Results are shown of an experimental study concerning the effects of viscosity, of the velocity gradient, and of the wall proximity on the readings of a total-head Pitot tube during the measurement of the velocity distribution in the viscous sublayer region of a turbulent boundary layer.

The use of total-head Pitot tubes for measuring the velocity in a boundary layer directly at the wall involves serious difficulties stemming from the lack of necessary data on the performance of such tubes under these conditions. As is well known, errors may occur in the measurements due to:

a) the effect of velocity gradients in the boundary layer and the effect of the wall proximity on the tube readings,

b) the effect of viscosity, i.e., the inapplicability of the ideal-fluid theory in the interpretation of total-head measurements made directly at the wall, where the Reynolds number is low.

The deviation of the measured velocity distribution in a boundary layer from the true distribution may be related either to the error in determining the magnitude of the velocity or to the error in determining the distance from the tube to the wall. The second alternative of defining the error is usually preferred, a correction being made here for the displacement of the effective center from the geometrical axis of the tube.

The error in velocity measurements due to velocity gradients in the stream has been evaluated in several studies theoretically (e.g., [1, 2]) and experimentally ([3, 4, 5]), but there is no consensus on this subject. Still not enough is known about the effect of the wall proximity on the readings of a total-head Pitot tube; such an effect being dependent on the tube geometry as well as on the flow mode in the boundary layer [5].

Using the total-head Pitot tubes with a small diameter for measuring the velocity in a thin viscous sublayer of turbulent boundary layers makes it necessary to take into account the effect of viscosity on the tube readings. In this case the Reynolds number, when calculated on the basis of local velocity and characteristic tube dimension, is very low and the Bernoulli equation, when derived by integrating the equations of motion simplified by neglecting the viscous forces, does not apply when the velocity is to be found from a pressure measurement with a total-head Pitot tube. The effect of viscous forces, which become comparable to the inertia forces, is to increase the total head relative to the head calculated according to the Bernoulli equation, because now the pressure coefficient $C_p = (P_0 - P)/(\rho U^2/2)$ becomes larger than unity. The data in [6] and [7] pertaining to the effect of viscosity on the readings of a total-head Pitot tube are very much at variance. Furthermore, no tests were made in those studies with the Reynolds number $Re < 10$, which would be of interest for measurements in a viscous sublayer.

For practical purposes it would be worthwhile to know the total correction $\delta_0$ accounting not only for the effect of viscosity but also for the effects of the velocity gradient and the wall proximity on the readings of a total-head Pitot tube.

We will present here the results of an experimental determination of the total correction and its components, to be used when the velocity distribution in a turbulent boundary layer of an incompressible fluid is measured by means of a total-head Pitot tube with a circular or elliptical inlet orifice.

The procedure in this experiment is based on the fact that the effects of viscosity, velocity gradient, and wall proximity are felt directly at the wall, namely in the region of the viscous sublayer where during a nongradient flow of liquid or gas the velocity distribution would be precisely linear (as many measurements by various optical methods have shown). The total correction $\delta_0$ to be applied to tube readings to account for all these effects will be determined by the difference between the true linear velocity distribution and the one measured with a total-head Pitot tube at a wall.

The slope of the line representing the true velocity distribution at a wall may be determined from a measurement of the shearing stress $\tau_w$, the accuracy of such a measurement affecting the reliability of the measured velocity distribution at that wall.

In our tests $\tau_w$ was determined directly by a measurement of the friction force by the weighing method with the aid of a "floating" element. For this, we used a high-sensitivity electromagnetic scale [8] in the 0.5-100 mg range. The relative mean-square error in this determination did not exceed 1.5%.

The magnitude of the correction $\delta_0$ as a function of the distance from a wall is shown in Fig. 1. for different values of the Reynolds number with a circular and with an elliptical total-head Pitot tube. The observed dependence of $\delta_0$ on the Reynolds number, as will be proved subsequently, is due primarily to the effect of viscosity.

The "pure" effect of viscosity on the tube readings was studied in a low-velocity vertical aerodynamic tunnel, especially designed for this purpose, where air was impelled directly from the atmosphere by means of a fan mounted at the outlet of the active tunnel segment (Fig. 2). The total-head Pitot tube for this test was placed along the tunnel axis near the profiled air impeller and beyond the boundary layer building up at its walls. It could be assumed, thus, that $P + (\rho U^2/2) = P_{atm}$ and the pressure coefficient $C_p = 1 + [(P_0-P_{atm})/(\rho U^2/2)]$. For an accurate measurement of the pressure drop $\Delta P = P_0-P_{atm}$, we had developed a differential-type precision U-tube manometer with alcohol as the operating medium [9], with the alcohol level and the instrument readings tracked automatically by means of photodiodes, optical lenses, a relay system, and an electromagnetic plotter. The mean-squared error of the manometer did not exceed $\sigma = 0.01 \text{ mm H}_2\text{O}$ within the $\Delta P = 0-2 \text{ mm H}_2\text{O}$ range. A reduction of the random error was achieved by performing a large number of measurements (up to twenty) under the same conditions.

The values of $C_p$ are shown in Fig. 2 for total-head Pitot tubes with circular and with elliptical inlet orifices. When $Re_R < 30$, evidently, $C_p$ increases sharply and for a circular tube $C_p \approx 2.5$ already at $Re_R = 5$. For a circular tube, the values of $C_p$ obtained in our tests are more than twice as high as