INFLUENCE OF PARTITIONS ON NATURAL-CONVECTIVE FLOW IN A CLOSED SPACE. 1. A SINGLE PARTITION

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Consideration is given to a numerical solution of the problem of a natural-connective gas flow exposed to a heat source in a two-dimensional closed rectangular cavity with a vertical partition placed in it. Investigation is made of the influence of relative cavity extension, relative height of the partition and its position on the upper or lower cavity wall on the flow structure.

Introduction. When investigating natural-convection processes caused by heat-release sources in a closed cavity, we are often concerned with regions of a more complicated geometry than rectangular. One of the cases most frequently encountered is a vertical partition stretching from the upper or lower horizontal walls. Such problems are little studied, though they are, undoubtedly, of essential practical interest.

Experimental studies of a fluid flow in a cavity with a horizontal-to-vertical ratio (relative elongation) L/H = 2 and with a partition placed in the center of the upper horizontal wall are described by Nansteel and Greif [1, 2]. The vertical walls of the cavity in these experiments were maintained at different constant temperatures; the horizontal walls were heat-insulated. The partition height was changed from 0 to 3/4 H. Experiments were conducted with water filling the cavity at Grashof numbers $10^{10} \le \mathrm{Gr} \le 5 \cdot 10^{10}$. Lin and Bejan [3] experimentally studied cavities with partitions, practically completely spanning a cavity cross section. Using a Mach–Lehnder interferometer, Bajorek and Lloyd [4] experimentally studied heat transfer in a square-section cavity with vertical walls of different temperatures and heat-insulated partitions stretching from the upper wall. Cavities were filled with air or carbon dioxide. Flow modes were investigated for the Grashof number range $1.7 \cdot 10^5 \le \mathrm{Gr} \le 3.0 \cdot 10^6$. Comparatively recently the works have appeared in which numerical flow calculations are made in two-dimensional cavities having partitions. A problem lies in the fact that in the presence of partitions in the flow there develop regions in which temperature and velocity gradients become rather essential, thus causing instability of numerical schemes. Therefore, ordinary numerical methods often fail to produce desirable results. In [5], to calculate the laminar natural-convective flow in a rectangular cavity having a symmetrical partition on its bottom, the method of finite elements was used. The thermal diffusivity of the partition was assumed to be finite. The Grashof number determined with respect to the horizontal dimension of the cavity ranged from $1.4 \cdot 10^5$ to $1.4 \cdot 10^{11}$. The flow structure was studied as a function of the relative height of the partition and its thermal diffusivity. A few works are known dealing with fire investigation in rooms having a partition on the upper wall. Lloyd et al. performed experiments [6] and numerical calculations [7] of fires in a room connected via a doorway to a corridor. The door was modeled as a vertical partition stretching from the ceiling. Numerical calculation of air flow in the corridor during a fire in a neighboring room is also given in [8]. Here, the transition from the room to the corridor is also modeled by a vertical partition on the ceiling with the height 1/3 H.

Mathematical Model and Results of Solution. We consider a closed cavity representing an extended horizontal channel with a rectangular cross section. The horizontal walls of the channel (a floor and a ceiling) are heat-insulated, the vertical walls are maintained at constant but different temperatures. There is a narrow heat-insulated protrusion on the upper or lower wall. Its relative height and location on the horizontal wall will be assumed variable magnitudes.

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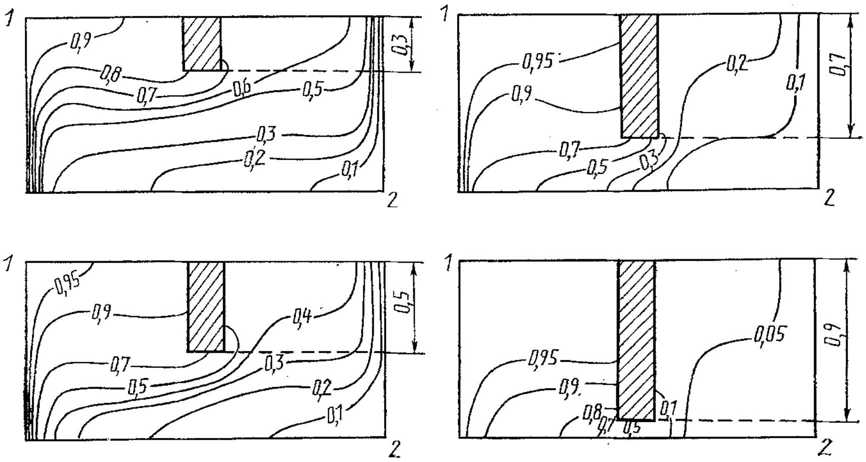

Fig. 1. Temperature distribution in a cavity for different relative partition heights; L/H = 2; Gr = $1.4 \cdot 10^5$.

The gas flow in such cavity is described by two-dimensional equations of motion and energy. Using the Boussinesq approximation for a gravitational term, we may write for the steady-state laminar flow the following system of equations in dimensionless form:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0; \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{\sqrt{\mathrm{Gr}}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right); \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \frac{1}{\sqrt{\mathrm{Gr}}}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + T; \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{1}{\mathrm{Pr}\sqrt{\mathrm{Gr}}}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right). \tag{4}$$

As the characteristic dimension for a Grashof number Gr, the cavity height H is chosen, the difference between the temperatures of the hot and cold walls is the characteristic temperature difference.

The boundary conditions are as follows: for velocities on the walls and on the protrusion u = 0, v = 0; for the temperature on adiabatic surfaces $\partial T/\partial n = 0$; on isothermal surfaces T = 1 for the hot wall and T = 0 for the cold wall.

Numerical solution of the system (1)-(4) was carried out by the method described in [9, 10] using natural variables, i.e., projections of the velocity, temperature, and pressure. In calculations, a uniform "staggered" network is used, in which the nodes for calculating velocities are displaced a half-step relative to the nodes for temperature and pressure calculation. The network is considered to be surrounded by one layer of "fictitious" cells, at the boundary of which the variables are specified. Network lines run in such a way that the boundary nodes for velocities coincide with the cavity boundaries. Finite-difference equations are solved by the Gauss–Seidel iteration method using the Patankar–Spalding procedure for pressure field determination [11]. We note that at such a choice of the difference approximation the fulfillment of adiabatic conditions of a partition imposes certain limitations on its thickness – inside the partition a minimum of two nodes of the temperature difference network must be located along the horizontal. In order to investigate small-thickness protrusions, it is necessary to decrease the network steps. In calculations, the protrusion thickness is chosen equal to L/(k – 2), where k is the number of network nodes along the horizontal. A cavity is considered to be filled with air at Pr = 0.72.

The calculated temperature fields for the cavity with relative elongation L/H = 2 and a protrusion in the center of the upper horizontal wall for different relative protrusion heights are shown in Fig. 1. Figure 2 shows the characteristic distributions of the horizontal and vertical velocities. Calculations show that at a relative protrusion height larger than 0.5, convective flow penetration into the cavity section adjoining the cold vertical wall, essentially decreases. The flow velocities and temperature in this zone are low and at h/H > 0.7 the hot wall effect in this zone is practically absent. The temperature is close to that of the cold wall; the gas does not move.

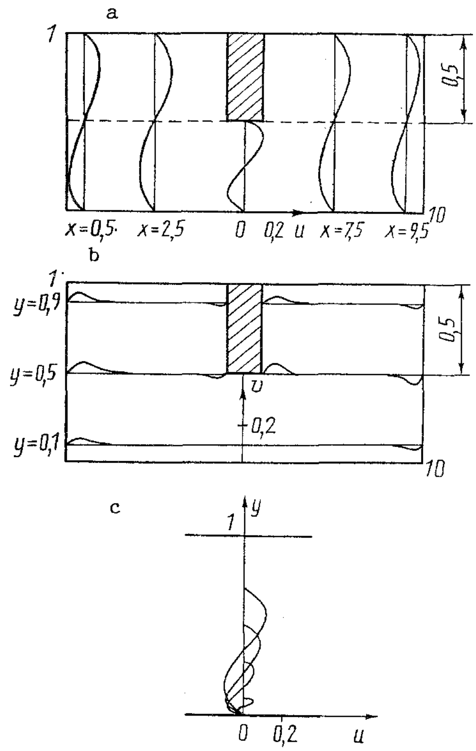

Fig. 2. Characteristic velocity distributions: a) horizontal component; b) vertical component; c) horizontal component in the section with a partition; L/H = 10; Gr = $1.4 \cdot 10^5$.

A comparison of the calculated results for different-extension cavities (for L/H = 2, 5, 10, and 20) reveals that with increasing L/H, the temperature distribution acquires a more linear character of changing along the longitudinal axis (the x axis) of the cavity. In cavities with a smaller L/H, gas temperature stratification with respect to cavity height is more essential on both sides of the protrusion.

A specific feature of the flow and, in particular, of velocity distribution is the fact that the partition does not cause the development of isolated flows in the cavity. In [1], in the presence of a partition, three regions are singled out in the flow field: 1) a flow of the type of a laminar boundary layer near the cavity boundaries; 2) a rather passive core with small velocities of motion; 3) a region in the upper quadrant, adjoining a heated wall, with clockwise circulation. The flow pattern for such case in represented in Fig. 3a. Here, the fluid velocity in thin boundary layers on vertical surfaces is higher than in comparatively thick layers on horizontal surfaces. The boundary layer on a hot wall does not extend up to the cavity top, at $y \approx (H - h)/H$ its larger part separates from the wall and passes into the horizontal flow reaching the lower edge of the partition. Then this flow turns upward and begins to ascend along the partition. In the upper quadrant of the cavity, adjoining the hot wall, slow fluid circulation is observed. The intensity of this circulation flow rather essentially depends on the thermal boundary condition over the partition. If the partition is heat-conducting, then slow circulation is observed in this region; in the case of the adiabatic partition, this circulation is almost absent, i.e., here a stagnant zone develops.

The flow structure at a relative partition height not exceeding 0.5, obtained in our calculations, is depicted in Fig. 3b. As is seen, in this case our calculations do not reveal either a distinct circulation region or flow separation from the hot wall, i.e., just those two specific features which have been discovered in [1]. This is explained not only by the adiabatic property of the partition but, to all appearances, by the fact that the experimental studies in [1] were conducted with water as a working fluid, $3 \leq Pr \leq 4.3$, while we have performed calculations for air with Pr = 0.72. In this connection, it is worth noting that the experimental results obtained by Bajorek and Lloyd [4] using air, also do not coincide with the data of [1] but give a flow pattern consistent with our calculated results. Moreover, calculations performed by us for Pr = 4.0 show the presence of a stagnant zone in the left upper quadrant of the cavity.

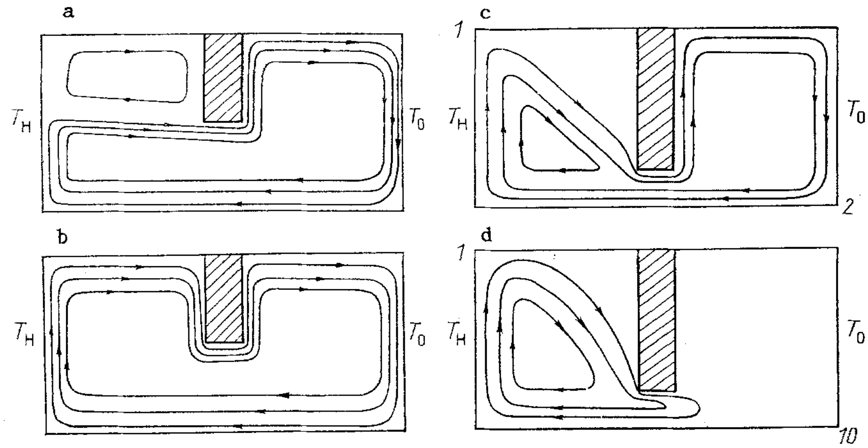

Fig. 3. Flow structure in the cavity with a partition: a) data from [1]; b) at a small relative partition height; c) at a large relative partition height; d) at a large cavity extension.

The flow structure for a large relative protrusion height (0.7 and more) for cavities with different relative elongation ($L/H = 2$ and 10) is shown in Fig. 3c, d. In this case, in the angular region of the left upper quadrant, adjoining to the protrusion, a stagnant zone develops, and the flow from the upper part of the hot vertical wall streams to the lower edge of the protrusion. At $L/H = 2$, in the right part of the cavity behind the protrusion a flow of the type of boundary layers develops along the cavity boundaries. At $L/H = 10$, such a flow is not observed (Fig. 3d). Apparently, at large cavity extensions and large relative heights of the protrusion, the amount and temperature of the fluid penetrating beyond the protrusion are insufficient for developing the natural-convective flow in the right part of the cavity.

Calculations of flow structure for different positions of a protrusion on the upper wall testify to the fact that the protrusion confines a near-ceiling zone at a heated wall, the temperature of which is sufficiently high. With displacement of the protrusion toward a cold wall, this zone also broadens. Calculations show that at a large relative protrusion height, the cavity demarcation by means of the protrusion into regions with higher and lower temperatures is more distinctly seen. At a higher intensity of a heat release source ($Gr = 1.4 \cdot 10^6$), a more pronounced penetration of the fluid beyond the protrusions is observed; the longitudinal temperature gradient behind the protrusion approaches zero.

The influence of a protrusion on a cavity ceiling on the flow pattern and temperature distribution manifests itself in the fact that if the protrusion is near a cold isothermal vertical wall, it prevents a cold descendent flow to stream along the cavity ceiling, and the temperature of the ceiling adjoining to the heated wall is higher than in the case in which protrusion is near the heated wall.

Conclusion. Thus, the method developed of numerical calculation of natural-convection flows for gas flow structure investigations in two-dimensional rectangular-closed cavities with vertical adiabatic partitions is proved to be efficient. Calculations have demonstrated that for the parameter ranges considered, the relative height of the partition and its location on the upper or lower horizontal wall exert determining influence on the flow structure and the temperature distribution. The results obtained are consistent with available experimental and calculated data for analogous conditions. The results of the work may find practical application in various fields of construction mechanics, helioengineering, etc.

NOTATION

Gr, Grashof number; H, cavity height; h, partition height; L, cavity extension in the horizontal direction; p, hydrodynamic component of gas pressure; Pr, Prandtl number; T, gas temperature; u, v, horizontal and vertical gas velocities; x, y, Cartesian coordinates; k, number of difference network nodes along the horizontal.

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