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Fialko Nataliia

Doctor of Technical Sciences, Professor,

Corresponding Member of the NAS of Ukraine, Head of the Department

Institute of Engineering Thermophysics of the NAS of Ukraine

Basok Boris

Doctor of Technical Sciences, Professor,

Corresponding Member of the NAS of Ukraine, Head of the Department

Institute of Engineering Thermophysics of NAS of Ukraine

Davydenko Boris

Doctor of Technical Sciences, Senior Scientific Researcher, Chief Researcher

Institute of Engineering Thermophysics of NAS of Ukraine

Sorokovyi Rodion

Junior Researcher

Institute of Engineering Thermophysics of NAS of Ukraine

Sorokova Nataliia

Doctor of Technical Sciences, Senior Scientific Researcher, Chief Researcher

National Technical University of Ukraine

"Igor Sikorsky Kyiv Polytechnic Institute"

Novikov Volodymyr

Candidate of Technical Sciences (PhD),

Senior Scientific Researcher, Leading Researcher

Institute of Engineering Thermophysics of NAS of Ukraine

MATHEMATICAL MODELING OF AIR FLOW IN ROOMS TAKING INTO ACCOUNT SOLAR RADIATION

Summary. *The article is devoted to the computational studies of the air flow in the of office rooms taking into account the effect of solar radiation coming through window openings. The study was conducted for a room with two windows using two heating devices installed under them. The air regime of rooms in winter, characterized by the highest thermal energy consumption for heat supply, is considered.*

The study is based on the solution of a three-dimensional nonlinear heat transfer problem described by a system of equations of turbulent momentum and energy transfer. The k-ε turbulence model is used to close this system. The results of numerical modeling of the physical situation under study are presented. The research data on the features of the air state of the rooms under solar radiation conditions are given.

Key words: *solar radiation; air regime of rooms; numerical modeling, energy-saving effect.*

Introduction. In modern conditions of constantly growing requirements for rational use of energy resources, the problem of increasing the energy efficiency of buildings is becoming increasingly relevant. Its solution is directly related to in-depth studies of air-temperature conditions of premises of different functional purposes [1-14].

A stable global trend in the study of these modes is the widespread use of mathematical and computer modeling tools. At the same time, the problem of increasing the adequacy of the applied mathematical models is of considerable interest. Thus, it is important to use multidimensional models, which allows analyzing local characteristics of the air-thermal state of rooms. Particular attention should be paid to taking into account solar radiation entering the rooms through window openings in the mathematical model. This accounting serves to increase the efficiency of heat supply to rooms, which is most significantly manifested in the winter period of the year in the presence of heating.

The aim of the work is to establish, based on mathematical modeling, the patterns of formation of the air condition of office rooms in the winter period of the year in the presence of solar radiation coming through window openings. To determine the contribution of solar radiation to the formation of the microclimate of the room, numerous studies of its air-thermal state were carried out in the absence and presence of solar radiation. As an example, the air-temperature regime of a room with two windows and two radiators installed under the windows is considered. The height of the room is 3 m; length 5.6 m; width 6.3 m. The thickness of the external concrete wall is 0.24 m. The internal walls, floor and ceiling are also made of concrete. The thickness of the internal walls is 0.12 m. The windows in the room are single-chamber. The glass thickness is 3 mm. The distance between the glass sheets is 60 mm. The area of the panel radiators is 0.5 m^2. The width of each panel is 10 mm. The distance between the panels is 100 mm. The case is considered when the temperature of the radiator panels is t_p=40 ºC. The outside air temperature is t_c = -10 ºC. The heat transfer coefficient value is set from the outside air environment as α_c = 23 W/(m^2 K) according to the recommendations in [15]. In the absence of solar radiation, the temperature regime of such a room was studied in [16]. In the presence of solar radiation, it is considered that it enters the room through the window and hits the section of the wall opposite the window and part of the floor.

Convective movement of the air environment in a room, arising due to uneven temperature distribution, is described by a system of equations of turbulent flow dynamics together with the energy equation. This system includes:

- continuity equation

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0;$$

- equation of turbulent transfer of momentum along the horizontal axis O*X*

$$\frac{\partial u_x}{\partial \tau} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} =$$

$$= -\frac{1}{\rho}\frac{\partial p}{\partial x} + 2\frac{\partial}{\partial x}\left[\nu_{ef}\frac{\partial u_x}{\partial x}\right] + \frac{\partial}{\partial y}\left[\nu_{ef}\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\nu_{ef}\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right)\right] \;;$$

- equation of turbulent momentum transfer along the horizontal axis OY:

$$\frac{\partial u_y}{\partial \tau} + u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} + u_z \frac{\partial u_y}{\partial z} =$$

$$= -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left[\nu_{ef}\left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right)\right] + 2\frac{\partial}{\partial y}\left[\nu_{ef}\frac{\partial u_y}{\partial y}\right] + \frac{\partial}{\partial z}\left[\nu_{ef}\left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y}\right)\right] \;;$$

- the equation of turbulent momentum transfer along the horizontal axis

$$\text{OZ}\frac{\partial u_z}{\partial \tau} + u_x \frac{\partial u_z}{\partial x} + u_y \frac{\partial u_z}{\partial y} + u_z \frac{\partial u_z}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + g\beta\Delta T +$$

$$+\frac{\partial}{\partial x}\left[\nu_{ef}\left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z}\right)\right] + \frac{\partial}{\partial y}\left[\nu_{ef}\left(\frac{\partial u_z}{\partial y} + \frac{\partial u_y}{\partial z}\right)\right] + 2\frac{\partial}{\partial z}\left[\nu_{ef}\frac{\partial u_z}{\partial z}\right],$$

where $\nu_{ef} = \nu_{ef} + \nu_t$; $\nu_t = C_\mu \dfrac{k^2}{\varepsilon}$;

- energy equation for air

$$\frac{\partial T}{\partial \tau} + u_x \frac{\partial T}{\partial x} + u_y \frac{\partial T}{\partial y} + u_z \frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left(a_{ef}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(a_{ef}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(a_{ef}\frac{\partial T}{\partial z}\right),$$

where $a_{ef} = a + a_t$

This system of equations is supplemented by the equations of the k-ε turbulence model:

$$\frac{\partial k}{\partial \tau} + u_x \frac{\partial k}{\partial x} + u_y \frac{\partial k}{\partial y} + u_z \frac{\partial k}{\partial z} =$$

$$= \frac{\partial}{\partial x}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right] + \frac{\partial}{\partial y}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right] + \frac{\partial}{\partial z}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right] + \nu_t S^2 - \varepsilon;$$

$$\frac{\partial \varepsilon}{\partial \tau} + u_x \frac{\partial \varepsilon}{\partial x} + u_y \frac{\partial \varepsilon}{\partial y} + u_z \frac{\partial \varepsilon}{\partial z} =$$

$$= \frac{\partial}{\partial x}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right] + \frac{\partial}{\partial y}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right] + \frac{\partial}{\partial z}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}\right] + C_1\frac{\varepsilon}{k}\nu_t S^2 - C_2\frac{\varepsilon^2}{k},$$

where

$$S^2=\left(\frac{\partial u_x}{\partial y}+\frac{\partial u_y}{\partial x}\right)^2+\left(\frac{\partial u_y}{\partial z}+\frac{\partial u_z}{\partial y}\right)^2+\left(\frac{\partial u_z}{\partial x}+\frac{\partial u_x}{\partial z}\right)^2+$$
$$+2\left(\frac{\partial u_x}{\partial x}\right)^2+2\left(\frac{\partial u_y}{\partial y}\right)^2+2\left(\frac{\partial u_z}{\partial z}\right)^2,$$

$C_\mu=0{,}09;\quad C_1=1{,}44;\quad C_2=1{,}92;\quad \sigma_k=1;\ \sigma_\varepsilon=1{,}3.$

The temperature field in enclosing structures is described by the heat conductivity equation.

$$\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\left(a_c\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(a_c\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(a_c\frac{\partial T}{\partial z}\right),$$

where ac is the thermal diffusivity of the enclosing structures of the room (room walls or window glass).

The system of equations of dynamics and heat transfer together with the limit conditions was solved by the control volume method [17].

The results of calculating the velocity and temperature fields in the room in the absence of solar radiation are shown in Fig. 1. The data are given for the vertical section B-B, parallel to the side walls intersecting the panels in the middle of one of the radiators.

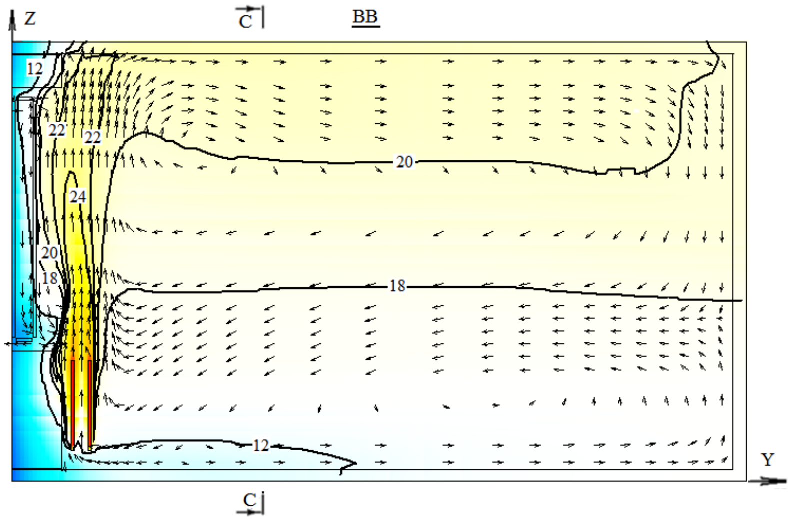

Fig. 1. Fields of air velocity vectors and temperature in vertical section B-B for t_p = 40 ºC; t_c = -10 ºC in the absence of solar radiation.

From Fig. 1 it is evident that circulation currents are formed in the upper and lower parts of the room. The temperature inside the room increases in the direction from the floor to the ceiling. Directly above the floor, the temperature is 12 ºC. At a height of 1.4 m from the floor, it increases to 16 ºC, and at the ceiling it reaches 19 ºC.

The results of the calculation studies obtained in the presence of solar radiation are shown in Fig. 1 and 2. These data refer to cloudless weather conditions on December 22 in Kyiv. The angle of the Sun's altitude, i.e. the angle between the horizon and the beam to the Sun, is 12-00 hours in Kyiv $\gamma = 0.28$ radians, and the maximum density of solar radiation $q_{sol} = 393$ W/m^2 (in the complete absence of clouds and pollination of the atmosphere). The direction of this flow coincides with the direction from the window cut to the Sun, i.e. is parallel to the beam, making an angle of $\gamma = 0.28$ radians with the earth's surface. Over time, the angle γ changes, and the density of solar energy flows falling on the wall and floor changes accordingly. In addition, the sky may be partially covered with clouds. Taking this into account, to calculate the effect of solar radiation on the temperature state of the room, it is assumed that in the interval from 11-00 to 13-00 the average time density of the heat flow from the Sun is somewhat less than the value given above. According to estimates, it is $q_{sol} \sim 300$ W/m^2. The density of the heat flow falling on the floor is qsom, $z = q_{sol} \times \sin(\gamma)$, and on the wall opposite the window – q_{sol}, $y = q_{sol} \times \cos(\gamma)$. The results of calculating the velocity and temperature fields in the room when considering the conditions of exposure to solar radiation are presented in Fig. 2.

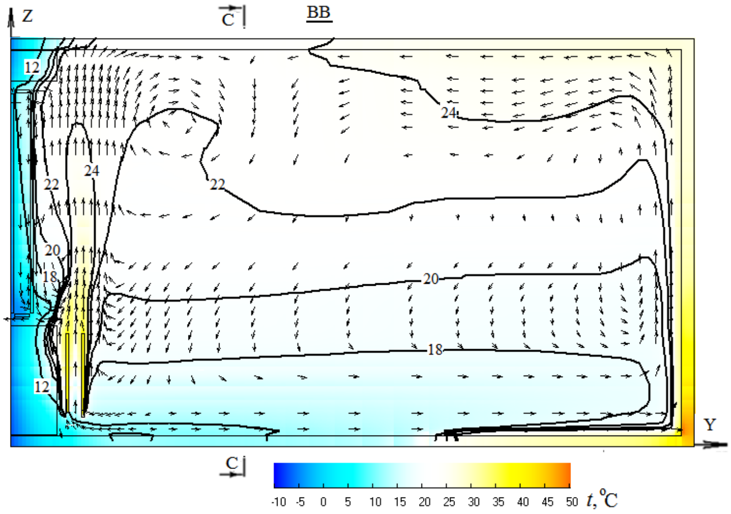

Fig. 2. Fields of air velocity vectors and temperature in vertical section B-B for t_p = 40 °C; t_c = –10 °C in the presence of heat input from solar radiation.

As can be seen from Fig. 1, 2, in the presence of solar radiation, the air condition of the room changes significantly. This primarily concerns the opposite window of the wall. In addition, a local circulation flow is formed near the ceiling. Also noteworthy is the fact that the overall level of air speeds increases.

Therefore, the presence of solar radiation coming through window openings has a significant effect on the characteristics of the air flow in the room.

Conventions of designation

a – coefficient of thermal diffusivity of air; *g* – acceleration of gravity; *k* – kinetic energy of turbulence; *p* – pressure; *q* – heat flux density; *T* – temperature, K; *t* – temperature, °C; u_x; u_y; u_z- projections of the velocity vector on the coordinate axes; *x*; *y*; *z*; – rectangular coordinates. Greek symbols – coefficient of air compressibility; ε – rate of dissipation of kinetic energy of turbulence; ν – kinetic coefficient of molecular viscosity; τ – time. Subscripts *t* – turbulent *c* – external environment; *ef*-effective, *r* – radiator; sol – solar

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