CHARACTERISTICS OF THE WORKING STREAM OF HYPERSONIC AERODYNAMIC TUBES IN THE PRESENCE OF SOLID PARTICLE IMPURITIES

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We considered the characteristics of the working stream in the track of a hypersonic aerodynamic tube (starting from the precombustion chamber and finishing with the shock layer ahead of a blunt model) in the presence of solid particle impurities.

It is well-known that almost the entire aerodynamic tube is affected by a large or small dust content in the working stream. In "cold" aerodynamic tubes, the level of dustiness is usually small and is assessed at hundredths or even thousandths parts of a percent of the weight of gas. In hypersonic aerodynamic tubes, however, the dust content reaches several percent and even tens of percent of the weight of the gas [1, 2]. As the dust content can have a considerable effect on the results of aerodynamic tests [1, 2], it will be of interest to explain the characteristics of a hypersonic stream when contaminated with solid particles.

Parameters and Prerequisites. The analysis to be undertaken is applicable to the following flow parameters, which are average for the majority of hypersonic tubes and facilities: $p_0 = 2000 \cdot 10^5$ N/m^2; $T_{go} = 1750$°K; working gas, nitrogen, $M_g = 10$ and 15; $d_d = 5$, 50 and 500 μ; $\rho_d = 3000$ and 8000 kg/m^3, $C_d = 0.8$ kJ/kg · °K. We consider an arbitrary layout of a tube consisting of a precombustion chamber and nozzle, at the outlet of which is located the model (blunt).

The analysis is carried out with the following premises: 1) the gas flow is adiabatic, uniform, steady-state, without the removal or supply of mass; 2) the working gas is calorific and thermally ideal, $\varkappa = 1.4$; $c_p = 1.1$ kJ/kg · °K, Pr = 0.71 and there is no condensation; 3) the coefficients of transfer and enthalpy of the gas are determined only by the temperature of the gas; 4) the particles are spherical and no change occurs of the properties or dimensions of the particles; 5) the volume of the particles is much less than the volume of the gas, so that their effect on the isentropy index and the specific heat of the gas is negligibly small; 6) the thermal conductivity of the particles is large and the temperature distribution inside the particles is uniform; 7) there is no interaction of the particles with one another and with the walls; 8) thermal exchange between particles and gas takes place only by convection and conduction; radiative heat exchange can be neglected; 9) only aerodynamic forces from the direction of the gas act on the particles; and 10) the gas parameters in the nozzle are determined relative to the surface area.

Analysis of the State of Particles Burnt in the Precombustion Chamber. The state of the gas in the precombustion chamber, in addition to the drag parameters mentioned, can be characterized by the existence of an average velocity (in the direction toward the nozzle) and pulsating components of the velocity.

The average velocity of motion of the gas, originating in consequence of the flow of the gas through the nozzle, is described approximately by the equation

$$w_{go} = \frac{\dot{G}}{g \cdot \rho_{go} \cdot f_0} \tag{1}$$

and is usually equal to 0.1 to 10 m/sec.

The pulsating velocity components may originate, for example, when the precombustion chamber is fitted in devices of the piston type [3] or as a result of the electric discharge in pulsed engines [1], etc.

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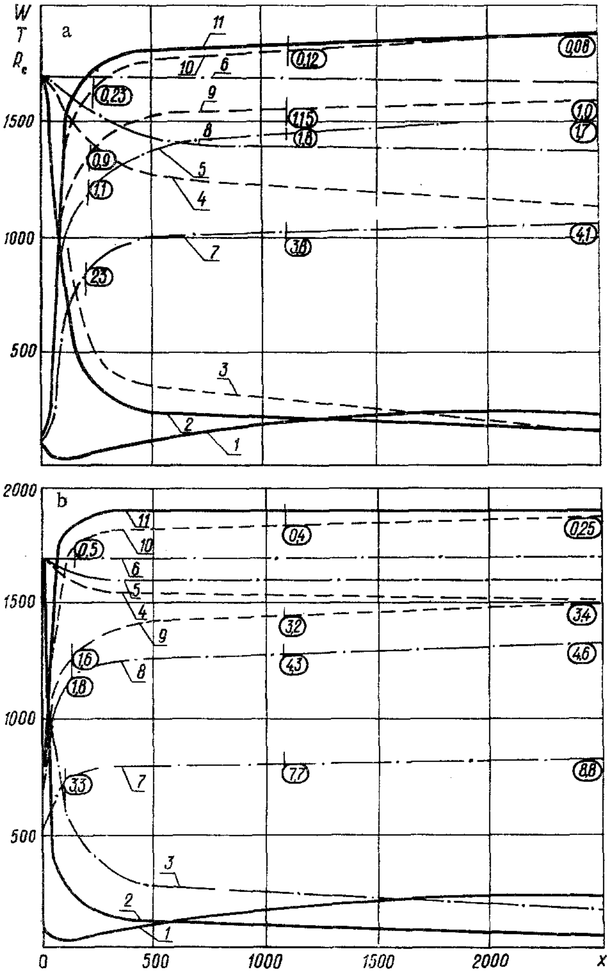

Fig. 1. Change of velocity (m/sec) and temperature (°K) of gas and particles, and cross-sectional radius of nozzle R_c (mm) along the length of the nozzle (mm), $M_g = 10$ (a) and $M_g = 15$ (b): 1) radius; 2) gas temperature; 3-6) temperature of particles respectively $\rho_p = 2000\ \mathrm{kg/m^3}$, $d_p = 5\ \mu$; 2000 and 50; 8000 and 50; 8000 and 500; 7-10) velocity of particles respectively $\rho_p = 8000\ \mathrm{kg/m^3}$, $d_p = 500\ \mu$; 8000 and 50; 2000 and 50; 2000 and 5; 11) gas velocity. Figures in circles give the local M_p number of streamline flow of particles with the gas in the corresponding section of the nozzle.

Due to the complexity of the processes causing the pulsations, it is not possible to estimate these components, although they may exert a decisive influence on the thermal exchange of particles.

The average velocity of motion of the particles burnt at the nozzle inlet is equal to or less than the average velocity of the gas, but it can be assumed that the velocity of the particles at the inlet is equal to zero, as the effect of this assumption on the result of future analysis is found to be negligibly small.

For the strict determination of the intensity of the heat exchange between the gas and the particles, it is essential to know the flow velocity of the particles which, for the reasons stated above, can be established only with difficulty. But even if it be assumed that the particle velocity in the precombustion chamber is $w_{do} \rightarrow w_{go}$, then, according to the estimate in this case, the temperature of the particles reaches the temperature of the gas after 10^{-3} to 10^{-2} sec, i.e., throughout almost the entire experiment dust particles arrive at the nozzle, having been heated up to the drag temperature. This indicates, at these drag temperatures, that the state of the dust in the precombustion chamber can vary in comparison with the initial state: dust of organic origin will be decomposed; ceramic dust may be cracked; and metallic dust is melted.

Flow of a Dust-Laden Gas in a Nozzle. It follows from Newton's Second Law and from the expression for the drag force that

$$w_p \frac{dw_p}{dx} = \frac{3}{4} \cdot \frac{c_x \rho_g (w_g - w_p)^2}{d_p \rho_p}. \tag{2}$$

In the general case, Eq. (2) can be integrated only numerically as w_g, ρ_p and c_x are varying along the nozzle in such a way that it is almost impossible to describe them by any function of x.

In this present paper, the values of c_x used, which take account of the effect of rarefaction, compression, and inertial and viscous forces [4-6] and are evidently quite reliable in that they are confirmed by the results of measurement of the velocity lag of the particles in the nozzle [7], were as follows:

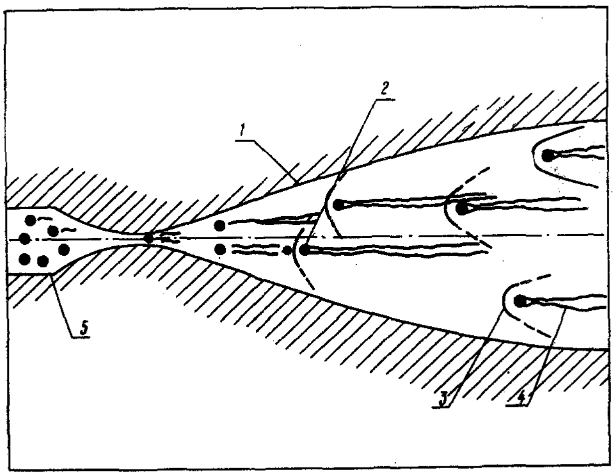

Fig. 2. Flow diagram of gas–particles in a hypersonic nozzle: 1) outline of nozzle; 2) particles; 3) shock wave; 4) track of particle; 5) precombustion chamber.

$$c_x = \bar{c}_x \frac{\left[1 + \exp\left(-\frac{0,427}{M_p^{4.63}} - \frac{3}{Re_p^{0,88}}\right)\right]}{(1 + 0.191\, M_p c_x)},$$

where

$$\bar{c}_x = \frac{24}{Re_p}(1 + 0.12\, Re_p^{0,873}); \quad 0.1 < Rep < 5.8;$$

$$\bar{c}_x = \frac{24}{Re_p}(1 + 0.175\, Re_p^{0,66}), \quad 5.8 < Re_p < 500.$$

When calculating the acceleration of particles with diameter 500 μ and density 8000 kg/m^3, for which in the greater part of the nozzle $Re_p > 10^3$ and $M_p > 1$, a value of $c_x = 0.4$ and later $c_x = 1$ was assumed in the accelerating section.*

The heating up of the particles by heat transferred from the gas through the surface of the particle is described by the equation

$$\frac{1}{6}\, d_p^2 \rho_p c_d \, \frac{dT_p}{dx} w_p = Nu_p \lambda_g (T_g - T_p), \tag{3}$$

where the quantity Nu_p over the range $0.1 < Re_p < 125$ and $0.1 < M_p < 0.7$ is determined by the relation [8]

$$Nu_p = \frac{(2 + 0.459\, Re_p^{0,55} Pr^{0,33})}{\left[1 + 3.42 \frac{M_p}{Re_p Pr}(2 + 0.46\, Re_p^{0,55} Pr^{0,33})\right]}.$$

In the case of supersonic streamline flows of particles with high M_p and Re_p numbers, the intensity of the particle heat exchange has been determined in accordance with [9]; the nonuniformity of the heat exchange through the surface of a hemisphere was taken into account by the introduction of a correction factor 0.5, corresponding to laminar conditions of streamline flow of the particles (bottom heat exchange was neglected).

In considering the results of the calculations (Fig. 1) attention is drawn first of all to the considerable lag of the particles behind the gas, as a result of which the flow of the latter in the greater part of the nozzle proves to be supersonic with an M_p-number of as much as 5-8. It is also interesting that the dynamic drag of particles with a diameter of a few tens of microns or more, originating in the accelerating section of the nozzle in consequence of the low density of the gas, undergoes almost no further reduction.

A similar pattern is observed also, and for the same reason, in relation to the cooling off of coarse particles with a size greater than a few tens of microns. The results obtained, which refute the widespread assumption of almost total balancing of the temperature and velocities of the gas and particles in long nozzles [1, 2], allow certain important characteristics of such flows to be explained.

Let us consider a simplified flow pattern of a gas–particle mixture in a hypersonic nozzle (Fig. 2). In the subsonic and sonic sections, and at the start of the supersonic sections of the nozzle, $M_p < 1$ and the intensity of the perturbations from the particles is small. Later in the supersonic section, the streamline velocity of coarse particles increases and becomes supersonic; outgoing shock waves are created ahead of the particles and change into Mach lines and gradually, at a certain distance from the particles they degenerate; a supersonic wake extends behind the particles.

Beyond each microshock wave the pressure is higher than the pressure in the surrounding flow: the maximum pressure is ahead of the particles themselves; the pressure falls with distance from the particles and becomes equal to the pressure of the unperturbed flow. In view of the variability of the quantity M_p and the velocity of motion of the particles relative to the gas, the boundaries of the perturbed region are blurred and therefore it is quite difficult to estimate the average intensity of the pressure pulsations in the flow which originate in consequence of the appearance of the microshock waves.

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*By the accelerating section is meant that section of the nozzle in which the gas is accelerated to $Mg \approx 5$; in this case the velocity of the gas almost attains the limiting velocity. The length of the accelerating section of profiled nozzles usually amounts to 3-10% of the nozzle length.

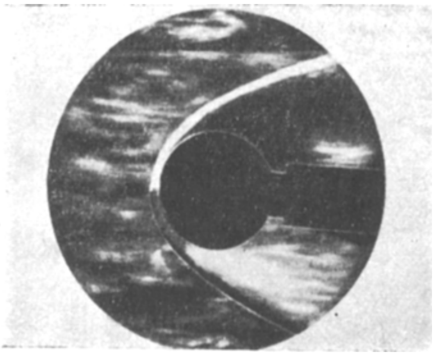

Fig. 3. Shadowgraph of hypersonic flow; a model is in the flow (sphere on a base support).

For the conditions considered the ratio of the wake length to the particle diameter may reach 10^3-10^5; in this case, the diameter of the wake, according to [10], exceeds the diameter of the particles by a factor of 50-100 and the flow in the wake is turbulent.

Estimates show that even when the dust content of the stream is insignificant (0.01 to 0.1% of the weight of gas) the latter is found to be completely filled with turbulent tracks from the particles and even multiple overlapping of the tracks can occur. In consequence of such a process, there should be turbulence of the flow which will have a nonuniformity of size of order of the thickness of the wake. Microshock waves should add to the turbulence of the flow.

In the investigations of the dustiness of a hypersonic flow, shadow photography of the stream by exposure from a spark source actually shows the presence of small-scale turbulence (Fig. 3) with an average size of the nonuniformity close to the calculated diameter of the wake (the ratio of the first quantity to the second is 0.3 to 0.5), which serves quite well as confirmation of the hypothesis put forward.

Flow in a Shock Layer. In a shock wave, solid particles are not retarded together with the gas because of their inertia, and therefore in a shock layer their velocity is greater than the velocity of the gas and the flow of the particles may be supersonic with a limiting value of the M-number close to 2.5 for $\varkappa = 1.4$.

In the case of supersonic flow of the particles, microshock waves are ahead and the wake stretches behind the particles; the "whiskers" of the microshocks and of the wake are always directed toward the nozzle. The existence of the microshocks was first noted and recognized by an indirect method during spectroscopic investigations of the parameters of a gas behind an outgoing shock wave.

The appearance of tracks and microshocks leads to turbulence of the shock layer, relative to which it may be assumed that in view of the small size of the shock layer and the lower M_p-numbers behind the shock wave in comparison with M_p in the nozzle, the dust turbulence of the shock layer is considerably less intense than in the nozzle.

Retardation and heating up of the particles in a shock layer are described by Eqs. (2) and (3). In the general case for determining c_x and Nu_p, the relations given above can be used. In the case being considered, according to calculations retardation and heating up of the particles in the shock layer of typical models does not exceed 100-200 m/sec and 100-200°K respectively, which can be neglected.

In consequence of the outflow of gas behind the shock wave, drift of the particles takes place toward the edge of the model. The calculations carried out on the assumption that the longitudinal velocity of the particles behind the shock wave is unchanged and is equal to the velocity of the oncoming particles and that the radial component of the gas velocity on the path of the particles from the shock wave up to collision with the body is constant show that the radial displacement of a particle in comparison with the distance of separation of the shock wave under the conditions being considered is less than 1% and it also can be neglected.

The results given, although they are to a definite degree of a qualitative nature, explain certain new features of dust-laden hypersonic flows and on this basis they permit the effect of dustiness on the results of an aerodynamic experiment to be described more accurately.

NOTATION

a_g is the velocity of sound in the gas;
c_d is the specific heat of dust particles;
c_p is the specific heat of gas with p = const;
c_x is the coefficient of drag of particles;
g is the acceleration due to gravity;

G	is the specific feed of gas through nozzle;
d_d	is the diameter of dust particle;
f_0	is the area of transverse cross section of precombustion chamber;
$M_d = \|w_g - w_d\| a_g$;	
$M_g = w_g / a_g$;	
$Nu_d = \alpha_d d_d / \lambda_g$;	
p_0	is the pressure in precombustion chamber;
$Re_d = \rho(w_g - w_d) d_d / \mu_g$;	
T_g and T_{go}	are the static and drag temperatures of gas;
T_d	is the temperature of particles;
w_d and w_g	are the velocity of particles and gas;
x	is the longitudinal coordinate;
α_d	is the coefficient of heat exchange of dust particles;
$\varkappa$	is the isentropy index;
λ_g	is the coefficient of thermal conductivity of gas;
μ_g	is the coefficient of dynamic viscosity of gas;
ρ_d and ρ_g	are the densities of dust particles and gas.

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