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An Innovative Flow-Measuring Device: Thermocouple Boundary Layer Rake

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AN INNOVATIVE FLOW-MEASURING DEVICE: THERMOCOUPLE BOUNDARY LAYER RAKE*

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ABSTRACT

An innovative flow-measuring device, a thermocouple boundary layer rake, was developed. The sensor detects the flow by using a thin-film thermocouple (TC) array to measure the temperature difference across a heater strip. The heater and TC arrays are microfabricated on a constant-thickness quartz strut with low heat conductivity. The device can measure the velocity profile well into the boundary layer, about 65 μm from the surface, which is almost four times closer to the surface than has been possible with the previously used total pressure tube.

SYMBOLS

c	chord length
p	static pressure
p_1	static pressure on streamline ahead of strut
Re	Reynolds number based on strut length
U	axial velocity, m/sec
U^+	U/u_τ
u_τ	frictional velocity, $\sqrt{\tau_w/\rho_w}$
ΔV	voltage differential
U_∞	velocity at edge of boundary layer
x	axial distance from leading edge of sensor strut
y	coordinate of measurement from surface, cm
y^+	yu_τ/ν_w
θ	momentum thickness
ν_w	kinematic viscosity on wall
ρ_w	density on wall
τ_w	shear stress on wall

INTRODUCTION

Several conventional flow-measuring devices can measure the flow velocity within the boundary layer: total pressure boundary layer rakes, hot-wire probes, and hot-film probes.[1–5] However, all of them have the limitation that measurement cannot be made very close to the surface. The physical size of a total pressure probe limits its ability to get close to the surface, and those that are too small are impractical because they are easily plugged or damaged. Therefore, the closest measurement that can be made is about 250 μm from the surface. The reason that hot-film and/or hot-wire probes cannot obtain measurements close to the surface is that inaccuracy is introduced by the rapid change in the heat convection pattern in the near wall region (wall proximity effect).

The newly invented thermocouple boundary layer rake (patent pending) shown in Figure 1 not only can measure the flow velocities throughout the boundary layer with great accuracy but also can measure the flow velocity at least four times closer to the surface than conventional instruments.

THEORY BEHIND INVENTION

Based on the results from the Navier-Stokes calculation using the WIND code, the velocity of a fluid over a constant-velocity region of a constant-thickness strut matches the velocity of the fluid ahead of the strut at the same height above the surface of a wind tunnel floor.

Figure 2 shows the three-dimensional particle traces obtained from the WIND code. Note that streamlines stay parallel with the floor when they pass over a strut with constant thickness.

The nondimensional pressure distributions along streamlines are plotted in Figure 3. The pressure is nondimensionalized by the static pressure on the same streamline ahead of the strut p_1. Nondimensional pressure equal to 1 is an indication of the recovering static pressure ahead of the strut along the same streamline after the leading edge pressure disturbance. The streamline tracing also indicates that the nondimensional pressure

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*Patent pending.

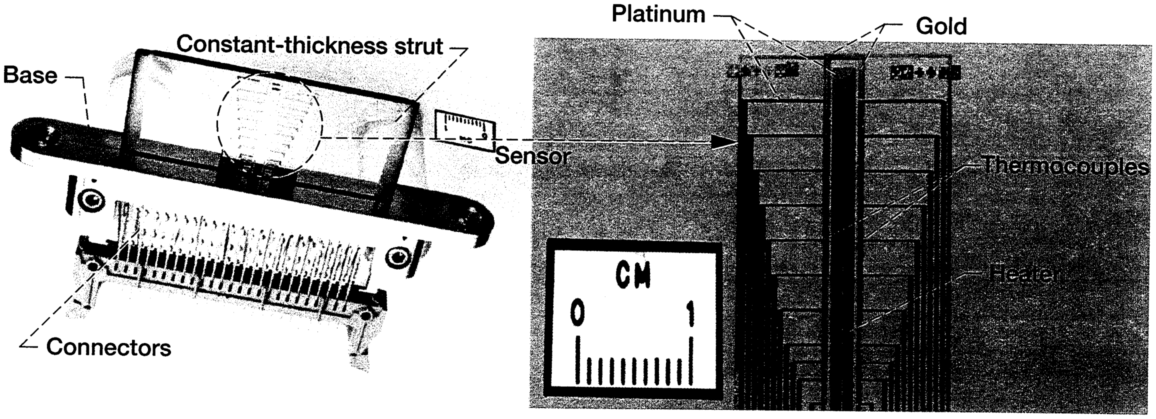

Figure 1.—Large size thermocouple boundary layer rake.

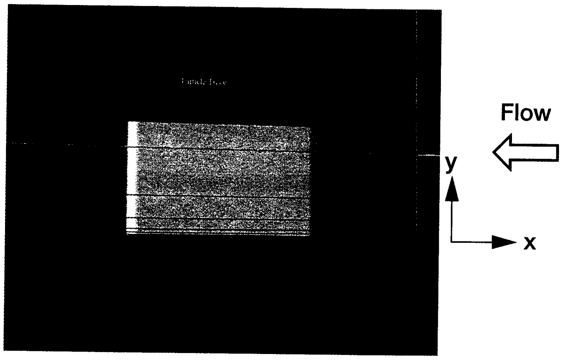

Figure 2.—Side view of three-dimensional particle traces over constant-thickness sensor strut.

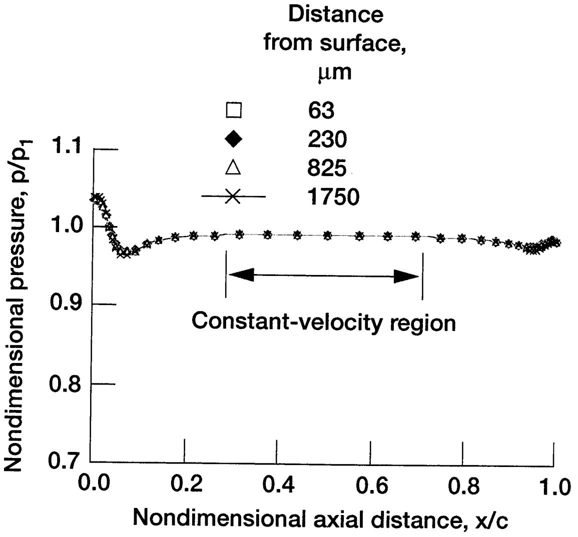

Figure 3.—Pressure distribution based on three-dimensional calculation on strut with constant thickness.

distribution is very consistent at different heights from the surface and that it is very close to 1 as seen in Figure 3. This small difference from 1 did not affect the calibration procedure. The constant-velocity region (or constant-pressure region) spreads over half the sensor strut from the center. Also, horseshoe vortices, which could occur at the intersection of the strut and the floor surface, were not observed on any streamline tracing for the subsonic flow conditions. The thermocouple pairs are mounted close to the center in this constant-velocity region to measure the velocities of the boundary layer flow.

DESCRIPTION OF THERMOCOUPLE (TC) BOUNDARY LAYER RAKE

The sensor consists of a platinum heater and an array of platinum and gold thermocouples (Fig. 1). Equal numbers of thermocouples are placed both upstream and downstream of the heater. The voltage difference generated by each pair at the same height from the surface is indicative of the difference in temperature between the upstream and downstream thermocouple locations. This voltage difference is a function of the flow velocity over the thermocouple pair; therefore, like a conventional total pressure rake, it can provide the velocity profile of the boundary layer.

FABRICATION OF FLOW SENSOR

The sensor is fabricated on a fused quartz substrate. The reason for this substrate choice is that the operation of the sensor depends upon the flow-induced temperature difference across the heater, and the low thermal conductivity of the quartz helps to maintain this difference. In addition, quartz has a low coefficient of thermal expansion, so it has excellent resistance to thermal shock and thermal stress. Thus, even if the heater is operated at a high temperature, the substrate will not crack.

The heater and thermocouple array are thin films, only a few microns thick, so as not to disturb the flow over the surface. The heater and one-half of the set of thermocouple junctions are platinum. The other half of the junction pair is gold (Fig. 1). Platinum is an ideal material for the heater because its electrical resistance varies with temperature in a very repeatable fashion, which allows automatic control of the heater temperature as part of a control circuit. The thermocouples are fabricated of pure metals to alleviate the problem of uneven composition that might occur with alloys; therefore, the platinum-gold pair is one of the most stable and repeatable materials.[6]

The actual deposition of the films is via a photolithographic process developed especially for the production of this sensor (another patent applied for) because the conventional process of using a photomask and positive photoresist is very difficult in that platinum and gold are almost impossible to etch. Instead, after copper is deposited over the entire substrate, the photoresist is applied and patterned. Next, the copper under the exposed photoresist is etched away with dilute nitric acid, and the platinum is sputtered over the entire area of the substrate. The remaining photoresist is washed away with acetone, leaving only copper and platinum on the substrate. Following another nitric acid wash, only the platinum is left. This process is then repeated for the gold film.

CALIBRATION PROCEDURE

The calibration of a TC boundary layer rake was conducted inside a wind tunnel[7] side-by-side with a conventional total pressure boundary layer rake, as shown in Figure 4. The cross section of the wind tunnel is 14.22 by 20.32 cm. Both the total pressure rake and the thermocouple boundary layer rake are 6.8 cm from the closest sidewall so that they will not be affected by the boundary layer on the sidewall. The radius of the total pressure tube is 0.0254 cm.

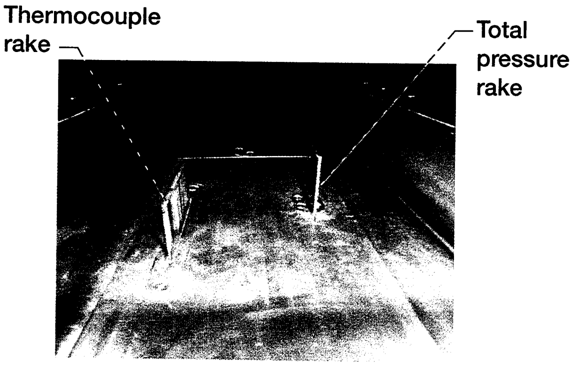

Figure 4.—Calibration setup on wind tunnel floor looking downstream.

It is assumed that the total pressure rake can provide good measurements of the boundary layer flow because they are used as the reference measurements for the calibration of the thermocouple boundary layer rake. The velocity profiles obtained from the total pressure rake at three Reynolds numbers are shown in Figure 5; the closest measurement from the surface is 0.0254 cm. The profiles were smooth and stable during the calibration. The thermocouple boundary layer rake was placed 6.8 cm sideways from the total pressure rake such that the axial location of the center of the sensor strut was at the same axial location as the tip of the total pressure rake (Fig. 4). Therefore, a one-to-one correlation could be obtained. During the calibration, one thermocouple pair was chosen to be the reference pair to set the voltage of the upstream TC as constant (constant temperature). The number 9 pair from the surface was chosen as the reference TC for the calibration. As shown in Figure 6, not all upstream TC's could be kept at the same voltage (same temperature). Therefore, the measurements from this sensor need to be adjusted as follows.

During each calibration measurement, the temperature of the upstream thermocouple at each location is recorded to find out how much the heater temperature varies from one location to another (Fig. 6). The heater temperature varies along its length because of the large difference in flow velocity between the boundary layer and the free stream; thus, each individual reading must be corrected for this difference. The correction for zero offset at each location is made by adjusting the heater current at no flow

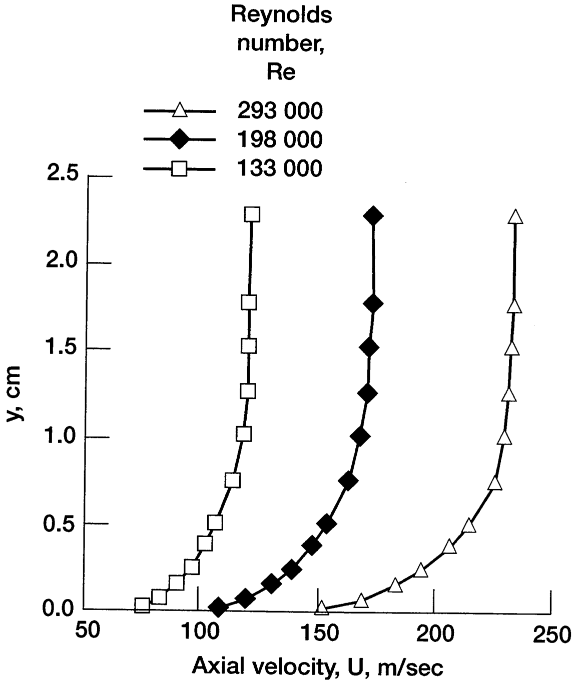

Figure 5.—Measurement from total pressure rake.

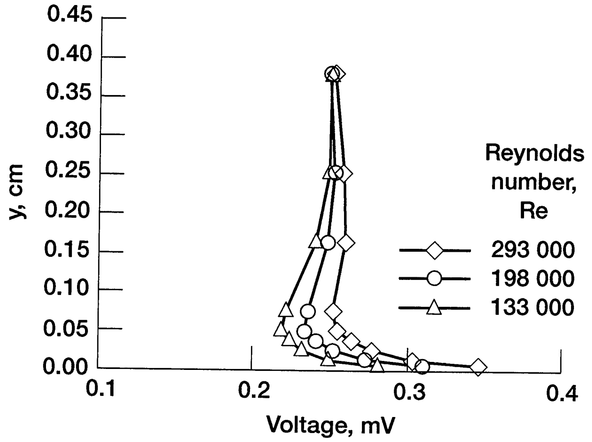

Figure 6.—Voltage of upstream thermocouples with number 9 upstream TC kept at 0.25 mV.

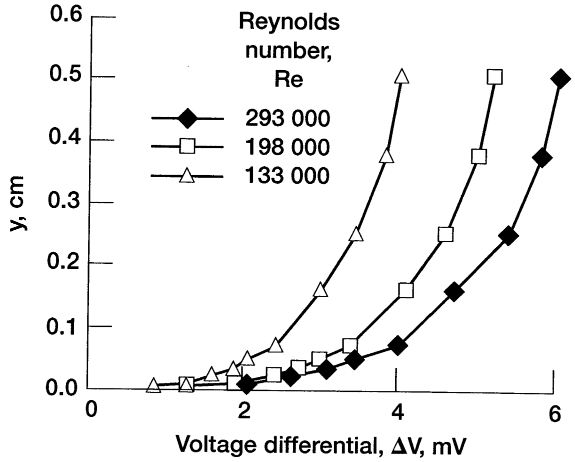

Figure 8.—Measurement from thermocouple rake including zero shift adjustment.

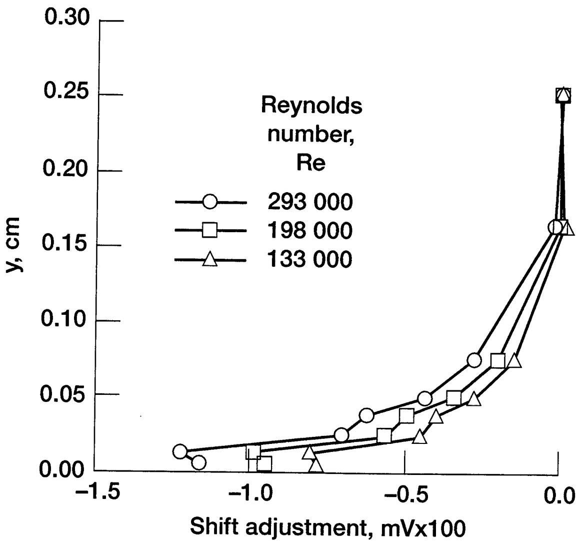

Figure 7.—Zero shift adjustment for thermocouple rake.

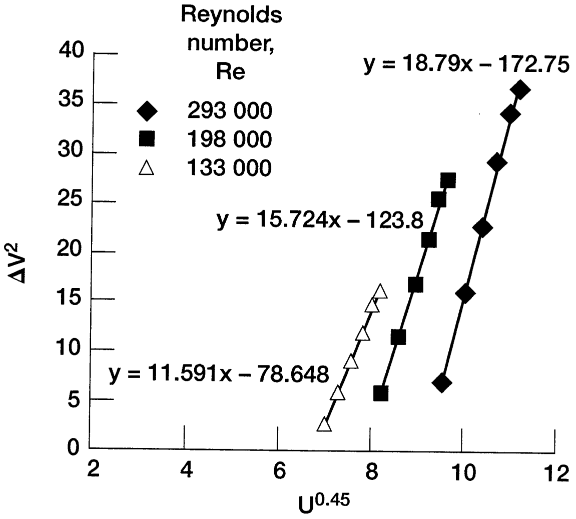

Figure 9.—Calibration lines.

to give the same reading of the upstream TC as occurred with flow. Then the differential signal is recorded. This is the zero shift adjustment at that location (Fig. 7), and it is subtracted from the calibration data.

Figure 8 shows the voltage differentials ΔV and the zero shift adjustment for three Reynolds numbers Re. The corresponding measurements between the total pressure rake and the TC rake were used to obtain the calibration lines (Fig. 9). For example, the calibration equation for a Reynolds number of 1.98×10^5 is given as

$$U = \left[\frac{\left(\Delta V^2 + 123.8\right)}{15.724} \right]^{1/0.45} \tag{1}$$

where U is the axial velocity. Using this equation, all the measurements from the TC rake, including two taken very close to the surface, can be converted to the flow velocities. (Some measurements did not correspond to those of the total pressure rake.) The results in Figure 10 show that the new rake not only gives measurements identical to those of a conventional total pressure boundary layer rake but it also measures four times closer to the surface (i.e., 65 versus 250 µm). Because the purpose of this paper is to develop a calibration procedure, no attempt was made to determine the uncertainty of the TC rake.

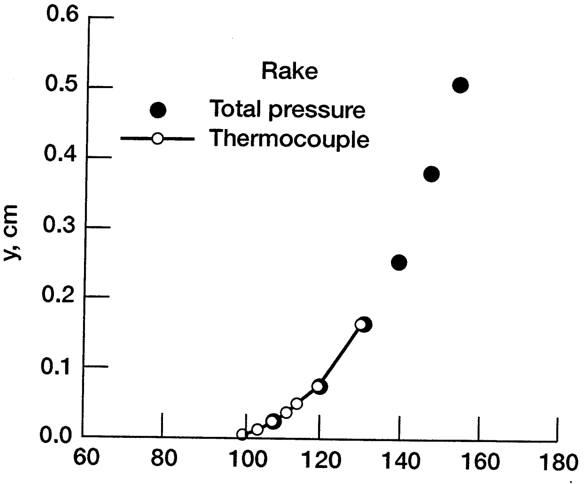

Figure 10.—Velocity profiles obtained from total pressure rake and thermocouple rake at Re = 198 000.

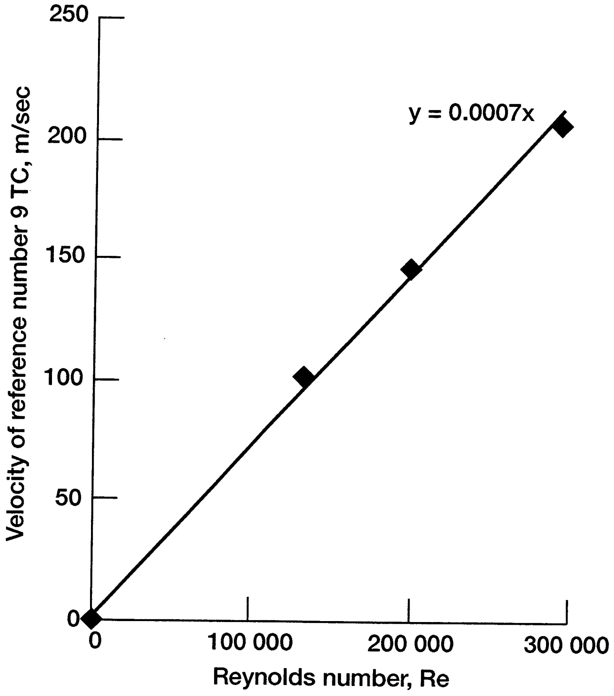

Figure 11.—Velocity at reference thermocouple.

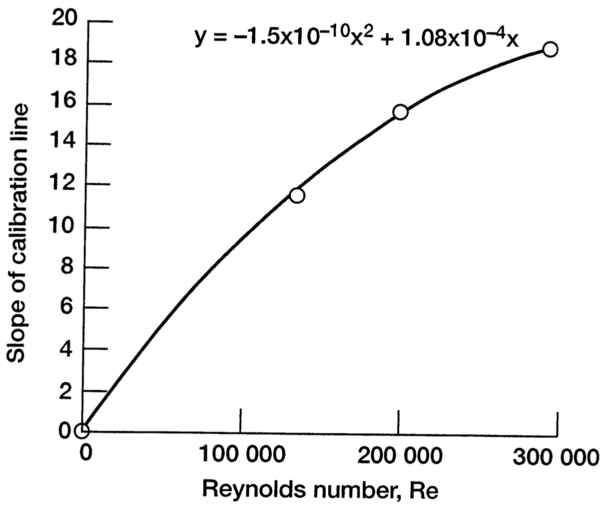

Figure 12.—Slope of calibration lines in figure 9.

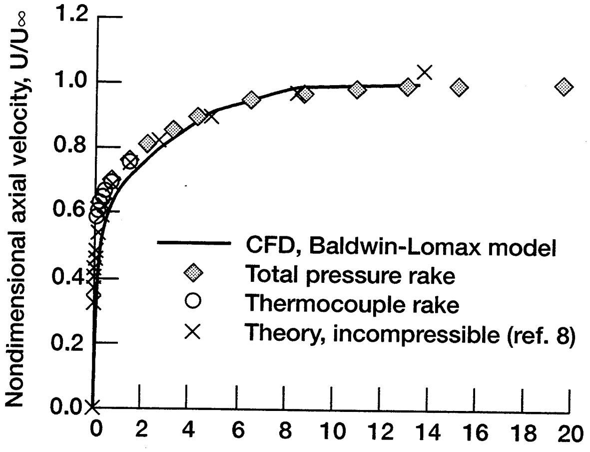

Figure 13.—Nondimensional velocity profile.

DISCUSSION

The measurements from the TC rake depend on Reynolds number. During the calibration, Figures 11 and 12 were also obtained and can be used for any flow conditions. The upstream TC is set at a reference value, say 0.25 mV. From Figure 11, the velocity of the reference TC is determined and the ΔV of the reference TC is measured. The slope of the calibration line is determined from Figure 12 and the calibration line similar to Figure 9 is determined. As seen from Figure 12, the slope of the calibration line decreases as the Reynolds number decreases, which indicates that the error introduced by this device is increased for the smaller Reynolds number. The velocity profile can be obtained from the TC rake by using a calibration equation that is similar to Equation (1) and is obtained from the calibration line. To determine how accurate the closest measurement to the surface is, the data are replotted in Figure 13 with different parameters: the ratio of the velocity to the velocity at the edge of the boundary layer U/U_∞ versus the ratio of the y-coordinate of the measurement from the surface to the momentum thickness y/θ. The measurement data are fairly close to the incompressible theory[8] of a flat plate

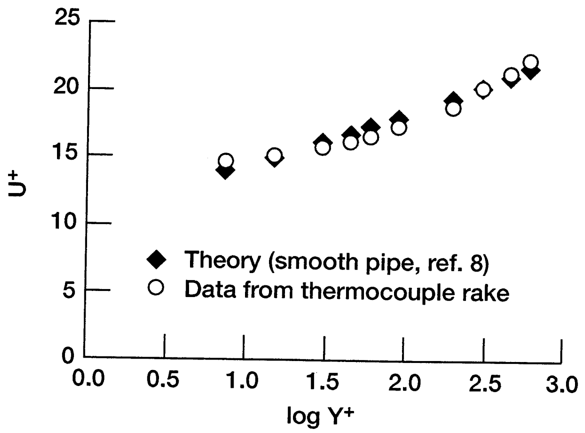

Figure 14.—Comparison of thermocouple data with theory.

$$\frac{U}{U_\infty} = 0.716\left(\frac{y}{\theta}\right)^{1/7}$$

and to the calculated results from a computational fluid dynamics code (WIND) using the Baldwin-Lomax turbulence model.

Figure 14 presents a plot of nondimensional U^+ versus y^+. The shear stress τ_w obtained from reference 7 was used to calculate U^+ and y^+.

The measurement data from the TC rake agree very well with the theory;[8] that is,

$$U^+ = 11.5\left(y^+\right)^{1/10} \tag{2}$$

Equation (2) is based on the universal velocity distribution law for smooth pipes. Although the current calibration is through a rectangular duct, it agrees very well even for the closest measurement, which is 65 μm from the surface.

CONCLUDING REMARKS

An innovative flow-measuring device, a thermocouple boundary layer rake, was successfully developed and calibrated. The sensor detects the flow by using a thin-film thermocouple (TC) array to measure the temperature difference across a heater strip. The newly invented TC boundary layer rake (patent pending) can measure the flow velocities throughout the boundary layer with great accuracy. It can also measure four times closer to the surface (about 65 μm) than conventional devices, such as total pressure rakes, hot films, and hot wires.

REFERENCES

1. Polak, T.A.; and Pande, C.: Engineering Measurements: Methods and Intrinsic Errors. Professional Engineering, London, 1999.
2. Bui, Trong T.; Oates, David L.; and Gonsalez, Jose C.: Design and Evaluation of a New Boundary-Layer Rake for Flight Testing. AIAA 2000–0503, 2000.
3. Ligrani, P.M.; and Bradshaw, P.: Subminiature Hot-Wire Sensors: Development and Use. J. Phys. E: Sci. Instrum., vol. 20, 1987, pp. 323–332.
4. Ligrani, P.M.; and Bradshaw, P.: Spatial Resolution and Measurement of Turbulence in the Viscous Sublayer Using Subminiature Hot-Wire Probes. Exp. Fluids, vol. 5, no. 6, 1987, pp. 407–417.
5. Doiron, M.D.; and Zingg, D.W.: Turbulent Flow Measurements With a Triple-Split Hot-Film Probe. AIAA J., vol. 32, no. 9, 1994, pp. 1929–1931.
6. Kinzie, P.A.: Thermocouple Temperature Measurement. John Wiley & Sons, New York, NY, 1973.
7. Hwang, Danny P.: A Proof of Concept Experiment for Reducing Skin Friction by Using a Micro-Blowing Technique. AIAA Paper 97–0546, 1997.
8. Schlichting, Hermann: Boundary Layer Theory. Fourth ed., McGraw-Hill, New York, NY, 1960.

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