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Study on daylighting mode of energy-efficient buildings

ABSTRACT: The research considers the aspect of the formation of interior lightning in conditions of extensive expenses on heating. In this regard there is important to study features not only of places and model of lightning, but also generation of heat in order to minimize expenses and find alternative technical solutions for building functioning. The relevance is determined by the fact that the problem of low efficiency of thermal energy used to ensure an appropriate microclimate in buildings is typical for many regions. The purpose of this article is to study features not only of places and model of lighting but also generation of heat to minimize expenses and find alternative technical solutions for building functioning. In the work, the methods of calculation methods and mathematical models such as the exergy model of humans were used. The authors have determined that daylight is only one of the complex solutions of the matter of building energy efficiency. Providing the conditions of heating comfort indoors is not less important in the conditions of increasing requirements to energy conservation. The authors consider the compromise between these two requirements without harming human health the main challenge to the energy conservation specialists. The authors have developed the model, which evaluates not only the achievements of technical parameters, but also orientation toward the model of energy consumption of human. The practical application of the

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developed methodology allows for forecasting not only building heating based on projected technical indicators but also tailored to individual needs.

KEYWORDS: building, energy-efficient, human, structure, lighting, heating

Introduction

The problem of low efficiency of thermal energy to provide respective microclimate in buildings is characteristic for many countries. The matter of thermal efficiency of building is connected with the choice of heat source and thermal properties of building envelopes. Since these solutions involve significant initial investment, there is a need for a feasibility analysis of a variety of alternatives (Jaffee et al. 2019). The energy efficiency of a building increases with an increase in the thermal resistance of building envelopes. In the context of constant changes in energy prices, taking the price in determining the optimal thermal properties of building envelopes of a building is highly relevant into account (Sarevet et al. 2020).

A building is a complicated system that is why the matter of choice of heating and thermal properties of barrier structures should be considered in complex (Li et al. 2014). During the usual calculation of thermal insulation thickness, a change of cost of money in time is not taken into account; apart from this, the designer often does not specify how a change of cost of energy carrier should be taken into account (Moreno 2016). The influence of thermal protection of a building on both quantitative and qualitative indicators of heating are not considered (Scott et al. 2008). There are suggestions to determine the expediency of an increase in thickness of thermal insulation by calculating an economy of energy carriers. Optimal thickness of thermal insulation can be determined through a maximum of the net present value (Rodrigues et al. 2020). This calculation only includes thermal energy tariff, but does not consider a chosen heat source, investments related to it, its decrease due to the improvement in protection properties of building envelope (Kok et al. 2012). There is inadmissibility of using discountless methods of investments calculation (the first two analyzed methods of discounting are not taken into account), the payback period of which is more than three years. Since the payback period of energy efficient heat sources and an additional insulation layer is long, the accounting of discounting is obligatory in choosing optimal values of thermal resistance of a building envelope (Hong et al. 2018).

Thus, a choice of optimal thermal protection properties of building envelope is a difficult matter, wherein the following should be taken into account: discounting, costs of different energy sources, which are tended at quick increase, energy efficiency and fundamental expenses on heat source, their change in the case of decrease of building heat load (Liu and Ren 2018). Since the matter of choice of heat source is relevant, it is necessary to evaluate expediency of use of different heat sources, considering their energy efficiency and a change of cost of energy carrier in time applying the method of cash flow (that is, to determine expediency of using different

heat sources from the energetic and economic perspectives). Modern requirements regarding technical and economical evaluation of projects implies considering such factors as: the influence of the cost of money in time; if a change in parameters of projects is possible; inflation; risk connected to project implementation.

Mathematical models of heat sense of a human by different parameters of environment are necessary to design heating systems and to regulate their work (Grande-Acosta and Islas-Samperio 2020). Apart from this, the provision of conditions is constrained because of the driving demand for energy conservation (Karuthedath et al. 2021). There is a number of thermopsychological human models, their development started in 1970 (Hanus et al. 2018). Two models providing humans' heat sense are basic and widespread. The A.P. Gagga model is a bimodal human energy model, which involves heat sensations in transient environmental conditions (Groumpos and Mpelogianni 2020). The international standard of defining indicators of thermal comfort has been developed on the basis of the empirical model (Li et al. 2020). This model allows to take the intensity of human activity, type of clothing, speed of air movement, relative humidity, air temperature in the room t_a and average radiation t_r into consideration. The model establishes a dependence between t_a and t_r for wintertime that depends on the intensity of human activity (Hinrichsen et al. 2020). There are also different models of thermal comfort of human connecting air temperature, average radiation temperature, speed of air movement, air pressure between each other. For example, the model of Van Zuylen (Drissi Lamrhari and Benhamou 2018):

$$S = 7,83 - 0,1t_v - 0,0968t_r - 0,0372r_p + 0,0367v^{0,5} (37,8 - t_v) \quad (1)$$

where:

- S – indicator of thermal state of human: 1 – hot, 2 – warm, 3 – pleasant warm, 4 – comfortable, 5 – pleasant cool, 6 – cold, 7 – very cold,
- t_v – air temperature in the room [°C],
- t_r – average air radiation temperature [°C],
- r_p – partial pressure [b],
- v – speed of air movement in the room [m/s].

Also, the model of S.E. Winslow and A.P. Gagge:

$$S = 11,16 - 0,0556t_v - 0,0538t_r - 0,0372r_p + 0,014v^{0,5} (37,8 - t_v) \quad (2)$$

However, in comparison with models of thermal comfort, the model of Fanger is built on the many researches and characterized by objectivity of the obtained data (Adinyira et al. 2018). Modern researchers consider the human as a complicated system, representing it in the form of 18 nodes, create a neural model to control blood flow to the skin, with the aim of ensuring and improving human thermal comfort.

The exergy approach is in defining the minimum of exergy consumption by the human body and based on the energy model, that is, it allows all the factors depending on environment and

human to be considered (Bozorgi 2015). Apart from this,, the model defines the minimum of destruction in two-nodes system of human and conditions, under which this minimum occurs (Krukovskii et al. 2017).

The adaptive model of thermal comfort is the dependence between operational temperature of the room and average monthly outdoor temperature (Goubran et al. 2017). There is American an adaptive model of thermal comfort, which is reflected in American standard ASHRAE 55: 2004, European – EN 15251 and building the Givolini bioclimatic chart. Consideration of comfortable conditions in a building during energy and exergy analysis of indicators of building energy efficiency is very important and insufficiently studied factor.

1. Materials and Methods

Depending on the goals of the research, scientists present different models of thermal control, which are based on energy and exergy balances. The introduction to the exergy concept, the exergy balance of the human body for typical and transient conditions have been present in a number of research studies. The further development of such an approach is reflected in comparison with the model of exergy consumption by the human body in stable and transient conditions. The analysis of the effect of the thermal protection of the building envelope on exergy consumption by human body for different climatic conditions showed that exergy consumption by human body declines by 0.6%, 6.4%, 10.1% and 35.9% for warm/humid, temperate, warm/dry and cold climate types, respectively, with an increase in thermal protection. The structure of energy and exergy balance of human body for summertime is reflected in the research of European scientists.

The process of thermoregulation in different types of climate with the application of exergy model of human has been analyzed. The method of exergy analysis to find the optimal ratio between the air temperature in the room and the mean radiant temperature for office workers in the summer has been used, as according to research the exergy approach to thermal comfort provides the highest labor productivity. It has been determined that that the minimum consumption of exergy by the human body, provided that the exergy readout starts from the air temperature in the room, responds to thermal senses as “a little bit cool”. During exergy analysis of the human body, the evaluation of the value of destroyed energy and exergy entering the environment has been suggested, as the minimum values of exergy destruction do not always correspond to comfortable conditions.

The stationary model of thermal comfort and value of exergy consumption by the human body is described using the program for the tables Excel Hideo Asada. Input data in the program are the parameters of the environment and human body, output is the percentage ratio between components of flow of exergy for the human body, PMV (projected average estimate of human heat sensation). The used method allow exergy consumption by the human body for set parame-

ters to be evaluated, but taking the air temperature in the room, which corresponds to the minimum consumption of exergy by the human body into account, is important to choose and design the proper heat source. The evaluation of the effects of the factors, which depend on the human and the building, comfortable temperature in the room, allow it to be lowered to a maximum degree and, accordingly, reduce building energy consumption.

There are six parameters that affect thermal comfort, among which there are four objective (air temperature in the room, average radiation temperature, speed of air movement, relative humidity) and two subjective (degree of metabolism, thermal resistance of human clothing). One of the parameters, which is harder to analyze, is mean radiant temperature of the room. Thus, mean radiant temperature is one of the most complicated variables in the human energy balance. There are two main methods to define average radiation temperature:

1. Measurement using a globe thermometer;
2. Calculation with use of empirical ratios basing on different approaches and considering such factors as solar radiation, parameters of building envelope and placement of human in the room.

2. Results and discussions

The method represented in the standard is applied to evaluate the level of thermal comfort. The method developed by Fanger and adapted in the standard ISO Standard 7730 is based on the equations of thermal balance of the human body:

$$\begin{aligned}
 PMV &= (0,303e^{-2,1M} + 0,028) [(M - W) - H - E_c - C_{res} - E_{res}] \\
 PPD &= 100 - 95e^{-(0,03353PMV^4 + 0,2179PMV^2)}
 \end{aligned}
 \tag{3}$$

where:

- M – degree of metabolism [W/m^2],
- W – effective shaft work [W/m^2],
- H – sensitive heat losses [W/m^2],
- E_c – heat exchange via evaporation off skin [W/m^2],
- C_{res} – heat exchange by convection, during breathing [W/m^2],
- E_{res} – heat exchange via evaporation during breathing [W/m^2].

$$H = 3,96 \cdot 10^8 \cdot f_{cl} \left[(t_{cl} + 273)^4 - (t_r + 273)^4 \right] - f_{cl} h_{cl} (t_{cl} - t_a)
 \tag{4}$$

$$E_c = 3,05 \cdot 10^{-3} [5733 - 6,99(M - W) - p_a] - 0,42 [(M - W) - 58,15] \quad (5)$$

$$C_{res} = 0,0014M(34 - t_a) \quad (6)$$

$$E_{res} = 1,7 \cdot 10^5 M(5867 - p_a) \quad (7)$$

where:

- f_{cl} – factor considering the surface area of clothing,
- t_a – air temperature [°C],
- t_r – mean radiant temperature [°C],
- t_{cl} – temperature of the surface area of clothing [°C],
- p_a – partial vapor pressure in air [Pa],
- I_{cl} – thermal resistance of clothing [m² °C/W],
- v_{air} – relative speed of air movement [m/s],
- h_{cl} – coefficient of convective heats exchange [W/(m² K)].

The data about metabolism depending on kind of activity of human and thermal resistance of clothing is listed in Table 1.

The main issue of calculation by this method is that the temperature of the surface area of clothing is not known beforehand, and is determined by the iteration method out of the equation of thermal balance for the clothing layer:

$$(t_{sk} - t_{cl}) = 3,96 \cdot 10^8 f_{cl} [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} h_{cl} (t_{cl} - t_a) \quad (8)$$

$$t_{sk} = 35,7 - 0,028(M - W) \quad (9)$$

The coefficient of convective heat exchange is determined as follows:

$$h_c = \begin{cases} 2,38 |t_{cl} - t_a|^{0,25}, & \text{if } 2,38 |t_{cl} - t_a|^{0,25} > 12,1 \sqrt{v_{ar}} \\ 12,1 \sqrt{v_{ar}}, & \text{if } 2,38 |t_{cl} - t_a|^{0,25} < 12,1 \sqrt{v_{ar}} \end{cases} \quad (10)$$

Factor considering the surface area of clothing:

$$f_{cl} = \begin{cases} 1,00 + 1,29 I_{cl}, & \text{if } I_{cl} \leq 0,78 \\ 1,05 + 1,645 I_{cl}, & \text{if } I_{cl} > 0,78 \end{cases} \left[\frac{\text{m}^2 \text{K}}{\text{Bm}} \right] \quad (11)$$

TABLE 1. Parameters of the human body

TABLE 1. Parametry ciała ludzkiego

Coefficient of clothing insulation	
Clothing	<i>clo</i>
Without clothing	0
Underwear	0.05
Shorts	0.1
Ordinary tropical suit: shorts, short-sleeved shirt, light underwear	0.3
Light summer clothes: long light pants, short sleeved shirt, underwear	0.5
Light tropical suit	0.8
Ordinary business suit	1
Traditional Northern European suit with waistcoat, long sleeve underwear, jacket	1.5
Polar clothing	3–4
Metabolic rate	
Activity	Met
Sleep	0.8
Siting	1
Printing	1.2
Standing	1.4
Ordinary standing work in laboratory, shop, kitchen	1.6–2
Slow manner of walking (3 km/h)	2
Normal manner of walking (5 km/h)	2.6
Quick manner of walking (7 km/h)	4
Work of carpenter/of builder	3
Running (10 km/h)	8

The method of determination of PMV (Predicted Mean Vote) implies the connection between optimal thermal conditions using the equation of thermal balance for human body in stationary conditions and the rating of providing thermal comfort. It is possible to calculate thermal comfort indicators using such internet developments. To calculate comfortable air temperature in the room and to study the effects of different factors on it, it is necessary to solve a system of nonlinear equations. This model is developed by Fanger, and the indicator if PMV is grounded on the basis of many experiments, but mechanism of thermoregulation is not considered here that is significant in the heat exchange calculation of a human.

In the basis of exergy model is two-nodes thermophysiological model of a human developed by A.P. Gagge. The human body is considered to be an open thermodynamic system in constant conditions. This model takes heat loss due to breathing, evaporation of moisture and heat loss due to convection and radiation into consideration.

Existing standards of microclimate in the room and indicators of thermal comfort is based on energy model of thermal comfort developed by Fanger, which is based on the energy balance used to determine the dissipation of heat by the human body. Mechanisms of thermoregulation in this case are not considered. At the same time, exergy model of thermal comfort allows processes of thermogenesis and thermolysis to be considered, because it is built on the basis of Gagge's energy model, which describes the mechanism of human thermoregulation. The energy balance of the human body (on the condition that ambient temperature is constant), considering that human consists of the core and the skin:

$$S_{sk} = K_{min} (T_{cr} - T_{sk}) + c_{bl} V_{bl} (T_{cr} - T_{sk}) - E_{sk} - DRY \quad (12)$$

$$S_{cr} = (M - E_{res} - W) - K_{min} (T_{cr} - T_{sk}) - c_{bl} V_{bl} (T_{cr} - T_{sk}) \quad (13)$$

where:

- S_{cr}, S_{sk} – accumulations of energy in core and shell [W/m²],
- K_{min} – coefficient of effective heat exchange between core and shell = 5,28 [W/(m²·K)],
- T_{cr} – core temperature [K],
- T_{sk} – skin temperature [K],
- c_{bl} – specific heat capacity of human = 4187 J/kg·[K],
- V_{bl} – blood flow to the skin [kg/s·m²].

Total heat loss by evaporation off the skin may be represented as follows:

$$E_{sk} = E_{diff} E_{rsw} \quad (14)$$

The magnitude $DRY = (R + C)$ is called dry heat exchange off a body surface and determined as follows:

$$DRY = h F_{cle} (T_{sk} - T_o) \quad (15)$$

where:

- h – combined coefficient of heat exchange [W/m²·°C]:

$$h = h_r + h_c \quad (16)$$

where:

- h_r – coefficient of heat exchange by radiation:

$$h_r = 4 \frac{A_r}{A_D} \sigma \varepsilon \left(\frac{t_{cl} + t_r}{2} + 273,2 \right)^3 \quad (17)$$

where:

- A_r – surface of radiation of human body [m²],
- A_D – coefficient of Dubois (coefficient of area surface of human body):

$$A_D = 0,202m^{0,425}l^{0,725} \quad (18)$$

where:

- m – human body mass [kg],
- l – human height [m],
- σ – Stefan–Boltzmann constant,
- ε – radiation capacity of clothing surface; to simplify $A_r/A_D = 0,72$,
- t_{cl} – temperature of clothing surface [°C],
- t_r – mean radiant temperature [°C],
- h_c – coefficient of convective heat exchange:

$$h_c = \max \left\{ \begin{array}{l} 2,384\sqrt{|t_{cl} - t_a|} \\ 12,1\sqrt{v} \end{array} \right. \quad (19)$$

where:

- t_a – air temperature in the room [°C],
- T_o – operating temperature [K],
- v – speed of air movement [m/sec].

$$t_o = \frac{h_c t_a + h_r t_r}{h_c + h_r} \quad (20)$$

where

- F_{cle} – coefficient of thermal efficiency of clothing:

$$F_{cle} = \frac{1}{1 + 0,155hI} \quad (21)$$

where:

- M – specific value of heat generation due to metabolism [W/m²],
- E – heat loss due to evaporation [W/m²],
- R – heat entry or loss by radiation [W/m²],
- C – heat entry or loss by convection [W/m²],
- W – work, which human doing [W/m²].

Heat loss due to evaporation is divided into three parts:

- E_{res} – heat from the evaporation of liquid due to breathing [W/m²],
- E_{res} – heat from evaporation of liquid that penetrates through the skin layer [W/m²],

E_{rsw} – heat from the evaporation of sweat to regulate body temperature [W/m²].
Heat from the evaporation of liquid due to breathing:

$$E_{res} = 0,0023M(44 - P_a) \quad (22)$$

where

P_a – vapor pressure in the room, mm Hg (torr) (2.49)

$$E_{sk} = wE_{max} \quad (23)$$

$$E_{sk} = (0,06 + 0,094w_{regsw})E_{max} \quad (24)$$

$$w_{regsw} = \frac{E_{regsw}}{E_{max}} \quad (25)$$

$$E_{regsw} = 0,7m_{regsw}2^{\frac{t_{sk}-34,1}{3}} \quad (26)$$

where:

E_{max} – maximum possible evaporation off the skin surface [W/m²],

w – skin humidity,

w_{regsw} – wetness of the skin due to regular generation of moisture,

0,7 – latent heat of sweat [W·h/gr.],

E_{regsw} – evaporation loss off the skin surface due to normal generation of moisture [W/m²],

m_{regsw} – degree of moisture covering the skin, gr/h·m².

Maximum possible evaporation off the skin surface:

$$E_{max} = kh_c(p_{sk} - p_a)E_{pcl} \quad (27)$$

where:

k – Lewis's coefficient = 2,2 [°C/mm Hg],

p_{sk} – pressure of saturated water vapor for temperature T_{sk} [mm Hg],

F_{pcl} – water vapor penetration efficiency coefficient from the skin through the clothing to the environment:

$$F_{pcl} = \frac{1}{1 + 0,143h_c I_{cle}} \quad (28)$$

where

I_{cl} – coefficient of clothing insulation, clo (1 clo = 0,155 m²·° C/W).

Temperature of clothing surface of human:

$$t_{cl} = \left(35,7 - 0,028(M - W) - I_{cl} \left(3,96 \cdot 10^{-8} f_{cl} \left((t_{cl} + 273)^4 - (t_r + 273)^4 \right) + f_{cl} h_c (t_{cl} - t_a) \right) \right) \quad (29)$$

The system of thermal regulation is described by the following equations; temperature signals of the core and the skin are being studied:

$$\sum_{sk} = t_{sk} - 34,1 \quad (30)$$

$$\sum_{cr} = t_{cr} - 36,6 \quad (31)$$

where

\sum_{cr}, \sum_{sk} – temperature signal from the skin and the core, respectively [°C].

On the basis of these two signals blood flow velocity and moisture mass generated by a human are determined:

$$V_{bl} = \begin{cases} \frac{6.3 + 75\sum_{cr}}{6.3} & , \text{ if } \sum_{cr} < 0 \cap \cup \sum_{sk} < 0 \\ 1 - 0.5\sum_{sk} & , \text{ if } \sum_{cr} < 0 \cap \cup \sum_{sk} < 0 \end{cases} \quad (32)$$

$$m_{regsw} = \begin{cases} 0, & \text{ if } \sum_{cr} < 0 \cap \cup \sum_{sk} < 0 \\ 250 + 100\sum_{cr} & \end{cases} \quad (33)$$

where

T_{cr}, T_{sk}, E_{sk} – calculated by equations (13)–(33) for certain parameters of the environment.

These indicators are based on the exergy balance to define exergy consumption by human body. Exergy balance for human body:

$$Ex_m + Ex_{gen,cr} + Ex_{gen,sk} + Ex_{inh,air} + Ex_{abs,sk-cl} = Ex_{rad,dc} + Ex_{conv} + Ex_{exh,air} + Ex_{sw,ha} + Ex_{stored,cr} + Ex_{stored,sk} + Ex_{cons} \quad (34)$$

where:

Ex_m – flow of exergy of heat due to metabolism [W/m²],
 $Ex_{gen,cr}$ – flow of exergy of liquid generated in the core due to metabolism [W/m²],

- $Ex_{gen,sk}$ – flow of exergy of liquid generated in the skin due to metabolism [W/m²],
 $Ex_{inh,air}$ – flow of humid air that human inhale [W/m²],
 $Ex_{abs,sk-cl}$ – flow of exergy of radiation absorbed by skin and clothing of human [W/m²],
 $Ex_{rad,dc}$ – flow of exergy of radiation from the body surface [W/m²],
 Ex_{conv} – flow of exergy transmitted by convection to air [W/m²],
 $Ex_{exh,air}$ – flow of exergy of humid air that human exhales [W/m²],
 $Ex_{sw,ha}$ – flow of exergy of water vapor due to skin secretion [W/m²],
 $Ex_{stored,cr}$ – flow of exergy accumulated in the core [W/m²],
 $Ex_{stored,sk}$ – flow of exergy accumulated in the skin [W/m²],
 Ex_{cons} – flow of exergy consumed by human body [W/m²].

All components of human energy and exergy balance are determined by 1 m² of the human body area, to include heat from the human body in the thermal balance of the room, the human body area is determined according to the following equation:

$$F_l = 0,203l^{0,725}p^{0,425} \quad (35)$$

where:

- F_l – human body area [m²],
 l – height [m],
 p – human body mass [kg].

Exergy of heat due to metabolism is calculated according to:

$$Ex_m = M \left(1 - \frac{T_0}{T_{cr}} \right) \quad (36)$$

Exergy of liquid generated in the core due to metabolism:

$$Ex_{gen,cr} = V_{w,core} p_w \left\{ c_{pw} \left[(T_{cr} - T_0) - T_0 \left(\ln \frac{T_{cr}}{T_0} \right) \right] + \frac{R}{X_w} T_0 \ln \frac{p_{sv,T_0}}{p_{v0}} \right\} \quad (37)$$

where:

- $V_{w,core}$ – volumetric rate of water generated in the core [(m³/s)/m²],
 p_w – density of water [kg/m³ ($p_w = 1000$ kr/m³)],
 c_{pw} – specific heat of water [J/kg·K ($c_{pw} = 4186$ J/kg·K)],
 R – gas constants [J/(mol * k) ($R = 8,314$ J/(mol·k))],
 X_w – molar mass of water [g/mol ($X_w = 18,05$ g/mol)],
 p_{sv,T_0} – pressure of saturated water vapor at ambient temperature [Pa],
 p_{v0} – pressure of water vapor, ambient temperature [Pa].

Exergy of liquid generated due to metabolism:

$$x_{gen,sk} = V_{w,shell} P_w \left\{ \begin{array}{l} c_{pw} \left[(T_{sk} - T_0) - T_0 \left(\ln \frac{T_{sk}}{T_0} \right) \right] + \\ + T_0 \frac{R}{X_w} \left[\ln \frac{P_{sv} T_0}{P_{v0}} + \frac{P - P_{vr}}{P - P_{v0}} \right] \end{array} \right\} \quad (38)$$

where:

- $V_{w,shell}$ – volumetric rate of water generated by the shell as sweat [(m³/s)/m²],
- P – atmospheric air pressure [Pa],
- P_{vr} – pressure of water vapor in the room [Pa].

Exergy of humid air that the human inhales:

$$Ex_{inh, fir} = V_{in} \left\{ \begin{array}{l} \left[c_{p,a} \left(\frac{X_{da}}{RT_{ra}} \right) (P - P_{vr}) + c_{p,v} \left(\frac{X_{da}}{RT_{ra}} \right) P_{vr} \right] \left[(T_{ra} - T_0) - T_0 \left(\ln \frac{T_{ra}}{T_0} \right) \right] + \\ + \frac{T_0}{T_{ra}} \left[(P - P_{vr}) \ln \left(\frac{P - P_{vr}}{P - P_{v0}} \right) + P_{vr} \left(\ln \frac{P_{vr}}{P_{v0}} \right) \right] \end{array} \right\} \quad (39)$$

where:

- V_{in} – volumetric rate of air blowing in [(m³/s)/m²],
- $c_{p,a}$ – specific heat of dry air [J/(kg K)] ($c_{p,a} = 1005$, J/(kg K)),
- X_{da} – molar mass of dry air [g/mol (28,97 g/mol)],
- $c_{p,v}$ – specific water heat vapor [J/kg·K] ($c_{p,v} = 1846$ J/kg·K),
- T_{ra} – air temperature in the room [K].

Energy of radiation absorbed by the skin a clothing of the human:

$$Ex_{abs,sk-cl} = f_{ef} f_{cl} a_i \varepsilon_{cl} h_{rb} \frac{(T_i - T_0)^2}{(T_i - T_0)} \quad (40)$$

where:

- f_{if} – ratio of efficient human body area that is being under heat radiation to human body area covered by clothing,
- f_{cl} – ratio of human body area covered by clothing to area without clothing,
- a_i – coefficient of absorption between human body surface area and surrounding surfaces,
- ε_{cl} – radiant ability of clothing surface,
- h_{rb} – relative heat transfer coefficient of dark surface,
- T_i – temperature of i surface [K].

Exergy of radiation off the body surface:

$$Ex_{rad,dc} = f_{ef} f_{cl} a_i \varepsilon_{cl} h_{rb} \frac{(T_{cl} - T_0)^2}{(T_{cl} - T_0)} \quad (41)$$

Exergy transmitted by convection to air:

$$Ex_{conv} = f_{cl} h_{ccl} (T_{cl} - T_{ra}) \left(1 - \frac{T_0}{T_{cl}}\right) \quad (42)$$

where

h_{ccl} – average coefficient of heat transfer of human body surface covered by clothing [W/(m²·K)].

Exergy of humid air exhaled by human:

$$Ex_{exh,air} = V_{out} \left\{ \begin{aligned} & \left[c_{p,a} \left(\frac{X_{da}}{RT_{cr}} \right) (P - P_{vs}(T_{cr})) + c_{p,v} \left(\frac{X_{da}}{RT_{cr}} \right) P_{vs}(T_{cr}) \right] \times \\ & \times \left[(T_{cr} - T_0) - T_0 \left(\ln \frac{T_{cr}}{T_0} \right) \right] + \\ & + \frac{T_0}{T_{cr}} \left[(P - P_{vs}(T_{cr})) \ln \left(\frac{P - P_{vs}(T_{cr})}{P - P_{v0}} \right) + P_{vs}(T_{cr}) \left(\ln \frac{P_{vs}(T_{cr})}{P_{v0}} \right) \right] \end{aligned} \right\} \quad (43)$$

where:

V_{out} – volumetric rate of exhaled air [(m³/s)/m²],

$P_{vs}(T_{cr})$ – pressure of saturated water vapor for temperature of the core [Pa].

Exergy of water vapor due to skin secretion:

$$Ex_{sw,ha} = V_{w,shell} P_w \left\{ \begin{aligned} & c_{p,v} \left[(T_{cr} - T_0) - T_0 \left(\ln \frac{T_{cr}}{T_0} \right) \right] + \\ & + \frac{R}{X_w} \left[\ln \left(\frac{P_{vr}}{P_{v0}} \right) + \frac{P - P_{vr}}{P_{vr}} \left(\ln \frac{P - P_{vr}}{P - P_{v0}} \right) \right] \end{aligned} \right\} \quad (44)$$

The components of the exergy balance have been calculated from empirical ratios given in the works of different authors where parameters of the environment are admitted as the constant, the accumulations of energy and exergy in the core and the skin are not considered.

The presented method of calculation built on the indicators of thermal comfort PMV, PPD and on exergy consumption by human body establishes the set of these and other factors that provide the needed level of comfort.

The algorithm for the calculation comfort temperature of air in the room has been developed according to the exergy approach. According to the approach, the human body functions the best under the condition of minimum consumption or destruction of exergy by the human body, that is why the main purpose it to determine the minimum value of energy consumption by the human body and corresponding to it to the air temperature in the room with other constant parameters of the microclimate. According to the proposed algorithm, the minimum functions of one variable are determined by the exhaustive method. The testing of the human exergy model is given in this work; data corresponds to the sources. The computer model implementing the algorithm is also built using empirical ratios (22–44) in Mathcad.

The proposed algorithm and computer model allow determining air temperature in the room that corresponds to minimum exergy consumption by the human body. That us, it meets the conditions, in which the human body functions best according to the second law of thermodynamics. That is why it is necessary to rely on conditions where exergy destruction is less expedient in designing a heating system than to rely on the indicator of expected average evaluation of human heat sense.

A method to define the mean radiant temperature on the basis of efficient flows of internal surfaces of barriers on the example of the computer model has been developed. The computer model describes the room with one outer wall and window. In the stationary thermal balance, the heating loss through outer walls and windows, thermal entries from solar radiation through windows and inner sources and heating loss due to ventilation of the room have been taken into consideration. There is an allowance for temperatures for every interior surface to settle. Solar radiation after entering the room through window as well as own thermal radiation and radiation characteristics of surfaces are of a diffuse nature. We also allow that thermophysical properties of material of the building envelope do not depend on temperature. The computer model of the building includes heating devices and its efficient thermal flow is considered. Ratios concerning a heating device are presented below. The equation of thermal balance of the room:

$$Q_B + Q_Z = Q_{0\Sigma} + Q_{TH} + Q_{p.a.2} \quad (45)$$

where:

- Q_B – heat loss due to ventilation [W],
- Q_Z – heat loss because of building envelope [W],
- $Q_{0\Sigma}$ – heating entry from heating devices [W],
- Q_{TH} – additional heating entries [W].

The equation of thermal balance for a heating device:

$$Q_{0\Sigma} = Q_0' + Q_0'' \quad (46)$$

$$Q'_0 = Q'_{ок} + Q'_{оп} \quad (47)$$

$$Q''_0 = Q''_{ок} + Q''_{оп} \quad (48)$$

$$Q'_o = F_o \alpha_o (t_o - t_{BH}) + A_{np} \sigma (T_o^4 - T_{BH}^4) \quad (49)$$

$$Q'_{ок} = F_o \frac{t_o - t_{zo}}{R_{\alpha z}} \quad (50)$$

$$A_{np} = \frac{1}{\frac{1}{A_{o1}} + \frac{1}{A_1} - 1} \quad (51)$$

where:

- $Q_{o\Sigma}$ – heating entry from the heating device [W],
- Q'_0 – amount of heat from the heating device [W],
- Q''_0 – amount of heat given by the heating device to the outer wall [W]
- $Q'_{ок}, Q''_{ок}$ – amount of heat transmitted by convective thermal exchange [W],
- $Q'_{оп}, Q''_{оп}$ – amount of heat transmitting by radiant thermal exchange [W],
- F_0 – area of heating device [m²],
- α_0 – coefficient of heating of the heating device [W·m²·°C],
- t_0, t_{BH}, t_z – temperature of the heating device [°C],
- t_{z0} – temperature on the surface of outer wall from the inside [°C],
- σ – Stefan–Boltzmann constant [($\sigma = 5,67 \cdot 10^{-8}$ W/(m²·K⁴))],
- A_{np} – reduced absorption coefficient for the heating device and the outer wall,
- A_{o1}, A_1 – coefficients of absorption for the heating device and the outer wall,
- $R_{\alpha z}$ – cell c-thermal resistance of heating of wall layer [m²·°C/W].

The equation of heat transfers out from interior surface of the wall from the heating device:

$$Q_z''' = F_0 \frac{t_{z0} - t_z}{R_{\alpha z} + R_z} \quad (52)$$

$$Q_0'' = Q_z''' \quad (53)$$

where:

- Q_z''' – heat loss through the outer wall by the heating device [W]
- R_z – thermal resistance of thermal conductivity of the outer wall [(m²·°C)/W].

The value of effective and resulting flows of thermal and solar radiation and own thermal flow for the heating device:

$$Q_{res.o.1} = Q_{ef01} - Q_{vo1}\Phi_{vo-o} \quad (54)$$

$$Q_{res.o.2} = Q_{ef02} - Q_{vo2}\Phi_{vo-o} \quad (55)$$

$$Q_{ef.o.1} = Q_{res01} \left(1 - \frac{1}{A_{01}} \right) + \frac{Q_{e.o.1}}{A_{01}} \quad (56)$$

$$Q_{ef.o.2} = Q_{res.o.2} \left(1 - \frac{1}{A_{02}} \right) \quad (57)$$

$$Q_{e.o.1} = F_0 \sigma A_{01} T_0^4 \quad (58)$$

where:

- $Q_{res.o.1}$ – resulting flow of thermal radiation of the heating device [W],
- $Q_{res.o.2}$ – resulting flow of solar radiation of the heating device [W]
- $Q_{ef.o.1}$ – effective flow of thermal radiation of the heating device [W],
- $Q_{ef.o.2}$ – effective flow of solar radiation of the heating device [W],
- $Q_{e.o.1}$ – own flow of thermal radiation of the heating device [W],
- A_{02} – coefficient of absorption of solar radiation for the heating device.

Such equations of effective, own and resulting flows of thermal and solar radiation are formed for the outer wall, windows and interior walls, erected in the energy balance, which is for the determining temperatures of surfaces.

To take the reflections of solar radiation and thermal radiation into account, a method to determine radiant temperature on the basis of effective flows of interior surfaces of barriers and the heating device has been developed:

$$t_i = \left((t_{im} + 273)^4 + \frac{0.179 \cdot 10^8 Q_{ef2i}}{F_i} \right)^{0.25} - 273 \quad (59)$$

$$t_r = \frac{\sum_{i=1}^n F_i t_i}{\sum_{i=1}^n F_i} \quad (60)$$

where:

- t_{im} – temperature of building envelope determined on the basis of the model considering own heat exchange of building envelope by solar and thermal radiation [°C],

- Q_{ef2i} – effective flow of solar radiation for building envelope [W],
 F_i – the area of building envelope [m²].

The computer model, which allows the influence of the reflection of solar and thermal radiation on air temperature in the room to be considered and to determine the mean radiant temperature, describes the room with the one outer wall and window. In the event there are two outer walls to consider the influence of solar radiation, it is possible to use the approach that defines the mean average temperature as the weighted average by areas (60) and temperature on the translucent interior surface of the building envelope is calculated as follows:

$$t_v = \sqrt[4]{\frac{P_s + P_v}{\sigma} - 273} \quad (61)$$

where:

- P_s – average solar radiated power entering the vertical surface of respective orientation [W],
 P_v – power of own radiation [W].

Temperature on the interior surface of the building envelope is determined as follows:

$$t_i = t_{\theta n} - \frac{t_{\theta n} - t_z}{R_z R_{\alpha z}} \quad (62)$$

The temperature of other building envelope is admitted as equal to air temperature in the room $t_{\theta n}$.

There have been proposed two approaches to calculate the mean radiant temperature of the room, which is the most influential factor in a human's heat sense. The first allows to consider effective and own flow of solar and thermal radiation from the building envelope and the heating device, but the computer model is developed for the room with one outer wall, the second provides simplification of calculations and allows to take entries of solar radiation into account.

Thermal and economic evaluation of energy system design is related to definition of each component of system of such characteristics:

1. Exergy efficiency ε_k ;
2. Exergy dissipation, E_D and exergy loss, E_L ;
3. Capital investment, Z_k , operating costs and cost of technical service, Z_e , their totals, Z ;
4. The cost of exergy dissipation, Z_D ;
5. Relative difference of costs, r_k ;
6. Exergy and economic factor, $f_k = \frac{Z_k}{Z_k + c_{p,k} (E_{D,k} + E_{L,k})}$.

To choose the source of heat in complex with building envelope the analysis of the following indicators is proposed:

1. Exergy efficiency for the heat source;
2. Unit cost of exergy consuming by the system;

3. Capital investment Z_k ;
 4. Cost of unit of exergy which is lost because of building envelope and ventilation.
 Exergy efficient of heat sources is determined:

$$\eta_{ex} = 1 - \frac{Ex_{1i}^D}{Ex_{1i}} \quad (63)$$

where:

- Ex_{1i}^D – value of exergy destruction,
 Ex_{1i} – exergy of fuel consuming by heat source.

The equation of balance of exergy cost for the system in general will be:

$$b_5 \sum_i Ex_{5i} = \sum_j b_{1j} Ex_{1j} + \sum Z \quad (64)$$

where:

- b_{1j} – cost of flow of exergy fuel for the system [\$/kW·h],
 b_5 – cost of exergy flow of a product [\$/kW·h].

According to the equation of exergy economic balance:

$$c_5 = \frac{\sum_j c_{pj} Ex_{pj} + \sum Z}{\sum_i Ex_{5i}} \quad (65)$$

where:

- c_p – cost of unit of exergy entering the system of fuel [\$/kW · h],
 Ex_p – fuel exergy entering the system [kW·h],
 Ex_{x5} – exergy which is lost by the building due to building envelope and ventilation [kW·h],
 j – source of heat.

Fundamental costs to improve thermal protection are determined according to the ratio (18), and the source of heat according to (14). The cost of exergy flow of a product is the main thermal and economic criterion of comparison and optimization of the heat pump work. Most research defines thermal and economic indicators for one hour of work of equipment. In this case we chose the time period equal to the heating period, considering the specifics of provision of thermal comfort in the system. The cost of exergy product flow for the system we chose as thermal and economic criterion of building optimality:

$$b_5 = \frac{b_p E_p + \sum_j Z_j k_j}{\sum_i E_{5i}} \quad (66)$$

where:

- k_j – shares of equipment cost,
- j – elements of the system, the fundamental costs of which are taken into account,
- E_{5i} – exergy loss on building envelope and ventilation [kW·h].

The cost of exergy spent on the production of a unit of product is widespread in thermal and economic analysis. Considering that exergy in buildings is lost because of the building envelope and ventilation, to provide appropriate thermal comfort, it is possible to determine the average cost per unit of exergy that is lost by building not during the heating period, but for a certain period of time equal to the life of the heating system. This approach allows to consider the change in time of consumed energy carriers; we suggest the calculation of the thermal and economic criterion as follows:

$$b'_5 = \frac{\sum_{r=1}^n \frac{b_p E_p (1+l_i)^r}{(1+E)^r} + \sum_n Z_{k,i} k_i + \sum_n \frac{Z_{e,i}}{(1+E)^n}}{\sum_n E_5} \quad (67)$$

where:

- n – depth of calculation [years],
- $Z_{i,j}$ – fundamental costs at every sector of thermal and economic model [rub.],
- E – discount rate substantiated according to the economic situation and financing,
- l – rate of costs increase on the unit of exergy of energy sources.

A method of exergy economic analysis of the system has been proposed. There are two exergy and economic criterion for the complex choice of heat source and building envelope: the first criterion determines the cost of exergy loss to provide comfort conditions in the building during the heating period, the second indicator evaluates the cost of exergy loss to provide comfort conditions in the building for n years and allows to take a change of cost of energy carriers in time into account.

Conclusions

A method of the complex choice of heat source and building envelope based on the integral function of the system cost that allows taking a change of cost of energy carriers in time and the level of inflation into account has been developed. Also, the use of the function of integral cost based on the fuzzy set theories to consider a change of cost of energy carriers in time has been proposed. Developing this method, it is important to take the possibility of zone account of

energy carriers into account, regulating the change of temperature in the room, and to carry out optimization of the system work based on economic criterion using certain heat sources.

The method of analysis of energy and exergy flow for the system has been presented. The expediency of applying the efficiency indicator of primary fuel and analogical exergy criterion to compare different buildings has been substantiated because it depends on the protection properties of the building envelope and the chosen heat source.

The stationary energy and exergy model of the human thermal comfort has been described and an algorithm to calculate comfort temperature by exergy approach has been developed. There are computer models, which can demonstrate the evaluation of the indicators of thermal comfort for the energy model and values of components of exergy balance and exergy consumption by the human body for certain parameters of the environment. To provide the appropriate level of thermal comfort and to decrease energy consumption without harming human health, it is necessary to focus on air temperature in the room, which is comfortable in connection with energy or exergy approaches, that is why the computer model has been developed for calculating the comfort temperature according to two approaches.

The method to define the mean radiant temperature based on efficient flows of internal surfaces of barriers on the example of the computer model has been developed. Another method to calculate mean radiant temperature considering solar radiation entry has been represented.

The method of exergy and economic analysis of the system has been represented. Two exergy and economic factors for the complex choice of heat source and building envelope have been proposed: the first criterion determines the cost of exergy loss to provide comfort conditions in the building during the heating period, the second indicator evaluates the cost of exergy loss to provide comfort conditions in the building for n years and allows to take a change of cost of energy carriers in time into account.

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Aspekty wykorzystania światła dziennego w budynkach energooszczędnych

Streszczenie

W artykule przedstawiono aspekty projektowania oświetlenia wewnętrznego w warunkach dużych nakładów na ogrzewanie. O trafności tematu decyduje fakt, że problem niskiej efektywności wykorzystania energii cieplnej w celu zapewnienia odpowiedniego mikroklimatu w budynkach jest typowy dla wielu regionów. Celem artykułu jest zbadanie cech nie tylko lokalizacji i modelu oświetlenia, ale także wydzielenia ciepła, aby zminimalizować wydatki i znaleźć alternatywne rozwiązania techniczne dla funkcjonowania budynku. W pracy posłużono się metodami obliczeniowymi oraz modelami matematycznymi, takimi jak model egzergii człowieka. Ustalono, że światło dzienne to tylko jedno z kompleksowych rozwiązań kwestii energooszczędności budynków. Zapewnienie warunków komfortu cieplnego w pomieszczeniach jest równie ważne w obliczu rosnących wymagań dotyczących oszczędzania energii. Autorzy uważają, że kompromis między tymi dwoma wymogami bez szkody dla zdrowia ludzkiego jest głównym wyzwaniem dla specjalistów od oszczędzania energii. Opracowano model, który ocenia nie tylko osiągnięte parametry techniczne, ale także orientację na model zużycia energii przez człowieka. Praktyczne zastosowanie tej metodyki pozwala prognozować ogrzewanie budynku nie tylko na podstawie przewidywanych wskaźników technicznych, ale także z uwzględnieniem indywidualnych potrzeb.

SŁOWA KLUCZOWE: budownictwo, energooszczędność, człowiek, konstrukcja, oświetlenie, ogrzewanie

