EFFECT OF CHANNEL BLOCKAGE ON MOTION IN THE SEPARATION ZONE BEHIND BLUFF BODIES

M. A. Gol'dshtik and B. A. Silant'ev

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ABSTRACT: The thermal differential method of determining stagnation points has been used to investigate the effect of channel blockage on the length of the separation zone behind shoulders and steps. In the case of a back step a theoretical solution obtained for the zone length and vorticity is found to be in satisfactory agreement with the experimental data.

Since they make very efficient flame holders the flow separation behind bluff bodies has received a great deal of attention. In [1–3] it was noted that the stabilizing capacity depends directly on the dimensions of the separation zone and, in particular, on its length L_0. In turn, the length of the separation zone is determined by the geometry of the body and the blockage of the body and the blockage of the channel $\varphi = d_0/H$, where d_0 and H are the bluff body dimension and the channel height, respectively.

However, most models describing flow behavior in the presence of a separation zone [4–6] completely disregard blockage. Thus, in Abramovich's scheme the length of the separation zone in a plane flow is assumed constant and equal to $L_0/d_0 = 6.0$ as φ varies from 0.2 to 0.75. Experimental data on the length of the separation zones behind plane bodies of the step and shoulder type, obtained by various authors [5, 7–9], are rather contradictory and cover a relatively narrow range of values of φ. Only in [5, 7] was the length of the separation zone determined over a broad interval of variation of the channel blockage; however, the results obtained differ sharply, at some values of φ by a factor of 1.5–2. To a considerable extent these discrepancies are associated with inadequacies in the method of determining the attachment point.

As a rule, the attachment point is determined indirectly as the point of intersection of the zero discriminating streamline and the surface or as the intersection of the zero streamline and the axis of symmetry in the case of axisymmetric flow over a bluff body. The zero streamline is calculated from the velocity field in the separation zone, which in the region of the attachment point cannot be reliably measured by ordinary methods owing to the intense turbulence of the flow. The direct "flag" method used in aerodynamics is also very rough, and the method of coating the surface with a reactive composition requires elevated temperatures.

Our aim was to study the effect of blockage of the cross section on the geometry of the separation zone behind bluff bodies of the step and shoulder type. In order to determine the flow attachment point we developed a direct method arbitrarily called the "thermal differential method." This method is based on the experimental fact that the direction of the flow velocity vector is reversed upon transition through the attachment point.

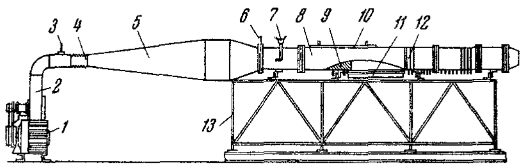

Fig. 1

If close to the attachment point we install a wire heater with two thermocouples, connected in a differential circuit, at equal distances up and downstream, we can register the direction and magnitude of the flow velocity vector in the form of an unbalanced thermal emf ΔE with a certain sign. On passing through the attachment point the thermo-emf changes sign. Thus, the attachment point is determined as the coordinate where $\Delta E = 0$. Estimates show that the error of the method does not exceed 2–3%.

By means of this method we measured the lengths of the separation zone behind a step and a shoulder in a flat channel as φ varied from 0.0385 to 0.962.

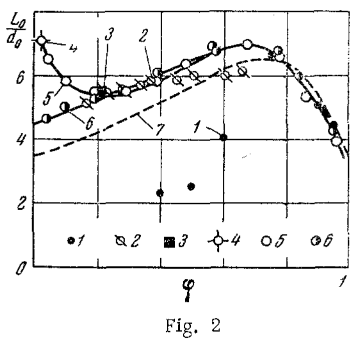

Fig. 2

A diagram of the experimental apparatus is shown in Fig. 1. It consists of a wind tunnel with a closed transparent-plastic working section 8 measuring 150 × 260 mm in cross section; the shoulder 9 is mounted on the bottom of the working section. The bluff bodies investigated were introduced in the tunnel through the upper removable cover 10 and could be moved along the bottom of the working section; the bodies were specially profiled for additional equalization of the velocity profiles at the trailing separation edge; the other components of the apparatus were as follows: 1) A063–414–RW motor, 2) fan, 3) thermometer, 4) damper, 5) diffuser, 6) screen, 7) flowmeter, 10) removable cover, 11) heat-transfer section, 12) positioning mechanism, 13) frame. In order to obtain steps plates of the same height (500 mm long) were introduced directly behind the shoulder.

The aerodynamics of the flow in the eddy region behind the body were investigated with cylindrical probes with a head diameter of 2 mm introduced into the flow by means of positioning mechanisms. The distance between the measuring point and the trailing edge of the body was varied by moving the latter along the bottom of the working section (along the x axis). Altogether we investigated eleven shoulders with d_0 = 10, 25, 50, 75, 100, 125, 150, 175, 200, 225 and 250 mm and six steps with d_0 = 10.25, 50, 100, 150 and 200 mm.

The Reynolds number of the approaching flow varied from $6 \cdot 10^4$ to $3 \cdot 10^5$. In all cases the flow was turbulent. As the experiments showed, the geometry of the separation zone and, in particular, its length for a body of given size does not depend on the freestream velocity; therefore all the measurements were made at a value of the free-stream velocity V_∞ = 15 m/sec.

The results of the experiments to determine the length of the separation zone by the thermal differential method, together (for comparison) with data obtained by other authors in various intervals of φ, are presented in Fig. 2, where points 1 correspond to the data of [5] for a half-body, 2 to the data of [7] for a step, 3 to the data of [8] for a step, 4 to the data of [9] for a step, 5 to the authors' data for a shoulder, and 6 to the authors' data for a step; the calculated curve is represented by a dashed line.

As may be seen from the graphs, the length of the separation zone depends significantly on the blockage of the channel, this dependence being a complex one with a clearly expressed maximum at φ = 0.68. In the region of variation of φ from 0.16 to 0.5 our data are in good agreement with the results of [7] obtained on water for steps, and also with the results of R. A. Seban [8] obtained on air for a step. In the region of variation of φ from 0.68 to 1.0 our results obtained for shoulders and steps are in perfect agreement with the known data of G. N. Abramovich [5].

We have also presented the results obtained theoretically for the case of flow past a step on the basis of the mixed motion model. According to this model, proposed by M. A. Lavrent'ev [10], flow in the

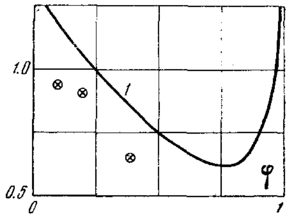

Fig. 3

separation zone is divided into two regions: a region of eddy motion with constant vorticity and a potential region, the velocity field necessarily remaining continuous when the boundary line is crossed. The problem reduces to the solution of the functional equation

$$\psi q \equiv \psi_0(u_0, q(u_0)) +$$

$$+\frac{\omega}{2\pi}\int_0^a du \int_0^{(q)u} \ln\frac{(u-u_0)^2+(v+q(u_0))^2}{(u-u_0)^2+(v-q(u_0))^2} D(u, v)\, dv, \qquad (1)$$

where

$$\omega = \pi\frac{\partial\psi_0(0,0)}{\partial q}\left[\int_0^a du \int_0^{q(u)} \frac{vD(u, v)}{u^2+v^2}dv\right]^{-1} \qquad (2)$$

and the parameter a satisfies the condition $q(a) = 0$. For the case of a step in a channel

$$D = \frac{H^2}{\pi^2}\left(\frac{u^2+v^2}{(u-2/\pi)^2+v^2}\right)^{1/2}\frac{1}{(u+b)^2+v^2},$$

$$b = \frac{2}{\pi}\frac{\alpha^2}{1-\alpha^2}, \qquad \alpha = 1-\frac{d_0}{H},$$

$$\psi_0(u_0, v_0) = \frac{H}{\pi}\,\mathrm{arc\,tg}, \quad \frac{v_0}{v_0+b}.$$

The relation between the variables u, v and the variables of the physical plane x, y is given by

$$z = \frac{H}{\pi}\left(\ln\frac{\sigma+1}{\sigma-1} - \alpha\ln\frac{\sigma+\alpha}{\sigma-\alpha}\right), \qquad \sigma = \left(\frac{f}{f-2/\pi}\right)^{1/2}$$

$$(z = x+iy,\ f = u+iv).$$

The solution of (1) was obtained numerically on a computer using Newton's method.

As may be seen from Fig. 2, the calculated values are in good agreement with the experimental curve for a step. In the region $0.68 \leq \varphi \leq 1.0$ there is complete quantitative agreement; elsewhere the deviation does not exceed 20%.

Figure 3 shows the results, obtained in accordance with (2), of calculating the vorticity ω_0 in the separation zone in the form of a graph of the parameter $\omega^* = \omega_0 d_0/V_1$ as a function of the blockage φ. The same figure shows the experimental data. As may be seen from Fig. 3, the experimental points lie below the calculated curve (by 20-25%), which is associated with the large errors in determining the vorticity of the flow. The vorticity was determined on the basis of Stokes theorem written for the separation region F_0 bounded by the line l:

$$\oint_l \mathbf{V}\cdot d\mathbf{l} = \oint_{F_0} \omega_0 dF. \qquad (3)$$

Since ω_0 is the same throughout the separation zone [11], we can rewrite Eq. (3) in the form

$$\omega_0 = \frac{1}{F_0}\oint_l \mathbf{V}\cdot d\mathbf{l} = \frac{\Gamma}{F_0}. \qquad (4)$$

Here, Γ is the circulation of the velocity vector along the boundary.

As already noted, the intense turbulence of the flow in the separation zone leads to considerable errors in the velocity measurements in the direction of an underestimation of the actual values, which also affects the vorticity calculations.

The results of calculating the vorticity ω_0 and the length of the separation zone, plotted in the form of a graph of the parameter $\omega_0 L_0/V_1$ as a function of the channel blockage coefficient φ, show that this parameter is almost (correct to ±6%) constant over the entire interval of φ and may be taken equal to 4.2. Here, $V_1 = V_\infty/1 - \varphi$.

Thus, the vorticity ω_0 can be determined from the condition $\omega_0 L_0/V_1^\infty \approx 4.2$, since the length of the separation zone is measured with sufficient accuracy by the thermal differential method.

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