PHYSICAL PROPERTIES OF THE FLOW IN THE SEPARATION REGION FOR THREE-DIMENSIONAL INTERACTION OF A BOUNDARY LAYER WITH A SHOCK WAVE

V. S. Avduevskii and K. I. Medvedev


In a supersonic stream we consider the three-dimensional flow in the plane of symmetry in the region of interaction of a boundary layer with a shock wave which arises ahead of an obstacle mounted on a plate. The principal characteristic of this flow is the penetration of a filament of the ideal fluid within the separation zone and the formation on the surface of the plate and obstacle of narrow segments with high pressures, high velocity gradients, and large heat transfer coefficients.

Pressure distribution measurements were made, shadow and schlieren photos were taken, and photographs of the flow pattern on the surface were made using dye coatings and low-melting models. The basic physical characteristics of the separation flow are established. The independence of the separation zone length of the boundary layer thickness is shown. Local supersonic flows are detected in the separation region, flow regimes are identified as a function of the angle of encounter of the separating flow with the obstacles, characteristic flow zones in the interaction region are identified.

NOTATION

\( s \) is the coordinate of separation point on the plate; 
\( l \) is the length of separation zone; 
\( H \) is the obstacle height; 
\( d \) is the obstacle transverse dimension; 
\( u \) is the freestream velocity; 
\( \beta \) is the velocity gradient on stagnation line of obstacle; 
\( b \) is the jet width; 
\( \Delta \) is the compression shock standoff from the body; 
\( \rho \) is the static pressure; 
\( p_s \) is the pressure at stagnation point on obstacle; 
\( \rho \) is the density; 
\( \mu \) is the viscosity coefficient; 
\( \delta \) is the boundary-layer thickness; 
\( \varphi \) is the compression shock angle; 
\( \theta \) is the effective angle of separation zone; 
\( \gamma \) is the setting angle of obstacle on plate; 
\( M \) is the Mach number; 
\( R \) is the Reynolds number; 
\( P \) is the Prandtl number. The subscript 1 applies to parameters at the outer edge of the boundary layer, the superscript 0 applies to relative quantities.

1. In a supersonic stream we study the flow ahead of an obstacle in the form of a cylinder or parallelepiped mounted on a flat surface. The shock wave 1 which occurs ahead of the obstacle causes separation of the boundary layer, which propagates upstream (Fig. 1). At the separation point \( s \) ahead of the three-dimensional separation zone there is formed, in turn, the weaker shock wave 2, in which the pressure drop is determined by the condition of interaction with the boundary layer. The outer stream of ideal fluid, deflected from the plate as a result of the formation of the separation zone, after passing through the system of shocks, impinges on the obstacle, forming a stagnation point with high pressure. Some quantity of the ideal gas, spreading from the stagnation point, enters the separation zone. From this zone the gas is partially ejected by the separating stream, but basically flows out in the lateral directions.

In the case of two-dimensional flow the lateral outflow is absent, and the amount of ejected gas is precisely equal to the amount of gas entering the separation zone. In this case the streamline which impinges on the stagnation point will be a line of constant mass and is located in the mixing layer between the deflected stream of ideal fluid and the viscous separation zone [1, 2]. In the case of the three-dimensional flow with lateral outflow, the stream velocity, pressure differentials, velocity gradients, and, consequently, the heat transfer coefficients are increased. There is a simultaneous...
increase of the pressure and the heat transfer coefficient at the stagnation point on the surface of the obstacle, since filaments of the ideal fluid with a stagnation pressure that is higher than the stagnation pressure behind the normal shock approach this point.

2. Let us denote the obstacle height by $H$ and the width by $d$. Let $d/H \ll 1$. Then as the characteristic length we may use the dimension $d$ or, in the more general case of flow in the plane of symmetry, the quantity $u_1\beta$, where $\beta = du/dz$ is the velocity gradient in the ideal fluid on the stagnation line of the obstacle above the separation zone and $z$ is the distance measured from the stagnation line. For the determination of the dimension $h$ of the separation region, the dimensionless relation in the isothermal flow may be written in the form

$$h\frac{\beta}{u_1} = f\left(M, P, \frac{u_1\rho\delta}{\mu}, \frac{\beta H}{u_1}, \frac{\beta h}{u_1}\right). \quad (2.1)$$

Let us consider the case in which the obstacle height is infinitely large $\nu = u_1/\beta H \ll 1$. Let $\varepsilon = \beta \delta / u_1 \ll 1$. Then, expanding in a series in the small parameters $\nu$ and $\varepsilon$, we have

$$h\frac{\beta}{u_1} = f_0 \left(M, P, \frac{u_1\rho\delta}{\mu}\right) +$$

$$+ \frac{\beta}{u_1} f_1 \left(M, P, \frac{u_1\rho\delta}{\mu}\right) + \frac{u_1}{\beta H} f_2 \left(M, P, \frac{u_1\rho\delta}{\mu}\right). \quad (2.2)$$

With unlimited decrease of $\nu$ and $\varepsilon$ (which is equivalent to simultaneous reduction of $\delta/d$ and $d/H$) for an arbitrary value of $u_1\rho\delta/\mu$, as shown by experiments, the dimension of the interaction region remains finite,

$$h\frac{\beta}{u_1} = f_0 \left(M, P, u_1\rho\delta/\mu\right). \quad (2.3)$$

Thus, in this important limiting case with constant conditions ahead of the separation zone the height $h$ of the separation zone is proportional to the obstacle width $d \sim u_1/\beta$ and is independent of the boundary layer thickness. In this sense the flow in the case $\delta/d \ll 1$ is qualitatively analogous to supersonic flow with two-dimensional separation ahead of a step, when the zone height is determined by the step height and is independent of the boundary layer thickness. The zone length $l$ is determined in this case by the separation angle $\theta$, which depends on the boundary layer characteristics at the separation point ($R_\delta = u_1\rho\delta/\mu, M$).

3. Special experiments were conducted to verify and find the limits of applicability of condition (2.3). The tests were conducted with $M = 2−6$. The model was a flat plate on which cylinders or parallelepipeds were mounted at various distances from the sharpened leading edge of the plate. The transverse dimension of the obstacles varied from 1 to 20 mm, the height varied from 3 to 100 mm. The flow regime in the boundary layer on the plate was laminar or turbulent. The Reynolds number $R_\delta$ at the separation point varied from $10^4$ to $10^5$.

We present the results of experimental studies, obtained basically in the laminar flow regime, although the physical characteristics of the flow in the three-dimensional separation zone remain valid qualitatively and manifest themselves more strongly in the turbulent regime.

We recall that the three-dimensional separation zone being studied is unsteady. This was discovered with the aid of spark photography. Study of the photos for the case of separation in the turbulent regime showed that the oscillations of the linear dimensions of the separation zone, the location of the stagnation point on the obstacle, the filament width, and the shock inclination reach 20%. Consequently, the shadow and schlieren photos presented below and the measurements made from them are averaged values.

Figure 2 shows shadowgraphs of the flow ahead of a cylinder mounted on a plate. The model was in a flow with $M = 6$ and $R_\delta = (0.2−0.8) \cdot 10^5$. A graph of the variation of the zone length $l$ and the inclination $\theta$ of the separation zone as a function of $R_\delta$ (Fig. 3) was obtained on the basis of measurement of the photos. The separation zone length $l$ was determined from the distance from the cylinder base to the intersection with the compression shock 2, and the angle $\theta$ was determined as the effective wedge angle from the measured

![Image](image-url)