EXPERIMENTAL VERIFICATION OF THE HYPOTHESIS OF THE CONSTANCY OF VORTICITY OF A FLUID IN A SEPARATION ZONE

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ABSTRACT: This article describes an experiment, making use of the analogy between vorticity and temperature, which shows that the vorticity is constant in the separation zone behind a poorly streamlined body.

In many cases of flows of liquids or gases with high Reynolds numbers, there is a separation of the flow characterized by the formation of one or several zones bounded by closed streamlines. There are several calculating schemes which describe the behavior of a flow in the presence of such zones [1–4]. The principal schemes are as follows.

1. The Foeppl scheme [1]. According to this scheme, two symmetric vortices whose position is determined by their stationarity are formed behind the stern of a poorly streamlined body. An important defect of this scheme is the unbounded velocity at the center of the vortex. The calculated length of the separation zone turns out to be considerably less than the experimental length. Moreover, a number of problems do not, in general, have any solution by the Foeppl scheme (for example, the problem of transverse flow across a plate).

2. The Vulis scheme [2]. In this scheme, a poorly streamlined body is replaced by a fictitious turbulent sink, which leads to the external flow losing momentum equal to the real loss due to the resistance of the body. By superposing a homogeneous flow on the flow field of such a sink, one obtains a flow pattern which possesses some properties of the actual motion in a wake.

3. A scheme based on the methods of boundary layer theory [3]. When the flow of fluid about the body reaches the edge of separation, it continues to propagate in the same direction as a free stream. In this case, an ejected flow of fluid flowing up to the edge appears along the stern of the body. Both flows mix and form a turbulent boundary layer. The boundary layers reach the axis and merge at some distance from the stern of the body, thus forming a closed region. This scheme is approximate and requires the introduction of experimental constants.

The scheme of separated flow proposed by M. A. Lavrent'ev [4] corresponds more closely to actual conditions.

According to this scheme, a flow of ideal fluid about a body, with separation, is divided into two regions—a region of vortical motion and a potential region; the velocity field should remain continuous on transition across the interface.

Special solutions of the problem of flow past a trench on the bottom obtained with this scheme are presented in [5] for a certain class of given profiles.

A formulation of the general problem of the theory of separated flows and its solution for the cases of flows around a projection, a recess, a cylinder, and a plate are given in [6, 7].

The important point in the scheme under consideration is the assumption of the constancy of vorticity ω in the separation zone.

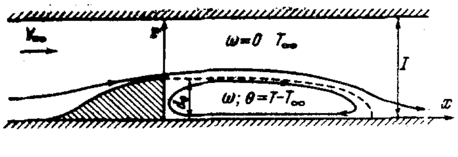

Fig. 1. Flow pattern behind a poorly streamlined body in a channel. The broken line is the zero flow rate line.

This hypothesis appears plausible since the intense turbulent exchange existing in the separation zone should lead to smoothing out of vorticity.

The aim of this work was experimental verification of the correctness of this hypothesis.

So far, there have not been any sufficiently reliable methods for measuring the local vorticity of flow, thus, an indirect method based on an application of the analogy between vorticity and temperature was applied. We shall write the equations of motion of the fluid in the separation zone in the Helmholtz form

$$\frac{\partial \omega}{\partial t} + (\mathbf{v}, \nabla)\,\omega = \nu \Delta \omega. \tag{1}$$

The equation for the propagation of heat also has an analogous form

$$\frac{\partial T}{\partial t} + (\mathbf{v}, \nabla)\,T = \chi \Delta T. \tag{2}$$

Henceforth, we shall consider only the stationary case. Coincidence of the boundary conditions for Eqs. (1) and (2) is required for complete analogy in the distribution of vorticity and temperatures in the separation zone. This will be the case if we place the heat sources along the zone interface on which the process of vortex formation appears to occur. On this basis, if the temperature in the zone turns out to be constant, then the vorticity also should be constant.

The experiments involving measuring the temperature distribution in the separation zone were conducted in a flat wind tunnel with a closed working section measuring $2500 \times 150 \times 260$ mm. The poorly streamlined body, which was profiled according to the Vitoshinskii formula, had a height $d_0 = 100$ mm. The aerodynamics of the flow in the separation zone behind the body was studied by means of a cylindrical probe having a head with a diameter of 2 mm,

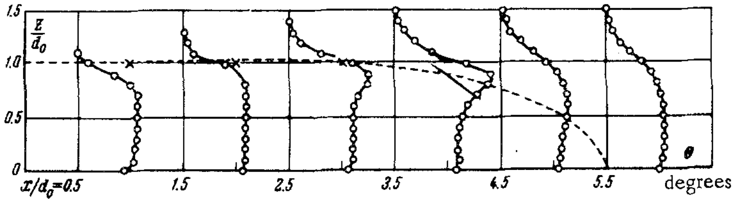

Fig. 2. Temperature field in the vortex zone behind a projection with d_0 = = 100 mm. The flow velocity above the body V = 24 m/sec. The power of the heat sources q = 675 W. The crosses denote places where heaters are installed. The broken line is the zero flow rate line. Scale: 1 mm corresponds to 0.4° K.

V_∞, m/sec	5.3		10		14.7		19		
q, J/sec	337.5	675	675	1350	675	1125	1350	675	1350
$\theta_{0,1}$	7.1	15.6	665	14.5	4.6	9.15	12.75	3.5	8.45
$\delta\theta_{0,1}$	12.3	4.2	8.4	9.35	18	9.1	2.1	15.2	14
$\theta_{1,2}$	8.7	17.1	6.8	15.8	5.65	9.45	13.1	4	10.7
$\delta\theta_{1,2}$	6.5	5.2	6.75	0.9	1.1	5.85	0.8	3.6	8.7
$\theta_{2,3}$	8.55	17.2	7.5	16.7	5.95	10.4	13.3	4.3	9.8
$\delta\theta_{2,3}$	5.2	6	3.15	4.7	6.2	3.7	2.3	3.9	0.2
$\theta_{3,4}$	9.05	16.9	8.15	17.8	6.9	11.3	14	4.6	9.85
$\delta\theta_{3,4}$	11.4	4.3	12.1	11.5	23.4	12.5	7.7	11.1	0
$\theta_{4,5}$	7.9	14.2	7.45	15.5	5.65	10.3	12.1	4.45	9.45
$\delta\theta_{4,5}$	2.6	12.3	2.2	3.1	1.1	2.5	6.7	7	3.8
$\theta_{5,6}$	7	12.8	6.6	13.3	5.25	8.8	10.9	4	8.5
$\delta\theta_{5,6}$	13.9	21.2	9.2	16.5	4.2	12.4	16.1	3.6	13.4
θ	8.15	16.25	7.25	16	5.6	10.05	13	4.15	9.85
$\delta\theta$	8.6	8.8	6.9	7.6	6.3	7.7	6	7.4	6.7

which was introduced into the flow with the aid of a coordinate device. The interface between the vortical region and the main flow was calculated from the direct velocity field behind the body as the total flowrate line. A diagram of the working section and the flow pattern behind a poorly streamlined body are shown in Fig. 1.

Three heaters were installed close to the calculated interface, at distances of $x/d_0 = 1, 2, 3$ from the stern of the body. The heaters were spirals of 0.5 mm nichrome wire wound on ceramic tubes. The following requirements were used to guide the selection of the number of heaters:

1) The heaters should have sufficient power to produce temperatures in the separation zone which could be measured reliably.

2) The heaters should encumber the channel as little as possible.

3) The heaters should be distributed along most of the length of the interface.

It turned out that three heaters were sufficient to meet these requirements. The heaters were fed by alternating current; the power supplies were the same and ranged in these experiments between 112.5 and 450 W for each heater.

After the heaters were switched on, the onset of the stationary regime was achieved in which the amount of heat liberated was equal to the heat removed from the zone by turbulent transfer. Then the temperature field was measured along the entire length of the separation zone, which turned out, according to the results of aerodynamic measurements, to be equal to $L/d_0 = 5.5$. These measurements were taken with nichrome-constantan thermocouples made of 0.2 mm diameter wire. Temperatures were read with the aid of a P 2/1 semi-automatic potentiometer. The temperature difference between the separation zone and the oncoming flow was measured. All temperature measurements were taken twice, after which the mean arithmetic average of the two measurements was taken.

The experiments were conducted for four values of the average discharge velocity of the oncoming flow: 5.3, 10, 14.7, and 19 m/sec which corresponds to Reynolds numbers $R = V_\infty d/\nu = 0.33 \cdot 10^5$, $0.62 \cdot 10^5$, $0.92 \cdot 10^5$, and $1.19 \cdot 10^5$.

The results of measuring the temperature distribution in the separation zone for a velocity of the oncoming flow $V_\infty = 14.7$ m/sec and a total heater power $q = 675$ W are presented in Fig. 2.

The temperature distribution for all remaining regimes (heating and velocities of the oncoming flow) is similar in nature.

As can be seen from Fig. 2, the temperature in the zone remains constant over its entire length. The temperature peaks in some sections are apparently explained by the influence of the proximity of heaters and their sufficiently large capacity; however, this effect very quickly ceases to register. The results from measurements of the temperature in various sections along the length of the separation zone for different values of the velocity of the oncoming flow and the power of the heat sources are shown in the table, where $\theta_{i,i+1} = T_{i,i+1} - T_\infty$ is the temperature between cross sections i and i + 1 along the length of the separation, θ is the average integral temperature of the separation line, $\delta\theta_{i,i+1}$ is the relative deviation (%) of the temperature $\theta_{i,i+1}$ from the average integrated value, $\delta\theta$ is the average relative error (%), V_∞ is the velocity of the oncoming flow, T_∞ is the temperature of the oncoming flow, and q is the total power of the heat sources.

It is necessary to note that the zone interface obtained from the results of temperature measurements is not the line discussed in the scheme of [4], but is some region. However, the temperature drop on the interface is sufficiently sharp for it to be considered, to a certain approximation, that the temperature in the separation zone and, consequently, the vorticity are actually constant. We note that by increasing the number of heaters and achieving a more uniform distribution of them along the zone interface, we succeeded in obtaining constancy of the temperatures in the separation zone with an average relative error $\delta\theta = 2\%$.

However, the second assumption of the scheme with respect to the potentiality of the flow outside the separation zone, is less acceptable, particularly in the end region of the separation zone where a wake appears. This fact must be taken into consideration in the further development of the theory of discontinuous flows.

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