EXPERIMENTAL FLOW ANALYSIS OF THREE-DIMENSIONAL SEPARATION ZONES IN FRONT OF WEIRS

B. E. Luzhanskii and V. P. Solntsev

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Some results of experimental studies are shown concerning subsonic flow in separation zones of three-dimensional turbulent boundary layers formed in front of cylindrical weirs and rectangular parallelepipeds or dashboards. The width to height ratio of the weirs was varied from 0.25 to 24, and the boundary layer thickness to weir height ratio at separation was varied from 0.2 to 2.0. Flow patterns are shown along with the effects of the setup geometry, of the weir width to height ratio, of the boundary layer parameters, and of the Euler and Reynolds numbers on the flow pattern and on the coordinates of characteristic points in the separation zone. Data are furnished for determining the dimensions of three-dimensional separation zones in front of weirs. The flow and the heat transfer in three-dimensional separation zones at subsonic velocities have not yet been explored adequately. The separation data published in [1, 2, 3] are not sufficient for determining the flow pattern, the static pressure distribution, and the characteristic dimensions of a separation zone – all of which are needed for calculating the heat transfer in the separation zone [4].

1. The experiments were performed in a subsonic aerodynamic tunnel with an open test segment. A Mach number close to 0.72 was maintained. The Reynolds number calculated from the incoming flow parameters and the weir height was varied from 10^4 to $3.5 \cdot 10^5$.

The test segment of the tunnel consisted of a plate 350 mm wide and 700 mm long, on which weirs with height H of 7.5-120 mm and width B or diameter D of 15-180 mm had been mounted. The frontal surface of most weirs was perpendicular to the plate surface. In the case of cylindrical weirs with the diameter to height ratio equal 1.0 – the height being considered that of the frontal generating surface (in the plane of symmetry) – the tests were performed with the inclination angle of the cylinder axis varied up to 45° against the stream and up to 43° with the stream.

The thickness δ of the turbulent boundary layer in the plane of symmetry of the separation section was varied from 2.7 to 20 mm. At the same time, the ratio δ/H was made smaller as well as larger than unity. For example, δ/H in front of a cylindrical weir with $D/H = 2$ was varied from 0.2 to 2.0.

2. In order to examine the flow pattern, drops of oil, dye, or a soot suspension in kerosine were deposited on the model surface. The flowing dye film was observed visually and was photographed during the operation of the aerodynamic tunnel.

The study has shown that the flow pattern in the vicinity of a weir is determined by the weir geometry (cylinder, parallelepiped, etc.) as well as by the D/H and δ/H or δ/D ratios. Moreover, the flow pattern of the separation zone in front of a weir depends, as in the case of a two-dimensional flow, on the Euler and the Reynolds number

$$E = p\,(\rho u^2)^{-1}, \qquad R = uH / \nu$$

where u, ρ, p, and ν are the velocity, the density, the static pressure, and the kinematic viscosity of the approaching stream.

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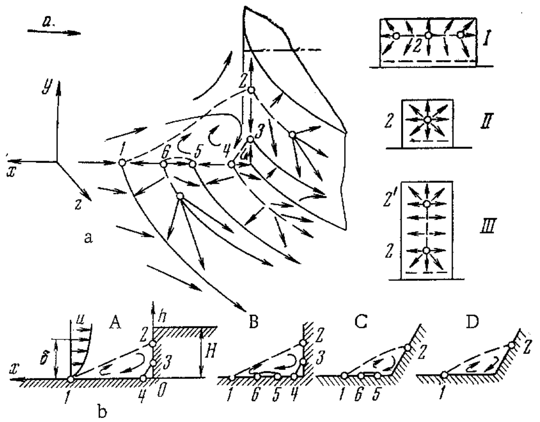

Fig. 1

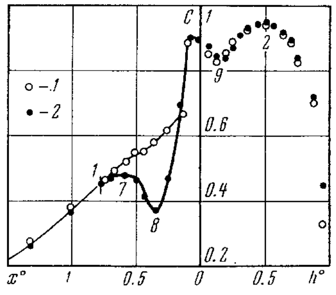

Fig. 2

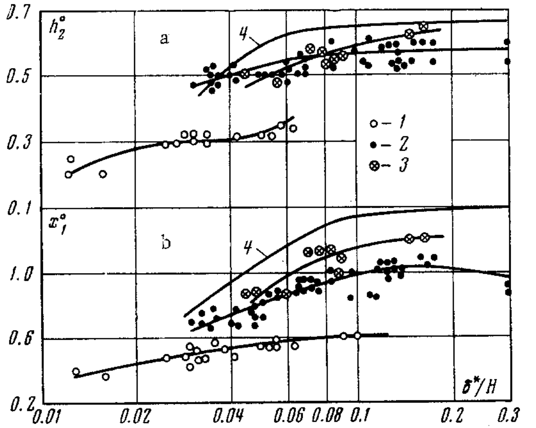

Fig. 3

The flow patterns of three-dimensional separation zones revealed by these studies are shown in Fig. 1. The three-dimensional boundary layer, which develops in the higher-pressure region in front of the weir, separates from the plate surface along line 1 and contacts the frontal weir surface while forming a spill line or point 2. Part of the stream enters the separation zone in front of the weir and from there partly spills laterally. The plane of symmetry in front of the weir is also the plane of symmetry of the spill.

The boundary layer at the wall, which forms when gas flows away from line or point 2, separates from the frontal weir surface along the separation line 3 and makes contact at the spill line 4 while forming in the corner at the weir base another three-dimensional separation zone 3-4. The flow pattern of one such additional separation zone 3-4 is indicated in Fig. 1b, A.

As in the case of a two-dimensional flow [4], the boundary layer at the wall may separate along line 5 and contact the plate while forming there a spill line or point 6. The flow pattern of a separation zone with two additional separation zones 3-4 and 5-6 is indicated in Fig. 1b, B. Flow patterns C and D were obtained with different inclination angles of the cylinder generatrix.

A comparison between the visually recorded flow data and the results of static pressure measurements has shown that a flow pattern change from A to B or from C to D is associated with qualitative changes in the static pressure distribution in the separation zone.

In Fig. 2 we show the distribution of the static pressure coefficient across the plane of symmetry in front of the weir with $D/H = 2$ and $\delta^*/H = 0.055$, where δ^* is the displacement thickness of the boundary layer in the plane of symmetry at the separation point 1:

$$C = 2\,(p_0 - p)\,(\rho u^2)^{-1}$$

p_0 is the static pressure at the surface and $x^\circ = x/H$, $h^\circ = h/H$ are dimensionless coordinates measured from the weir base (Fig. 1b).

Within a specific range of Euler and Reynolds numbers (e.g., $Eu = 430$ and $Re = 2 \cdot 10^4$ corresponding to test points 1 in Fig. 2) the static pressure in the return stream zone at the plate decreases monotonically from a maximum value at the spill line 4 to the lowest value at the separation line 1. Such a pressure profile along the plate corresponds to flow pattern A or D (Fig. 1b).

At other Euler and Reynolds numbers (e.g., $Eu = 13$ and $Re = 1.2 \cdot 10^5$ corresponding to points 2 in Fig. 2) a pressure minimum appears under the vortex center. If the positive pressure gradients in the return stream zone become sufficiently large, then the boundary layer separates from the wall and the flow proceeds according to pattern B or C.

The critical Eu and Re numbers, at which there occurs a qualitative change in the static pressure distribution in the return stream zone and at which the flow pattern changes, depend on the weir shape as well as on the ratios D/H and δ/H or δ/D.

The flow patterns at the frontal surfaces of weirs are shown in Fig. 1c. When the flow is only slightly three-dimensional in the separation zone, the stream makes contact according to pattern I with a formation of the spill line 2 analogous to the spill line at a two-dimensional weir. A highly three-dimensional flow is represented by pattern II or III with a formation of the spill point 2 or the spill line 2-2'.

It is to be noted that the flow pattern at the frontal surface depends not only on the weir shape and the D/H ratio but also on the relative thickness of the boundary layer. When $D/H=1$, for example, a decrease of δ^*/D from 0.03 to 0.02 will result in a change of the flow pattern from II to III.

A rough criterion characterizing the three-dimensionality of a flow in the separation zone around point 2 is best expressed as

$$K \sim \frac{du}{dz} \Big/ \frac{du}{dh}$$

where z is the coordinate normal to the plane of symmetry.

An analysis of data on the static and the total pressure distributions has shown that, within the given range of controlling parameters, one may assume approximately,

$$du / dz \sim u / D, \qquad du / dh \sim u (\Delta C)^{0.5} / h_2$$

Then

$$K = h_2 D^{-1} (\Delta C)^{-0.5}$$

where $\Delta C = C_2 - C_9$ is the maximum drop in the pressure coefficient in the plane of symmetry of the separation zone at the weir surface (see Fig. 2). The subscripts 1, 2, 3, ... refer to values at the corresponding points in the plane of symmetry as designated in Fig. 1 and Fig. 2.

This criterion may be used for determining the boundary within which flow pattern I exists, in order to generalize the data obtained with different δ^*/D, D/H ratios, and inclination angles of the cylinder generatrix. When $K<0.5$, the flow is only slightly three-dimensional around point 2 in the plane of symmetry of a cylindrical weir, and the separated stream contacts the weir while forming a spill line according to pattern I. When $K>0.5$, spilling occurs at point 2 in all directions (pattern II) or within a limited space sector (pattern III). At weirs with a flat frontal surface the flow follows pattern I when $K<1$.

3. We will now analyze the measured coordinates of spill points or lines at the plate and at the weir surface. The coordinates of the separation points 1 and of the contact points 2 in the plane of symmetry of separation zones in front of cylindrical weirs are shown in Fig. 3 as functions of the ratio δ^*/H. The test points 1, 2, and 3 have been obtained with $D/H=1.0$, 2.0, and 4.0, respectively. Curve 4 represents the average dimensions of two-dimensional separation zones measured and plotted in [4].

The dimensions of separation zones vary similarly in front of rectangular parallelepipeds and dashboards, with the test points for $B/H=2.0$, 4.0, and $\delta^*/H \leq 0.12$ almost falling on curve 4 in Fig. 3.

We also show the average coordinates of points 1 and 2 in front of parallelepipeds with $B/H=1.0$ ($x_1^\circ = 0.72$, 0.74, 0.72 and $h_2^\circ = 0.5$, 0.53, 0.63, respectively for $\delta^*/H = 0.03$, 0.07, and 0.1) and in front of cylindrical weirs with $D/H=0.25$ ($x_1/D = 0.51$, 0.57, 0.62 and $h_2/D = 0.47$, 0.61, 0.7, respectively, for $\delta^*/D = 0.03$, 0.06, and 0.11). No tests were performed with $D/H<0.25$, because, according to the data in [1], a further decrease of this parameter does not change the flow pattern at the weir base.

An analysis of these results has shown that the coordinates of points 1 and 2 are determined by the weir shape as well as by the ratios D/H and δ^*/H or δ^*/D, but do not depend on the Reynolds number. A change of the Euler number up to $Eu \geq 2$, corresponding to Mach numbers $M \leq 0.55$, also has no effect on the coordinates x_1° and h_2°.

At high Mach numbers as, e.g., $M=0.72$ ($Eu=1.1$), one observes some increase in the dimensions of the separation zones in front of weirs with $D/H \leq 2$. This has, apparently, to do with the appearance of local supersonic flow regions in the vicinity of the weir, as indicated by the presence of $C \approx -1$ segments on the lateral weir surface and on the plate near which the rated flow velocity at $M>0.7$ exceeds the velocity of sound.

It is evident, according to the data in Fig. 3, that increasing the ratio D/H results in increased relative dimensions of the separation zone, which in the plane of symmetry approach the dimensions of a two-dimensional zone. The critical value of ratio D/H, beyond which it ceases to affect the magnitudes of x_1° and h_2°, depends on the weir shape and on the ratio δ^*/H. In the plane of symmetry of a separation zone in front of a rectangular parallelepiped or dashboard, for example, x_1° and h_2° when $\delta^*/H = 0.12$ are identical with the dimensions of a two-dimensional zone when $B/H \geq 2$. A decrease of δ^*/H down to 0.03 will make x_1° and h_2° independent of the weir width to height ratio already when $B/H \geq 1$.

It is to be noted, however, that the flow pattern and the static pressure distribution in the separation zone here differ from those in the two-dimensional case. Visual examination of the flow pattern showed that, even when $B/H = 16$, the flow at the plate surface between separation lines 5 and 1 was three-dimensional in the immediate vicinity of the plane of symmetry, although the coordinates of the separation line 1 and of the contact line 2 remained constant all the way to a distance $z/H = 6$ (z was measured from the plane of symmetry).

In addition to coordinates x_1 and h_2, the coordinate of the separation line x_5 was also measured. An analysis of the test data has shown that the coordinate x_5° depends not only on the ratios D/H and δ^*/H (or δ^*/D) but, as in the two-dimensional case, also on the Euler and the Reynolds number.

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LITERATURE CITED

1. D. M. Sykes, "The supersonic and low-speed flows past circular cylinders of finite length supported at one end," J. Fluid Mech., 12, No. 3 (1962).
2. A. Heyser and F. Mauer, "Experimentelle Untersuchungen an festen Spoilern und Strahlspoilern bei Mach'schen Zahlen von 0.6 bis 2.8," Zeitschr. Flügwiss., 10, Nos. 4-5 (1962).
3. D. R. Chapman, D. M. Kuehn, and H. K. Larson, "Investigation of separated flows in supersonic and subsonic streams with emphasis on the effect of transition," NASA Report No. 1356 (1958).
4. B. E. Luzhanskii and V. P. Solntsev, "Experimental study of heat transfer in separation zones of a turbulent boundary layer in front of a weir," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 1 (1971).