from thermocouple readings at $\varphi = 0$ for different loads. The theoretical relations satisfactorily (to within 10-15%) describe the experimental data, which is evidence of the possibility of making practical use of the proposed method to diagnose friction in movable couplings.

## NOTATION

$Q(t)$, intensity of heat release in the region of the friction contact; $T_0$, initial temperature; $T$, temperature of bearing; $u$, temperature of shaft; $t$, running time; $z$, coordinate along the shaft; $r$, $\varphi$, polar coordinates; $t_m$, test time; $S$, $P$, area and perimeter of shaft cross section; $\rho$, density; $c$, heat capacity; $\lambda_1$, thermal conductivity of the bushing material; $\lambda_2$, thermal conductivity of the shaft and housing material; $\alpha_s$, coefficient of heat transfer from the surface of the shaft; $\alpha$, heat transfer coefficient of the free surfaces of the bushing and housing; $\chi$, $\psi$, Lagrangian multipliers.

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# NUMERICAL STUDY OF THE EFFECTS OF SLIP AND A TEMPERATURE DISCONTINUITY ON THE SURFACE OF A SPHERE IN A SUPERSONIC FLOW

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This article examines the effect of boundary conditions for slip and temperature discontinuity on drag and heat-transfer characteristics. Numerical solutions of the Navier–Stokes equations are used to analyze the dependence of these effects on the governing parameters of the flow.

Deviations from the continuum model begin to occur with an increase in negative pressure. These deviations can be accounted for in a gas of moderately low density by means of slip and temperature-discontinuity boundary conditions. The effect of these conditions in problems involving supersonic flow about bluff bodies has usually been studied with the use of the Navier–Stokes equations (see [1], for example). The authors of [2] used the example of unidimensional flow on the stagnation line to show that the complete equations need not be used when the above-mentioned effects are negligible. Well-known solutions of the complete two-dimensional Navier–Stokes equations with slip and temperature-discontinuity conditions [3-6] demonstrate the importance of these effects but are not accompanied by an analysis of their dependence on the governing parameters of the flow. Below we present results of a study of the dependence of the effects of slip and temperature discontinuity on the Reynolds number, surface temperature, energy accommodation coefficient, and the properties of the gas.

1. We examine the steady supersonic flow of an ideal gas about a sphere at Reynolds numbers $Re \gtrsim 20$. The Reynolds number Re was calculated from the radius of the sphere and parameters of the gas behind a forward-traveling shock wave. As is known, the use of such a similarity criterion nearly eliminates the dependence of the characteristics of the flow about the sphere on the Mach number of the incoming flow.

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The theoretical region was bounded by the surface of the body, the retreating shock wave, the symmetry axis, and the ray $\theta = \pi/2$. The flow is described by the complete Navier–Stokes equations. The heat capacity of the gas is assumed to be constant. The viscosity coefficient is calculated from the Sutherland formula.

The boundary conditions of the problem are formulated as follows. The surface of the body is considered impermeable. Slip and temperature-discontinuity conditions obtained in [7] are imposed on the surface, these conditions having been obtained with the use of a model kinetic equation of the relaxation type and the assumption of diffuse reflection of molecules from the wall with a Maxwell distribution. The conditions have the form

$$u = 1{,}431 \frac{\mu}{\sqrt{\rho p}} \frac{\partial u}{\partial n} + 0{,}84 \frac{\mu}{\rho T} \frac{\partial T}{\partial \theta}, \tag{1}$$

$$T = T_w + \frac{0{,}627}{p} \sqrt{\frac{T}{R}} \frac{2 - 0{,}827\alpha}{\alpha} \lambda \frac{\partial T}{\partial n}. \tag{2}$$

The second term in the formula for slip velocity plays an important role only at Reynolds numbers approaching unity [7]. Calculations performed with allowance for this term showed that, under the conditions being considered ($Re \geqslant 20$), its contribution to the slip velocity is no greater than 2%. Thus, only the first term in boundary condition (1) was considered. To analyze the effect of slip and temperature discontinuity, we also performed calculations with nonslip conditions and equality of the temperature of the gas on the surface of the body to the temperature of the surface $T_w$.

The values of the gasdynamic functions behind the main shock wave are determined from the generalized Rankine–Hugoniot relations. Symmetry conditions are used on the flow axis, while approximate conditions of the form $\partial^2 f/\partial\theta^2 = 0$ are used on the ray $\theta = \pi/2$, where f is any of the sought functions.

Stationary solutions are found by the establishment method with the use of a second-order difference scheme [8]. Most of the results shown below were calculated on a grid containing 10 rays $\theta = \text{const}$, with 31 nodes on each ray. At low values of the temperature factor, the nodes of the grid were condensed toward the surface of the body by means of a logarithmic transformation of the normal coordinate. According to the results of verifying calculations performed with different numbers and locations of the grid nodes, the error of the difference approximation was 2-3%.

2. Figure 1 shows the results of calculation of heat transfer at the frontal point of the sphere in comparison with experimental data [9]. These results were obtained for the case of a flow of air about the sphere with a temperature factor $k = 0.18$. The temperature factor was defined as the ratio of the temperature of the body surface to the stagnation temperature $k = T_w/T^*$. The heat-transfer coefficient was determined by the expression

$$C_\text{n} = \frac{Q}{\rho_\infty V_\infty (h^* - h_w)}. \tag{3}$$

Heat flux to the body surface, with allowance for slip, was determined from the formula

$$Q = \lambda \frac{\partial T}{\partial n} + \mu u \frac{\partial u}{\partial n}. \tag{4}$$

The second term of Eq. (4) vanishes at the frontal point of the sphere. The good agreement between the theoretical and experimental results is evident from Fig. 1.

The subsequent figures show some results of study of the effect of slip and temperature discontinuity on the heat-transfer and drag parameters. The quantities q and $\tau$ represent the maximum heat flux and shear stress on the surface of the sphere when referred to their values calculated with the boundary conditions

$$u|_{n=0} = 0, \quad T|_{n=0} = T_w. \tag{5}$$

Figure 2 shows the dependences of q and $\tau$ on the Reynolds number. The solid lines correspond to a flow of air about the sphere, while the dashed lines correspond to an argon flow. They were constructed from the results of calculations for $M_\infty = 3$ and $k = 0.48$. To illustrate the universal character of these relations, we also plotted the results of calculations for air at Mach numbers $M_\infty = 2, 4, 6$, and 10 and the same value of the temperature factor.

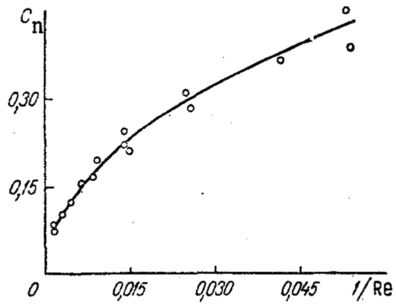


Fig. 1

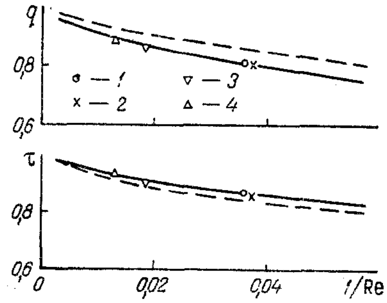


Fig. 2

Fig. 1. Dependence of the heat-transfer coefficient on the Reynolds number. The curve shows calculated results, while the points show experimental results [9].

Fig. 2. Dependence of the effects of slip and temperature discontinuity on the Reynolds number: 1) $M_\infty = 2$; 2) 4; 3) 6; 4) 10.

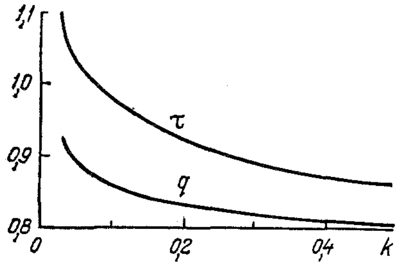


Fig. 3. Dependence of the effects of slip and temperature discontinuity on the temperature factor; air; $M_\infty = 3$; Re = 25.

The above results were obtained with an accommodation coefficient $\alpha = 1$ on the surface. The value of this coefficient has a significant effext on heat flow to the surface of the body. For example, for $M_\infty = 3$, Re = 25, and k = 0.48, heat flow at the frontal point of the sphere for $\alpha = 0.5$ turns out to be 35% less than at $\alpha = 1$. The effect of the accommodation coefficient decreases with increasing distance from the frontal point, which is related to an increase in the contribution of the second term of Eq. (4) to the heat flux. This term is slightly dependent on $\alpha$.

The effect of the temperature of the surface in the flow is shown in Fig. 3. It is evident that at $k \leqslant 0.075$, the shear stress is somewhat greater than the value obtained using the nonslip condition. This result is attributable to an increase in the viscosity of the gas due to the temperature discontinuity on the surface of the body. The effect of the temperature discontinuity on the heat flux at the frontal point of the sphere decreases with a decrease in the temperature factor. On a relatively hot surface, these effects also lead to a marked reduction in pressure. The maximum reduction in the drag coefficient for the front surface of the sphere $(0 \le \theta \le \pi/2)$ was 12% under the conditions examined here.

The results reported here offer a quantitative representation of the range of applicability of nonslip boundary conditions on the surface of bluff bodies when studying their immersion in a supersonic flow.

## NOTATION

M, Mach number; Re, Reynolds number; $\theta$, angular coordinate; n, distance from the surface of the body; V, modulus of gas velocity vector; u, velocity component tangential to the body surface; $\rho$, density; p, pressure; T, temperature; h, enthalpy; $\mu$, viscosity coefficient; $\lambda$, thermal conductivity; R, universal gas constant; $\alpha$, accommodation coefficient; k, temperature factor; Q, heat flux; $C_n$, heat-transfer coefficient; q, relative value of heat flux at the frontal point of the sphere; $\tau$, relative value of the maximum shear stress on the surface of the sphere. Indices: w, $\infty$, surface of body and undisturbed incoming flow; *, stagnation parameters.

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# STUDY OF TRAJECTORIES AND COMBUSTION OF FUEL-OIL DROPLETS IN THE COMBUSTION CHAMBER OF A POWER-PLANT BOILER WITH THE USE OF A MATHEMATICAL MODEL

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A mathematical model is developed to permit study of the behavior of fuel-oil droplets in a combustion chamber, and results are presented from a computer calculation performed for the 300-MW model TGMP-314P boiler of a power plant.

A mathematical model has been developed for power-plant boilers having burners installed vertically on the hearth of the combustion chamber. This arrangement was chosen due to the simplicity of the aerodynamics of such a combustion chamber and the possibility of performing a detailed empirical check of the calculated results.

In contrast to completely vaporized liquid fuel, fuel oil burns with the formation of a solid phase. The complete combustion of this phase is subject to the laws of heterogeneous chemical reactions and proceeds at a rate considerably below the rate of complete combustion of liquid-fuel vapors. Complete combustion of the solid phase is one of the main limiting factors in the combustion process and ultimately determines the length of the fuel-oil flame.

Studies conducted by the All-Union Institute of Heat and Power Engineering have shown that the coke residues of unburned fuel-oil droplets consist mainly of hollow spherical particles containing one coarse hole. The solid particles are spherical mainly because of the formation of a coke shell on their surface during combustion and vaporization of the droplet, the rupture of this shell being accompanied by the ejection of some of the vapors and liquid therein. Studies of the combustion of single droplets of fuel oil have shown that the diameter of the coke residue is usually 0.5-0.7 of the initial diameter of the drop [1]. According to our data, its inside diameter is approximately $0.3d_{po}$.

The program written to perform the calculations was organized so that the first stage would entail calculation of the combustion (vaporization) of a droplet of liquid fuel to a diameter corresponding to 0.6 of the initial droplet size $d_{po}$. The program then provided for a sudden decrease in the mass of the fuel particle, simulating rupture of the coke shell and ejection of some of the liquid. The program then considered the combustion of a hollow coke particle with an outside diameter of $0.6d_{po}$ and an inside diameter of $0.3d_{po}$. In accordance with this plan, physicochemical parameters characteristic of fuel oil M-100 were introduced in the program in the first stage of computations, while parameters characteristic of the coke particle associated with an unburned fuel-oil droplet were included in the second stage.

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