the ratio of peak sizes increasing with enthalpy from a value near zero, and this is not consistent with the presence of a substantial number of O ions due to dissociative ionization. On the other hand, it must be observed that results of the ex tunnel tests shown in Fig. 2c demonstrate that substantial dissociative ionization does indeed take place in air that is supplied from a room temperature source. It may be speculated that this difference is due to thermal excitation of the O_2 molecules in the tunnel flow, leading to an increased velocity spread and consequent lowered collection efficiency of the O ions resulting from dissociative ionization. However, until this apparent anomaly is resolved, some doubt must be attached to the experimental results of Fig. 2c. Therefore, notwithstanding the remark made later concerning their validity, their worth is mainly in indicating the stagnation enthalpy at which the rise in O atom concentration due to freestream dissociation takes place.

The overall ratio of the number of atoms of oxygen in any form to nitrogen in any form can be obtained from the results in Fig. 2. If the ex tunnel result in Fig. 2a is used to generate a calibration factor for the O_2/N_2 ratio, values of 0.33 ±0.04, 0.27 ±0.03, and 0.30 ±0.04 are obtained for the overall ratio at stagnation enthalpies of 8.3, 10, and 12.5 MJ kg^{-1}, respectively. The expected value is 0.27 ±0.05, the quoted error limits resulting from residual uncertainties in the ionization cross sections, together with the mass separation and ion collection efficiencies, after the calibration for the O_2/N_2 ratio has been taken into account. Thus, the values for the overall oxygen/nitrogen ratio fall within the quoted limits of error and provide confirmation of the experimental measurements.

It is worth remarking that, at 12.5 MJkg^{-1}, the measured O/O_2 value in Fig. 2c contributes a substantial 0.08 of the total oxygen/nitrogen ratio of 0.30, thereby providing an indirect confirmation of the O/O_2 measurement.

It can be seen that the experimental measurements in Fig. 2 generally fall outside the theoretical limits indicated by the broken lines. In Fig. 2a the proportion of molecular oxygen exceeds theoretical limits as the stagnation enthalpy is increased. This is consistent with the results in Fig. 2c, which shows the proportion of atomic oxygen remaining at low levels for much higher enthalpies than predicted. The proportion of nitric oxide is shown in Fig. 2b and is seen to be in excess of predicted values, at least for the range of stagnation enthalpies covered by the results. The numerical model[4] on which the theoretical curves are based gives freestream compositions that are consistent with those given by other numerical models.[9] Therefore, even when allowance is made for the experimental uncertainties, there are clear discrepancies between the theory of nonequilibrium nozzle flow and the results of these experiments, indicating a need for further experimental and theoretical work. Until these discrepancies are resolved, predictions of the composition of test section flows in high enthalpy facilities should be treated with caution.

Acknowledgments

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Calibration of Preston Tubes

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Introduction

IN this Note, a simple equation is provided that relates Preston tube pressure output and wall shear stress. The Preston tube technique[1–6] probably is the most convenient method to measure turbulent skin friction. The classical arrangement consists of a pitot tube mounted onto a wall surface. In addition, a hole in the wall in the vicinity is required to measure the static pressure; see Fig. 1. The pressure difference between pitot tube and static pressure hole represents the output Δp of the probe. In some applications,[3] the static pressure is collected by a second tube with one or more holes on its side. This arrangement permits the dual probe to move easily on a given surface. Albeit inferior in its precision to, e.g., floating element balances, a Preston tube produces an accuracy of about 5% or better,[5] which is perfectly satisfactory in many applications. One such application is the determination of the surface shear stress on a wind-tunnel model to select the proper riblet spacing of a drag-reducing riblet film.

Calibration

A general calibration curve relating the output Δp to the wall shear stress τ has been compiled by Rechenberg[3,4]; see Fig. 1. The quantities in this plot are nondimensionalized as follows:

$$\Delta p^+ = \Delta p d^2/\rho \nu^2; \qquad \tau^+ = \tau d^2/\rho \nu^2 \tag{1}$$

where d is the diameter of the probe, and ρ and ν are density and kinematic viscosity of the fluid. The only disadvantage of the data in Fig. 1 is that they are not available in the form of a simple equation being valid over the whole parameter range. Asymptotic equations have been derived for the upper parameter regime, assuming either a logarithmic or a $\frac{1}{7}$ power law for the mean flow distribution. For the latter, the result turns out to be very simple:

$$\tau^+ = \frac{(\Delta p^+)^{\frac{7}{8}}}{19.72} \tag{2}$$

Close to the wall, at low Δp^+ and τ^+, however, the probe is immersed in the Couette-type flow regime of the viscous sublayer, and there Eq. (2) is not valid anymore. With the same momentum considerations as the ones used by Rechenberg[4] to derive Eq. (2), we find for a Couette flow impinging on the probe with circular cross section

$$\tau^+ = 4\sqrt{\Delta p^+/3} \tag{3}$$

Besides fitting the data at low Δp^+ in Fig. 1, this equation also permits the use of Preston tubes in laminar flows. As in turbulent flows, however, the probe size must be significantly smaller than the

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Table 1 Validation of the general calibration formula

	Measured data: $\log(\Delta p/\tau)$			Calculated: $\log(\Delta p/\tau)$,
$\log \Delta p^+$	Rechenberg[3]	Head and Ram[7]	Zurfluh[8]	with Eq. (5)
3	1.150	1.162	——	1.136
4	1.588	1.615	1.582	1.614
5	1.898	1.907	1.898	1.906
6	2.063	2.064	2.062	2.044
7	2.176	2.182	2.180	2.170
8	2.290	2.296	——	2.295
9	2.402	——	——	2.420

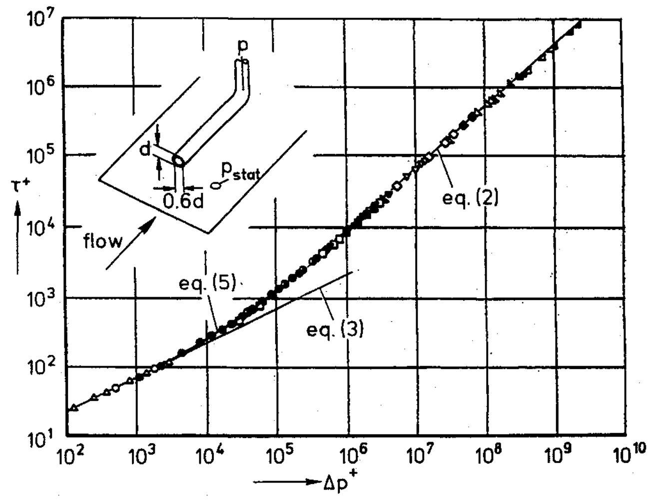

Fig. 1 Schematic and calibration curve for Preston tubes, according to Rechenberg.[4]

boundary-layer thickness. It should be mentioned here that Patel's[5] empirical equation for low Δp^+ exhibits the same root behavior but deviates slightly in its numerical value.

Obviously, the complete measured data set of Fig. 1 can be computed with the same momentum considerations, based on measured boundary-layer data or semi-empirically calculated[3] velocity distributions. Unfortunately, this does not lead to an explicit expression for τ as a function of Δp. However, our desired explicit formula should work in the whole parameter range of Fig. 1. Hence, it has to exhibit the correct asymptotic behavior of Eqs. (2) and (3). A simple addition of both equations would fulfill this requirement, but it would produce wrong results in the intermediate regime. Nevertheless, a more general addition ansatz

$$\tau^+ = \{[\text{Eq. (2)}]^n + [\text{Eq. (3)}]^n\}^{1/n} \tag{4}$$

turns out to be suitable. The coefficient n can be determined easily by comparing the values of both the measured data and the asymptotic equations at the point where both asymptotes intersect. We find $n = 4$. In this way, we obtain a general Preston tube calibration formula,

$$\tau^+ = [28.44\Delta p^{+2} + (6.61 \cdot 10^{-6}) \cdot \Delta p^{+3.5}]^{\frac{1}{4}} \tag{5}$$

In Table 1, we compare Rechenberg's[3] as well as Head and Ram's[7] and Zurfluh's[8] experimental data with numbers calculated with our Eq. (5).

A validation of our calibration formula can be seen in Table 1. Our Eq. (5) overpredicts the shear stress at very low $\Delta p^+ \leq 10^3$ (in the near-wall Couette regime) by about 6% as compared with the experimental data by Head and Ram.[7] However, the deviation is smaller if we compare with Rechenberg's[3] measurements. Thus, we rely on our theoretical asymptote, Eq. (3), rather than on experimental results. If desired, one can obtain a better fit with these previous data by reducing the first coefficient in Eq. (5). For the rest of the available data from the literature, our equation more or less wiggles in between them. A fit with less than 1% deviation from Head and Ram's[7] data is obtained at about $\Delta p^+ \approx 10^4$, 10^5, and 10^8.

Besides the calibration issue, the question of a suitable probe size usually arises with Preston tube measurements. With our calibration curve, it is reasonably straightforward to select the minimal probe diameter. Usually, a rough estimation on the expected shear stress can be made by either assuming a flat plate or a tube flow, depending on whether one has an external or an internal flow, respectively. In addition, we know which minimal pressure difference we are able to measure accurately with our equipment. Using this information and Eqs. (1) and (5), we can estimate the minimal diameter of our probe.

Obviously, there is also a limit for the maximal probe diameter. The operation of Preston tubes requires the validity of the logarithmic law of a turbulent flow above the wall. This law is not valid anymore in the outer parts of the boundary layer. In particular, for flows with pressure gradients, the logarithmic region near the wall becomes smaller; see, for example, Patel.[5] Thus, a choice of the diameter according to the preceding (minimal size) constraint is preferable, but in any case the diameter should be a small fraction of the boundary-layer thickness.

In our Note, we have not considered the aspect of compressibility. In a recent paper, Finley and Gaudet[9] investigated this issue and provided transformation functions that can be used in conjunction with low-speed calibration equations such as ours.

To check the reliability of our calibration formula by ourselves, we have carried out measurements in our oil channel.[10] By a comparison between Preston tube data and data from our mechanical shear stress balance we could again confirm Eq. (5).

Conclusions

The practical use of Preston tubes for shear stress measurements can be made more effortless by using a single calibration equation, such as the one provided in this Note, Eq. (5). This equation can be processed (even in its dimensional form) with a programmable pocket calculator and can thus be utilized by poor scientists, students, and persons who have to produce results quickly.

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