THE EFFECT OF A CHANGE IN THE BOUNDARY LAYER OF A SPHERICAL PARTICLE ON ITS AERODYNAMIC DRAG UNDER NONISOTHERMAL CONDITIONS

I. P. Basina and I. A. Maksimov

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We use a shadowgram of the streamlining of a sperical particle giving off heat to explain the factors responsible for the change in the magnitude of the particle's aerodynamic drag.

In examining the problem of the aerodynamic drag of particles releasing heat in a gas flow, we have frequently heard expressed the opinion that the changes taking place within the boundary layer of such a particle exerts considerable influence, as opposed to the case of isothermal streamlining [1-3]. However, we know of no attempts to investigate these changes through direct experimentation and this, in our opinion, would have made it possible to demonstrate the physical nature of the phenomenon. In this connection, we felt it advisable to produce the streamlining pattern for a heated spherical particle in a flow of cold air, making the boundary layer visible, and recording the changes in the latter as a function of the temperature difference between the particles and the flow when such parameters as particle dimensions and flow velocity are varied.

We employed the following method for this purpose. A heated spherical particle rigidly attached to a thin quartz rod is placed into the flow axis of a cold air stream in the immediate vicinity of a nozzle outlet, i.e., in the core of the flow (this makes it possible to determine the streamlining velocity for the particle with an accuracy sufficient for the purposes of this problem). The particle is illuminated with a spot light source from a great distance. The shadow produced by the particle is projected onto a film and photographed without any additional optics. The light rays from the spot source, on passing through the air heated near the particle, are deflected toward the boundary of the thermal layer and are made visible on a screen as a lighter strip. It is important that the position of this strip is independent both of the distance between the particles and from the light source, nor should the distance between the particle and the screen have any effect. In connection with the noted feature, we assume that this strip can be regarded as the boundary between the hot and cold air (the air not heated by the particle), while that portion of the air situated between the strip and the particle can be treated as the thermal boundary layer.

The particle is heated by means of a special heater made of a platinum wire capable of producing temperatures up to 1400°C. The heater has an inside diameter of 3 mm and it is 4 mm long; it is covered on the outside with heat insulation and it is placed over the particle to heat it, thus not affecting the thermal state of the nozzle walls, nor distorting the main flow. The surface temperature of the particle is defined as the temperature produced by the heater at the instant that the heating operation is stopped. It is natural that the surface temperature differs slightly from the above definition in the experiment (at the instant of photography). However, since the described experiments sought to achieve only a qualitative pattern of the changes taking place and did not seek to achieve an exact quantitative evaluation of these, the noted measurement errors in this case played no significant role.

For the purposes of the study, the spherical particles were made of platinum (0.68 and 1.36 mm in diameter) and of aluminum oxide (2.45 mm in diameter).

The experiment was carried out in the following sequence. The particle was positioned at the axis of the flow and the required flow rate was established; this flow rate corresponded to the theoretical air

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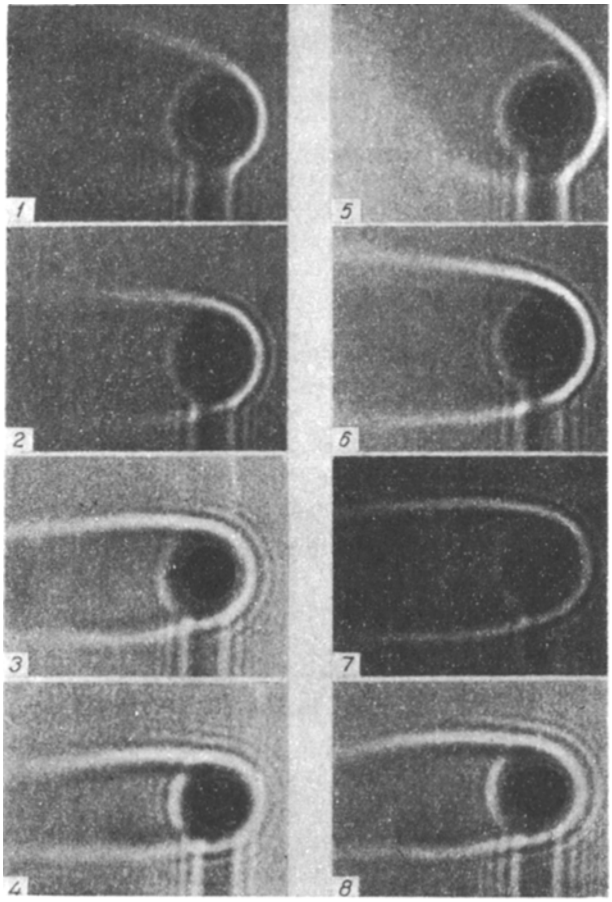

Fig. 1

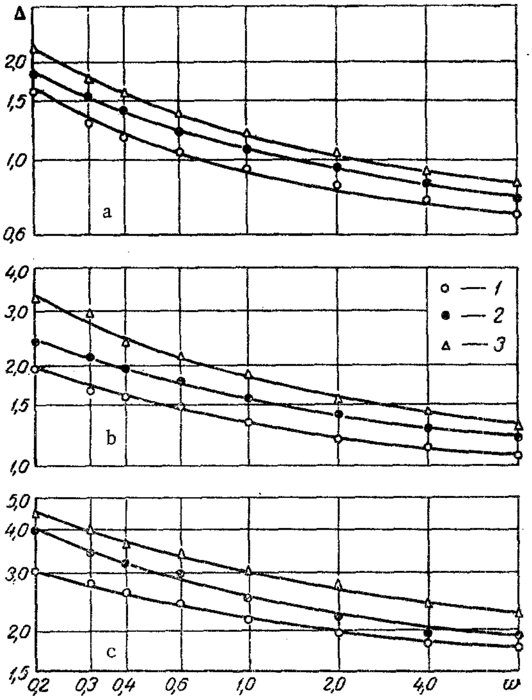

Fig. 2

Fig. 1. A heated particle with a diameter of d = 2.45 mm streamlined by cold air (t_a = 20°C): 1) w = 0.2 m/sec, t = 500°C; 2) 0.6 and 500; 3) 2 and 500; 4) 8 and 500; 5) 0.2 and 1400; 6) 0.6 and 1400; 7) 2 and 1400; 8) 8 and 1400.

Fig. 2. Relative thickness of the thermal boundary layer as a function of the relative velocity at an air temperature t_a = 20°C and as a function of the particle temperature: 1) 500°C; 2) 900; 3) 1400; a) d = 2.45 mm; b) 1.36; c) 0.68.

velocity. The lighting was then turned on. The heater was lowered over the particle and it was removed as soon as the particle reached the required temperature. The particle was photographed on film by the above-described shadow method at the instant that the heater was removed.

With this procedure we obtained photographs showing the streamlining of particles with dimensions of 0.68, 1.36, and 2.45 mm as these were heated to temperatures of 500, 900, and 1400°C, subsequently being subjected to a flow of cold air (about 20°C) whose velocities varied from 0.2 to 8.0 m/sec. The investigated range of Reynolds numbers thus encompassed values from 8 to 1300. As an example, Fig. 1 shows such photographs for a particle 2.45 mm in size, heated to 500 and 1400°C.

The photographs clearly show the change in the nature of the flow, as well as the shape and dimensions of the boundary layer with a change in the indicated parameters. The most significant and most convenient for the characteristic of the phenomena of interest to us seems, in our opinion, to be the changes in the thickness of the boundary layer. An examination of these photographs easily shows that this quantity increases with a rise in temperature, with a drop in the relative velocity, and with a reduction in particle size.

For greater clarity, the noted changes are shown in Fig. 2 in the form of the relative thickness Δ of the thermal boundary layer (for the indicated quantity Δ we have taken the ratio of the thickness of the layer at the midsection of the particle to its radius) as a function of the freestream velocity w.

The results clearly show the existence of a direct relationship between the thickness of the thermal boundary layer and the excess of particle surface temperature over the temperature of the stream flowing past the particle: the thickness of the boundary layer increases with a rise in temperature and this occurs the more intensively, the smaller the particle and the lower the relative velocity at which the particle is streamlined by the flow.

If we proceed from the generally accepted concept to the effect that the factor responsible for the appearance of aerodynamic drag forces in the motion of a body through a medium is primarily the force of viscous friction in the boundary layer, it is obvious that an increase in the thickness of this layer must necessarily lead to an increase in the drag forces. We noted such an increase in special experiments, not covered here, as well as in the work of numerous other investigators, analyzed in detail in [4].

We can describe the mechanism for the increase in the drag forces in the following manner. As a result of a change in the temperature of the gas medium (air) around the particle as a result of being heated by the latter, the layers adjacent to the particle surface acquire elevated viscosity which diminishes with increasing distance from the particle. Therefore, as the particle is set in motion (relative) it carries with it a large quantity of gas (as opposed to isothermal motion), i. e., there is an increase in the thickness of its hydrodynamic boundary layer, which results in an additional drag force.*

Here, the change in the density of the medium as a result of particle heating may affect the magnitude of the resulting additional force: when the gas is heated near the surface of the particle, it expands, producing the phenomenon of an impulse directed against the motion of the particle. A similar impulse, appearing with the cooling of the gas in the wake behind the particle and moving in the direction of particle motion, will obviously be smaller than the former. The resultant will therefore be directed against the motion of the particle, i. e., it will also lead to an increase in particle drag.

In addition to these forces, leading to an increase in the aerodynamic drag of a heated particle as a result of an increase in the thickness of the particle's boundary layer, we should also remember that the change in the very nature of particle streamlining, as noted in our experiments (see Fig. 1), must necessarily affect the magnitude of the resulting additional force: an increase in the width of the wake behind the particle (along the boundary of the thermal layer) with a rise in particle temperature.

The resulting data thus provide an explanation for the physical essence of the phenomena occurring in the nonisothermal streamlining of a spherical particle, leading to a change in the magnitude of the force of aerodynamic drag (in comparison with the isothermal problem): the factor responsible for these phenomena can be found in the changes in the thermal boundary layer of the particle and in the nature of the flow past the particle.

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*It is characteristic that in studying the motion of spherical particles releasing heat in a liquid (water) we noted a drop in the resistance (drag), which the authors of this research project [5] also explained by a reduction in the viscosity of the liquid layer surrounding the particle.