THE EFFECT OF DUST IN THE WORKING STREAM OF HYPERSONIC WIND TUNNELS ON THE RESULTS OF HEAT-TRANSFER MEASUREMENTS

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The nature of the distorting effect of dust in the working stream of hypersonic wind tunnels on the results of heat-transfer measurements is discussed. Experimental data obtained at M = 10-15 and dust levels of up to 0.5 wt. % are presented.

In a number of studies dealing with the effect of dust in the working stream on the results of heat-transfer measurements (see, for example, [1]) it is pointed out that the dust may cause an intensification of the heat exchange which increases as the dust level increases. The nature of this phenomenon is explained according to the following simplified scheme: it is assumed that the velocity and temperature of the particles before collision are equal to the velocity and temperature of the incident stream, respectively; and that the intensification of heat exchange occurs only because of the transfer to the model of the entire kinetic energy of the particles in the form of additional heat flux.

However, the available data permit a more precise picture of the effect of dust to be constructed: the following determinative factors can be distinguished, or refined.

Conversion of the Energy of the Particles into Additional Heat Flux. The particles approaching the model have a certain amount of kinetic and thermal energy. In order to determine how much of this energy is transferred to the model, we should consider that a typical wind-tunnel velocities (1.0-3.0 km /sec), collisions between particles measuring 5-500 μ last a very short time (0.1-1.0 μsec [2]), and under these conditions the particles do not stick to the surface of the model (according to the data of [3] and our own observations). Therefore, the heat energy of a colliding particle, according to estimates, cannot be transferred to the model in such a short time; most probably, the kinetic energy converted into heat energy as a result of the mechanical distortions and deformations of the particle and the model is distributed equally between them after such a conversion, and the energy remaining in the particle also fails to be transferred to the model. In this case we find that

$$q = 0.5\,\frac{w_{g\infty}}{A}\left(\frac{1}{2}\;w^2_{du\infty}\,\rho_{g\infty}\,z\right). \tag{1}$$

Dust-Induced Turbulence of the Incident Stream and the Impact Layer. Because of the substantial lag in the particles, the stream becomes turbulent in the hypersonic nozzle and the impact layer; this can lead to a substantial intensification of heat exchange at blunt bodies [4]. It should be noted that the turbulence (and the accompanying intensification of heat transfer must increase with the size, density, and number of particles with the passage of the shock wave in front of the model, and with decreases in the density of the flow and the length of the accelerating segment of the nozzle [5].

Distortion of the Character of the Flow Past the Model. As a result of interaction with particle tracks, there may be deformations of the shock wave in the form of "liquid" cones or protuberances [6]. In the process of the appearance and disappearance of these distortions there is a simultaneous restructuring of the boundary layer, which must lead to an intensification of the heat exchange. However, to estimate the effect of this factor is practically impossible, because the processes taking place are so complex.

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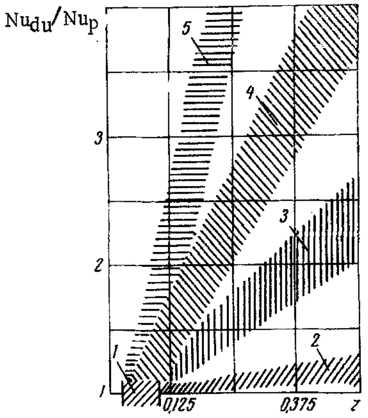

Fig. 1

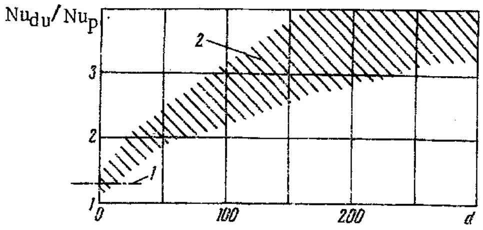

Fig. 2

Fig. 1. Intensification of heat exchange, Nu_{du}/Nu_p, as a function of z, the percentage of dust by weight: 1) results obtained at "normal" dust levels; 2) values calculated from Eq. (1); 3) d = 5–7 μ; 4) d = 40–80 μ; 5) d = 150–300 μ.

Fig. 2. The effect of particle diameter d, μ, on the intensification of heat exchange, Nu_{du}/Nu_p, for z = 0.2%: 1) calculated from Eq. (1); 2) experimental values.

Dust-Induced Roughness. When dust particles collide with the surface of the model, depressions (craters) appear on the surface; the size of these depressions depends on the velocity of the collision, the mass of the particles, the density of the target material, and a number of other factors [2, 3]. Dust-induced roughness may lead to an intensification of the heat exchange or may accelerate the transformation of the boundary layer; this phenomenon may also damage heat-flux sensors with external sensing elements.

The above factors should affect the heat exchange most strongly at the frontal surface of a blunt body.

We may also point out a number of other factors, such as turbulence in the boundary layer [7], change in the thermophysical properties of a dusty gas in comparison with a pure gas [8], etc. However, at typical wind-tunnel dust levels (of the order of 1% by weight) the influence of these factors is negligible.

The effects of dust were investigated in a wind tunnel in short-term operation at M = 10–15 and Re $\approx 10^7\ m^{-1}$; the characteristic "normal" dust level of the tunel was approximately 0.05%, with an average dust-particle diameter $\dot{d} \approx 50\ \mu$. The dust level was changed by filling the entrance section with a quantity of dust of the required composition. As the investigations showed, because of a number of characteristics of the wind tunnel the amount of dust entering the stream was proportional to the rate of flow of gas through the nozzle.

The model investigated had the shape of a cylinder with a flat front face. The heat flux was measured at the forward critical point of the front face by means of a thick-walled heat-flux sensor [9]. The measurement results obtained in a stream with an artificially increased dust level were compared with results obtained at a "normal" dust level; in all cases the latter were in good agreement with the calculated values, i.e., the influence of "normal" dust levels was negligible, and therefore the stream could be regarded as pure. The results of the investigations are shown in Figs. 1 and 2.

From Fig. 1 we can draw the following conclusions.

Firstly, the actual intensification exceeds the intensification calculated from Eq. (1). This confirms the assumption that all the factors enumerated above exert a complex effect.

Secondly, the high degree of intensification of the heat exchange is noteworthy. According to Eq. (1) and the given conditions, the intensification cannot exceed 50%, and the intensification due to stream turbulence cannot exceed 50–70% [4]. In these experiments the effect of the roughness was within the limits of measurement error. Thus, these influences can increase the heat transfer by no more than a factor of 2–2.2. In fact, however, the intensification was much greater than this, which means that the distortions of the shock wave played a decisive role.

Thirdly, the degree of intensification becomes greater as the particle size increases. We can understand the nature of this phenomenon if we consider that as the particle size increases, the degree of distortion of the shock wave and likewise the turbulence of the stream increase with it [5, 6], i.e., the effect of fundamental factors.

Fourthly, the intensification is found to vary almost linearly with z, within the limits of experimental error. This agrees with the observed linear dependence on z of the number of shock-wave distortions, with Eq. (1) and with the assumed linear dependence on z of the dust-induced turbulence of the stream [5].

By applying interpolation to the data of Fig. 1, we obtain a graph of the degree of intensification of heat-exchange as a function of particle size (see Fig. 2). From Fig. 2 we can see that, as $d \to 0$, the intensification value tends to a limit which coincides with the value found from Eq. (1). This result both confirms the reliability of Eq. (1) and indicates that, as $d \to 0$, the influence of all the factors other than those expressed in Eq. (1) is negligible. This is the case because, under these conditions, the dynamic lag of the particles tends to zero, at the same time, the turbulence of the stream and the distortions of the shock wave both cease.

As the flow of a dusty gas, and hence the effect produced by the dust level, will be subject to the complex influence of a large number of parameters (such as the geometry of the nozzle, the pressure, the temperature and composition of the gas, the size and density of the particles, the shape and size of the model, etc.), we should regard the results obtained as essentially qualitative. However, our findings confirm that dust can affect the measurement results in a great many ways and therefore they show that it is necessary to pay more careful attention to such effects whenever dust may be present.

NOTATION

A	is the thermal equivalent of work;
d	is the dimension (diameter) of the dust particles;
q	is the additional heat flux due to the transfer of the kinetic energy of the particles;
M	is the Mach number;
Nu_{du}, Nu_p	are Nusselt numbers, respectively, for the cases of dusty and pure flow past the model;
$w_{du\infty}$	is the velocity of dust particles in the incident stream;
$w_{g\infty}$	is the velocity of the incident stream;
z	is the weight content of dust in the flow;
$\rho_{g\infty}$	is the density of gas in the incident stream.

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