, and for t_0 = -21°C PMV varies from -0.36 to -0.24 and PPD varies from 7.6 to 6.1%.

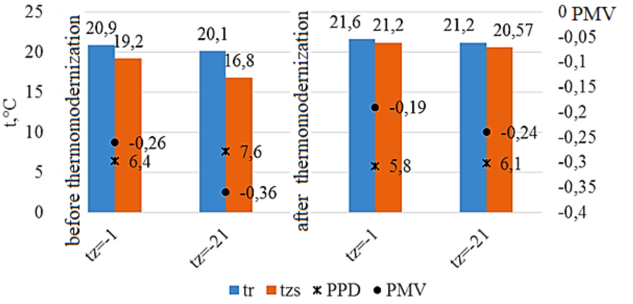
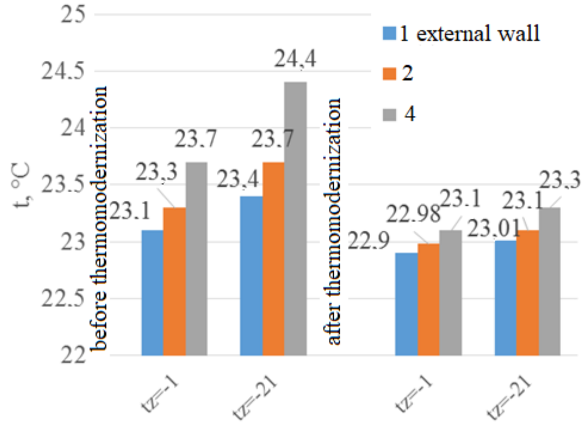


Fig. 3: Change in the average radiant temperature and comfort level conditions during thermo-modernization

For the analysis of thermo-modernization effect on the possible room air temperature reduction, which meets the comfortable conditions in accordance with the energy and exergy approaches, the change in room air temperature after thermo-modernization for various geometric characteristics of the virtual room is shown in Fig. 4.

Analysis of comfortable temperature reduction during thermo-modernization due to an increase in the average radiant temperature is shown in Fig. 4. It is established that with the average radiant temperature increase during thermo-modernization it is possible to reduce the comfortable room air temperature by 0.3-0.6°C. This is also due to the fact that the room air temperature decrease also causes a decrease in the average radiant temperature.



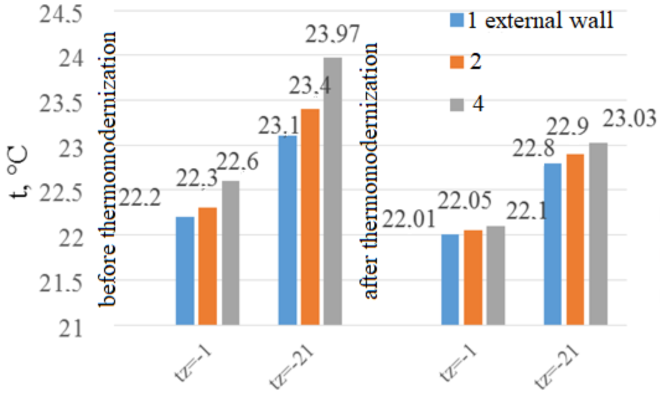
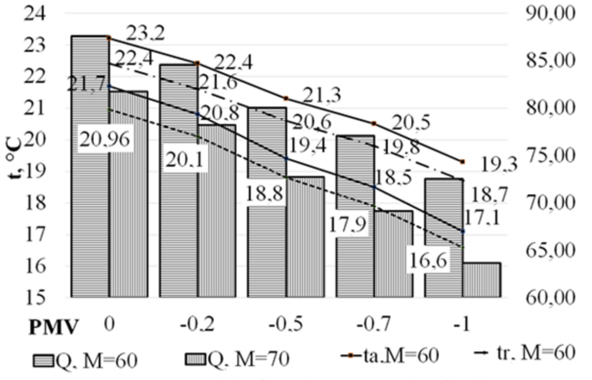
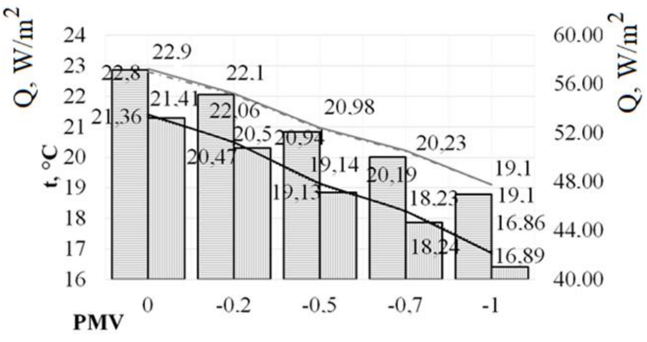


Fig. 4: Comfortable room air temperature values before and after thermo-modernization for different room geometry:
a) energy approach to comfortable conditions; b) exergy approach to comfortable conditions

The dependence of the energy need for heating on the building category in terms of comfortable conditions, as well as on human activity before and after the modernization, is presented in Figures 5a and 5b, respectively. Analyzing the data presented in Fig. 5 it can be stated that thermo-modernization reduces the energy need for heating by 53%, reducing the thermal comfort to the second category of the building leads to a decrease in energy needs for heating by 9%, and the combination of thermo-modernization and comfort level reduction causes a 68% decrease in energy consumption.



a) before thermomodernization



b) after thermomodernization

Fig. 5: Dependence of energy need for heating on the building category in terms of comfortable conditions:
a) before thermo-modernization; b) after thermo-modernization

To assess the influence of microclimate parameters on the primary fuel exergy consumption, investigation has been carried out for a virtual room model with a centralized heating system where the heat source is a gas boiler and the thermal resistance of the enclosures meets the modern requirements. The variation of microclimate subjective parameters is following: M = 60 - 70 W/m^2; I_{cl} = 0.5 - 1 clo. Objective microclimate parameters such as the average radiant temperature and the room air temperature are determined taking into account the thermal characteristics of the building envelope, solar heat gains and thermal comfort models (exergy and energy models are considered). The results of the primary fuel consumption calculation for building system (Fig. 6), where the district heating system is chosen as a heating source and the heating device uses 90/75°C temperature schedule, and the thermal resistance of building envelope corresponds to the 2008 norms, showed that the primary fuel exergy consumption varies by 27% and by 18% when changing the subjective parameters of the microclimate from point 1 ($M = 60\ W/m^2$, $Icl = 0.5$ clo) to the point 2 ($M = 70\ W/m^2$, $I_{cl} = 1$ clo), while the comfortable air temperature changes by 25% and by 16% when using exergy and energy approaches to providing comfortable conditions respectively. Therefore, taking into account the requirements for human thermal comfort will allow in certain cases to reduce energy consumption from 25 to 27%, and in certain cases to increase, with the aim of providing the appropriate level of thermal comfort.

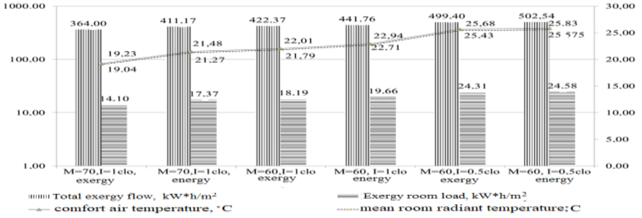


Fig. 6: Dependence of primary fuel exergy consumption on subjective parameters of thermal comfort

4. Conclusion

Due to the high requirements for buildings energy efficiency and microclimate quality in occupied spaces, there is a need for in-depth study of the complex system "heating source – human – building envelope", which applies the energy, exergy, economic and exergo-economic analyzes, the development and the use of energy and exergy human comfort models during the buildings design and operation phases.

On the basis of the energy and exergy human thermal comfort model, regression equations are developed for determining the comfortable room air temperature, which will greatly simplify the calculations in the future when designing and regulating the heating systems operation.

The joint effect of thermo-modernization and the change of the building comfort category on building are shown. More than 13% of energy need for heating reduction can be provided in general due to a decrease in the room air temperature regarding lower thermal comfort and an increase in the average radiant temperature.

The influence of microclimate parameters on the primary fuel exergy consumption by the centralized heat supply system is estimated. It is stated that taking into account the requirements for human thermal comfort will allow in certain cases to reduce energy consumption from 25 to 27%, and in certain cases to increase, with the aim of providing the appropriate level of thermal comfort.

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