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NUMERICAL MODELING OF HEAT-EXCHANGE PROCESSES IN A GAS CURTAIN

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The authors give results of calculating the distribution of the efficiency of a gas curtain and heat transfer behind a row of individual orifices in a solid wall through which a coolant is injected into the main flow. A complete system of Navier–Stokes equations that are Reynolds-averaged and supplemented with a low-Reynolds k–ε model of turbulence is used.

To calculate the efficiency of a gas curtain formed by injection of a coolant through a row of individual orifices, use is usually made of mathematical models which are based on a calculation of the primary layer of mixing of the coolant with the main flow [1]; these models are subsequently used for calculation of the limiting laws of heat exchange in a turbulent boundary layer downstream [2]. Such calculations yield no distributions of the values of the curtain efficiency on a surface protected against overheating. Direct attempts at modeling numerically a gas curtain behind a row of orifices based on the boundary-layer models [3, 4] also failed, since one is unable to allow for separation zones in the vicinity of the orifices within the framework of these models. Therefore, the numerical modeling that is based on a complete system of Reynolds-averaged Navier–Stokes equations and in which the corresponding turbulence models are used should be considered to be promising.

We present below some results of numerical modeling of a three-dimensional turbulent flow and heat-exchange processes in a gas curtain formed behind a row of round orifices on a plane wall.

Method of Modeling and Configuration of the Calculated Region. We solved a system of complete dimensionless Navier–Stokes equations that were Reynolds-averaged and supplemented with the low-Reynolds k–ε turbulence model of Chien [5]. The similarity numbers Re_0, M_0, and Pr_0 involved in the system of equations were constructed based on the scale parameters of the flow and were determined by universally adopted expressions. The dimensionless variables were obtained using the ratio of the dimensional variables to the scale quantities. In order to make the problem universal in the Mach number, we employed the method of scaling of compressibility [6], whose essence is in using the pressure p rather than the density ρ as the main variable. The system of Navier–Stokes equations was split in spatial directions and a system of finite-difference equations was obtained by the control-volume method; this system was solved using vector (3×3) and scalar runs. The equations of the k–ε model were solved using a vector (2×2) run, which ensured high consistency of k and ε in the process of establishment. The calculation was performed on a nonuniform orthogonal grid with bunching of the nodes in the wall region. The universal coordinate of the first wall node Y^+ did not exceed 1.5–2.0.

A calculated region is shown in Fig. 1. It represents an elementary cell of a periodic structure formed by an extended row of orifices (of diameter d and with a step of $3d$) which are made in a plane perpendicular to the direction of the flow. The length, width, and height of the calculated region constitute $26d$, $3d$, and $11.4d$, respectively, in gauges of the orifice diameter. At the entrance to the calculated region (plane ABCD)

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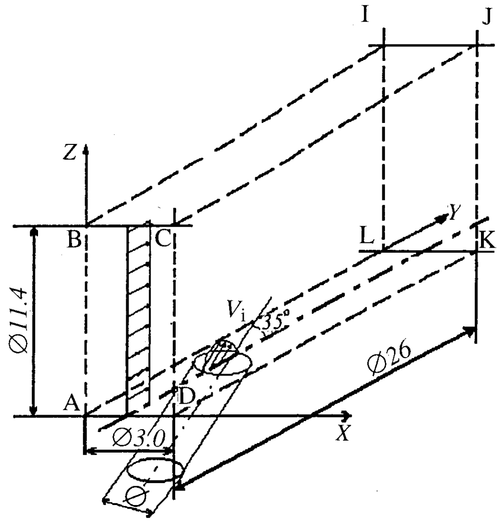

Fig. 1. Configuration of the calculated region.

we assigned uniform dimensionless (equal to 1) distributions of the temperature, the density, and the longitudinal velocity of the main flow and also the turbulent characteristics k and ε. We set conditions of periodicity (in the first derivatives of the calculated values) on the lateral faces of the calculated region and a condition of impermeability on the upper face. The solid wall in the figure is represented by plane XAY. On it, the condition of sticking was fulfilled by velocities ($V_X = V_Y = V_Z = 0$), $k = 0$, and $\partial\varepsilon/\partial z = 0$. We solved two model problems. The first one was the calculation of the efficiency of curtain cooling. The condition of adiabaticity of the solid wall ($\partial T/\partial z = 0$) was used. The ratio of the inlet temperatures of the injected flow and of the main flow T_i/T_0 was taken to be equal to 0.5. The second problem was the calculation of the coefficients of heat transfer from the hot main flow to the solid wall (Nusselt numbers). A uniform dimensionless heat flux was assigned in the direction from the flow to the wall ($\partial T/\partial z$ = const), and the ratio of the temperatures T_i/T_0 was maintained at unity. In both cases, the injection through the orifices was assigned similarly to the conditions on an impermeable wall — in terms of the velocity components V_Z and V_Y from the condition of the uniform profile of the velocity V_i and the uniform temperature of the coolant T_i at the outlet from the orifice at $z = 0$. The regime of the problem was assigned in terms of the numbers M_0 and Re_0. The injection parameter m was realized from the assigned V_0, T_0, V_i, and T_i and from the pressure field restored in the course of calculation. On the exit face of the calculated region (plane IJKL), we set "soft" boundary conditions — zero derivatives with respect to the coordinate y for all calculated parameters — and assigned the dimensionless pressure. The results presented below were obtained for the conditions $M_0 = 0.3$, $Re_0 = 3333$, and $m = 0.5$; the angles of injection were $\alpha_0 = 35$ and 60^o; the values of k and ε at the entrance to the calculated region provided a 0.3% inlet intensity of turbulence of the main flow. The calculated region contained about 100 thousand nodes.

The method was tested on the plane problem of a turbulent boundary layer developing at a solid wall on condition of the absence of jet injection of the coolant. The calculated Nusselt numbers were compared to those determined for similar conditions from known analytical dependences. We obtained satisfactory agreement — the discrepancy did not exceed 30% and referred to the entrance portion of the region.

Results of Numerical Modeling. The obtained dimensionless fields V, ρ, T, p, k, and ε in the calculated region were processed with a visualizer program and reduced to a form convenient for analysis.

Figure 2a shows the distribution of the efficiency of curtain cooling θ on the adiabatic wall behind the orifice for the case $m = 0.5$, $\alpha_0 = 35^o$, and $T_i/T_0 = 0.5$. It is seen that the curtain behind the orifice is arranged as a band somewhat wider than the diameter of the orifice. Judging by the arrangement of the isolines of θ on the wall, no interaction with the neighboring jets in the row is observed.

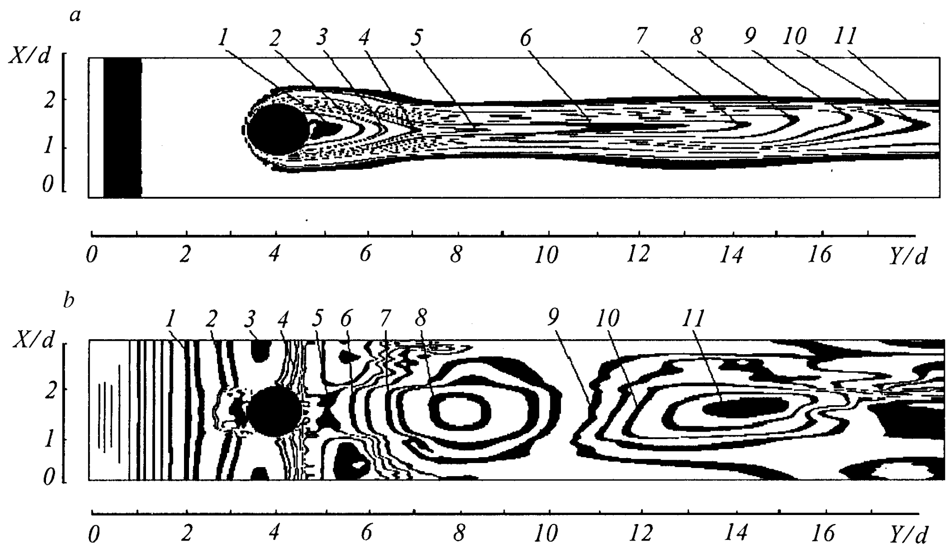

Fig. 2. Distribution over an adiabatic wall (m = 0.5 and $\alpha_0 = 35^o$) of the: (a) efficiency of curtain cooling [1) θ = 0.97; 2) 0.93; 3) 0.85; 4) 0.73; 5) 0.66; 6) 0.594; 7) 0.524; 8) 0.46; 9) 0.376; 10) 0.284; 11) 0.014] and (b) dimensionless pressure [1) p = –0.061; 2) –0.103; 3) –0.152; 4) –0.075; 5) 0.0122; 6) –0.012; 7) –0.068; 8) –0.103; 9) –0.033; 10) 0.0085; 11) 0.057].

Figure 2b shows the field of the dimensionless pressure on the adiabatic wall. It is seen that behind the orifice we have a vacuum region (negative values of p) caused by the separation of the jet from the wall. The presence of this region accounts for the sharp nonuniformity (see Fig. 2a) in the distribution of θ in the transverse direction — the hot main flow rushes into the vacuum region under the jet. On the whole it should be noted that in the calculation the separation of the jet from the wall turns out to be overstated (it is known that the experiment for $\alpha_0 = 35^o$ and m = 0.5 yields a practically separationless regime of the jet's outflow with a more uniform distribution of θ in the transverse direction [7]). This can be a consequence of the use of boundary conditions of the first kind in assigning an outflowing jet. The position of the isolines of the pressure p shows periodicity in the coordinate x.

Figure 3a presents the distribution of Nu numbers on the wall in injection of jets with the conditions $\alpha_0 = 35^o$, m = 0.5, and T_i/T_0 = 1 and in the case of an assigned uniformly distributed heat flux on the wall. It is seen that the values of Nu numbers are distributed on the wall nonuniformly. At the beginning of the region, they decrease downstream up to the orifice, and their level lines are parallel straight lines. This resembles the similar position of Nu numbers for the boundary layer on a plate, but the values themselves exceed the corresponding values for the boundary layer. On the sides of the orifice there are the closed lines of the level of Nu numbers with lower values. Immediately behind the orifice the Nu numbers have values of ~56–57. The closed region of relatively low values of the Nu numbers (~22 at the center) lies further downstream. It is approximately here that the separation region behind the jet is located. Downstream beyond this region the Nu numbers increase again. It should be noted that one can clearly track the interaction of the jets in the row from the distribution of the Nu numbers.

Figure 3b gives the pressure field on the wall obtained in calculation of the distribution of Nu numbers. It is seen that in comparison with the pressure field shown in Figure 2b in the vacuum region behind the orifice the values of the pressure p are much lower, which points to a more developed separation of the jet from the wall. This is due to the fact that for one and the same injection parameter m the ratio of the specific pulses of the jet and the main flow q for T_i/T_0 = 1 turns out to be 2 times greater than for T_i/T_0 =

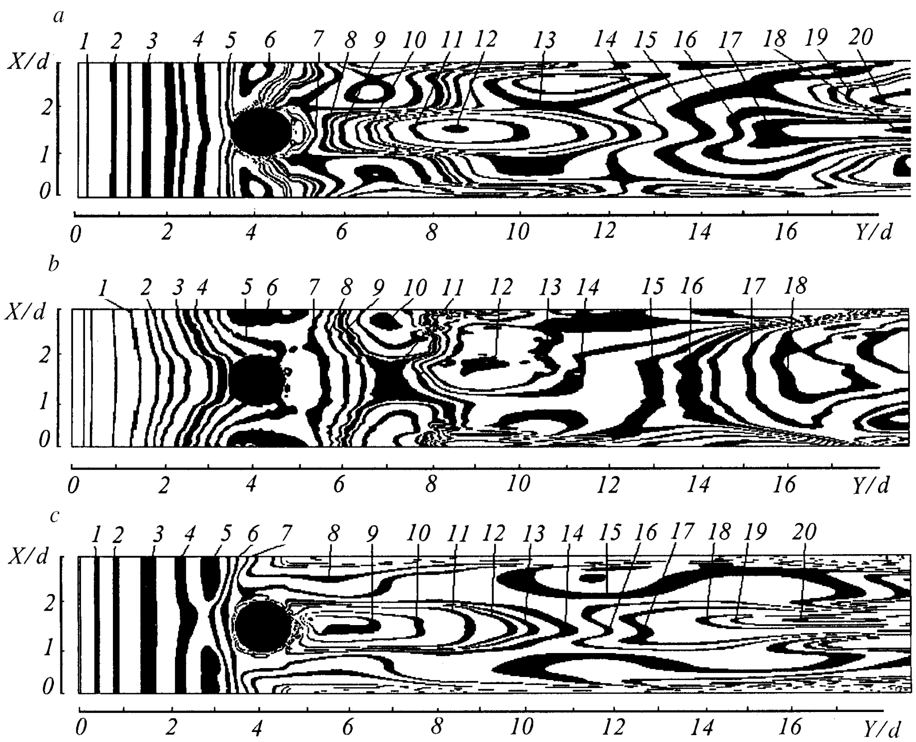

Fig. 3. Distribution on the wall, in the case of the assigned uniform heat flux (m = 0.5 and T_i/T_0 = 1), of the: (a) Nu numbers for $\alpha_0 = 35^o$ [1) Nu = 146.2; 2) 79.4; 3) 58.3; 4) 43.2; 5) 34.3; 6) 29.4; 7) 56.5; 8) 50.2; 9) 43.2; 10) 34; 11) 25; 12) 22.3; 13) 34; 14) 37.9; 15) 43.2; 16) 46.3; 17) 49; 18) 56.5; 19) 32.6; 20) 29.4]; (b) dimensionless pressure for $\alpha_0 = 35^o$ [1) p = –0.0645; 2) –0.1362; 3) –0.1991; 4) –0.244; 5) –0.2979; 6) –0.3338; 7) –0.2979; 8) –0.2709; 9) –0.244; 10) –0.1362; 11) –0.222; 12) –0.3248; 13) –0.2979; 14) –0.2709; 15) –0.244; 16) –0.226; 17) –0.1632; 18) 0.1362]; (c) Nu numbers for $\alpha_0 = 60^o$ [1) Nu = 68.7; 2) 56.9; 3) 46.6; 4) 39.9; 5) 37.9; 6) 48.7; 7) 58.5; 8) 73.3; 9) 20.3; 10) 25.3; 11) 32.2; 12) 37.9; 13) 40.4; 14) 44.7; 15) 44.7; 16) 55.6; 17) 73.3; 18) 202; 19) 220; 20) 225].

0.5 (1/4 and 1/8 respectively). This leads to an increased depth of penetration of the jet into the main flow and hence to a more intense separation behind the jet.

Figure 3c presents the distribution of Nu numbers on the wall for $\alpha_0 = 60^o$ and m = 0.5. The increase in the angle of injection leads to a deeper, compared to $\alpha_0 = 35^o$, penetration of the jet into the main flow and hence to a more developed separation. Compared to Fig. 3a, the region of closed Nu lines behind the orifice shifted upstream, and the values of the Nu numbers became somewhat lower. Beyond this region downstream the values of the Nu numbers are almost 2 times higher than for the case $\alpha_0 = 35^o$.

CONCLUSIONS

1. Numerical modeling of processes occurring in a gas curtain behind a row of orifices for injection made it possible to obtain the fields of the curtain efficiency θ and the numbers Nu on a protected wall.

2. Great nonuniformity of θ, Nu, and other parameters of the flow is noted. The calculations yielded a more developed separation of the jet from a protected wall in comparison with known data. Perhaps, this is a consequence of the method of assigning the jet in terms of conditions of the first kind in velocity.

3. Increase in the angle of injection leads to a growth in the nonuniformity of the distribution of Nu numbers on the wall. At the same time, the values of the Nu numbers immediately behind the orifice, in the separation region, decrease, but further downstream, behind the separation region, they increase.

4. Testing the developed method of modeling, the boundary conditions, and the turbulence model requires the accumulation of experimental and calculated data on the fields of physical parameters in the flow for gas curtains formed by the injection of the coolant through a system of discrete orifices.

NOTATION

d, diameter of the orifice for injection; V, velocity; ρ, density; $p = (p' - p_0)/\rho_o V_0^2$, dimensionless pressure; T, temperature; λ, thermal conductivity; μ, dynamic viscosity; α_0, angle formed by the axis of the orifice and the protected wall; α, local coefficient of heat transfer from the main flow to the solid wall; $\mathrm{Nu} = \alpha d/\lambda_0$, local Nusselt number; k, kinetic turbulence energy; ε, dissipation rate of the kinetic turbulence energy; $\mathrm{M}_0 = V_0/\sqrt{\gamma R T_0}$, Mach number; $\mathrm{Pr}_0 = \mu_0 C_p/\lambda_0$, Prandtl number; $\mathrm{Re}_0 = \rho_0 V_0 d/\mu_0$, Reynolds number; $m = \rho_i V_i/(\rho_0 V_0)$, injection parameter; $q = \rho_i V_i^2/(\rho_0 V_0^2) = m^2 (T_i/T_0)$, ratio of the specific pulses of the injected and main flows; $\theta = (T_0 - T_{ad})/(T_0 - T_i)$, efficiency of curtain cooling; C_p, heat capacity. Subscripts: 0, scale physical quantities; they are assigned at the entrance to the calculated region and refer to the main flow; i, parameters of the injected flow; ad, adiabatic wall; prime, dimensional pressure at an arbitrary point of the flow.

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