LENGTH OF THE SEPARATION ZONE BEHIND AN UNSTREAMLINED BODY IN A RESTRICTED STREAM

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The effect of channel obstruction on the length of the circulation zone behind bodies of the projection-type in a restricted turbulent stream has been studied experimentally and the results are analyzed here.

One problem in the design of combustion chambers for gas turbines is to ensure a stable combustion of fuel during all modes of plant operation.

The most widespread method of stabilizing a flame is based on the laws of fluid flow in the immediate trail behind an unstreamlined body. It must be emphasized that the use of unstreamlined bodies for flame stabilization, which until now has been limited to blended fuel mixtures only, is since recently found more often in the design of stationary gas turbines with a diffusive combustion process in so-called jet stabilizers [1].

Many studies have been made concerning the kinematics of flow and the structure of the separation zone in a turbulent fluid behind unstreamlined bodies of various shapes [2-6].

The test data pertaining to the geometry of the backcurrent zone were analyzed and evaluated there in terms of dimensionless parameters characterizing the flow around unstreamlined bodies in an unrestricted stream [2, 7-9]. When a fluid flows behind an unstreamlined body, the structure of the separation zone is a result of interference between two modes of jet flow: a semirestricted jet developing along the inside channel wall and an immediate trail behind the unstreamlined body in an unrestricted stream. Depending on the relative surface area of the unstreamlined body (the degree of obstruction of the channel cross section), the laws governing one or the other type of flow will predominate here.

It is well known that the decisive factor in determining the stabilizing capability of unstreamlined bodies is the length of the recirculation zone which builds up behind the body and which, in turn, depends mainly on the shape of the body as well as on its relative cross-section area.

We will consider here the effect of obstruction on the length of the separation zone developing in a turbulent stream in a channel behind a projection [5, 6, 10-14].

Such a flow with characteristic discontinuities at the edges, parallel to the stream axis, constitutes the basic principle of jet stabilized burners for high-power gas turbine plants.

In a stream around a projection in a channel the $b_0 = D - d$ wide zone may be treated as a nozzle discharging a semirestricted jet. At the inside channel surface there forms a boundary layer of thickness δ, and behind the projection there appears a circulation zone of length l_c with backcurrents and a pressure dip. As a result of turbulent mixing between the jet and the stream of the separation zone, there forms an external boundary layer. This boundary layer of thickness b and the internal boundary layer of thickness δ become wider in the mainstream direction and they narrow down the jet core, which then vanishes completely at the end of the initial stage of $x = x_i$. This situation is depicted schematically in Fig. 1, without both the transition stage of the jet and the boundary layer developing at the surface of the unstreamlined body. A kinematically analogous pattern prevails around flat and axiosymmetric half-solids [2, 3, 15, 6], stairs [6], closed cavities [17], and twin projections [12, 18].

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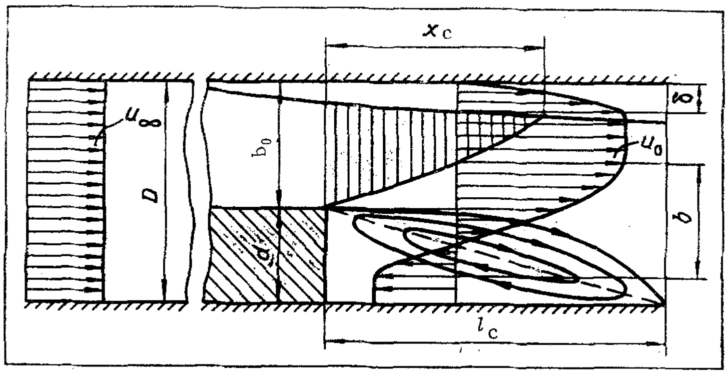

Fig. 1. Schematic diagram of flow around a projection in a restricted stream.

At low values of the channel obstruction factor ψ, when the separation zone over its entire length interferes with the potential-flow core of the jet ($l_c < x_i$), the stream past a projection in the channel follows the pattern characteristic of a free turbulent trail. In this case the length of the recirculation zone $\bar{l}_{c0}$, measured in characteristic diameters d (which is valid for the case of a body in an unrestricted stream), remains approximately constant and independent of the channel obstruction factor ψ. As can be seen in Fig. 2a, the test points obtained by various authors with $\psi \le 0.3$ [3, 5, 6, 10, 13] cluster closely (with a maximum scatter of 15%) around the value $l_{c0} = 5.65$ and agree with the test points obtained for projections in an unrestricted stream [9, 11, 19].

As the channel obstruction factor increases, the relative length of the circulation zone increases too, while the initial stage becomes shorter. At the same time, more significant become those phenomena which are associated with semirestricted jet streams [2, 15] where the nozzle width b_0 is the original dimension which governs the geometry of the aerodynamic flow structure. As has been shown in [12, 16], the length of the separation zone l_c in a stream past a projection in a channel is most conveniently measured in terms of the dimension b_0. The results of data evaluation on this basis are shown in Fig. 2b. The test points obtained by various authors for unstreamlined bodies of the projection type in a semirestricted stream are well described by a single curve with a scatter not exceeding 13% at $\psi \le 0.3$.

It is to be noted that these tests were performed with unstreamlined bodies in air and water [12] streams under conditions of plane and axiosymmetric flow [12, 15, 16] within a rather wide range of the Reynolds number Re = 10,000-500,000. According to the graphs, only the data of Abramovich [2] disagree with the general trend. This is explained by the effect of lateral channel edges on the structure of the recirculation zone behind the body in these tests, which is characteristic of relatively narrow channels. According to [2], in addition to the usual recirculatory flow with backcurrents in planes perpendicular to the channel base, vortices develop near the lateral walls behind an unstreamlined body in planes parallel to the channel base. These vortices cause a further pressure dip in the recirculation zone and, consequently, reduce its length. Such "radical" vortices are noted behind turbine blades and also near face plates behind flame stabilizers.

The relation between l_c and ψ can be generalized by a rather simple and convenient engineering design formula

$$l_c = \exp(k\psi) - 1, \quad k = 4.05. \tag{1}$$

The channel obstruction factor ψ can vary from 0 to 1. In the first extreme case $\psi = 0$ when $d \rightarrow 0$ and we have a flow in a channel without an unstreamlined body present. Naturally, in this case there exists no recirculation zone. The same conclusion follows from Eq. (1): $\bar{l}_c = 0$ when $\psi = 0$. When $\psi = 1$, with the characteristic channel dimension D and the characteristic body dimension d both tending toward infinity so as to make their difference $D-d = b_0 \rightarrow 0$, we have a semirestricted submerged jet along a flat surface. In this case there is also no recirculation zone in the space around the jet. From Eq. (1) for $\psi = 1$ and $b_0 = 0$, we have here analogously $\bar{l}_c = 0$. Thus, formula (1), which generalizes the test data of 12 different studies concerning the flow around unstreamlined bodies of the projection type in a restricted stream, satisfies both extreme conditions. Therefore, it faithfully reflects the physical aspect of phenomena associated with such modes of flow.

For a channel obstruction factor within the range $0 < \psi < 0.3$, the test values for the length of the separation zone behind a projection are much higher than those calculated by formula (1). Evidently,

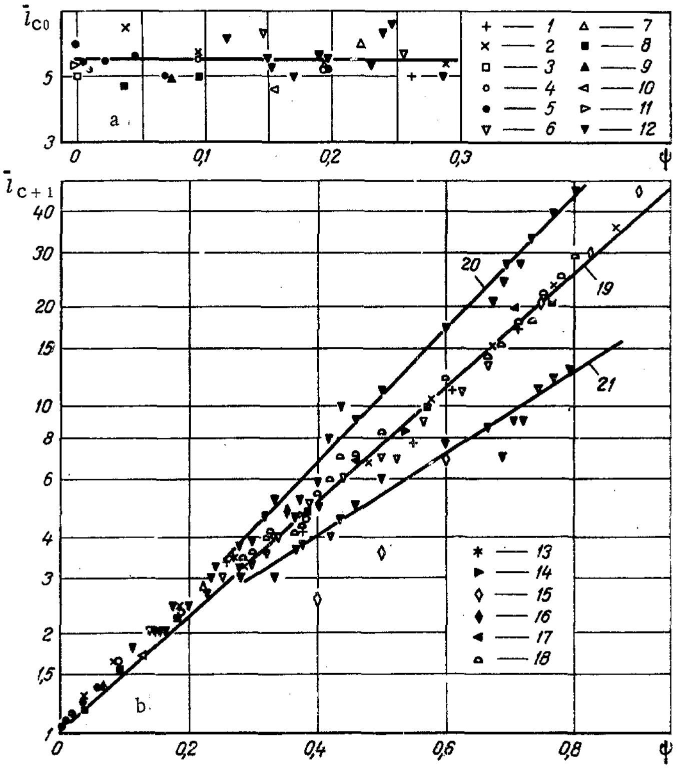

Fig. 2. Length of the separation zone: a) at low values of the channel obstruction factor ($\psi \leq 0.3$), based on test data for projections according to [5] (1); [6] (2); [9] (3); [10] (4); [11] (5); [12] (6); [13] (7), for stairs according to [6] (8); for a half-solid according to [3] (9); for a closed cavity according to [7] (10); [19] (11); for a twin projection according to [12] (12). b) For flow in the channel around an unstreamlined body of the projection type, based on test data for a projection according to [14] (13); for a twin projection according to [18] (14); for a half-solid in a flat channel [2, 15] (15); for a half-solid in an axiosymmetric channel [2, 15] (16); [16] (17); for a twin projection with $\bar{l}_c = 0.5\,(\bar{l}_{c1} + \bar{l}_{c2})$ [12] (18); formulas for $\bar{l}_c$, $\bar{l}_{c1}$, $\bar{l}_{c2}$ according to Eq. (1) with k = 4.05, 4.83, 2.83, respectively (19, 20, 21); other symbols the same as in Fig. 2a.

beginning at $\psi \simeq 0.3$, a stream around an unstreamlined body of the projection type in a channel approaches an unrestricted stream. This is confirmed not only by the data shown in Fig. 2a but also by the results of a special study in [12] concerning the kinematics of flow in a flat channel past single and twin projections. With $\psi < 0.3$, the recirculation zone becomes equally long behind single and twin projections (points 6 and 12, Fig. 2b), i.e., the flow patterns past projections from opposite channel walls are mutually independent. As the degree of obstruction increases, the separation zones behind a twin projection begin to interfere and their lengths become different (lines 20 and 21, Fig. 2b). This is due to a high degree of turbulence in a jet with backcurrents. According to [2, 15, 16], with a channel obstruction factor $\psi = 0.36$-0.46, the length of the initial jet stage is $x_i = 2$-3 and the transition stage of the jet vanishes completely. For this reason, already at such relatively slight channel obstructions the flow mode differs from that of an unrestricted stream.

It is interesting to note that the lengths $\bar{l}_{c1}$ and $\bar{l}_{c2}$ of the separation zones behind a twin projection do also obey Eq. (1) with the coefficient k = 4.83 and 2.83, respectively. The average length of the recirculation zone in an unrestricted stream past a twin projection $\bar{l}_c = 0.5\,(\bar{l}_{c1} + \bar{l}_{c2})$ comes close to the test values obtained for single projections (points 18, Fig. 2b).

It is well known that the stabilizing capability of a stream with backcurrents of fluid is proportional to the volume of the separation zone. In the design of jet stabilizers it is important, therefore, to establish the optimum channel obstruction factor ψ_{opt} which will ensure the longest separation zone for an unstreamlined body of given dimensions.

Considering that $b_0 = d[(1/\psi) - 1]$, we transform Eq. (1) to

$$l_c = d\left(\frac{1}{\psi} - 1\right)[\exp(k\psi) - 1]. \tag{2}$$

A conventional analysis of Eq. (2) for extrema will yield $\psi_{opt} = 0.64$. This value has been verified by a combined experimental and theoretical study in [6].

NOTATION

D, F	are the characteristic dimension and area of a channel cross section;
d, f	are the characteristic dimension and cross-section area of an unstreamlined body;
$b_0 = D - d$;	
x_i	is the characteristic dimension and length of the initial stage of a semirestricted turbulent jet;
$\bar{x}_i = x_i/b_0$;	
δ	is the thickness of wall (internal) boundary layer;
b	is the thickness of jet (external) boundary layer;
l_c $(\bar{l}_c = l_c/b_0)$,	
l_{c0} $(\bar{l}_{c0} = l_{c0}/b_0)$	are the length of separation zone behind an unstreamlined body of the projection type in a restricted stream and in an unrestricted stream, respectively;
l_{c1} $(\bar{l}_{c1} = l_{c1}/b_0)$,	
l_{c2} $(\bar{l}_{c2} = l_{c2}/b_0)$	are the length of longer and of shorter separation zone behind twin projections in a channel;
ν	is the kinematic viscosity;
u_∞, u_0	are the mean velocities in a channel in front of an unstreamlined body and at a projection section, respectively;
$Re = u_\infty d/\nu$	is the similarity (Reynolds) number;
k	is a coefficient;
$\psi = f/F$	is the channel obstruction factor;
ψ_{opt}	is the optimum channel obstruction factor.

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