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Abstract

Full Text

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AERODYNAMICS

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FLOW PAST A SPHERE BY A RAREFIED GAS STREAM

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When bodies are flowed around by a stream of rarefied gas, the character of the flow and the mechanism of interaction between the stream and the body differ from the conditions of flow in a continuum. This is manifested in a thickening of the shock wave and of the boundary layer, which affects the aerodynamic characteristics of the flow and heat transfer.

Of particular interest is the region of transition from continuum flow to free-molecular flow. In this region the continuum theory does not fully describe the phenomena occurring in gas flows, and, as the rarefaction factor increases, it gives way to the kinetic theory of gases.

A number of works, mainly theoretical in character ([1–3]), have been devoted to the study of flow parameters in the transition region; a feature of these works is the very substantial divergence in the results of the investigations and in their interpretation. From what has been said above follows the importance of experimental study of gas flows in the transition region.

The authors have carried out an investigation of the flow past a sphere of radius $R = 5$ mm by a supersonic stream of rarefied gas with Mach numbers of the incident stream $M_\infty = 3.85 \div 4.02$, and Reynolds numbers (computed from the flow parameters behind the jump and the radius of the sphere) $\mathrm{Re}_2 = 75 \div 230$. The method of multiple-beam interferometry ([4]) was used; it possesses high sensitivity owing to the multiple passage of the light beam through the gas flow under study. The interferograms were interpreted by a photometric method ([5]); in this procedure the local density values were determined with allowance for axial symmetry.

Fig. 1. Density field in front of the sphere at $\mathrm{Re}_2 = 75$

Fig. 2. Structure of the shock wave at $\mathrm{Re}_2 = 75$ (A) and $\mathrm{Re}_2 = 230$ (B). 1 —experimental curve; 2 —Mott-Smith curve; 3 —discontinuity according to Hugoniot

Figure 2: Fig. 2. Structure of the shock wave at $\mathrm{Re}_2 = 75$ (A) and $\mathrm{Re}_2 = 230$ (B). 1 —experimental curve; 2 —Mott-Smith curve; 3 —discontinuity according to Hugoniot

Figure 1 presents the experimentally obtained density field in front of the sphere at $M_\infty = 3.85$ and $\mathrm{Re}_2 = 75$. Along the ordinate axis is plotted the distance from the flow axis r, along the abscissa axis—the axial coordinate z; the origin of coordinates is combined with the center of the sphere. The curves are lines of equal densities ρ/ρ_∞, where ρ is the current value of the density, and ρ_∞ is the density value in the incident stream.

Figure 2 gives the density distribution across the thickness of the shock wave along the stagnation line in the region of the front critical point of the sphere at Re_2 equal to 75 and 230. For a comparative estimate of the shock-wave thickness, the Mott-Smith curves ([6]) are plotted on the graphs; these represent the profile of a normal shock wave calculated as a function of the Mach number and the mean free path of the particles of the incident stream. For a comparative estimate of the shock-wave stand-off distance and of the ratio ρ/ρ_∞, shown—

discontinuities according to Hugoniot ([7]). Similarly ([8,9]), the experimental curves and the Mott-Smith curves were superposed in such a way that the inflection point of the Mott-Smith curve coincided with the point of the experimental curve z^* having the same ordinate r. From an analysis of the graphs it is seen that, in the investigated range of Re_2 numbers, the shock wave is smeared. The calculations performed show that its thickness is $8 \div 10$ mean free paths of the particles of the incident stream. These values are somewhat larger than those given in ([1,2,8,9]).

Fig. 2. Structure of the shock wave at $\mathrm{Re}_2 = 75$ (A) and $\mathrm{Re}_2 = 230$ (B). 1 —experimental curve; 2 —Mott-Smith curve; 3 —discontinuity according to Hugoniot.

The difference is explained by the fact that, as the thickness of the shock wave, we take those values of z at which ρ differs from the density values in the incident stream and behind the jump by approximately 5%. At $\mathrm{Re}_2 = 230$ a rather extended region is observed within which the density in the shock layer practically does not change; the density value behind the jump, within the accuracy of the measurements ($\sim 10\%$), coincides with the continuum values calculated from the Hugoniot relations. At $\mathrm{Re}_2 = 75$ the thickness of the shock wave increases, the Hugoniot relation is satisfied within the experimental error, and there is no zone of constant density. In this case, apparently, there is no separate inviscid flow zone. The boundary layer and the shock wave begin to merge. Both regimes are characterized by a gradual change of density in the

Fig. 3. Dependence of the shock-wave standoff distance on the Reynolds number. 1 —experimental curve; 2 —theoretical curve

Figure 3: Fig. 3. Dependence of the shock-wave standoff distance on the Reynolds number. 1 —experimental curve; 2 —theoretical curve

shock wave, with the change being slower on the side of the incident stream; the part of the shock-wave profile facing the incident stream is flatter.

In ([8,9]), the distance from the body to the point z^* (Fig. 2) was taken as the magnitude of the stand-off distance of the shock layer. In our opinion, it is more correct to take as the beginning of the shock-wave stand-off that region of the flow where the ratio ρ/ρ_∞ begins to differ from unity (for example, by 5%). The shock-wave stand-off values Δ/R measured in this way for various Reynolds-number values are shown in Fig. 3 (curve 1). With increasing density, the thickness of the shock layer decreases and the shock wave approaches the model. For comparison, the theoretical curve 2 is presented, obtained by solving the Navier—Stokes equations in the region of the critical point. It was assumed that the shock wave is thin (the relations are valid

the Hugoniot condition at the shock), the region between the wave and the body is occupied by a viscous incompressible gas. Slip and the temperature jump at the body were not taken into account. The sphere was assumed to be thermally insulated, which most closely reflected the experimental condition.

A solution of the system of equations was obtained for a diatomic gas at $M_\infty = 5$ and $\mathrm{Re}_2 = 100;\ 200;\ 500;\ 800$ and 1000. As a result of the integration, the dependence of the thickness of the shock layer on the numbers Re_2 was obtained.

Fig. 3. Dependence of the shock-wave standoff distance on the Reynolds number. 1 —experimental curve; 2 —theoretical curve

From Fig. 3 it is seen that in the region of large numbers the discrepancy between the experimental curve and the theoretical one is the greatest. This corresponds to the case in which a continuum gas flow exists behind the shock wave. In the region of smaller Re_2 numbers the discrepancy decreases, which can be explained by the existence behind the shock wave of a fully viscous dissipative layer (Fig. 2A). However, in the range under study the shock wave is smeared out, which contradicts the adopted model of a "viscous shock layer." At the same time, the Hugoniot relation at the shock (within the experimental error) is satisfied before the gas flow reaches the body. This explains the fairly satisfactory agreement between the experimental and theoretical dependences in Fig. 3.

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Note: Figure translations are in progress. See original paper for figures.