Numerical investigation of conjugate heat transfer in a local working area in conditions of its radiant heating

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Abstract. Mathematical modeling of unsteady conjugate heat transfer in a closed rectangular area with a local heat-conducting object in a gas cavity in conditions of radiative heat supply is conducted. Fields of temperatures and stream functions, illustrating the influence of Grashof number on the character of heat transfer are formulated. The dependence of average Nusselt number from time at different Grashof numbers is given. The influence of heat-conductive object on the intensity of heat transfer in under study solution domain is shown.

1.Introduction

Use of gas infrared radiators (GIR) [1] is the most prospective at the local heating of working area.

For investigation the temperature regimes of premises heated by GIR, a model [2], which allows the unsteady dimensional character of conjugate conductive - convective heat transfer was developed. However, in study [2], an assumption that the flow of radiant energy coming from GIR is only evenly distributed over the inner surface of the lower boundary was made. Also, the model [2] doesn't describe the effect of heat-conducting objects located in the working area on the intensity of heat transfer.

Experimental study [3] of radiant heating system has a number of significant defects, since it ignores, as a rule, the dimensional dynamics of heat transfer.

The aim of this study is the numerical investigation of unsteady radiant heating process of a typical heat-conducting manufacturing object in the gas cavity of a closed rectangular area in conjugate formulation.

2.Problem formulation

The boundary value problem of conjugate heat transfer in area consisting of six rectangular subdomains (fig. 1) is considered. Heat insulation conditions were adopted at external borders. At internal borders "air – enclosure structures", "air – heat supply object" are the fourth type boundary conditions.

Assumptions that thermal properties of air and enclosure structures don't depend on temperature are introduced. Flow regime is laminar. The air is considered as a Newtonian fluid, incompressible, satisfying the Boussinesq approximation and absolutely transparent for thermal radiation. Total radiant flux coming from the GIR can be represented as the sum of heat fluxes values of which were determined by zonal method as shown in [4].

Investigated heat transfer process is described by the unsteady Navier - Stokes equations and the energy for the air and the heat conduction equation for enclosure structures within the adopted model. Dimensionless equations of Navier - Stokes and energy in variables "vorticity Ω - stream function Ψ - temperature Θ " are as follows [2, 5]:

$$\frac{\partial \Omega}{\partial \tau}+U\frac{\partial \Omega}{\partial X}+V\frac{\partial \Omega}{\partial Y}=\frac{1}{\sqrt{\mathrm{Gr}}}\cdot\nabla^2\Omega+\frac{1}{2}\frac{\partial \Theta_1}{\partial X}, \quad (1)$$

$$\nabla^2\Psi = -2\cdot\Omega, \tag{2}$$

$$\frac{\partial\Theta_1}{\partial\tau} + U\frac{\partial\Theta_1}{\partial X} + V\frac{\partial\Theta_1}{\partial Y} = \frac{1}{\Pr\sqrt{\mathrm{Gr}}}\cdot\nabla^2\Theta_1, \tag{3}$$

$$\frac{\partial\Theta_2}{\partial Fo_2} = \nabla^2\Theta_2, \tag{4}$$

$$\frac{\partial\Theta_3}{\partial Fo_3} = \nabla^2\Theta_3, \tag{5}$$

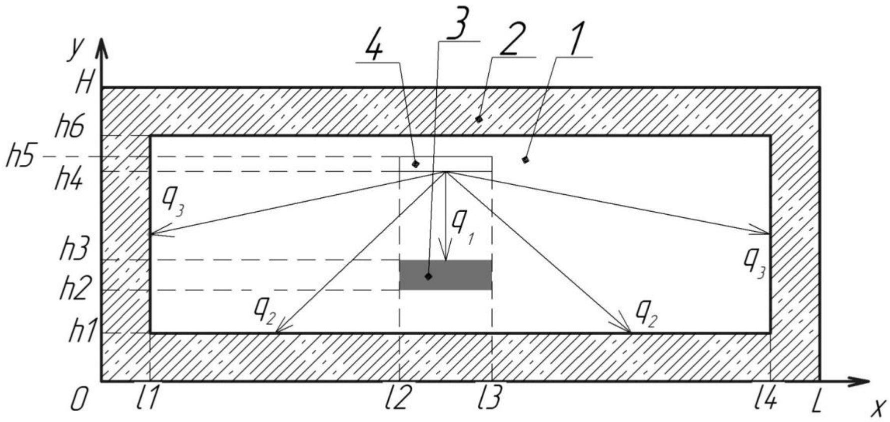

Figure 1. Solution domain: 1) air; 2) enclosure structures; 3) heat supply object; 4) gas infrared radiator (symbolic notation).

The initial conditions for the system of equations (1) – (5) are as follows:

$$\Psi(X,Y,0)=0,\ \Omega(X,Y,0)=0,\ U(X,Y,0)=0,\ V(X,Y,0)=0,$$
$$\Theta_1(X,Y,0)=\Theta_2(X,Y,0)=\Theta_3(X,Y,0)=0.$$

The boundary conditions at the outer boundaries of the solution domain are as follows:

$$X=0,\ X=1,\ 0<Y\le 1:\ \frac{\partial\Theta_2(X,Y,\tau)}{\partial X}=0,$$
$$Y=0,\ Y=1,\ 0<X\le 1:\ \frac{\partial\Theta_2(X,Y,\tau)}{\partial Y}=0.$$

at internal interfaces "heat supply object – air", "solid wall – air", parallel to the axis OX:

$$\Psi=0,\ \frac{\partial\Psi}{\partial Y}=0,\ \begin{cases}\Theta_i=\Theta_j,\\ \dfrac{\partial\Theta_i}{\partial Y}=\dfrac{\lambda_j}{\lambda_i}\cdot\dfrac{\partial\Theta_i}{\partial Y}+Ki_{q_k},\end{cases}\ \text{где}\ \left|\begin{array}{l} i=\overline{1,3}\\ j=\overline{1,3}\\ k=1,2.\end{array}\right.$$

at internal interfaces "heat supply object – air", "solid wall - air", parallel to the axis OY:

$$\Psi=0,\ \frac{\partial\Psi}{\partial X}=0,\ \begin{cases}\Theta_i=\Theta_j,\\ \dfrac{\partial\Theta_i}{\partial X}=\dfrac{\lambda_j}{\lambda_i}\cdot\dfrac{\partial\Theta_i}{\partial X}+Ki_{q_3},\end{cases}\ \text{где}\ \left|\begin{array}{l} i=\overline{1,3}\\ j=\overline{1,3}\end{array}\right.$$

where $Fo-$ Fourier number; $Gr-$ Grashof number; $Ki-$, Kirpichev number; $\Pr-$ Prandtl number; *X*,*Y* – dimensionless Cartesian coordinates; *U*, *V*– dimensionless velocities along *X*,*Y* directions correspondingly; $\nabla -$ dimensionless Laplace operator. Indexes: 1,2,3 - design elements; for Ki: - heat flow values. Indexes: 1, 2, 3 – element number; for Ki: q_1, q_2, q_3 – heat flux values.

Equations (1) – (5) with the corresponding initial and boundary conditions were solved by applying the finite difference method, as in [5]. Locally one scheme of A.A. Samarskiy was used for approximation of equations (1), (3) – (5) [6]. Approximation of Poisson's equation was done by the scheme of variable directions [6]. Woods condition [6] was used to determine the boundary conditions for the vortex velocity. One - dimensional difference analogues were solved by the sweep method [5]. In order, to evaluate the reliability of results of the computational modeling, the conservatism of the difference scheme was checked analogously to [7].

3.The results of the numerical simulation

Numerical investigation was performed for the following values of dimensionless criteria: $10^5 \le \mathrm{Gr} \le 10^7$, Pr=0,71, Ki_1=42, Ki_2=25, Ki_3=5. The results of solving boundary value problem for different Gr are shown in figures 2 and 3.

Evolution of the air flow with increasing Gr is shown in figure 2 and 3. Lifting force is insignificant at low Grashof numbers and heat transfer in solution domain under study occurs mostly by heat conduction. Increasing Gr leads to a modification of convective cells on the left and right of the heat supply object. Boundary layer with a considerable temperature gradient at the surface y = h1, l1 <x <l4 is formed at $\mathrm{Gr} = 10^7$ and ascending air is created at section X = 0,6. As the heat supply object is conductive, it absorbs radiant flux directed at its upper surface. Consequently, the air near the surface of the object is heated not as intense as at the lower base of the solution domain.

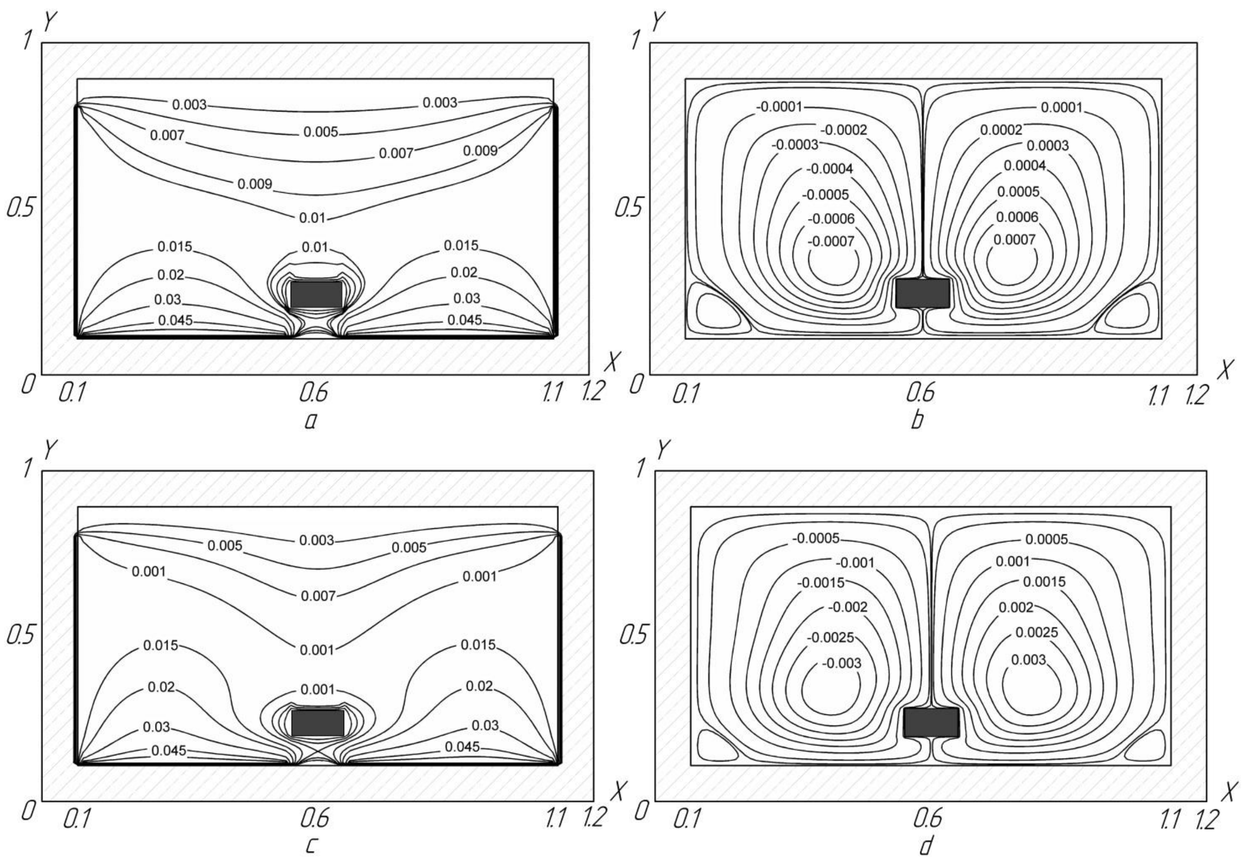

Figure 2. Fields of temperature (a,c) and the stream function (b,d) at при τ = 3600: $\mathrm{Gr} = 10^5$ (c, d) $\mathrm{Gr} = 10^6$ (c, d).

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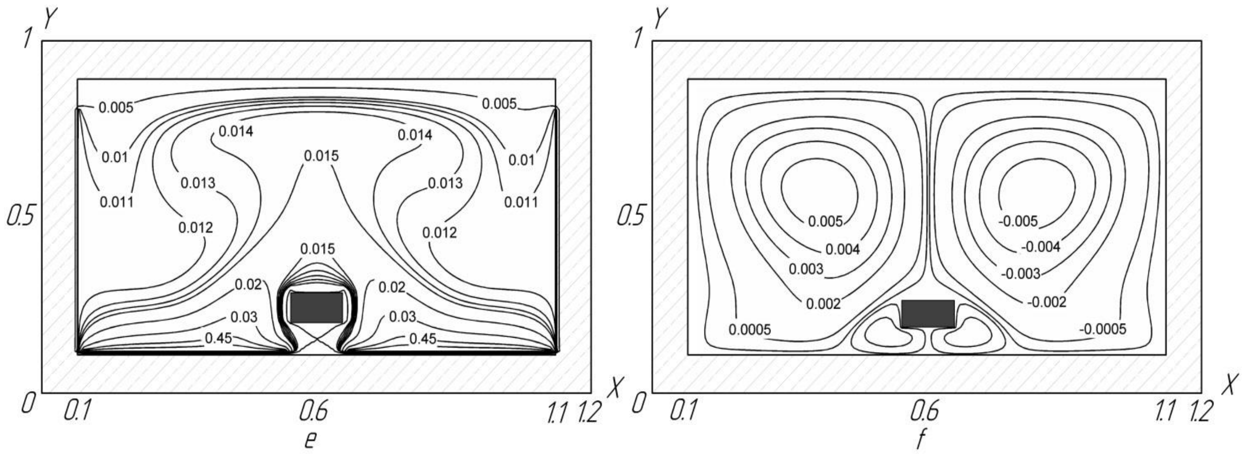

Figure 3. Fields of temperature (e) and the stream function (f) at при τ = 3600: $\mathrm{Gr} = 10^7$.

Analysis of the influence of the Grashof number on the average Nusselt number at the interface of "enclosure structure - air» (y = h1, l1 <x <l4) is carried out by analogy with [8]:

$$\overline{Nu} = \int_{0,1}^{1,1} \left| \frac{\partial \Theta}{\partial Y} \right|_{Y=0,12} dX.$$

Dependences $\overline{Nu}$ from τ for different Gr are presented in figure 4.

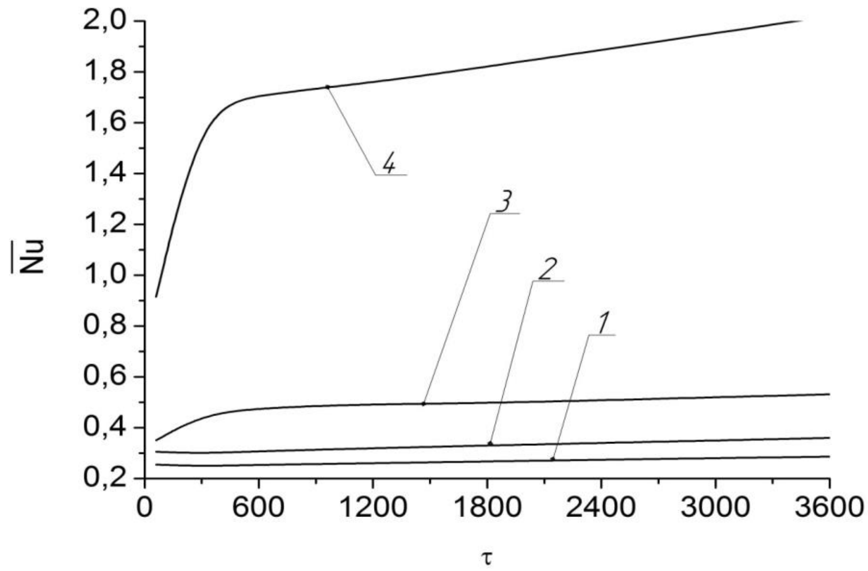

Figure 4. Dependences $\overline{Nu}$ from τ: 1 – $\mathrm{Gr} = 10^5$; 2 – $\mathrm{Gr} = 10^6$; 3 – $\mathrm{Gr} = 10^7$;
4 - $\mathrm{Gr} = 10^7$, heat-conducting object in gas cavity is absent.

$\overline{Nu}$ is increased with rising Gr. Average dimensionless heat transfer coefficient varies insignificantly with time at $\mathrm{Gr} = 10^5, 10^6$, because the heat exchange rate for such values of similarity criterion is low. Increasing the average Nusselt number occurs before $\tau \approx 600$ at $\mathrm{Gr} = 10^7$. Average dimensionless heat transfer coefficient varies insignificantly in the sequel. The presence of heat-conducting object in the gas cavity decreases $\overline{Nu}$ 5 times, and therefore significantly effects the heat transfer rate in the solution domain

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4.Conclusion

The numerical analysis of the radiant heating process of manufacturing heat-conducting object in a closed rectangular area in conjugate formulation is done. It was established that Grashof number significantly effects both the movement of air masses and the temperature regime in the solution domain under study. The influence of heat-conducting object in a gas cavity on the intensity of heat transfer is shown.

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