CALCULATION OF LOSSES IN DIFFUSERS

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Calculations on diffusers are difficult, particularly in the presence of flow separation. Moreover, in engineering practice, separation is the rule, since attached flow is possible only at small angles, which means large, usually unacceptable dimensions. The lack of a theoretical basis for such diffusers, on the one hand, and the existing demand for them, on the other, have led to the formulation of simple methods of calculation, based on a generalization of test data. In developing these methods it is natural to compare the experimentally observed losses with values determined by analogy with what has been done for tubes on the basis of one-dimensional considerations. If it is assumed that at each section of a diffuser the friction coefficient ζ is the same as in a tube, then the loss coefficient for a conical diffuser found in this way will be [1]

$$\xi_f = \frac{\zeta}{8\sin(\Theta/2)}\left(1-\frac{1}{n^2}\right), \tag{1}$$

where n is the expansion ratio and Θ the expansion angle. Accordingly, losses computed in this way are conventionally called friction losses.

It turns out that the loss coefficient ξ found experimentally exceeds ξ_f, the difference being greater, the greater the expansion angle of the diffuser. The difference $\xi_d = \xi - \xi_f$ is called the expansion loss coefficient. Experimental data [1] for conical diffusers have shown that the quantity

$$\varphi = (\xi - \xi_f)/(1-1/n)^2 \tag{2}$$

depends on the expansion angle and is practically independent of n. Knowledge of the experimental relation $\varphi(\Theta)$ has made it possible to develop a method for calculating diffusers with straight generators, which are widely used in various branches of engineering.

This method has been extended to curved diffusers by introducing local expansion angle [2].

It should be noted that at comparatively large expansion angles, when flow separation occurs, which is the most frequent case in engineering situations, the above methods are apparently most reliable. Moreover, in view of the absence of an adequately developed theory of separated flow, it is still not possible to formulate an effective method of designing separated-flow diffusers based on a multidimensional model of a viscous fluid.

As regards small-angle diffusers without separation, modern methods of boundary layer theory allow the losses to be determined in the simplest cases [3, 4]. Such methods, however, are very laborious, because of the need to allow for the boundary layer reaction. Nevertheless, use of the methods of boundary layer theory allows one, in principle, to modify the described method for designing diffusers [1, 2]. Notably, the coefficient ξ_f should not be found from (1), but should be determined from the calculated boundary layer data up to separation [3, 4]. Knowing ξ_f and the experimental dependence of ξ on Θ and n, we can still find the dependence of φ on Θ and n from (2). If it turns out, as before, that φ is practically independent of n, then the function $\varphi(\Theta)$ may be taken as the basis of a modified method of calculating losses in the diffuser. In this case, the division of the losses into two parts would have greater justification.

It should be noted that modification of the method would lead to improvement in designing small-angle diffusers and would make practically no difference in the majority of diffuser applications, since separation occurs close to the entrance section.

This point of view was discussed in detail at the 1960 All-Union Conference on Diffuser Design at Kiev, where a controversy arose over Zaryankin's papers [8] and [5-7]. Zaryankin argued against dividing the losses in diffusers into friction losses and expansion losses. If it is merely a question of names, such a dispute is superfluous, since the components ξ_f and ξ_e of the total losses need not, in general, be given names at all. The results of a calculation do not depend on this at all. As far as the physical meaning of the coefficients is concerned, calling ξ_f the friction coefficient in the modified method described above is actually more natural. The situation described is well known to workers in the diffuser flow field, and the insistence with which Zaryankin repeats his explanation in each paper [5-8] is surprising.

On this note the matter might rest, but unfortunately there are several errors in papers [5-8], of which the most important are analyzed below.

1. It is asserted in [5-7] that existing methods of evaluating the losses from the characteristics at the exit sections of the channel are unsuitable, if an appreciable change of velocity occurs there. It is obvious, however, that in any case

the losses are determined by the values of the pressure and the velocity distributions at the entrance and exit sections. In the case of an external problem, the pressure at the end section is determined by the potential flow, with allowance for the boundary layer reaction (see [9], for example). In the case of channel flow with a potential core, the pressure at the channel exit is determined by the integral characteristics of the boundary layer and the area ratio n of entrance and exit sections. On the basis of these arguments, for unseparated flow in channels with a potential core it is easy to obtain a formula giving the loss coefficient ξ as a function of n and the conventional boundary layer thicknesses at the exit section [3].

The attempt to derive a similar formula with the same assumptions in [5-7] contains a crude error in that the author takes what are essentially variables out from behind the differentiation sign. This error was pointed out in a review of paper [5]. As a direct result of this error, Zaryankin obtained a formula for ξ, from which stemmed the above erroneous assertion that ξ is not determined solely by the characteristics at the end section of the channel. A similar mistake was also overlooked in calculating the losses in annular diffusers [6].

2. There is thus no doubt that it is possible to determine the losses from the formula given in [3]. The only question is in the method of calculating the boundary layer thickness at the end section. It is known that, when there are large positive pressure gradients, single-parameter methods of calculation give very approximate values of the boundary layer thickness. It is precisely in the unreliability of the method of calculating the conventional thicknesses at large pressure gradients that we ought to seek the cause of the discrepancy between the experimental data and theory. It is therefore quite inconclusive that in an experiment on one diffuser ($n = 2$, $\Theta = 10°$) Zaryankin [5] obtained better agreement with his incorrect formula than with the correct formula of [3]. It is even less convincing that the internal losses in the diffuser concerned are small compared to the losses due to the exit velocity and are determined from the experimental data as the small difference of two large numbers. Agreement is obtained in [7] between experimental and theoretical data for a diffuser with $\Theta = 10°$ and $n = 3.46$. This agreement can only create confusion, however, since Zaryankin showed in [5] that in this diffuser separation must occur at a section where n is somewhat greater than 2, while the theoretical formula was derived on the assumption of attached flow.

3. In [8] the author attempted to justify theoretically for all angles Θ the formula

$$\xi = \varphi(1 - 1/n)^2, \tag{3}$$

in which φ is a function only of the expansion angle. The derivation of (3) contains a number of errors and unsupported assumptions. The author expands $\xi = f(\Theta, n)$ in a power series in $1/n$:

$$\xi = \varphi_0 + \varphi_1 \frac{1}{n} + \varphi_2 \frac{1}{n^2} + \ldots, \tag{4}$$

truncates the series at the term containing $1/n^2$, and then puts $n = 1$ in determining the coefficients in the expansion. The unsoundness of this procedure hardly needs explanation. Moreover, for some reason it is assumed that $\left.\frac{\partial \xi}{\partial n}\right|_{n=1} = 0$, while the ratio φ_2/φ_0 is constant and even equal to unity. Such arbitrary assumptions about the coefficients of (4) could result in any formula.

As regards the use of the well-known representation of losses in the form (3), the value of this formula lies in the fact that at sufficiently large Θ, φ is found in practice to depend only on Θ, and therefore there is only one function $\varphi(\Theta)$ requiring experimental determination. This function has been found on the basis of a large number of experiments. The use of (3) ceases to make sense at small angles Θ, because then φ depends appreciably not only on Θ, but also on n. In view of this, experimental determination of $\varphi(\Theta, n)$, is equivalent to experimental determination of $\xi(\Theta, n)$, and for small angles there is no advantage in representing the losses in the form (3). This is precisely why it becomes necessary to separate the friction losses or the losses in the unseparated part of the diffuser.

We note, finally, that in [8] the wish is expressed that the "general concepts of aerodynamics" be applied to determine losses in curved diffusers. The authors of this note concur in this wish, but deem it advisable that, while general methods of calculating viscous fluid flow are being evolved, efforts should also be directed to creating engineering methods of design based on the generalization of experimental results. One such attempt was made in [2] and later in [10, 11].

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A NOTE ON THE CALCULATION OF FLOW FRICTION IN CHANNELS WITH AND WITHOUT SEPARATED FLOW

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The theoretical determination of total pressure losses and other aerodynamic parameters in two-dimensional and axisymmetric channels is often difficult. In connection with the recent appearance of certain misleading papers on this subject and the existing confusion of terminology, further discussion is very desirable.

In the two preceding notes two main questions were raised: the use of methods of boundary layer theory to calculate hydraulic losses in unseparated diffuser flow and the possibility of dividing losses in diffusers with separated flow into "friction losses" and "expansion losses" using generalized empirical relations.

Zaryankin is right in criticizing the lack of a physical basis for dividing the losses in diffusers into two components This was clear even to the author of the method, Idelchik, who stressed that the separation was arbitrary [1]. It is difficult to agree with Zaryankin, however, when he rejects the approximate engineering method, without offering anything in its place other than the statement that a solution of the problem is desirable "on the basis of the general concepts of the aerodynamics of the mechanism of losses" [26].

The status of both issues is correctly outlined in [27], where a sound review of Zaryankin's position is offered.

Let us discuss the above points in more detail.

An arbitrary division of the total pressure losses in diffusers into two components ("friction losses" and "expansion losses") was proposed by Idelchik in deriving an engineering method for calculating the losses in diffusers for all possible values of the expansion angle [1]. Since the so-called "friction losses" are very small at comparatively large expansion angles, while the "expansion losses" are determined on the basis of a generalization of the experimental data, it is natural that Idelchik's proposed interpolation formulas for not very small diffuser expansion angles should give results close to reality.

Both terms – "friction losses" and "expansion losses" – are very imprecise. If, in using the term "friction losses," we have in mind friction within the fluid, then the term "expansion losses" loses its meaning, since all the losses stem from viscosity of the fluid, i.e., friction. Since the quantitative determination of the friction losses involves calculating the friction force at the walls of the diffuser channel, the question arises whether the friction losses may not be reduced to friction at the walls. In this case it would be wrong to assert that in diffusers without separation only friction losses occur. Indeed, in unseparated flow of a fluid in a diffuser, the total pressure losses are due both to fluid friction at the diffuser walls and to deformation of the velocity field in cross sections of the diffuser ("expansion losses").

This remark will become clear enough after examination of the possible patterns of unseparated flow in channels with straight axes. This is especially desirable in that in both notes, in speaking of the application of the methods of boundary layer theory to the calculation of flow in diffusers, the authors have in mind only one particular flow system, namely, flow with a potential core. However, a much wider class of unseparated flows may be studied by the methods of boundary layer theory.

Linear stabilized flow in channels of constant cross section. It is known that this flow becomes steady at quite large distances from the inlet. The dynamic pressure at individual cross sections of the tube is then constant, as a result of which the total pressure losses are wholly determined by the static pressure drop along the flow. Only in this special case are the hydraulic losses in a tube uniquely associated with the friction coefficient at the wall. Thus, for example, in the case of an annular tube (inside radius r_2, outside r_1), the following relation holds [3]: