A NOTE ON CALCULATING LOSSES IN DIFFUSER ELEMENTS

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In connection with recent attempts to extend the method of designing conical diffusers proposed in [4] to curved diffusers and, in general, to any diffuser element [1, 2] without proper critical analysis of the basic method, it would appear advisable to reexamine its underlying assumptions.

At present, losses in diffusers are assumed to be divided into friction losses ζ_f and expansion losses ζ_e, which have been estimated, in the general case, by the authors of [1, 2] using the formulas

$$\zeta_f = \frac{\xi}{4}\int_1^n \frac{df}{f^3 \sin(\alpha/2)}, \tag{1}$$

$$\zeta_e = 2\int_1^n \varphi(\alpha)\left(1-\frac{1}{f}\right)\frac{1}{f^2}\,df, \tag{2}$$

where

$$\xi = 0.314\,\mathrm{Re}^{-1/4}.$$

When α = const, (1) and (2) assume the usual form [4]

$$\zeta_f = [\xi/8\ \sin(\alpha/2)](1-1/n^2), \tag{3}$$

$$\zeta_e = \varphi(1-1/n)^2. \tag{4}$$

The above division of losses is the result, on the one hand, of a serious mistake made in deriving (1) and (3), and, on the other, of a purely formal treatment of the term "expansion losses."

Indeed, in deriving (1) the friction coefficient was assumed constant and independent of the expansion ratio of the diffuser; moreover, it was calculated from the Blasius expression [2, 5] obtained for the main part of a cylindrical tube, i.e., for the zone with a steady-state velocity profile over the cross section and fusion of the boundary layer developing at the walls of the tube. The section where the Blasius formula is applicable is normally located at 20-40 diameters from the tube entrance. At the same time, in analyzing flow in a diffuser, it should be noted that a boundary layer and a potential core may exist over much of its length.

To illustrate this point, Fig. 1A gives the results of a calculation of the boundary layer in a plane diffuser with expansion ratio n = 2 and relative length L/D_i = 6.6; it is clear that fusion of the boundary layer occurs in the outlet section, and the whole flow may be divided into a boundary layer region adb and a potential flow region abc.

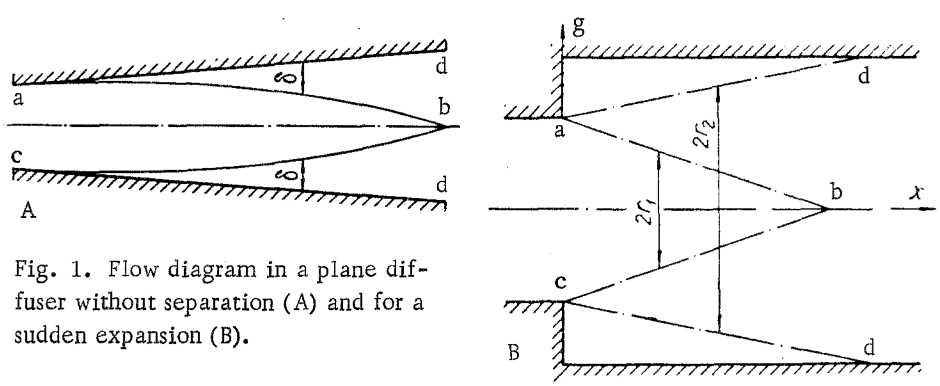

Fig. 1. Flow diagram in a plane diffuser without separation (A) and for a sudden expansion (B).

It should also be noted that the velocity profile in a diffuser section located beyond the initial section differs substantially from that in the main part of a tube, for which the Blasius formula was obtained.

Therefore, the use of this formula to calculate friction losses is incorrect, and is to some extent equivalent to determining the losses at the entrance of a tube from relations valid for its main part. The friction losses calculated from (1) therefore differ appreciably from the experimental values.

This difference may be reduced considerably if in the expression for ξ we use as the characteristic dimension not the hydraulic diameter, but the boundary layer thickness [5]. In that event, however, ξ becomes a function of the velocity distribution along the axis of the diffuser, i.e., a function of the expansion ratio of the diffuser, n, and the integration of (1), even for α = const, is considerably more complicated.

If we also take into account the difference between the velocity profiles in a diffuser and in a tube, we can reduce all the losses in a diffuser without separation to friction losses alone, without resort to physically doubtful expansion losses.

Such calculations, carried out in [3] for plane diffusers without separation, led to a formula analogous to (3), but with a coefficient ξ_1 depending on the expansion ratio and the relative length of the diffuser (L/D_i):

$$\xi_1 = 0.24n^{1.75}/\mathrm{Re}^{0.2}(L/D_i)^{0.2}. \tag{5}$$

A calculation based on [5] showed satisfactory agreement with the experimental data.

Let us examine further the significance of expansion losses [4]. It is clear from the foregoing that for diffusers without separation these losses are a kind of compensation for the incorrectly calculated friction losses, and from this viewpoint are also friction losses. Indeed, their very definition shows this:

$$\xi_e = \xi_0 - \xi_f.$$

It is, however, easy to show that (4) includes (5) and is a general formula for calculating the internal diffuser losses, comprising friction losses and losses in eddy zones, when separation occurs.

Indeed, the losses in conical and plane diffusers are functions of the Mach number M, Reynolds number Re, and the geometric parameters, for which any two of the following three quantities may be taken: expansion angle α, relative length L/D_i, and expansion ratio n, i.e.,

$$\zeta_0 = f(\mathrm{M}, \mathrm{Re}, \alpha, n). \tag{6}$$

Expanding (6) as a series in powers of 1/n and truncating it at the quadratic term, we obtain:

$$\zeta_0 = \varphi_0(\mathrm{M}, \mathrm{Re}, \alpha) + \varphi_1(\mathrm{M}, \mathrm{Re}, \alpha)\frac{1}{n} + \varphi_2(\mathrm{M}, \mathrm{Re}, \alpha)\frac{1}{n^2} + \ldots = \varphi_0\left[1 + \frac{\varphi_1}{\varphi_0}\frac{1}{n} + \frac{\varphi_2}{\varphi_0}\frac{1}{n^2} + \ldots\right]. \tag{7}$$

As the expansion ratio is reduced, its influence declines, and at n = 1 neither this quantity nor α are important. We may therefore write

$$(\partial\zeta_0/\partial n)_{n=1} = 0. \tag{8}$$

It follows from (8) that $\varphi_1/\varphi_0 = -2\varphi_2/\varphi_0$. The remaining coefficients φ_0 and φ_2 must be determined on the basis of experimental data. With the ratio φ_2/φ_0 constant and equal to unity, in the first approximation Eq. (7) takes the form

$$\zeta_0 = \varphi_0(1 - 1/n)^2, \tag{9}$$

where the empirical coefficient φ_0 is a function of the angle α and the flow parameters, the influence of which is, according to experiment, small when $M < 0.4$ and $\mathrm{Re} \approx 10^5$-10^6, i.e., in (9) we may assume $\varphi_0 = \varphi_0(\alpha)$.

It is easy to see the equivalence of (9) and (4). However, if φ_0 is simply an empirical value representing the internal losses in the diffuser, and if, for unseparated flow at large n, (9) gives the same numerical values as (5), then $\varphi < \varphi_0$ in (4) does not reflect the physical nature of the losses occurring in the diffuser.

In separated flow, when the wetted surface, and hence the friction losses in the boundary layer are reduced, φ_0 $\varphi_0 \to \varphi$, and in the case of a sudden expansion $\varphi_0 = \varphi = 1$.

The losses for this particular flow have been called expansion or impact losses. This terminology, which does not reveal the true nature of the losses at a sudden expansion, led as a result of a format treatment to the division of diffuser losses into friction and expansion losses, although the latter, as calculated from (4), give a certain part of the internal diffuser losses as a fraction of the sudden expansion losses. It is easy to establish, from a consideration of the free-stream flow (Fig. 1B), that here, too, the fundamental physical cause of the losses is friction.

Indeed, in the sudden expansion of the flow area of a cylindrical channel in a free jet, it is possible to distinguish, as in a diffuser, a "potential" core abc and a region cbd where the velocity across the jet changes from the core value to zero on some line cd. In this case a circulation flow is established in the region bad, the intensity of which, according experiment, is very small for axisymmetric channels.

A typical velocity distribution in the region cbd, taken at different distances from the entrance section (Fig. 2), indicates that the velocity profile obtained closely resembles the preseparation profile in a diffuser, i.e., in the region in question the flow is similar to that in the diffuser boundary layer.

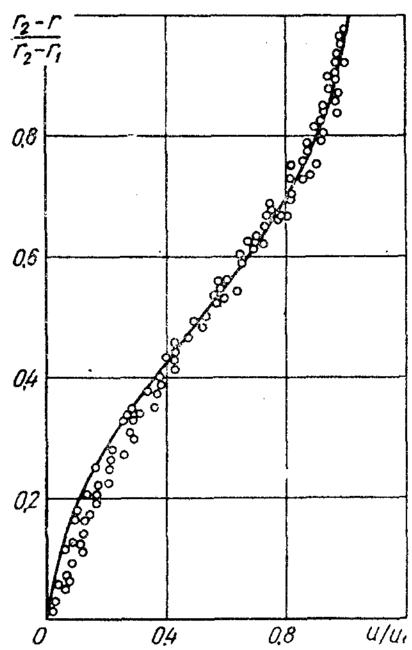

Fig. 2. Velocity profiles along a jet with a sudden expansion of the flow.

Measurements show that all the losses in the jet are concentrated in the region bcd and are essentially friction losses in this conventional boundary layer.

Thus the term "expansion" losses does not represent any new kind of loss, but only expresses the fact that losses in axisymmetric and plane diffusers may be represented as a fraction of the losses occurring at a sudden expansion.

Consequently, the simultaneous use of formulas (1), (2) or (3), (4) is meaningless from the viewpoint of the flow mechanism in diffusers, and the single formula (9) is quite sufficient for diffuser calculations, if the experimental dependence for the coefficient φ_0 is known.

Considering now the question of the possible extension of (2) to include calculations for curved diffusers, it should be noted that then the function φ_0 should not be considered as depending only on the local expansion angle α, since the number of characteristic geometric parameters is considerably greater for these diffusers, and φ_0 now depends, not on one, but on four dimensionless values, the influence of which is not yet adequately understood.

Moreover, formal integration of (2) makes it appreciably more difficult to analyze the influence of the various factors on the operation of diffuser elements.

Thus, it is more promising to seek a solution of the problem on the basis of the general concepts of the aerodynamics of the mechanism of losses.

NOTATION

ζ_f – friction losses; ζ_e – expansion losses; α – local diffuser angle; φ – impact damping coefficient; n – expansion ratio; ξ – friction coefficient; F – variable area of diffuser; F_i – area at diffuser inlet; $f = F/F_i$; $Re = u_i D_i/\nu$ – Reynolds number, based on hydraulic diameter and velocity at diffuser inlet; L – length of generator of diffuser; ζ_0 – coefficient of internal losses in diffuser; u_1 – velocity in potential core; u – velocity in boundary layer; ν – kinematic viscosity.

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