MEASURING THE COEFFICIENT OF AERODYNAMIC DRAG FOR A SPHERE SUBJECT TO NONISOTHERMAL STREAMLINING

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UDC 533.95.15.082

We present the results from an experimental measurement of the coefficient of aerodynamic drag on spherical particles in an argon plasma at temperatures as high as 10,000 K, and for Mach numbers of M ~ 0.05 and Reynolds numbers of Re ~ 0.4-10.

Extensive use is made of the methods of mathematical modeling to study the plasma processing of dispersed materials, the application of coatings, and the production of composition materials. Here one of the important parameters of interaction between the particles and the plasma is the coefficient of aerodynamic drag C_D. At low temperatures, in isothermal incompressible and compressible flows the coefficient C_D is known with adequate reliability over a broad range of Reynolds and Mach numbers (see, for example, [1-3]) and the entire large amount of experimental results from the study of C_D is to be found in the form of the averaged, so-called "standard," resistance curves $C_D = f(Re)$ [1], which describes the resistance in the flow of a single nonrotating solid sphere with a smooth surface. For engineering estimates and theoretical calculations we have on hand more than 30 expressions approximating this standard curve with adequate accuracies in the broadest possible range of Reynolds numbers. Detailed systematization with analysis of these formulas is to be found in considerable detail in [3]. Under the actual conditions of the streamlining of the sphere by a flow we note a complex pattern of interaction, and the drag coefficient is additionally affected by acceleration, turbulence, compressibility, and the nonisothermicity of the flow, as well as by the roughness, nonsphericity, rotation, combustion, and vaporization of the particles. Turbulence in gas flows leads to a strong change in the pattern of sphere streamlining and shifts the points of separations downstream, which in the final analysis may lead to a reduction in the coefficient of drag for the sphere [4, 5]. The compressibility of the medium significantly affects C_D at Mach numbers $M > 0.1$ [6]. Provision is made in [7-9] for the effect of roughness, rotation, and particle acceleration. It is demonstrated that roughness may lead to local separation in the acceleration region of the flow behind the sphere and may lead to an increase in drag, whereas the effect of rotation in many cases of particle acceleration can be neglected. It was demonstrated in [5, 9] that combustion and vaporization of particles leads to a reduction in drag. However, results of studies [10] show an increase in C_D for burning particles of coal. Utilization of the values for the drag coefficients obtained in cold gases for purposes of calculating the trajectories and interactions of particles in the nozzles of rocket engines showed that C_D may differ significantly from the standard values [8]. It has been established that in the general case the coefficient of resistance can be a function of the Reynolds and Mach numbers, as well as of the adiabatic exponent $C_D = f(Re, M, \gamma)$.

The nonisothermicity of the streamlining plays a significant role at high temperatures. However, we know of only a limited number of references devoted to the experimental determination of the coefficient of aerodynamic drag for a sphere in a plasma, or to an estimate of the influence exerted by nonisothermicity. Individual estimates of the drag force and the coefficient C_D in plasma streams were obtained in the works of Seymour, Lewis, and Gauvin [11, 12]. Theoretical and experimental investigations were undertaken in [11] into the resistance of a sphere in an argon plasma for the range of numbers Re = 0.3-1.5. The author demonstrated that the resistance formulas of Stokes and Oseen, derived for the invariant properties of the fluid, cannot be applied to a sphere in a plasma, since a pronounced change in the properties of the plasma is observed in the vicinity of the sphere.

Physics Institute, Academy of Sciences of the Kirghiz SSR, Frunze. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 4, pp. 554-562, October, 1989. Original article submitted April 27, 1988.

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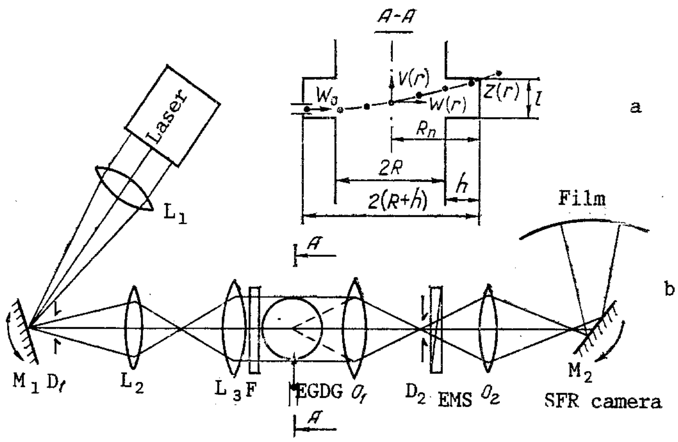

Fig. 1. Diagram illustrating the introduction of a particle into a plasma flow in an arc channel with an intersectional cavity (a) and the optical system for the high-speed registration of particle motion in the plasma (b). L_1-L_3) Lenses; M_1) mirror vibrator; D_1, D_2) diaphragms; F) framer; O_1, O_2) SFR objectives; EMS) electromagnetic shutter; EGDG) electrogasdynamic gun; M_2) rotating SFR mirror.

The calculated value of the resistance at a sphere surface temperature of $T_S < 2\cdot10^3$ K and a free stream temperature T_∞ = 4000-10,000 K, with consideration given to the nonlinear changes in the properties of the medium with temperature, said temperature approximately 40% lower than the Stokes temperature, calculated on the basis of the flow temperature. The experimental values of the resistance in the case of Re = 0.3-1.5 is larger by 10-30% than those calculated for the zeroth approximation of the Reynolds number.

The motion of glass microspheres [$d = (30\text{-}140)\cdot10^{-6}$ m] was studied in [12] in a free-burning argon arc by means of high-speed photography at Re = 0.2-20. The values of C_D were elevated by 40% in comparison with standard values. The authors regard their results to be preliminary, and in need of further refinement.

The value of the Reynolds number was calculated in [13] on the basis of some "mean arithmetic" temperature, and this value was then used to determine the drag factor from the standard curve. However, we know of no reasonable criterion to establish the "mean arithmetic" temperature. In [14] we find data on the experimental determination of C_D in an argon plasma for Re = 4-7. In [15] we have results from a study of the streamlining nonisothermicity insofar as this relates to the drag of spherical particles in the case of Re = 50-220. Determination of the function $C_D = f(\mathrm{Re}, T_\infty)$ was undertaken both for a fixed and a moving sphere in the near-axis region of the plasma jet (T = 2500-12,000 K). It is demonstrated that the calculation of the Re number on the basis of the temperature of the plasma stream leads to a substantial reduction in the value of the coefficient C_D. The authors explain this by the reduction in the viscosity of the gas in the boundary layer, which in turn reduces the probability of the appearance of vortices in the trailing portion of the sphere. The introduction of viscosity into the boundary layer in the form of $\mu_f = \sqrt{\mu_\infty \mu_S}$ made it possible for us to take into consideration the streamlining nonisothermicity and to combine the experimental data with the standard curve. However, the indeterminacy in the value of the particle wall temperature T_S prevents us from adequately utilizing the proposed relationship. In this connection, the carrying out of a correct experiment so as to exclude all factors affecting the value of C_D, with the exception of the temperature factor, would enable us to evaluate the influence of nonisothermicity in the case of particle streamlining by the plasma flow.

The method of determining the coefficient of aerodynamic drag, such as we have used in this paper, adequately makes provision for such factors and is based on recording of the trajectory and the corresponding calculation of acceleration in a test spherical particle, introduced in the lateral cross section of the axisymmetric plasma flow, and exhibiting specific properties (Fig. 1a) [16].

TABLE 1. Values of Forces Calculated on the Basis of the Plasma-Flow Parameters

r/R	F_a	F_B	F_G	F_M	F_{TP}
	F, N				
0	$4{,}4\cdot10^{-3}$	$0{,}6\cdot10^{-8}$	$3{,}7\cdot10^{-7}$	$1{,}2\cdot10^{-6}$	$6{,}6\cdot10^{-9}$
2/3	$2{,}3\cdot10^{-5}$	$1{,}9\cdot10^{-8}$	$3{,}7\cdot10^{-7}$	$2{,}9\cdot10^{-6}$	$1{,}8\cdot10^{-6}$
1	$2{,}8\cdot10^{-6}$	$4{,}1\cdot10^{-8}$	$3{,}7\cdot10^{-7}$	$7{,}9\cdot10^{-7}$	$0{,}8\cdot10^{-7}$

r/R	F_{CM}	F_D	F_{PE}	F_{EV}
	F, N			
0	$3{,}6\cdot10^{-9}$	$7{,}1\cdot10^{-9}$	$3{,}4\cdot10^{-6}$	$3{,}5\cdot10^{-10}$
2/3	$1{,}8\cdot10^{-8}$	$3{,}8\cdot10^{-8}$	$1{,}1\cdot10^{-7}$	$8{,}8\cdot10^{-10}$
1	$1{,}4\cdot10^{-8}$	$1{,}4\cdot10^{-7}$	$5{,}5\cdot10^{-8}$	$3{,}6\cdot10^{-9}$

We know that such forces as that of aerodynamic drag F_a participate in the formation of the particle trajectory; in addition, we have that force generated by the pressure gradient in the flow, i.e., F_D; in addition, the force F_B, produced by the nonsteadiness of the process and one that is dependent on the nature of particle motion within the preceding time segment (Bassé force); then we have the force F_{CM} which reflects the acceleration of those plasma layers (the connected mass) adhering to the particle surface; we also have the force F_{EV} which is generated by the inertia of the plasma volume expelled by the particle; we have the gravitational force F_G of the particle; the thermophoresis force F_{TP} which is due to the presence of a temperature gradient in the flow and is directed toward the lower temperatures; the force F_M which is brought about by the rotation of the particle because of the velocity gradient (the Magnus force); finally we have the force F_{PE} which is due to the dynamic pressure gradient of the flow (the profile effect, [16]). Analysis of the experimental conditions shows that in the near-axial zone of the arc ($r/R \le 2/3$) the force of aerodynamic resistance plays a fundamental role in the formation of particle trajectories, while the contribution of the remaining forces is insignificant, which is in agreement with [17, 18]. Table 1 shows data on an estimate of the forces acting on an aluminum particle exhibiting dimensions of $\sim 300\cdot10^{-6}$ m in the flow of an argon plasma with an axial temperature of ~10,000 K and a velocity ~100 m/sec. In addition, the movement of the particles must also be governed by the influence exerted by the electrostatic forces, the forces of light pressure, and the forces engendered by pulsations and the diffusion of the gaseous components. However, since we are speaking here of rather small particles in a stable source of an electrically neutral plasma, we can neglect the influence of the latter.

With consideration of the above, the sought magnitude of C_D is calculated as a function of the local characteristics of the plasma and the particle from the equation of motion

$$ma(r) = \frac{\pi d^2}{8} C_D(r)\rho(r)[U(r)-V(r)]^2. \tag{1}$$

To construct the complete profile of the acceleration $a(r)$ we make use of a method that is based on the projection of a single particle in the vertical plasma flow along the diameter of the lateral cross section [16]. The particles introduced by means of an electrogasdynamic gun whose barrel is fashioned out of a hypodermic needle with an inside diameter of $0.15\text{-}0.35\cdot10^{-3}$ m. A voltage of 3 kV is applied to the electrode of the gun. The pulse discharge ($\tau \sim 2\cdot10^{-6}$ sec) between the electrodes expands the gas in the capillary and propels the particle out of the barrel. The flight of the particle in the plasma is recorded by means of frame-by-frame motion-picture photograph with an SFR-1 camera (Fig. 1b). The shadow which the sphere casts against a laser-beam background is recorded on the film frame. The initiation of the pulse discharge is synchronized to the operation of the SFR camera. Such an optical system makes it possible to obtain up to 100 frames on the film of the process of particle displacement within the plasma without reduction in image size. This is accomplished by the fact that the double or quadruple lens inserts have been removed from the SFR camera and by virtue of the fact that rectangular mutually parallel planes are registered on the film with the aid of a framing mechanism and a vibrating mirror. In each case a single particle was fired through the plasma, and this particle was captured and used in repeat experiments. The firing velocity of the particle was chosen so as to avoid its melting during the time that it spent within the plasma. After it had been fired, the sphere's surface was kept under visual observation by means of a microscope and it was then weighed with an analytical balance. The particles were fabricated by impulse electromelting of aluminum wire in an argon medium. The particles were carefully sorted as to roughness, sphericity, and diameter $d = (0.15\text{-}0.3)\cdot 10^{-3}$ m by means of an IZA-7 comparator accurate to $\pm 1\cdot 10^{-6}$ m. The motion-picture photograph results for each particle firing provided the trajectory of motion Z(r) and the horizontal velocity W(r). Acceleration was defined as the second derivative of the particle displacement trajectory in the direction of plasma motion

$$a(r) = \frac{d^2[z(r)]}{dt^2} = W_0^2 \frac{d^2 z(r)}{dr^2}, \tag{2}$$

since with accuracy of ±1%, $W(r) \approx W_0$ (W_0 is the initial velocity of particle firing). For purposes of mathematical processing, the function $a(r)$ was assumed to have the form of the parametric function $a(r) = a_0(1-\delta)^n(1+n\delta)$, $\delta = r/R$ (a_0 denotes acceleration of the particle at the axis of the flow). The existence of approximately 100 experimental points provided for rather good accuracy in the determination of the parameters of the approximation function, with utilization of the method of least squares.

To generate a high-stability plasma flow we used a vertically positioned electric direct-current arc stabilized by cold walls [19], exhibiting a channel diameter ($2R = 3$ and $1.5\cdot 10^{-2}$ m) and a channel lengths $L/2R = 60\text{-}65$, the entire setup being fabricated out of water-cooled copper disks separated by $1\cdot 10^{-3}$ m and a depth of $2\cdot 10^{-3}$ m. The arc current and the flow rate of the plasma-forming argon varied within limits of $I = 70\text{-}190$ A, $G = (0.2\text{-}2.75)\cdot 10^{-3}$ kg/sec. Measurements were carried out within the electric-arc channel of the distribution of the electric potential, of the static pressure, of temperature, and of velocity. The change in the electric potential was measured by means of a digital voltmeter, where the disks of the arc channel served as the electrical probes. The static pressure was measured by an MMN-type micromanometer, in the ring clearances between the disks. The temperature distribution was determined on the basis of emissions of absolute intensity from the Ar type II ion line with a wavelength of 4806 Å by the lateral photography method, where a SI-8-200 tungsten lamp with an incandescent filament served as the standard source of reference. The velocity of the plasma was measured by means of total head tubes ($d = 3\cdot 10^{-3}$ m) where provision was made for the viscosity correction factors and for pressure resulting from the pinch effect of the method employed in [19]. The limits of change in the flow rate of the gas were determined from the conditions of flow laminarity.

The particles were introduced and recorded by means of a special interelectrode insert with a rather large radial cavity (Fig. 1a) having dimensions $\ell/h = 1$ ($h = R_{cav} - R = 1\cdot 10^{-2}$ m), and this might lead to a disruption of the cylindrical nature of the arc discharge, as well as to other changes in the parameters of the plasma. Therefore, in order to evaluate the influence exerted by this cavity on the flow characteristics of the plasma stream and in order to determine within it the local values of the temperature and velocity fields a numerical calculation was undertaken, which was based on a complete system of MHD equations in which provision is made for natural convections [20]. Certain of the following assumptions were made in the construction of the model: the flow is steady-state, stationary, axisymmetric, laminar, the plasma is quasineutral and is in a state of local thermodynamic equilibrium, there is no external magnetic field, viscous dissipation and the work of the pressure forces are insignificant in comparison with Joule heat liberation. These calculations demonstrated that the presence of such an intersectional cavity leads to no noticeable restructuring of the arc characteristics and a toroidal vortex is created within the cavity, said vortex limiting the inflow of the gas from the channel which functions in the role of a stabilizing gasdynamic wall and enhances the transport of heat from the plasma stream to the walls of the cavity. The results of the calculation are in satisfactory agreement with the experimental data in the asymptotic region of the channel. Below we show the axial values of the plasma parameters for the case in which $I = 110$ A, $G = 2.75\cdot 10^{-3}$ kg/sec, $2R = 30\cdot 10^{-3}$ m:

Parameters	T_0, K	E, V/m	U_0/G, m/kg	$\frac{dp}{dz}\Big/G$, $\frac{\text{Pa·sec}}{\text{(kg·m)}}$
Theory	9680	$2.1\cdot 10^2$	$23.5\cdot 10^3$	$0.69\cdot 10^5$
Experiment	9200	$1.7\cdot 10^2$	$25\cdot 10^3$	$0.65\cdot 10^5$

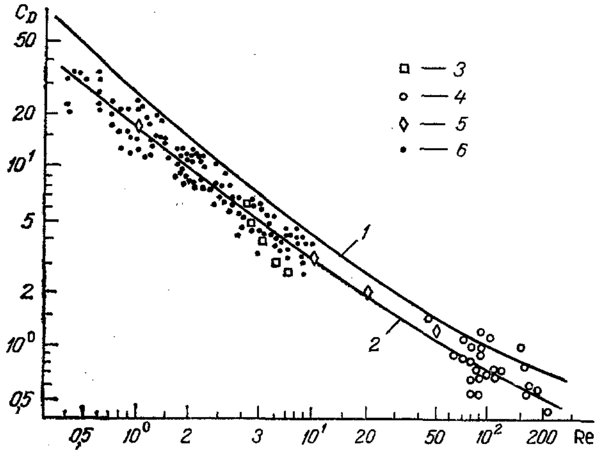

Fig. 2. The coefficient of aerodynamic resistance on the part of the sphere as a function of the Reynolds number in an argon plasma: 1) standard curve [1]; 2) approximation curve $C_D = 16.6\ Re^{-0.75} + 0.2$; 3) data from [14]; 4) data from [23]; 5) data from [18]; 6) data from the present paper.

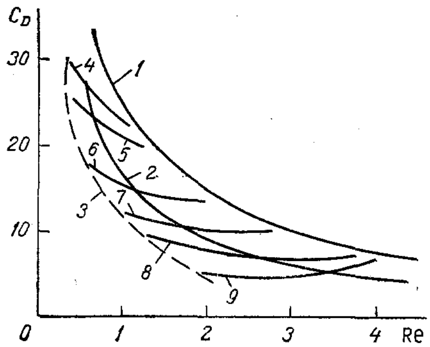

Fig. 3. The family (4-9) of experimental curves $C_D(r) = f[Re(r)]$, derived at various parameters of the plasma flow in the region of small Reynolds numbers. The curves: 1) standard; 2) approximation; 3) constructed on the basis of the plasma parameters at the axis of the flow; 4, 7) I = 110 A; 5, 8) 90 A; 6, 9) 70 A; 4-6) d = $212 \cdot 10^{-6}$ m, G = $1 \cdot 10^{-3}$ kg/sec; 7-9) d = $255 \cdot 10^{-6}$m, G = $1.75 \cdot 10^{-3}$ kg/sec.

The found distributions of T(r), U(r), and $\alpha(r)$ are used to determine the local values of the resistance factor for the sphere in the plasma. On the basis of the results from each firing it was possible to calculate the values of C_D, and these were subsequently averaged over a series of five shots for each regime. Using various values of I, G, 2R, and d made it possible on the one hand to expand the range of Re numbers and, on the other hand, to increase the reliability of the obtained results. The local averaged values of C_D are shown in Fig. 2 in the form of the function of the local Reynolds number $Re = \rho(U - V)d/\mu$, bound from the parameters of the unperturbed approaching stream. In these calculations we made use of the relationships to temperature for the plasma density ρ from [21] and for the viscosity from [22]. The maximum error in the determination of C_D and Re for random uncorrelated errors in the measurement of the original quantities amounts to 20-25%. The cited measurements of C_D for various values of the arc current I, the gas flow rate G, the channel diameter 2R and the diameter d of the particles made it possible, by the method of least squares, to construct the approximation relationship $C_D = f(Re)$ for a wide range of Re number values, which proved to be systematically below the standard resistance curve. Figure 2 shows the standard resistance curve for the isothermic flow of an inviscid incompressible gas (curve 1), the measurement data in the plasma [11, 12, 14], as well as the proposed function $C_D = 16.6\,Re^{-0.75} + 0.2$ (curve 2), approximating the experimental results of this paper and the data of [23] in the range Re = 0.4-220. This same figure also shows the theoretical

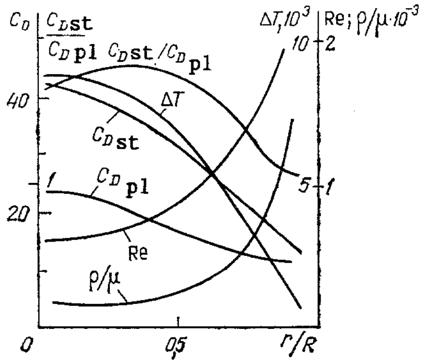

Fig. 4. Values of the local parameters of the plasma and the particles for one of the experimental regimes: I = 70 A, G = $1 \cdot 10^{-3}$ kg/sec, d = $212 \cdot 10^{-6}$ m. ΔT, K; ρ/μ, sec/m².

data [18] where the authors employed numerical methods to analyze the motion of aluminum particles with diameters ranging from 5 to $50 \cdot 10^{-6}$ m in the laminar flow of an argon plasma at atmospheric pressure, with consideration given to the markedly changing properties of the plasma in the boundary layer, and these also show the significant reduction in the values of C_D as a function of the flow and particle temperatures. We must necessarily take note of the absence of experimental data for C_D as regards the conditions of the plasma in the range Re = 10-50. Bearing in mind the nature of the monotonic relationship $C_D = f(\mathrm{Re})$, we can assume that within this range we will observe no significant deviations in the values of C_D from the expression approximating the experimental data for Reynolds numbers Re = 0.4-220.

The characteristic form of the function $C_D = f[\mathrm{Re}(r)]$, obtained in the region of small Re numbers, for various values of d, 2R, I, and G, enables us to analyze the influence exerted by the nonisothermicity of the streamlining on the value of C_D in the plasma (Fig. 3). As we can see, the set of experimental curves $C_D(r) = f[\mathrm{Re}(r)]$ exhibits a unique quantitative relationship. The values of C_D obtained at the axis of the flow, if these are combined into some curve 3, exhibit a maximum ~100% deviation from the standard curve 1. The values of C_D obtained in the colder peripheral regions of the arc are systematically located closer to standard curve 1 and may even be combined in curve 1. Approximation curve 2, obtained through the averaging of C_D in a series of measurements for each Re number, is situated in the corridor of C_D values between curves 1 and 3 and shows an average reduction in C_D from 30-40%. Curve 2 makes provision for the average level of streamlining nonisothermicity, characteristic of the plasma temperatures, since it has been obtained for various values of ΔT in the process of particle motion through the region of the flow exhibiting diverging temperature.

Figure 4 shows the "standard" values of the coefficient of aerodynamic drag $C_{D\,st}$, the experimental values of C_D in the plasma, and namely $C_{D\,pl}$, the ratio $C_{D\,st}/C_{D\,pl}$, the level of streamlining nonisothermicity ΔT, obtained from the calculation of the particle heating dynamics, the parameter ρ/μ for the argon along the arc radius r/R for one of the experimental regimes. In the region $r/R \le 0.4$-0.5 the experimental values have been obtained on the basis of quantitative data, in the region $r/R > 0.5$ the values of $C_{D\,pl}$ are shown approximately in view of the failure to take into consideration the temperature nonequilibrium and the gradients of the flow parameters in the equation of particle motion. As we can see, with an increase in ΔT the deviation of the coefficient $C_{D\,pl}$ from $C_{D\,st}$ increases. In the range ΔT 7000-9000 K the ratio $C_{D\,st}/C_{D\,pl}$ is at a maximum and equal to 1.6-1.8, i.e., the deviation in $C_{D\,pl}$ from $C_{D\,st}$ amounts to 30-40%. Since the number $\mathrm{Re} = \rho/\mu U d$ is calculated on the basis of the parameters of the unperturbed flow, its deviation can probably be explained by the relationship between the parameter ρ/μ for the argon and the temperature. With an increase in temperature, i.e., with a reduction in r/R, the parameter ρ/μ diminishes and shifts the experimental points into the region of smaller Re numbers, thus increasing the deviation of $C_{D\,pl}$ from $C_{D\,st}$. In the region $r/R \le 0.5$, where T > 8000 K and, consequently ΔT > 7000 K, the deviation in $C_{D\,pl}$ from $C_{D\,st}$ changes but slightly, which is explained by the weak relationship between the parameter ρ/μ and the temperature in this region.

Under realistic conditions the flow above the particle is agitated and the effect of the markedly changing properties of the plasma in the boundary layer is expressed in a systematic (~30-40%) reduction in C_D relative to the standard resistance curve. In the area of small Reynolds numbers Re < 10, where the forces of viscosity play a significant role in the resistance to particle motion, the reduction in the value of C_D can be explained by the reduction in the viscosity of the gas as a function of the temperature in the boundary layer, where the temperature of the free flow and of the particle surface differ by an order of magnitude. The authors of [23] explain the systematic reduction in C_D in the region Re = 50-220, where the resistance is basically determined by the distribution of pressure over the surface of the sphere, by the reduction in the viscosity of the gas in the boundary layer, which reduces the probability for the appearance of separated vortices that are characteristic of this range of Re numbers under conditions of isothermal streamlining, while the streamlining nonisothermicity is taken into consideration through the effective viscosity μ_f in calculating the small Re number. The authors of [18] proposed to take into consideration the inconstancy of the gas properties in the boundary layer by means of the following expression:

$$C_D = C_{Df}(\rho_\infty \mu_\infty / \rho_S \cdot \mu_S)^{0,45}, \tag{3}$$

where C_{Df} is the coefficient determined for $T_f = (T_S + T_\infty)/2$. The average reduction in the value of C_D on the basis of this formula at a nonisothermicity level of ΔT = 7500 K in the region of small Re numbers amounts to 30-40%, and the results are in good agreement with the approximation curve in Fig. 2. However, calculation of C_D on the basis of formula (3) requires, just as in the calculation of C_D in accordance with [23], knowledge of the particle wall temperature T_S for each specific case, which is not always possible and makes the calculation difficult.

Thus the correct exclusion in the conditions of the experiments of such factors as the rarefaction, compressibility, and turbulence of the flow, combustion, vaporization, roughness, and nonsphericity of the particles, enabled us to estimate in explicit form the influence of streamlining nonisothermicity on the sphere's coefficient of resistance in the plasma. It was demonstrated that the nonisothermicity of the streamlining leads to a systematic (30-40%) reduction in the coefficient of aerodynamic drag in the case of Reynolds numbers determined from the parameters of the unperturbed flow. This influence is most significant at a nonisothermicity level of 7000-9000 K. The proposed approximation relationship $C_D = 16.6\,\mathrm{Re}^{-0.75} + 0.2$, averaged over the nonisothermicity level ΔT, characteristic of the processes involved in the plasma treatment of the particles, is rather simple and can be used to calculate the dynamics of particle motion in plasma streams.

NOTATION

C_D, coefficient of aerodynamic drag for the sphere; Kn, Re, M, Knudson number, Reynolds number, and Mach number; γ, adiabatic exponent; F, force; m, a, d, V, mass, acceleration, particle diameter, and the axial velocity of the particle; T, U, ρ, μ, temperature, axial velocity, density, and plasma viscosity; Z, W, deflection and horizontal velocity of the particle; 2R, r, diameter and instantaneous radius of plasma flow; I, G, current and flow rate of plasma-forming arc gas; R_{cav}, radius of intersectional cavity; ∞, S, values of the parameters in the unperturbed plasma stream and at the wall of the sphere; f, effective values; $dp/\partial z$, gradient of static pressure; E, electric field strength.

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THE GENERATION OF SOUND IN THE FLOW OF AN EXCITED GAS

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UDC 534.14:533.6.011

We examine the development of sonic perturbations in the bounded subsonic flow of a gas excited by oscillations.

1. In a number of practical problems it is necessary to have adequate uniformity in the parameters of the active gas flow. Thus, for example, in the utilization of thermodynamically nonequilibrium gas media in lasers the nonuniformity of the flux density may, to a great extent, determine the quality of the light bundle (brightness and angular dispersion). In the case of large Reynolds numbers, the flux is made turbulent, which leads to chaotic nonuniformities in the index of refraction for the medium. The effect of flux turbulization on the gradient dispersion has been investigated in detail in [1].

In the presence of V–T relaxation, the medium exhibits a second viscosity [2], which may exceed the magnitude of the first, and in the case of considerable nonequilibrium it becomes negative. The dissipation of the sound under these conditions in the case of stationary nonequilibrium has been studied in [3, 4]. The present paper is devoted to a study of the unique features involved in the development of sound perturbations in the flow of a gas excited by oscillations. The nonuniformity of the parameters of the medium in the direction of the flow leads to refraction of the wave and to the departure of the perturbations from the region of intensification. It is demonstrated that considerable growth in sound waves is possible only when turning points are present, and under certain specific conditions the flow is absolutely unstable with respect to the generation of the sound. Corresponding increments have been determined.

2. The flow of a gas excited by oscillation will be described by the equations of gasdynamics, by the equation of state, and by the equation for oscillation energy:

$$\frac{\partial\rho}{\partial t}+\operatorname{div}\rho\mathbf{v}=0,\quad \rho\frac{\partial\mathbf{v}}{\partial t}+\rho(\mathbf{v}\nabla)\mathbf{v}=-\nabla P,$$

$$\frac{\partial S}{\partial t}+(\mathbf{v}\nabla)S=c_V\frac{T_0-T}{\tau T}+\frac{q}{T},\quad \frac{\partial\varepsilon_{os}}{\partial t}+(\mathbf{v}\nabla)\varepsilon_{os}=\frac{\varepsilon_{os0}-\varepsilon_{os}}{\tau}+n,$$

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 4, pp. 562-566, October, 1989. Original article submitted April 20, 1988.

