A NEW METHOD OF EXPERIMENTAL DETERMINATION OF SURFACE FRICTION IN A TURBULENT BOUNDARY LAYER

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A description is given of the construction and of the results of an investigation of a new miniature friction gauge which is insensitive to the downwash of the oncoming stream.

1. The method of balance measurement of the frictional force using a "floating element" has come to be considered the most reliable in the zero-gradient flow of a liquid or gas. This measurement method, however, is distinguished by extreme complexity and demands great skill of the experimenter. Moreover, it is not applicable in practice when a longitudinal pressure gradient is present in the stream. Indirect methods of friction measurement, based on one or another assumptions about the character of the flow in the boundary layer, are widely used in experimental practice. It was shown in [1] that under the conditions of a turbulent stream with a longitudinal pressure gradient preference should be given to those indirect methods based on a linear velocity distribution in the boundary layer, valid in the immediate vicinity of the wall not only in a zero-gradient stream but also in streams with $dP/dx \neq 0$. These methods are based on the use of miniature friction gauges whose size is comparable with the thickness of the viscous sublayer of the turbulent boundary layer. It also follows from [1] that for miniature friction gauges located directly at the surface over which the flow occurs, the calibration equations obtained with $dP/dx = 0$ also remain valid for the case of nonseparation flow with a longitudinal pressure gradient.

In the case of flow over bodies of complicated and arbitrary shape with a longitudinal pressure gradient, when the direction of the stream velocity vector over the surface of the body over which the flow occurs is not strictly determined, it becomes necessary not only for the friction gauge to have a small size but also that the gauge readings not depend on the downwash of the stream.

The construction and the results of an investigation of a new "protruding-tube" friction gauge which satisfies all the above-indicated requirements [2] are described in the present article.

2. The construction of the "protruding-tube" friction gauge under investigation (Fig. 1) consists of a round cylindrical tube with a diameter D having an open end, mounted perpendicular to the surface over which the flow occurs, and projecting above it by a very small fixed distance h not exceeding 0.4-0.5 mm.

The measured value of the shear stress τ_w is a function of the pressure drop ΔP, defined as the difference between the pressure P' at the open end of the cylindrical tube when it protrudes slightly into the stream and the static pressure P_{st} at the surface over which the flow occurs, when the tube is set flush with the surface (initial position). The calibration function for the friction gauge is constructed in the Preston variables [3]

$$\frac{\tau_w h^2}{4\rho\nu^2} = f\left(\frac{\Delta P h^2}{4\rho\nu^2}\right),$$

which follow from the "wall law"

$$\frac{u}{u_*} = f\left(\frac{y u_*}{\nu}\right).$$

Here $u_* = \sqrt{\tau_w/\rho}$, ρ and ν are the stream density and viscosity, and y is the distance from the wall.

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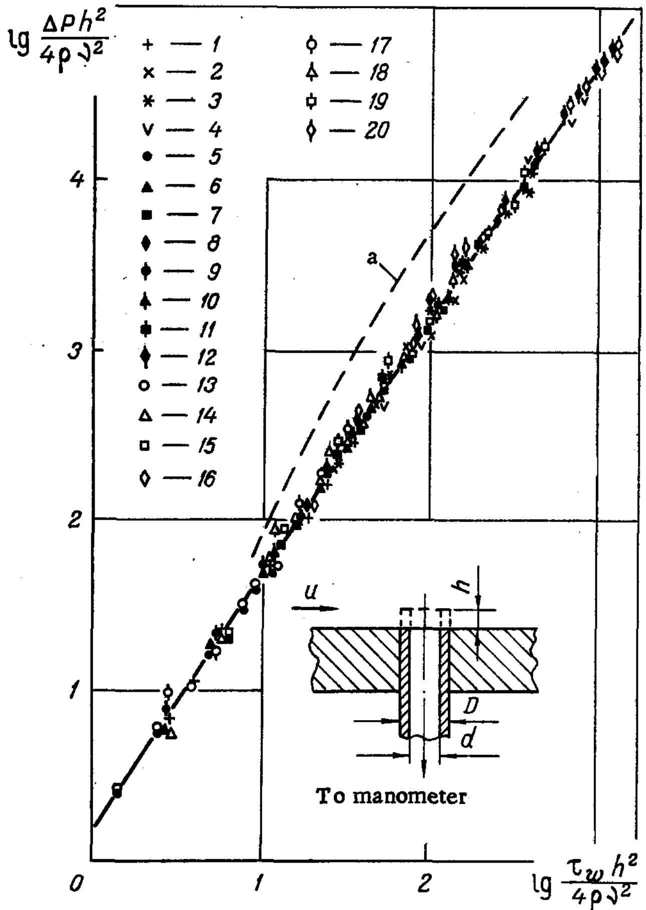

Fig. 1. Calibration function for "protruding-tube" friction gauge. With d/D = 0.5, D = 1 mm: 1) h/D = 0.1; 2) 0.2; 3) 0.3; 4) 0.5. With d/D = 0.6, D = 1 mm: 5) 0.1; 6) 0.2; 7) 0.3; 8) 0.5; D = 2 mm: 9) 0.1; 10) 0.2; 11) 0.3; 12) 0.5. With d/D = 0.7, D = 1 mm: 13) 0.1; 14) 0.2; 15) 0.3; 16) 0.5; D = 2 mm; 17) 0.1; 18) 0.2; 19) 0.3; 20) 0.5. a) Calibration curve for a "Preston-tube" friction gauge with an outer diameter D with h = D.

The working characteristics of the "protruding-tube" gauge were investigated at Reynolds numbers Re** = 10^3–$3 \cdot 10^3$ and stream velocities of up to 30 m/sec. The boundary layer was generated at a side wall of the working section of a wind tunnel. The longitudinal pressure gradients were created with the help of profiled inserts mounted in a measurement compartment on the opposite wall of the wind tunnel.

As the control values of the shear stress we used values of τ_w measured with a gauge having a heated element [4], set flush with the surface over which the flow occurs, which has obtained wide popularity both in domestic and foreign practice. The gauge having a heated element (thermal gauge) was preliminarily calibrated under conditions of a zero-gradient stream using a balance measurement of the frictional force [5].

Five "protruding-tube" gauges with different values of D and different ratios of the inner to the outer tube diameter (d/D) were subjected to investigation, and the value of h/D was varied within wide limits. The results of the investigation for dP/dx = 0 are presented in Fig. 1. As is seen, the test points for all the investigated "protruding-tube" gauges and at all the values of h/D considered can be described by a single function with an approximation acceptable for practical purposes:

$$\frac{\tau_w h^2}{4\rho\nu^2} = 0.776\left(\frac{\Delta P h^2}{4\rho\nu^2}\right)^{0.668}.$$

A calibration curve (see [5]) for a "Preston-tube" friction gauge [3] is also presented in Fig. 1 for comparison. As is seen, the "protruding-tube" friction gauge and the "Preston-tube" friction gauge have about the same sensitivity.

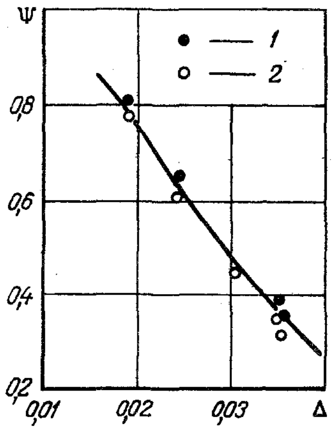

Fig. 2. Dependence of relative coefficient of surface friction on form parameter of pressure gradient: 1) "protruding-tube" friction gauge; 2) thermal friction gauge.

The results obtained can also be used to estimate the errors in measuring static pressure due to drain tubes projecting above the surface over which the flow occurs, similar to the way this was done in [6].

We also investigated the influence of a "protruding-tube" gauge protruding into the stream on the static pressure distribution over the surface over which the flow occurs in the case when one of the ready-made drain openings for static pressure is used in mounting the gauge. It was found that in a zero-gradient stream the protrusion of a "protruding-tube" gauge by a height of up to 0.5 mm above the surface over which the flow occurs gives an insignificant deviation (up to 1%) in the values of the static pressure both upstream and downstream from the gauge. This makes it possible in some cases to simplify the process of friction measurement by determining P_{st} using the drain openings.

The experimental dependence of the relative coefficient of surface friction $\Psi = (c_f/c_{f_0})_{Re^{**}=idem}$ on the form parameter $\Delta = (\nu/\rho u^3_*)dP/dx$ of the longitudinal pressure gradient is presented in Fig. 2. Here c_{f_0} and $\bar{c}_f$ are the values of the surface friction with $dP/dx = 0$ and $dP/dx \neq 0$, respectively. The values of Ψ were determined both with the "protruding-tube" friction gauge and with a control thermal gauge, which allows one to obtain the most reliable results [1], under conditions when the direction of the velocity vector of the stream flowing onto the gauge was strictly defined. The latter condition is necessary in the case of the measurement of surface friction with a thermal friction gauge. For a "protruding-tube" gauge, built in the form of the end of a round tube protruding above the surface, the direction of the stream flowing onto the gauge does not affect its readings.

As is seen, good agreement is observed between the values of Ψ measured by the two gauges, which indicates the workability of the "protruding-tube" friction gauge in the presence of a longitudinal pressure gradient in the stream.

The fact that the calibration equations for a "protruding-tube" friction gauge depend weakly on its geometrical dimensions, on the one hand, while the simplicity of construction of the gauge assures good reproducibility of its geometry during fabrication, and hence reproducibility of its calibration equations, on the other hand, makes the use of a "protruding-tube" detector very convenient in practical measurements. Its small size and the independence of the readings from the downwash of the stream are also advantages of the gauge.

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MASS TRANSFER FROM A SINGLE BUBBLE TO THE DENSE PHASE OF A FLUIDIZED BED AT LARGE PECLET NUMBERS

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Possible modes of mass exchange between a growing bubble and the dense phase under conditions of predominance of convective transfer are discussed.

The productivity and quality of operation of catalytic chemical reactors and of a number of other apparatus containing an inhomogeneous fluidized bed depend on the intensity of gas exchange between the dilute and dense phases of the bed. The determination of the corresponding coefficient of mass exchange, which plays a very important role in modern systems of calculation of such apparatus (see the review in [1-3], for example), represents one of the central problems in modeling them.

The number of experiments on the determination of mass-exchange characteristics is very large (there is also a summary of them in [1-3]), but generalizing correlations which would permit the construction of a complete representation of the variation of these characteristics with variation in the fluidization conditions and of ways to intensify mass exchange are practically absent. This is connected both with the variety of the mechanisms of mass transfer in two-phase systems and of the factors influencing it and with the fact that the majority of the experimental data have been obtained by indirect means (by methods of a model chemical reaction or a tracer gas) from a comparison of the observed concentrations of the reagents at the exit from the reactor or of washing curves with results following from one or another model.

A theoretical analysis of the specific roles of different mechanisms of the process of mass transfer under different conditions and possible limiting modes of realization of the process becomes especially necessary under such conditions. Very little has been done in this direction up to now. The theoretical model in [4], within the framework of which only the mass exchange of a bubble with the cloud of closed gas circulation surrounding it was allowed for, neglecting the diffusional resistance of the dense phase, evidently was the first. Unfounded assumptions of such a type were adopted later in [5-7]. Conversely, an equally unfounded assumption about the total gas mixing in the bubble and the cloud was adopted in [8, 9], and then in [10] also, and attention was concentrated on the investigation of convective diffusion in the dense phase outside the cloud. An attempt made by Kunii and Levenspiel [11] to simultaneously allow for the resistance to mass exchange both outside and inside the cloud has an especially empirical character.

It is important that in all these reports the influence of the variation of actual bubbles as they rise in a bed on the mass exchange was entirely ignored. The volume of bubbles which are not too small grows in the process, i.e., there is a gas flux directed into the bubble. The convective transfer by this flux must hinder the removal of an impurity into the dense phase and, conversely, facilitate its penetration into the bubble, which is confirmed, in particular, by the tests in [12, 13], conducted on a plane model of a bed containing "two-dimensional" bubbles. The necessity of allowing for the influence of the growth of a bubble on its mass exchange with the dense phase was noted in [14, 15], where a theoretical analysis of the motion and growth of a bubble in a developed fluidized bed was proposed. Experimental data on bubble growth obtained by various authors are discussed in [16, 17], where empirical relations are proposed for the description of this effect.

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