Vol. 12, 2023, 191-200

DOI: 10.17512/bozpe.2023.12.21

Construction of optimized energy potential

Budownictwo o zoptymalizowanym potencjale energetycznym

ISSN 2299-8535 e-ISSN 2544-963X

Features of heat exchange in office premises with radiant cooling

Olena Savchenko[1*] (*orcid id: 0000-0003-3767-380X*)
Oleksandra Dzeryn[1] (*orcid id: 0000-0003-2727-2252*)
Anna Lis[2] (*orcid id: 0000-0001-9497-5754*)
[1] Lviv Polytechnic National University, Ukraine
[2] Czestochova University of Technology, Poland

Abstract: Decarbonization of the engineering systems of buildings and structures is extremely important both for achieving zero emissions of greenhouse gases and for ensuring energy security of countries. One of the main consumers of energy in public buildings, in particular in office premises, are cooling systems, which maintain the temperature of the internal air in the premises during warm periods of the year. To achieve the goals of energy saving and high thermal comfort in the premises, it is advisable to use radiation cooling systems. Modeling methods are used to describe the behavior of radiation cooling systems and to assess the influence on them of various factors. In this article, modeling of thermal interactions in an office premises is performed using graph theory. As a result of mathematical modeling, heat balances for the heat capacities of the room were drawn up and systems of balanced equations were proposed. In addition, the article provides a graphic dependence of the area of the ceiling cooling panel on the temperature of the internal air and heat gain from solar radiation in the office premises.

Keywords: radiation cooling system, mathematical modeling, heat balance, heat gain

Please, quote this article as follows:

Savchenko O., Dzeryn O., Lis A., Features of heat exchange in office premises with radiant cooling, Construction of Optimized Energy Potential (CoOEP), Vol. 12, 2023, 191-200, DOI: 10.17512/bozpe.2023.12.21

Introduction

In 2022, Ukraine received the status of a candidate country for joining the European Union, and soon it will become a full member. Therefore, the issue of

* Corresponding author: o.savchenko@i.ua

decarbonization engineering networks of buildings of various purposes is extremely relevant today (Lis, 2020; Savchenko & Kozak, 2019; Savchenko & Lis, 2020; Voznyak et al., 2023; Zhelykh et al., 2021; Zhelykh et al., 2022). One of the main consumers of energy in houses is the cooling systems, which maintain the indoor temperature in the premises during the warm period of the year. Most often around the world, air cooling systems, known as air conditioning systems, as well as radiation cooling systems are used. Radiant cooling systems have been gaining popularity in recent years due to their ability to save energy and the potential to achieve high thermal comfort. In addition, the use of radiant cooling systems reduces the apparent excess heat in the premises, and therefore reduces the need to supply ventilation air. This reduces the energy consumption of the mechanical ventilation system (Karmann et al., 2017).

According to ASHRAE, radiant cooling systems include systems in which more than 55% of heat transfer occurs by radiation. The radiant cooling system works as follows. The refrigerating machine produces a coolant, which is supplied to the cooling devices through a system of pipelines. In cooling devices, the refrigerant circulates through the tubes and cools the panel mass, while the refrigerant itself is heated. Due to the process of heat conduction in the panel of the cooling device, the entire massif of the plate is cooled, in particular the surface that is in contact with the internal air in the room. The surface of the cooling radiant panel cools the internal surfaces and internal air in the room due to radiant and convective heat exchange. Thus, the process of cooling the room takes place.

Most often, radiant cooling systems are used in countries that fully or partially have a hot and humid climate, that is, located, for example, in subtropical and tropical climate zones. Most research on radiation cooling systems has been conducted in China, as well as India and Egypt (Mohamed, 2018; Sastry, 2012). However, there are studies of radiation cooling systems in countries with a temperate climate, in particular Germany, France, and Poland (Cepiński & Jadwiszczak, 2016; Henze et al. 2008; Merabtine et al., 2019).

Radiant cooling systems are most often used in public buildings, such as educational institutions, offices, museums, hospitals, etc. (Choi et al., 2021; Echarri et al., 2014; Mustakallio et al., 2017). Such buildings have rooms with a large area that can be used for installing radiant panels. Less often, radiant cooling systems are used in residential buildings (Tian & Love, 2009). In all cases of the use of radiant cooling systems, special attention should be paid to the humidity of the air in the room, because moisture condensation may occur on the surface of the cooling devices due to low temperatures. This can lead to the mold formation on the enclosing surfaces, and, accordingly, to the deterioration of the microclimate parameters in the room.

Currently, various types of radiation cooling systems are known, which differ in the parameters of the microclimate in the room, power, type and place of installation of cooling devices. Building enclosures, into which pipelines with coolant are integrated, or a chilled beam can be used as cooling devices in the premises (Latif et al., 2022; Villar-Ramos et al., 2022; Yu & Li, 2018).

1. Purpose of work

The purpose of this work is to establish the features of the heat exchange of a radiant cooling system in an office and to determine the dependence of the area of the cooling panel on heat gain from solar radiation and the temperature of the indoor air in the room.

2. Analysis of existing research

It is commonly known that the microclimate parameters in a premises have a significant impact on human productivity (Wargocki & Wyon, 2017). Therefore, during the design and construction of energy-efficient buildings, it is mandatory to maintain a comfortable microclimate, in particular on office premises.

Office premises are characterized by the presence of a large number of employees and computer equipment, which directly affect the processes of heat exchange in the premises. People and computer equipment have temperatures higher than the temperature of the internal air in the room, and therefore, through convection and radiation, give their heat into the room, creating an additional load on the cooling system. In addition, the presence of heat income from solar radiation significantly increases the thermal capacity of the cooling system (Perino, 2009).

When designing air cooling systems, the main indicator that determines the comfort of the microclimate conditions is the temperature of the internal air in the room. When designing radiant cooling systems, in addition to the temperature of the indoor air, it is necessary to take into account the average radiant temperature of the surfaces and the relative humidity of the indoor air.

Modeling methods are used to effectively describe the behavior of radiation cooling systems and to assess the impact of various factors on them (Bizzarri et al., 2023; Hu et al., 2023). At the same time, numerical, analytical and semi-analytical methods are distinguished. In the literature, a significant number of studies dealing with modeling the operation of the elements of the radiation cooling system are cited. However, due to the complexity of heat and mass transfer phenomena, various simplifications and assumptions are taken into account when modeling them.

Thus, a large number of works are focused on the study of conductive heat transfer in a radiant plate, while considering that other internal surfaces in the room and the air temperature are fixed boundary conditions that are not affected by the thermal effect of the cooling panel by radiant or convective heat transfer. In these models, attention is focused only on the conduction mechanism occurring inside the floor slab, which is the defining aspect of the simulation. Thermal conductivity in radiant cooling devices is an attractive topic for research, since the heat transfer process is three-dimensional and involves heat exchange between the array and pipes or coils arranged in a certain configuration. Moreover, the temperature of the coolant changes along the length of these tubes (Larsen et al., 2010; Li et al., 2014).

Other models take into account the full connection between the radiant cooling panels and the rest of the building. Thus, they can fully reflect the behavior of the studied room, as it is exposed to certain climatic conditions. Such modeling is used to perform full dynamic modeling of the cooling efficiency of the entire building system. However, these complex models are more general methods that can include the study of thermal conductivity inside the cooling panel (Henze et al., 2008; Lim et al., 2006; Radzai et al., 2022).

Quite a lot of research has focused on investigating the effect of radiant temperature on skin temperature and human thermal sensation, since radiant heat transfer affects the thermal balance of the human body and is related to thermal comfort. (Deng et al., 2023). However, little attention has been paid to the heat exchange of the human body in asymmetric radiation environments.

There are also models that focus on modeling indoor air behavior, estimating air movements and possible temperature stratification in the studied room (Ayoub et al., 2006; Catalina et al., 2009). Such models are used for radiant systems that are integrated with air cooling systems.

When modeling, it is also necessary to take into account other important phenomena, such as convective heat exchange from the cooling panel to the air in the room, the influence of solar radiation entering the room through the glazed elements of the building, additional internal heat gains from people, equipment, etc.

3. Construction of graphs of thermal interaction for an office premises

Graph theory is used as a basis for modeling thermal interactions in an office premises (Fialko et al., 2013). The office premises is presented as a system of thermal capacitances, between the elements of which heat exchange occurs and which interacts with heat sources (Fig. 1).

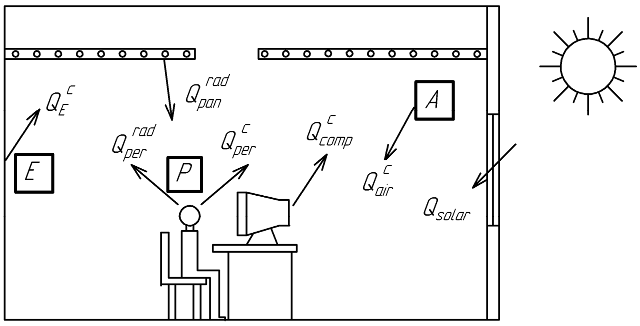

Fig. 1. A simplified model of heat flows in an office premises (*own research*)

A simplified model of heat flows (Fig. 1) clarifies the characteristics of the radiant cooling process and makes it possible to estimate the heat exchange between the thermal capacitances involved in this process. The following thermal capacitances are singled out in the studied area: air in the office premises (A), envelope (E), person (P), which is depicted as nodes of the graph. The following heat sources are considered for the office premises: cooling panel (Q_{pan}), person (Q_{person}), computer equipment (Q_{comp}), solar radiation (Q_{solar}). Thermal interactions of the capacitances of the office premises with sources of heat (cold) and with each other are shown on the graph in the form of edges that connect the nodes (Fig. 2).

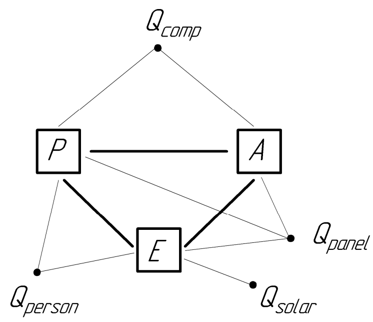

Fig. 2. Graph of heat flows of the office premises (*own research*)

On the basis of this graph, an extended matrix of the interaction of thermal capacities (1) was constructed, where Q_{ij} is the element of the matrix corresponding to the thermal effect of the capacity j on the capacity i; Q – the element of the column of the heat source, which corresponds to its thermal effect on the container in the row of which it is placed:

$$\left[\begin{array}{c|ccc|c} & P & E & A & Q \\ \hline P & 0 & Q_{P\text{-}E} & Q_{P\text{-}A} & \pm Q_{pan}^{rad} \pm Q_{air}^{c} \pm Q_{solar} \\ E & Q_{E\text{-}P} & 0 & Q_{E\text{-}A} & \pm Q_{per}^{rad} \pm Q_{pan}^{rad} \pm Q_{solar} \pm Q_{air}^{c} \\ A & Q_{A\text{-}P} & Q_{A\text{-}E} & 0 & \pm Q_{E}^{c} \pm Q_{P}^{c} \pm Q_{comp}^{c} \end{array}\right] \quad (1)$$

where:
Q_{pan}^{rad} – the amount of heat gain from the cooling panel by radiation [W]; Q_{air}^{c} – the amount of heat gain from the air by convection [W]; Q_{solar} – amount of heat gain from solar radiation [W]; Q_{per}^{c}, Q_{per}^{rad} – heat release from a person by convection and radiation, respectively [W]; Q_{E}^{c} – the amount of heat gain from the envelope by convection [W]; Q_{comp}^{c} – amount of heat gain from computer equipment by convection [W].

Taking into account the above aspects, the heat balance of the thermal capacitance “air” (A) of the office premises has the form:

$$\pm Q_{E}^{c} \pm Q_{per}^{c} \pm Q_{comp}^{c} = 0 \quad (2)$$

And the system of balance equations for this capacitance is as follows:

$$\begin{cases} Q_{E}^{c} = h_{E}^{c} \cdot F_{E} \cdot \left(t_{E}^{rad} - t_{in.air}\right); \\ Q_{per}^{c} = h_{per}^{c} \cdot F_{per} \cdot \left(t_{per}^{rad} - t_{in.air}\right); \\ Q_{comp}^{c} = h_{comp}^{c} \cdot F_{comp} \cdot \left(t_{comp}^{rad} - t_{in.air}\right) \end{cases} \quad (3)$$

where:
h_E^c – coefficient of heat transfer from the inner surface of the envelope to the air by convection [W/(m^2·K]; F_E – area of the enclosures [m^2]; t_E^{rad} – average temperature on the surface of the envelope in the room [°C]; $t_{in.air}$ – temperature of the internal air in the room [°C]; h_{per}^c – coefficient of heat transfer from the person body to the air by convection [W/(m^2·K)]; F_{per} – the area of the person body [m^2]; t_{per}^{rad} – the temperature on the surface of the human body [°C]; h_{comp}^c – the coefficient of heat transfer from the surface of the computer equipment to the air by convection [W/(m^2·K)]; F_{comp} – the surface area of the computer [m^2]; t_{comp}^{rad} – temperature on the surface of the computer equipment [°C].

The heat balance for the thermal capacitance of envelope (*E*) of the office premises looks as follows:

$$\pm Q_{per}^{rad} \pm Q_{pan}^{rad} \pm Q_{air}^{c} \pm Q_{solar} = 0 \tag{4}$$

And the system of balance equations for the thermal capacitance "envelope" (*E*) of the office premises is:

$$\begin{cases} Q_{per}^{rad} = h_{per}^{rad} \cdot F_{per} \cdot \left(t_{per}^{rad} - t_E^{rad}\right) \\ Q_{pan}^{rad} = h_{pan}^{rad} \cdot F_{pan} \cdot \left(t_{pan}^{rad} - t_E^{rad}\right) \\ Q_{air}^{c} = h_{air}^{c} \cdot F_E \cdot \left(t_{in.air} - t_{w.a}\right) \\ Q_{solar} = F_w \cdot q_w \cdot A_w + F_{roof} \cdot q_{roof} \cdot U_{roof} \end{cases} \tag{5}$$

where:
h_{per}^{rad} – the coefficient of heat transfer from a person to the envelope by radiation [W/(m^2·K)]; F_{per} – the area of the person [m^2]; t_{per}^{rad} – the temperature on the surface of the person [°C]; t_E^{rad} – the average temperature on the surface of the envelope in the room [°C]; h_{pan}^{rad} – the coefficient of heat transfer from the envelope to the cooling panel by radiation [W/(m^2·K)]; F_{pan} – the area of the cooling panel [m^2]; t_{pan}^{rad} – the temperature on the surface of the cooling panel [°C]; h_{air}^c – the coefficient of heat transfer from the indoor air to the envelope by convection [W/(m^2·K)]; F_E – the area of envelope in the room (not including the cooling panel) [m^2]; $t_{in.air}$ – the temperature of the indoor air [°C]; $t_{w.a}$ – the air temperature in the working area of the room [°C]; F_w, F_{roof} – the area of the windows and the roof, respectively [m^2]; q_w, q_{roof} – heat gain from solar radiation through 1 m^2 of window and roofing [W/m^2]; A_w – coefficient that takes into account the type of sun protection devices for the window; U_{roof} – heat transfer coefficient for roofing [W/(m^2·K)].

The heat balance for the thermal capacitance "person" (*P*) of the office premises is:

$$Q_{pan}^{rad} \pm Q_{air}^{c} \pm Q_{solar} = 0 \tag{6}$$

And the system of balance equations for the thermal capacitance "person" (*P*) of the office premises is:

$$\begin{cases} Q_{air}^{c} = h_{air}^{c} \cdot F_E \cdot \left(t_{in.air} - t_{w.a}\right) \\ Q_{pan}^{rad} = h_{pan}^{rad} \cdot F_{pan} \cdot \left(t_{pan}^{rad} - t_{E}^{rad}\right) \\ Q_{solar} = F_w \cdot q_w \cdot A_w + F_{roof} \cdot q_{roof} \cdot U_{roof} \end{cases} \tag{7}$$

Determining the operating parameters of the radiant cooling system and their influence on the cooling system capacity is carried out by solving the systems of balance equations (3), (5) and (7).

4. Results

As the analysis of literary sources showed, one of the determining parameters that affect the power of the cooling system is heat gain from solar radiation (De Carli & Tonon, 2011). Therefore, it was interesting to investigate the influence of heat input from solar radiation on the size of the cooling plate in the office premises. Heat from solar radiation enters the room mostly through glazed structures and the roofing of the house. Heat gain from solar radiation through window structures depends, first of all, on its orientation to the cardinal points and the geographical latitude of the area. In addition, the amount of heat that enters through the windows from solar radiation depends on the design of the window, the type of glazing and sun protection devices. The amount of heat from solar radiation that enters through the roofing of the house depends on the geographical latitude of the area, the heat transfer coefficient of the roofing, the presence of an attic and the type of the outer surface of the roofing.

In order to establish the dependence of the area of the ceiling cooling panel on the temperature of the internal air at different values of heat input to the room from solar radiation, an office premises in the city of Lviv with dimensions of 4 x 6 m and a height of 3 m was considered. The premises are located on the 3rd floor of a 5-story building, the area of windows in the room is 5 m^2. 5 people work in the premises and 8 pieces of computer equipment are installed.

Mathematical modeling was carried out using the MATLAB program, which made it possible to determine the thermal balance of the studied room when solving systems of equations (3), (5) and (7). Since the office premises are located on the intermediate floor, there is no heat gain from solar radiation through the roofing. Heat input from solar radiation through 1 m^2 of windows was taken in the range q_w = 450-750 W/m^2.

The results of the mathematical modeling of the effect of heat gain from solar radiation of the area on the size of the ceiling cooling panel and the temperature of the internal air in the office premises are shown in Figure 3.

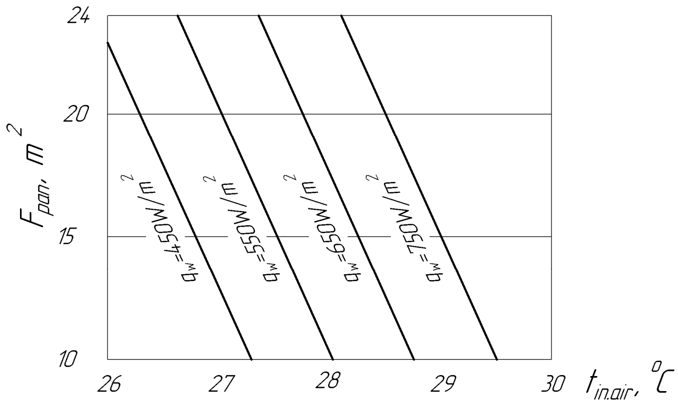

Fig. 3. Dependence of the area of the cooling panel on heat gain from solar radiation and internal air temperature (*own research*)

As can be seen from Figure 3, with an increase in heat gain from solar radiation for the same area of the cooling panel, the temperature of the internal air in the room increased. In order to achieve the temperature of the internal air in the room under different heat inputs from solar radiation, it is necessary to increase the area of the cooling panel. These studies showed that the presence of heat gain from solar radiation significantly affects the size of the cooling panel in the room. Therefore, when designing a radiant cooling system in the premises, it is necessary to reduce heat gain from solar radiation through window structures and roofing with the help of non-southern orientation of windows, solar protection equipment, solar protection glass and covering, or by reducing the area constructers. If the indoor air temperature is unsatisfactory in the warm period of the year, it is necessary to provide additional cooling devices.

Conclusions

In this article, modeling of thermal interactions in an office premises is carried out using graph theory. The office premise is presented as a system of thermal capacitances, between the elements of which heat exchange occurs and which interacts with heat sources. As a result of mathematical modeling, a thermal balance for the thermal capacitances of the premise was proposed and a system of balance equations was compiled. Mathematical modeling of the indicated balance equations using the MATLAB program made it possible to determine the dependence of the area of the ceiling cooling panel on the temperature of the internal air and heat gain from solar radiation in the office premise. As studies have shown, with an increase in heat gain from solar radiation for the same area of the cooling panel, the indoor air temperature in the premise increases. In order to achieve the temperature of the internal air in the room under different heat gains from solar radiation, it is necessary to increase the area of the cooling panel.

Bibliography

Ayoub, M., Ghaddar, N. & Ghali, K. (2006) Simplified thermal model of spaces cooled with combined positive displacement ventilation and chilled ceiling system. *HVAC & R Research*, 12, 1005-1030.

Bizzarri, M., Conti, P., Glicksman, L.R., Schito, E. & Testi, D. (2023) Radiant floor cooling systems: a critical review of modeling methods. *Energies*, 16(17), 6160.

Catalina, T., Virgone, J. & Kuznik, F. (2009) Evaluation of thermal comfort using combined CFD and experimentation study in a test room equipped with a cooling ceiling. *Building and Environment*, 44(8), 1740-1750.

Cepiński, W. & Jadwiszczak, P. (2016) Możliwość wykorzystania chłodzenia radiacyjnego w budynku jednorodzinnym. http://www.eko-dok.pl/2016/102.pdf (30.09.2023).

Choi, N., Yamanaka, T., Sagara, K., Momoi, Y. & Suzuki, T. (2019) Displacement ventilation with radiant panel for hospital wards: Measurement and prediction of the temperature and contaminant concentration profiles. *Building and Environment*, 160, 106197.

De Carli, M. & Tonon, M. (2011) Effect of modelling solar radiation on the cooling performance of radiant floors. *Solar Energy*, 85(5), 689-712.

Deng, Y., Ding, Y., Chen, S., Li, J. & Zhou, Ch. (2023) Study on radiant heat exchange between human body and radiant surfaces under asymmetric radiant cooling environments. *Thermal Science and Engineering Progress*, 37, 101617.

Echarri, V. et al. (2014) Conditioning systems by radiant surfaces: comparative analysis of thermal ceramic panels versus the conventional systems in a museum. *WIT Transactions on Engineering Sciences*, 83, 287-301.

Fialko, N.M., Zhelykh, V.M. & Dzeryn, O.I. (2013) Modeling of thermal regime of manufacturing premises using graph theory. *Theory and Building Practice*, 756, 47-50.

Henze, G.P., Felsmann, C., Kalz, D.E. & Herkel, S. (2008) Primary energy and comfort performance of ventilation assisted thermo-active building systems in continental climates. *Energy and Buildings*, 40, 99-111.

Hu, R. et al. (2023) A review of studies on heat transfer in buildings with radiant cooling systems. *Buildings*, 13, 1994.

Karmann, C., Schiavon, S., & Bauman, F. (2017) Thermal comfort in buildings using radiant vs. all-air systems: A critical literature review. *Building and Environment*, 111, 123-131.

Larsen, S.F., Filippín, C. & Lesino, G. (2010) Transient simulation of a storage floor with a heating/ cooling parallel pipe system. *Building Simulation*, 3, 105-115.

Latif, H. et al. (2022) Performance evaluation of active chilled beam systems for office buildings – A literature review. *Sustainable Energy Technologies and Assessments*, 52, 101999.

Li, Q.-Q. et al. (2014) Analytical solution for heat transfer in a multilayer floor of a radiant floor system. *Building Simulation*, 7, 207-216.

Lim, J.-H. et al. (2006) Application of the control methods for radiant floor cooling system in residential buildings. *Building and Environment*, 41(1), 60-73.

Lis, A. (2020) Renewable energy sources and rationalisation of energy consumption in buildings as a way to reduce environmental pollution. *Heating, Ventilation, Sanitation*, 6, 332-339.

Mohamed, S.S.S. (2018) Radiant cooling system between theory and practice. *International Journal of Current Engineering and Technology*, 8(5), 1220-1231.

Merabtine, A. et al. (2019) New transient simplified model for radiant heating slab surface temperature and heat transfer rate calculation. *Building Simulation*, 12, 441-452.

Mustakallio, P. et al. (2017) Thermal environment in a simulated double office room with convective and radiant cooling systems. *Building and Environment*, 123, 88-100.

Perino, M. (2009) Experimental and numerical analysis of air and radiant cooling systems in offices. *Building and Environment*, 44(4), 801-806.

Radzai, M.H.M. et al. (2022) A brief review on radiant cooling panel with different chilled water pipe configurations. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 89(2), 1-14.

Sastry, G. (2012) First Radiant Cooled Commercial Building in India – Critical Analysis of Energy, Comfort and Cost. https://portal.aeecenter.org/files/newsletters/ESMS/Sastry.pdf (30.09.2023).

Savchenko, O. & Kozak, K. (2019) Influence of type of solar modules anchorages on power of solar power station. *Energy Engineering and Control Systems*, 5(1), 23-28.

Savchenko, O. & Lis, A. (2020) Economic indicators of heating system of a building in Ukraine and Poland. *Construction of Optimized Energy Potential*, 9(2), 97-102.

Tian, Z. & Love, J.A. (2009) Application of radiant cooling in different climates: Assessment of office buildings through simulation. In: *Eleventh International IBPSA Conference*, Glasgow, 2220-2227.

Villar-Ramos, M.M. et al. (2022) A review of thermally activated building systems (TABS) as an alternative for improving the indoor environment of buildings. *Energies*, 15, 6179.

Voznyak, O. et al. (2023) Efficiency improvement of eco-friendly solar heat supply system as a building coating. *Sustainability*, 15, 1-17.

Wargocki, P. & Wyon, D.P. (2017) Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. *Building and Environment*, 112, 359-366.

Yu, W. & Li, H. (2018) Application of the active chilled beam in air-conditioning engineering. In: *IOP Conference Series: Earth and Environmental Science*, 189, 022080.

Zhelykh, V., Voznyak, O., Yurkevych, Y., Sukholova, I. & Dovbush, O. (2021) Enhancing of energetic and economic efficiency of air distribution by swirled-compact air jets. *Production Engineering Archives*, 27(3), 171-175.

Zhelykh, V., Ulewicz, M., Furdas, Y., Adamski, M. & Rebman, M. (2022) Investigation of pressure coefficient distribution on the surface of a modular building. *Energies*, 15, 4644.