3 Bertelrud, A., "Pipe Flow Calibration of Preston Tubes of Different Diameters and Relative Lengths Including Recommendations on Data Presentation for Best Accuracy," Aeronautical Research Institute of Sweden, FFA Rept. 125, Sept. 1974 (available from NTIS as N75-15000).

4 Simpson, R. L., and Whitten, D. G., "Preston Tubes in the Transpired Turbulent Boundary Layer," *AIAA Journal*, Vol. 6, No. 11, Sept. 1968, pp. 1776–1777.

5 Depooter, K., Brundrett, E., and Strong, A. B., "The Calibration of Preston Tubes in Transpired Turbulent Boundary Layers," ASME Journal of Fluids Engineering, Vol. 100, Mar. 1978, pp. 10–16.

6 Bradshaw, P., and Galea, R. V., "Step-Induced Separation of a Turbulent Boundary Layer in Incompressible Flow," *Journal of Fluid Mechanics*, Vol. 27, Part 1, 1967, pp. 111–130.

7 Sigalla, A., "Measurements of Skin Friction in a Plane Turbulent Wall Jet," *Journal of the Royal Aeronautical Society*, Vol. 62, Dec. 1958, pp. 873–877.

8 Brown, K. C., and Joubert, P. N., "The Measurement of Skin Friction in Turbulent Boundary Layers with Adverse Pressure Gradients," *Journal of Fluid Mechanics*, Vol. 35, Part 4, 1969, pp. 737–757.

9 Prahlad, T. S., "Yaw Characteristics of Preston Tubes," *AIAA Journal*, Vol. 10, No. 3, Mar. 1972, pp. 357–359.

10 Power, J. L., "Wall Shear Stress and Mean-Velocity Measurements in a Three-Dimensional Turbulent Boundary Layer," Naval Ship Research and Development Center, Report 4056, Sept. 1973 (available at AD 768297).

11 Preston, J. H., "The Determination of Turbulent Skin Friction by Means of Pitot Tubes," *Journal of the Royal Aeronautical Society*, Vol. 58, Feb. 1954, pp. 109–121.

12 Head, M. R., and Rechenberg, I., "The Preston Tube as a Means of Measuring Skin Friction," *Journal of Fluid Mechanics*, Vol. 14, Part 1, 14, Part 1, 1962, pp. 1–17.

13 Ferriss, D. H., "Preston Tube Measurements in Turbulent Boundary Layers and Fully Developed Pipe Flow," A.R.C. 26 678, 1965 (available as AD 479412).

14 Smith, D. W., and Walker, J. H., "Skin-Friction Measurements in Incompressible Flow," NACA TN 4231, Mar. 1958.

15 Staff of the N.P.L., "On the Measurement of Local Surface Friction on a Flat Plate by Means of Preston Tubes," N.P.L. Report No. 3185, May 1958.

16 Bertelrud, A., "Preston Tube Calibration Accuracy," *AIAA Journal*, Vol. 14, No. 1, Jan. 1976, pp. 98–100.

17 Head, M. R., and Ram, V. V., "Simplified Presentation of Preston Tube Calibration," *Aeronautical Quarterly*, Vol. 22, Part 3, Aug. 1971, pp. 295–300.

18 Patel, V. C., "Calibration of the Preston Tube and Limitations on Its Use in Pressure Gradients," *Journal of Fluid Mechanics*, Vol. 23, Part 1, 1965, pp. 185–208.

19 Miller, B. L. P., "The Measurement of Wall Shearing Stress in Turbulent Boundary Layers," Ph.D. thesis, University of Leicester, Great Britain, Aug. 1972.

20 Tennant, M. H., Pierce, F. J., and McAllister, J. E., "An Omnidirectional Wall Shear Meter," ASME Journal of Fluids Engineering, Vol. 102, Mar. 1980, pp. 21–25.

21 Kline, S. J., and McClintock, F. A., "Describing Uncertainties in Single-Sample Experiments," *Mechanical Engineering*, Jan. 1953, pp. 3–8.

22 Bradshaw, P., "The Effect of Wind-Tunnel Screens on Nominally Two-Dimensional Boundary Layers," *Journal of Fluid Mechanics*, Vol. 22, 1965, pp. 679–687.

23 Furuya, Y., and Osaka, H., "The Spanwise Non-Uniformity of Nominally Two-Dimensional Turbulent Boundary Layer (1st Report Characteristics of Spanwise Velocity Distribution)," *Bulletin of the Japan Society of Mechanical Engineers*, Vol. 18, 1975, pp. 664–672.

24 Furuya, Y., Nakamura, I., Osaka, H., and Honda, H., "The Spanwise Non-Uniformity of Nominally Two-Dimensional Turbulent Boundary Layer (2nd Report Wall Shear Stress and Flow Field)," *Bulletin of the Japan Society of Mechanical Engineers*, Vol. 18, 1975, pp. 673–680.

25 deBray, B. G., "Some Investigations into the Spanwise Non-Uniformities of Nominally Two-Dimensional Incompressible Boundary Layers Downstream of Gauge Screens," ARC R&M3578, 1967.

26 Favre, A., and Gaviglio, J., "Turbulence et Perturbations dans la Couche Limite d'une Plaque Plane," AGARD Report 278, Apr. 1960.

27 Carnahan, B., Luther, H. A., and Wilkes, J. O., *Applied Numerical Methods*, Wiley, 1969, p. 577.

28 Frei, D., and Thomann, H., "Direct Measurements of Skin Friction in a Turbulent Boundary Layer with a Strong Adverse Pressure Gradient," *Journal of Fluid Mechanics*, Vol. 101, Part 1, 1980, pp. 79–95.

DISCUSSION

V. C. Patel[1]

I am, of course, gratified to note that the calibration of [18] has been vindicated once again. Without adding to an old controversy, I should perhaps make a few comments. First, the different calibration formulae of table 1 resulted from genuine differences in the experimental data and, to this day, we have not been able to find a suitable explanation for the discrepancies among carefully conducted experiments in a relatively simple geometry. Secondly, the three formulas of [18], like all others, are curve fits to the experimental data, although there is some rationale for the expressions given in [18] for the upper and lower ranges of x^*. Unfortunately, as pointed out by Head and Ram [17], the intermediate formula, which is the range of the present experiments, does not match perfectly with the other two formulas at the ends. I hope the authors have avoided these regions. Thirdly, for the record, it would be desirable to quote the x^* range associated with the data in Fig. 2, in order to emphasize that none of the four calibration equations has been used outside its prescribed range of validity. I presume only the data from the largest tube was used for this comparison in order to ensure this. Finally, it should be noted that in many practical applications the boundary layer may be too thin for a Preston tube of reasonable size to operate in the intermediate range of x^*. I am hopeful that the upper-range formula will also withstand the test of time.

P. Bradshaw[2]

Papers that attack the conventional wisdom always attract more attention than those which confirm it, but in the case of turbulence studies so little of our wisdom is conventional that papers like the present one are very welcome. The results can be interpreted either as support for Patel's pipe-flow calibration and its use in boundary layers, or as a demonstration of the reliability of the floating element developed in Professor Pierce's group: the small discrepancies found in the tests at lower Reynolds number suggest that a re-run of the pipe-flow calibration of Preston tubes may be in order, although the differences are practically within the error bounds quoted by Patel in 1965.

J. Mathieu[3]

Previous works carried out by the N.P.L. (1958), Head and Rechenberg (1962), Patel (1965) brought into light useful information about Preston method specially concerning the original law given by Preston himself. Mr. McAllister et al. relate new interesting features.

A good agreement had been pointed out between the two methods by Mr. Alcaraz et al. (1968). These authors had made comparisons between experimental data given by a

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Preston tube and by a floating element. Any information mentioned in the report under consideration are already included in this paper. This previous work is not related in the publicaton.

Experimental data relative to several tubes different in diameter are interesting. These experimental data are compared with direct measurements, the amount of error is precised for a defined range of Preston tube. Comparisons are clearly presented in table form.

One can regret the comparisons to be made in a limited range of the Reynolds number 0.6 to 1.4 10^6. Pressure gradients are not taken into account in this comparison.

Authors' Closure

The authors appreciate the comments of Professors Bradshaw, Patel, and Mathieu.

Initially, the comparisons between the direct force measurements and the Preston tube predictions were made to add confidence to the results of the mechanical shear meter, rather than to question the Preston tube correlations. The difficulty in making such direct force measurements, especially in low speed flows with very small shear forces, coupled with a shear meter design and transducer selection, both somewhat different than generally used in such measurements, suggested some comparison of this sort. Fortunately, or fortuitously, the generally excellent agreement shown in Fig. 3 between the direct force measurements and the Patel intermediate correlation, for four sizes of Preston tubes, permitted the authors to escape a direct challenge to the conventional wisdom. But as noted by Professor Bradshaw, a paper title which even suggests an attack on the conventional wisdom does generate a little more audience interest.

In reply to Dr. Patel, as he noted only the largest tube (2.11mm OD) was used in the comparisons of Fig. 2. The x^* range for this largest tube was between 4.96 and 5.56. Table 1 shows that this range taxes the lower limit of the Smith and Walker, and NPL Staff correlations. For this reason Fig. 2 does not show Preston tube values for these two correlations at the lower end of the unit Reynolds number range. For Fig. 3 the x^* range of the tubes varied from 3.16 to 3.94 for the smallest tube (0.46mm OD) to 4.96 to 5.56 for the largest tube (2.11mm OD). Again, from Table 1, only the largest tube at the highest unit Reynolds number approached, but never reached, the upper limit of the range of validity for Patel's intermediate range correlation formula and the small mismatch of the correlations at this interval boundary was not encountered here.

The authors especially acknowledge the remarks of Professor Mathieu. We regret not citing the earlier excellent and similar work of Alcaraz, Guillermet, and Mathieu (1968). Since extensive literature searches were conducted with this work, we can only presume that the data bases searched are weak in the inclusion of less recent and non-English titles – an undesirable but nonetheless all too often real problem. Alcaraz et al., show similar good agreement, typically $\pm$ 5 percent, between direct force and Preston tube C_f coefficients for five tubes between 1 and 4mm OD. Their data are for a Reynolds number range based on boundary layer thickness of 4×10^3 to 10^4. The authors measurements are for a range of about 6×10^4 to 1.3×10^4 and hence to provide data outside the range of the Alcaraz et al., measurements. It is also noted that three of the authors' Preston tubes are smaller than those of Alcaraz et al. For the five tube sizes used by Alcaraz et al., (1, 1.5, 2, 3, and 4mm OD) their correlation formula ($y^* = -1.412 + 0.882\,x^*$) is nearly identical to the Ferriss formula ($y^* = -1.422 + 0.881\,x^*$) and while the present study shows good agreement between the Ferriss correlation and the direct force measurements, the Patel intermediate correlation does appear to handle the smaller tube diameters a little better. While no x^* range of validity is offered for the Alcaraz et al., correlation, one might reasonably assume it to be similar to that of Ferriss.