NOTATION

a, channel height; ℓ, channel length; $L = \ell/a$, reduced channel length; $\mathbf{r} = (x, y)$; P, pressure; T, temperature; m, molecule mass; $v_t = (8kT/\pi m)^{1/2}$, mean thermal velocity; f, distribution function; λ, mean free path; k, Boltzmann constant; η, dynamic viscosity; $\mathbf{c}$ and , reduced velocities of molecules and gas; $\mathbf{q}$, heat-flux density; J_k, thermodynamic flows; $\Lambda_{k\ell}$, kinetic coefficient; h, perturbation function; X_k, thermodynamic forces. Subscripts: x, y, longitudinal and transverse components.

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STATIC PRESSURE MEASUREMENT ERRORS WHEN DRAINAGE ORIFICES ARE USED

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We present the results from an experimental study of the influence exerted by the characteristic dimensions of a drainage orifice on the static-pressure measurement error.

Static pressure in a moving medium is usually measured by means of drainage orifices located on the streamlined surface. However, the presence of such orifices on the streamlined surface unavoidably leads to the perturbation of the flow in the boundary layer near that orifice and, consequently, to a deviation in the measured static pressure from the true value. The size of the perturbation zone near the drainage orifice depends on the diameter (d) of the orifice. It was demonstrated in [1] that these perturbations are propagated primarily through the thickness of the boundary layer and the thickness of the perturbation zone in this case varied from d/10 to d/40.

According to [2], the streamline adjacent to the streamlined surface, as it descends into this drainage pore, leads to the appearance of a field of centrifugal forces, as a consequence of which the pressure within the hole exceeds the actual pressure. The instability of the process involved in the formation of a system of vortices within the static-pressure hole also exerts its influence on the magnitude of the static pressure. In a number of cases, it is possible for the Pitot effect to set in at the edge of this hole downstream. When the stream is detached from the leading edge of the drainage orifice, the measured pressure (P_{meas}) will be smaller than the true pressure (P_{tru}). All of this may

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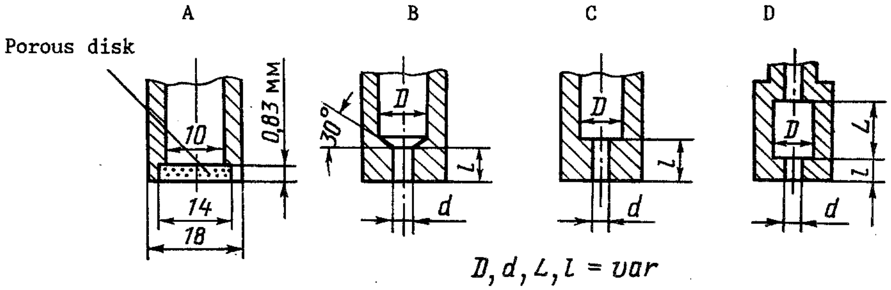

Fig. 1. Types of drainage inserts.

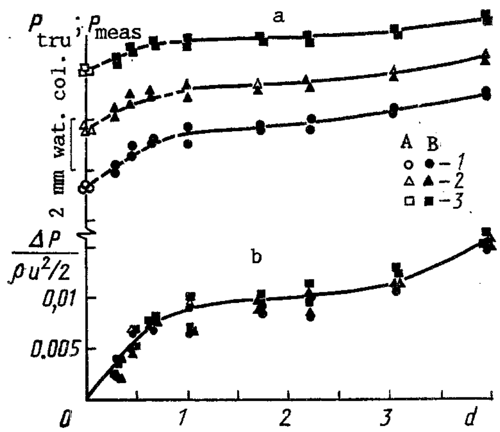

Fig. 2. Static pressure as a function of the diameter of the drainage orifice: a) absolute value of static pressure; b) ratio of the quantities P_{meas} and P_{tru} to the velocity head at the channel axis: 1) u = 60 m/sec; 2) 54 m/sec; 3) 47 m/sec (d, mm). The open points represent P_{tru} (A type insert), while the filled points represent P_{meas} (B type insert for $\ell/d = 8$ and $D/d = 3$).

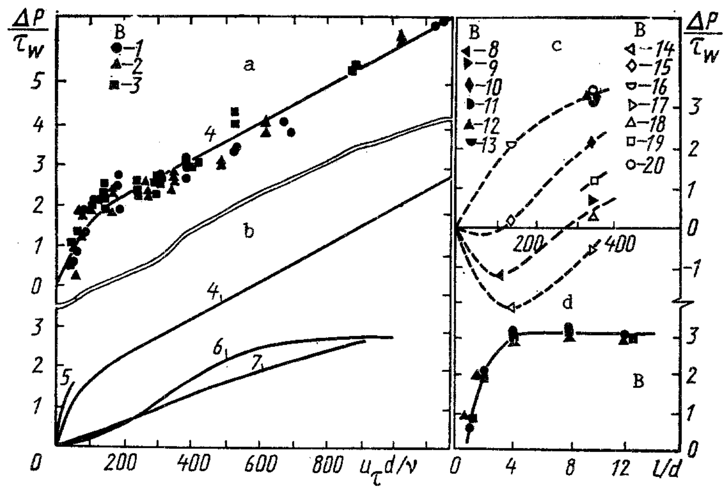

Fig. 3. Effect of the Reynolds number and of relative depth of drainage orifice on the value of the relative measurement error: a) effect of Reynolds number ($\ell/d = 8$ and $D/d = 3$); b) comparison of relationship (3) with experiments [1, 3, 6]; c) effect of Reynolds number for various values of ℓ/d, D/d and d, u = 60 m/sec; d) effect of relative depth of drainage orifice for various flow velocities, $D/d = 3$, d = 2 mm: 1) u = 60 m/sec; 2) 54; 3) 47; 4) relationship (3); 5) [1] ($\ell/d = 1.75$, d = 1-10 mm); 6) [3] ($\ell/d = 1.5$-6, d = 0.64-4.45 mm); 7) [6] ($\ell/d > 5$, d = 0.25-6.35 mm); 8) $\ell/d = 1$ ($D/d = 3$, d = 0.65 mm); 9-13) respectively, ℓ/d = 1, 2, 4, 8, 12 ($D/d = 3$, d = 2 mm); 14-16) respectively, ℓ/d = 0.9, 2, 3 ($D/d = 5$, d = 0.8 mm); 17-20) respectively, ℓ/d = 0.8, 1, 1.8; 3 ($D/d = 5$, d = 2 mm); c) axis of abscissas, i.e., $u_\tau d/\nu$.

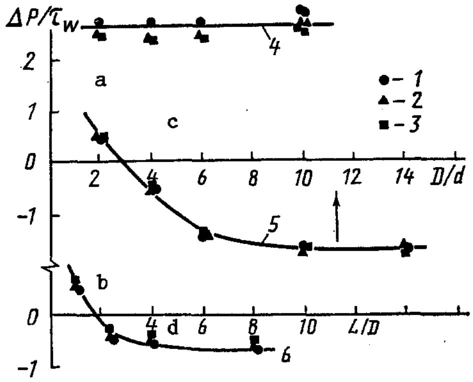

Fig. 4. Relative measurement error as a function of the parameters D/d (a) and L/d (b): 1) u = 60 m/sec; 2) u = 54 m/sec; 3) u = 47 m/sec; 4) ℓ/d = 8, d = 1 mm; 5) ℓ/d = 1, d = 1 mm; 6) ℓ/d = 0.8, d = 2 mm; D/d = 5.

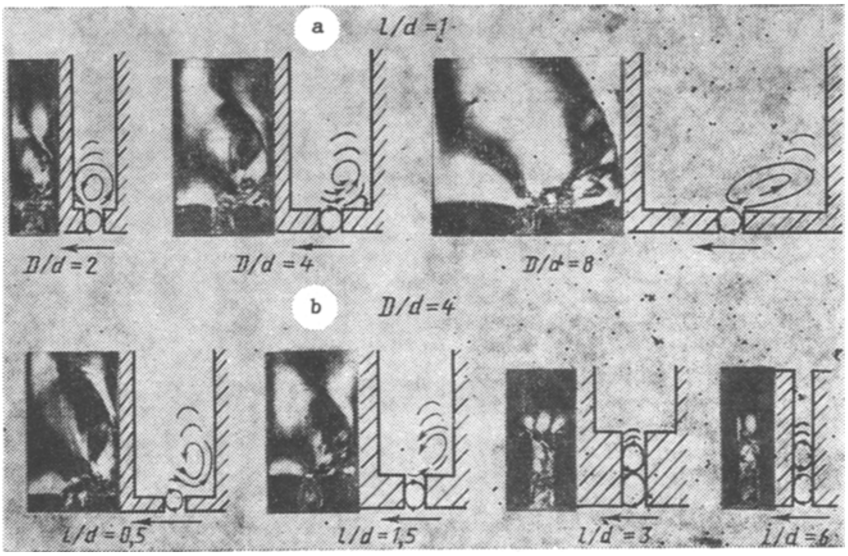

Fig. 5. Visualization of the vortex motion of the liquid within the drainage orifice.

lead to a pronounced distortion of the static pressure measured by means of the drainage pore. The magnitude of the measurement error can be reduced in direct proportion to the extent to which the diameter d of the drainage orifice is made smaller and as d → 0 the measured static pressure will approach the true value.

In the experiments described in [1-3], in which the effect of the geometric dimensions of the drainage orifice relative to the static-pressure measurement error was studied, the quantity P_{tru} was extrapolated to d = 0 for the pressure values measured by means of an entire complex of such drainage holes of various diameters, situated at one and the same point on the streamlined surface. However, because of the technical difficulties involved in the attainment of orifices of such small size, and because of the considerable scattering of the experimental data, determination of P_{tru} through extrapolation of the experimental points proved to be exceedingly unreliable and not uniquely defined. This circumstance turned out to be one of the basic reasons for the poor agreement among the experimental data [1, 3].

In the present article we present new experimental data obtained with a method which eliminates the need to extrapolate the experimental points to d = 0, thus significantly elevating the accuracy in the determination of P_{tru}. The experimental results presented in this article enhance and refine existing data on the question under consideration.

It follows from dimensional analysis that the error in the measurement of the static pressure $\Delta P = P_{meas} - P_{tru}$ can be written in the form:

$$\frac{\Delta P}{\tau_w} = f\left(\frac{u_\tau d}{\nu};\ \frac{l}{d};\ \frac{D}{d};\ \frac{\delta}{d}\right). \tag{1}$$

Here $u_\tau d/\nu$ is the Reynolds number calculated from the diameter of the drainage pore and from the dynamic velocity $u_\tau = \sqrt{\tau_w/\rho}$, where τ_w represents the tangential stress on the streamlined surface at the point at which the drainage orifice is located; ℓ, D represent the depth of the drainage pore and the diameter of the pneumometric discharge channel (see Fig. 1); δ is the thickness of the boundary layer.

Let us also note that in the determination of the relative measurement error we frequently used the ratio of the magnitude of the deviation from true in the measured values of static pressure to the velocity head of the approaching flow ($2\Delta P/(\rho u^2)$).

In the present investigation, as the true magnitudes of the static pressure P_{tru}, we took those values of the pressure that were measured with a drainage pore closed with a porous metal disc made flush with the streamlined surface [4]. The pores within the discs exhibited an average dimension of 10 μm and the surface of the porous disc was aerodynamically smooth. The use of a porous drainage orifice in these experiments, said orifice exhibiting very small pore dimensions, eliminated the need for extrapolation and, consequently, eliminated the possible nonunique definition of P_{tru}. To reduce inertia in the measurement of P_{tru} by means of a porous drain, the static-pressure borehole closed off with the porous disc exhibited a large diameter of 10 mm.

The tests were carried out in a rectangular channel with a closed turbulent boundary layer. The shape of the open portion of the channel and the ratio of the channel width (W) to its height (H) were chosen so that the flow conditions within the channel corresponded to the conditions of a two-dimensional flow ($W/H \geq 6$), while the static pressure dropped linearly along the length of the channel. In this case, the value of the tangential stress is independent of the quantity W/H and constant over the length of the channel (τ_w = const), which significantly elevates the accuracy in the measurement of the tangential stress, which may be determined from the following relationship [5]:

$$\tau_w(x) = -\delta dP/dx, \text{ where } \delta = H/2. \tag{2}$$

The small pressure differences along the length of the channel were recorded with a high-sensitivity alcohol manometer calibrated for 0.003 mm H_2O, in which the alcohol level, the monitoring, and the recording of the readings were all accomplished automatically by means of photodiodes, optical lenses, and an electronic relay control circuit.

Figure 2a shows the change in the static pressure at a given point on the channel wall as a function of the diameter d of the drainage hole at constant values of $\ell/d = 8$ and $D/d = 3$. The measurements were carried out for three flow velocities of 47, 54, and 60 m/sec along the channel axis.

We can see that with a reduction in the diameter of the drainage hole the measured values of the static pressure diminish markedly, and this reduction in the pressure in this case is well coordinated with the true values of the static pressure, measured by means of the porous drainage hole.

Figure 2b shows these same experimental data in the form of a ratio between the deviations $\Delta P = P_{meas} - P_{tru}$ and the velocity head at the channel axis $\rho u^2/2$ as a function of the diameter of the drainage hole.

However, if the experimental data shown in Fig. 2a are presented in dimensionless form $\Delta P/\tau_w = f(u_\tau d/\nu)$, then all of the experimental points fall out on a single curve (Fig. 3a), which can be approximated by the following relationship:

$$\begin{gathered} \Delta P/\tau_w = -0{,}96\cdot 10^{-4}(u_\tau d/\nu)^2 + 2{,}67\cdot 10^{-2} u_\tau d/\nu,\ 0 < u_\tau d/\nu \leqslant 115, \\ \Delta P/\tau_w = 0{,}46\cdot 10^{-2} u_\tau d/\nu + 1{,}27,\ 115 < u_\tau d/\nu < 1150. \end{gathered} \tag{3}$$

Figure 3b shows a comparison of relationships (3) with the experimental relationship obtained in [1, 3, 6]. We can see that all of the curves differ significantly from one another. However, as is demonstrated by an analysis of the experiments conducted in [1] and [3], this divergence falls within the limits of the possible error in the extrapolation of the experimental data to the case d = 0, which was used in these experiments. As regards the experiments performed in [6], where the value P_{tru} was determined through the introduction of correction factors for the measured value of the static pressure, the observed divergence can be ascribed to the lack of validation for the assumptions and hypotheses relative to the nature of the flow perturbations within the area of the drainage hole, under which these correction factors were obtained.

We can draw conclusions with regard to the influence of the geometric shape and the dimensions of the drainage orifice on the measurement error for the static pressure on the basis of the experimental data shown in Fig. 3c, where with consideration of (1) for two typical forms of the drainage orifice (B and C) we find the relationship $\Delta P/\tau_w = f(u_\tau d/\nu)$ for various values of the parameter ℓ/d.

We see that for Reynolds numbers $u_\tau d/\nu < 400$ and for small values of ℓ/d ($\ell/d \leq 2$) the measured static-pressure values may be smaller than the actual, and in this case the smaller ℓ/d, the larger the value of $u_\tau d/\nu$ at which negative values of ΔP are possible. When $\ell/d > 2$ the values of $\Delta P/\tau_w$ assume positive values for all values of $u_\Delta d/\nu$ and increase with an increase in ℓ/d and $u_\tau d/\nu$. However, with $\ell/d \geq 4$ the function $\Delta P/\tau_w = f(u_\tau d/\nu)$ becomes stabilized and at a constant value of $u_\tau d/\nu$ remains unchanged with a further increase of ℓ/d (Fig. 3d). In this case, the measurement error is also independent of the ratio of the diameter of the pneumometric channel to the diameter of the hole, whereas for small values of ℓ/d ($\ell/d = 1$) we observe a clearly expressed relationship $\Delta P/\tau_w = f(D/d)$ (Fig. 4a).

The relationship between $\Delta P/\tau_w$ and D/d with a constant value for $\ell/d = 1$ (Fig. 4a), just as the increase in the values of $\Delta P/\tau_w$ as a function of ℓ/d with a constant ratio D/d = 3 (Fig. 3d) can be explained by the instability of the process involved in the formation of the system of oppositely rotating paired vortices, such as seen in Fig. 5, which represents a visualization of the vortical motion of water in a drainage hole, obtained by means of an optical-polarization method [7].

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