EXPERIMENTAL DETERMINATION OF THE RESISTANCE OF A SPHERICAL PARTICLE IN AN ARGON PLASMA STREAM

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The authors present results of measurements of the resistance of a sphere in an argon plasma stream. It was found that the flow being nonisothermal strongly influenced the resistance coefficient.

Mathematical modeling of the motion and heating of particles of various materials in high temperature gas flows customarily uses the aerodynamic (frontal) drag coefficient of a sphere C_d as a function of Reynolds number. This is obtained experimentally, and in some cases theoretically, in isothermal flow over the sphere [1], or in conditions close to that. There are practically no measurements in high temperature flows. For example, in [2] experimental data were given for an argon plasma at temperature 10^4 K and Reynolds number 4-7. With the small volume of data the authors could not explain the reason for the measured values of C_d deviating from the relation corresponding to isothermal flow over the sphere. The influence of stream high temperatures was investigated in [3] in the example of a cylinder in transverse flow in the Reynolds number range 30-90. Good agreement was shown with the values of C_d obtained for low flow temperatures, if the Reynolds number was computed from the parameters of the unperturbed incident plasma stream. Inadequate and conflicting experimental data make it difficult to analyze the motion and heating of particles in high temperature flows.

To carry out detailed investigations of the resistance of a sphere in an argon plasma stream, and also to increase the reliability of the results, the measurements were made using a stationary (mounted) and a moving spherical particle.

The resistance of the mounted sphere in the argon plasma stream was measured using the expression

$$F_p = C_d \frac{\rho_p v_p^2}{2} \frac{\pi d_s^2}{4}, \tag{1}$$

which is valid for zero-gradient flow [1]. Therefore, to determine C_d it is enough to measure the force F_n, the velocity head, and the sphere diameter, and to create a stream with zero gradient of temperature and velocity. To achieve this the measurements were made in the axial region of a plasma jet, where the transverse gradients of plasma velocity and temperature are near zero, while the longitudinal gradients are small and can be neglected [1].

The scheme for the experimental investigations is shown in Fig. 1. A steel sphere of diameter 1.75 mm was mounted on a quartz tube protected by tungsten, and the free end of the tube was attached to the measuring rod of a type 6MKh8B force sensor, which gives precision measurements of force in the range 0-0.2 N. Subsequently the measured signal was amplified and recorded with the aid of a type M017-400 galvanometer on the chart of a drift oscillograph. The plasma velocity head and temperature were determined with the aid of the longitudinally washed enthalpy sensor [3]. In the "no gas suction" regime we measured the plasma velocity head (using an LPI micromanometer or a U-tube manometer) and the heat flux to the sensor — using cooling water calorimetry. To increase the accuracy of the measurements we set up a bank of Chromel—Copel differential thermocouples (TB). In the "gas suction" regime we measured the heat flux to the sensor and the flow rate of gas suction using a calibrated flowmeter. From the difference in the heat flux in the two regimes of operation of the enthalpy sensor and the suction gas flow rate we determined the plasma enthalpy. To obtain the plasma

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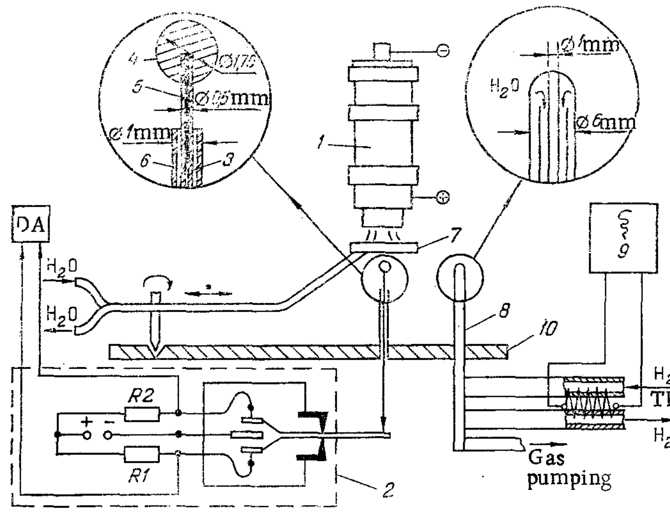

Fig. 1. Scheme for measuring the frontal drag coefficient of a mounted sphere: 1) plasmotron; 2) the type 6MKh8B mechanotron in a water-cooled screen; 3) quartz rod; 4) sphere model; 5) protective tungsten rod; 6) quartz screen; 7) water-cooled valve; 8) enthalpy sensor; 9) LKD XY recorder; 10) thermally insulated mounting table with a mechanism for horizontal displacement; DA) differential amplifier; TB) block of Chromel—Copel thermocouples.

flow we used a sectioned arc plasmotron [1] with a stabilizing cylindrical exit nozzle. The arc current was measured in the range 60-200 A, and the argon flow rate was 0.08 to 1.5 g/sec.

Prior to the measurements the mounted sphere was screened by the water-cooled valve 7. After the plasmotron was switched on, brought up to the given conditions, and a stable plasma flow was formed, the valve was opened, and simultaneously the chart of the film oscillograph was switched on. The end of the measurements was dictated by melting or combustion of the sphere. Thereafter the displacement mechanism 10 was used to bring in the enthalpy sensor, and the plasma flow parameters were measured.

Preliminary flushing of the measuring system with cold ($T_p \sim 300°K$) laminar air flow showed that the effect of mounting the sphere on the computation of the resistance coefficient can be neglected. The deviation of the measured values of C_d from the known values is random, and does not exceed 25%. Such a high error is associated only with measurements with cold air washing the model sphere, since one of the components of this error, equal to 15%, is due to errors of measurement of the small values of the velocity head, corresponding to the small Reynolds number. With an increase of the Re_p number to 1000, or with an increase of the velocity head, the total error of this method is reduced to 10%. This level of error is typical of high temperature flows, since with increase of temperature the velocity head increases due to decreased gas density. As was shown in [3], the error of determining the velocity head in the near-axial flow region is $\sim$5%, while the error in determining the force acting on the sphere in the flow is also $\sim$5%. Allowing for the error in determining the diameter of the spherical particle and for some instability of the flow parameters, one finds that the error of determining C_d is ±15%.

The measurement of drag of the moving sphere in the argon plasma flow was conducted in accordance with the equation

$$ma_s = C_d \frac{\rho_p (v_p + v_s)^2}{2} \frac{\pi d_s^2}{4} - \rho_s g \frac{\pi d_s^3}{6},$$

which applies, as does Eq. (1), for zero-gradient flow. In this case, as before, the measurements were made only in the axial flow region. Particles passing through peripheral flow regions were eliminated from consideration. In addition, to create the high-temperature gas stream we used the previously developed type PRD-19 three-anode plasmotron [1] with a split electric arc. This plasmotron provided stable low speed plasma flows, and the diameter of the

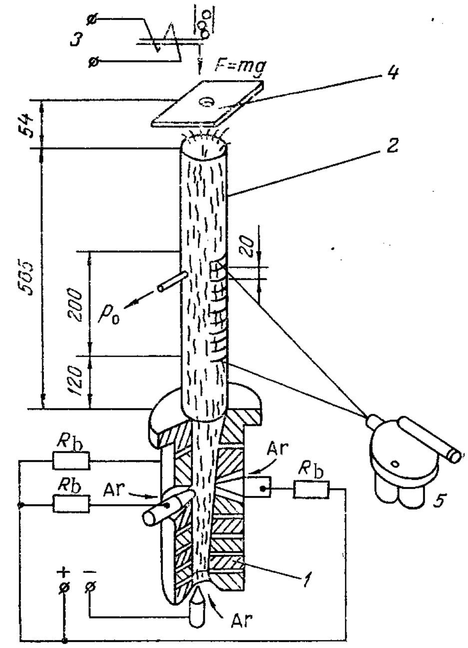

Fig. 2. Scheme for measuring the drag coefficient of a moving sphere: 1) the PRD-19 three-anode plasmotron; 2) quartz tube; 3) electromagnetic valve; 4) protective screen; 5) type SKS-1M high-speed camera; R_b) ballast resistors.

arc channel was 2 cm. The exit of its diffusor nozzle was joined to a stabilizing quartz channel with an inside diameter of 6.3 cm and a length of 58.5 cm (Fig. 2).

The temperature distribution along the flow axis was measured with the aid of a platinum/platinum-rhodium thermocouple located in a thermally stabilized screen, and, in addition, the calculation was corrected for thermocouple radiation. The dynamic head was measured with a water-cooled total head sensor, and the static pressure was monitored via an aperture in the wall of the quartz channel, and practically did not differ from atmospheric in the conditions of the experiment.

After the flow parameters were measured three steel spheres of 1.75-mm diameter were injected simultaneously (the distance between the particles in motion in the flow was 2-6 mm, which allows us to neglect their mutual influence). Simultaneously, the type SKS-1M high-speed camera was switched on and was used to record the trajectories of the spheres in the given section of the channel. The size of the recording zone was determined from calculating the possible measurement of the sphere acceleration in a section with constant flow parameters. By determining the variation of velocity of the individual spheres in traversing the monitored section, using the movie pictures obtained, one can find the corresponding frontal drag coefficient. For the given flow regime (Re_p = 80-90 and T_p = 2100 ± 30°K) the value of the drag coefficient was 0.75 ± 0.2. The absolute error, equal to 0.2, was found from the maximum deviation of C_d from its mean value, taking into account repeat measurements of the drag coefficient. In this case the relative error of measuring C_d of the moving sphere (±28%) exceeded the error of determining the C_d of the mounted sphere, due to the additional errors of recording and computing the velocity of the flying particles in the high-temperature gas flow.

As a result of conducting the two independent experiments using the moving and fixed spheres was found, as in [2], that the drag coefficient of a spherical particle at high flow temperatures is reduced compared with the known values.

To analyze the influence of C_d of the degree to which the high temperature gas flow over the sphere is nonisothermal it is desirable to represent the measured drag coefficients in the form of the correlation $C_d = f(T_p, Kn)$, where the number Kn characterizes the rarefaction of the gas flow arising from the considerable reduction of medium density in the region of plasma temperatures. The Knudsen number was determined from the expression $Kn = M/Re^{0.5}$,

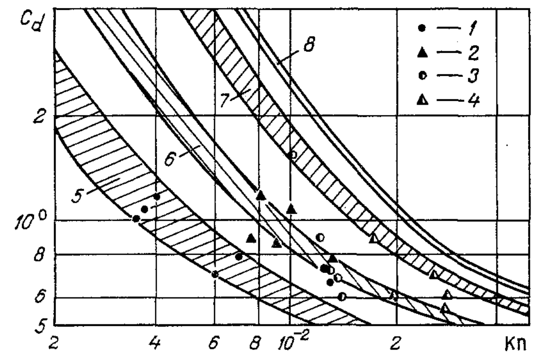

Fig. 3. Drag coefficient of a spherical particle as a function of the Knudsen number at various flow temperatures: 1, 5) 2500-3500°K; 2, 6) 4500-5500; 3, 7) 7500-8500; 4, 8) $(10\text{-}12)\cdot 10^3$°K (1-4) results of measurements; 5-8) values of C_d computed from the relation $C_d = f(Re_p)$.

and the Mach number ($M = v_p/a_s$) from the speed of sound for argon in thermal equilibrium at atmospheric pressure [1]. Here for the sake of clarity the values of C_d obtained were arbitrarily divided up according to the following temperature intervals (Fig. 3): T_p = 2500-3500°K 4500-5500°K; 7500-8500°K and 10,000-12,000°K. The part of the data which did not fall in these intervals is omitted here. Figure 3 also shows the boundaries of these intervals, as determined by transition of the known correlation $C_d = f(Re)$. The necessary values of M for this were obtained for incident flow velocities calcuated for the values of Re corresponding to the known values of C_d and the argon parameters (ρ_p and T_p) at the temperatures of the above intervals. For this we used the following relations:

$$M = Re \frac{\mu_p}{a_s \rho_p d_s}, \quad Re_p^{0.5} = Kn \frac{\mu_p}{a_s \rho_p d_s} = Kn\, f(T_p),$$

where ρ_p and μ_p are the gas density and the kinematic viscosity at T_p. By analyzing the results shown in Fig. 3 we can observe that as we increase the degree to which the gas is nonisothermal the deviation of the results obtained from the known values increases: for example, for the interval T_n = 2500-3500°K all the experimental points do not fall outside the corresponding zone, and for the temperature $(10\text{-}12)\cdot 10^3$°K the drag coefficient decreases on the average by more than 60%. Taking into account that all the values of C_d were obtained for knudsen numbers less than 0.3, we can neglect the influence of gas rarefaction in the conditions of the experiment. But the reduction of the spehre drag coefficient compared with the known values can be explained by the influence of the nonisothermal nature of the flow over the spherical particle, since the temperature of the particle surface is roughly an order less than that of the incident stream.

Investigation of the nature of the flow of high-temperature argon over a sphere on a shadowgraph [4] using a type SKS-1M high-speed camera has shown that in the test range of Reynolds number separation of the boundary layer from the sphere surface is observed only at isolated times. On the whole, the flow over the sphere can be described as nonseparated. Clearly, the reduced gas viscosity due to the high temperature of the flow reduces the probability of seeing separated vortices that are typical for the test range of Re_p number under isothermal flow conditions [5, 6].

We can take account of the influence of the flow not being isothermal on the drag of a spherical particle by using the effective value of the viscosity $\mu_{eff} = \sqrt{\mu_p \mu_s}$ in defining the Reynolds number. In this case we have

$$Re_{eff} = \frac{\rho_p v_p d_s}{\mu_{eff}} = Re \left(\frac{\mu_p}{\mu_s} \right)^{0.5}.$$

The possible use of the effective viscosity in computing nonisothermal flow was checked by the authors of [7] while investigating the motion of spherical particles for $R_{eff} \ll 1$.

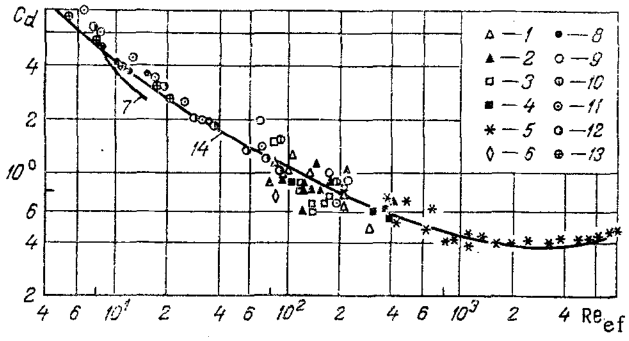

Fig. 4. The frontal drag coefficient of a spherical particle as a function of the Reynolds number based on the effective viscosity: 1-5) measured C_d data for a mounted sphere for various T_p: 1) $(2.5-4.5)\cdot 10^3$ °K; 2) $(4.5-6.5)\cdot 10^3$; 3) $(6.5-9)\cdot 10^3$ °K; 4) $(9-12)\cdot 10^3$ °K; 5) 300°K; 6) measured C_d data for a moving spherical particle for T_p = 2100°K; 7, 8) data from [2] for $T_p = 10^4$ °K; 9-13) from [8] for T_p = 300°K for a sphere; 9) T_s = 1773°K; 10) 1270°K; 11) 1100°K; 12) 723°K; 13) 523°K; 14) the known correlation (isothermal flow over a sphere).

According to their estimate, the error in the results of calculating the drag force when replacing the viscosity by its effective value, compared with the exact solution for $Re_p \ll 1$, does not exceed 11%. The results of the present work, and also the data of [2] are shown in Fig. 4. Figure 4 also shows the results of [8], obtained for heated spheres washed by a cold stream of air. Within the limits of experimental error these values of the sphere drag coefficient coincide with the known values.

NOTATION

C_d, frontal drag coefficient of a sphere; F_p, drag force acting on the sphere; d_s, sphere diameter; ρ_p, gas density; μ_s, gas viscosity at the sphere wall temperature; μ_p, gas viscosity at the incident stream temperature; μ_{eff}, effective value of the gas viscosity; v_p, flow velocity; v_s, velocity of motion of the sphere; g, acceleration due to gravity; T_p, temperature of the incident flow; T_s, sphere wall temperature; Kn, Knudsen number; m, particle mass; a_s, particle acceleration in a fixed coordinate system; ρ_s, particle material density, a_s, sound speed; Re_p, Reynolds number based on the parameters of the incident flow; Re_{eff}, effective value of Reynolds number; M, Mach number.

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