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Simultaneous temperature and velocity measurements

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Abstract. A technique for making simultaneous temperature and velocity measurements, required for measuring temperature–velocity correlations used to determine turbulent heat fluxes, and temperature–velocity correlation coefficients, is described. This technique uses a two-component laser Doppler velocimeter (LDV) which gives a direct measure of velocity fluctuations and a 0.64 μm cold-wire which gives a direct measure of the temperature fluctuations. This technique has the advantage over multi-element hot- and cold-wire anemometry systems in that there is no sensor interference between the velocity and temperature sensors, and there are no corrections which need to be applied to the velocity measurements because of temperature influences of the surrounding fluid.

1. Introduction

It is evident from the lack of data given in the literature on temperature–velocity correlations, $\overline{ut}$ and $\overline{vt}$, that these measurements are quite difficult. Although the data is very scarce, simultaneous measurements of these fluctuating quantities are needed to better understand how the surface heat transfer is affected by physical mechanisms such as freestream turbulence, rough walls, and pressure gradients. The technique described here uses a two-component laser Doppler velocimeter (LDV), which gives a direct measure of the fluid velocity, and a 0.64 μm cold-wire, which gives a direct measure of the fluid temperature.

Measurements of flow velocities, to obtain turbulence statistics, are commonly done with either a hot-wire or LDV. Not so common are measurements of fluctuating temperatures. The accuracy of measuring the temperature fluctuations is limited by the frequency response of the sensor. Antonia *et al* (1981) point out that the overriding problem in finding a fast-responding temperature sensor is to account for the thermal capacitance of the sensor. The time constant of the sensor depends on the flow conditions (type of fluid and velocity) and the sensor's thermal capacitance (diameter, wire properties, and current). Because the flow conditions are generally fixed, the sensor characteristics must be chosen such that the minimum time scale (highest frequency) of interest is measured. Whereas most thermocouples are too large for measuring temperature fluctuations in a turbulent boundary layer, a micrometre-sized cold-wire can. Cold-wires can be constructed with wire diameters as small as 0.64 μm.

2. Previously-used simultaneous measurement techniques

Most studies of simultaneous temperature and velocity measurements have used multi-sensor hot- and cold-wire anemometry systems. Use of these multi-sensor probes have two distinct disadvantages in that there may be interference effects among the prongs and/or sensors and the need for corrections to the hot-wire data when using it in a heated fluid medium. Multi-sensor anemometry systems have been used by Chen and Blackwelder (1978), Subramanian and Antonia (1981), and Blair and Bennett (1987).

Both Chen and Blackwelder (1978) and Subramanian and Antonia (1981) used a cold-wire located upstream of an X-configured hot-wire probe. Chen and Blackwelder used a 2.5 μm diameter cold-wire with a separation distance between the wires of less than $\Delta x = 1$ mm, whereas Subramanian and Antonia used a 0.64 μm cold-wire with a separation distance of $\Delta x = 1.2$ mm. In order to compare these separation distances with respect to the boundary layer, the spacing Δx can be normalized using the friction velocity, u_τ, and viscosity, ν, such that $\Delta x^+ = \Delta x u_\tau/\nu$. A common reference of $u_\tau = 0.429$ m s^{-1} and $\nu = 15.44x10^{-6}$ m^2 s^{-1}, based on the boundary layer study done by Thole (1992) at a freestream velocity of air at 9.60 m s^{-1}, will be used to compare the sensor spacings in terms of wall units. Hence, Chen and Blackwelder's sensor spacing was $\Delta x^+ = 28$ while Subramanian and Antonia's sensor spacing was $\Delta x^+ = 33$. Although Subramanian and Antonia had a smaller diameter wire, thereby having a better frequency response, the separation distances between the probes was slightly larger than that used by Chen and Blackwelder.

Blair and Bennett (1987) used only hot-wires run at different overheat ratios to resolve both the temperature and velocity. They constructed a probe in which a third wire was placed between two X-configured wires. The spacing between the wires was $\Delta z^+ = 9$. All three sensors, each having a wire diameter of 2.5 μm, were operated in a constant temperature mode with one of the wires being operated at a much lower overheat ratio allowing that wire to have a higher temperature sensitivity. By operating their system in a constant temperature mode, their anemometer system had a frequency response of 50 kHz. Their correlation measurements were corrected using a correction factor they developed based on the lateral correlation coefficient between sensors.

Only Heitor *et al* (1985) have reported using an LDV in combination with a temperature sensor. They used a 15 μm diameter thermocouple which has a poor frequency response. Compensation for the low frequency response was done in the signal processing using a time-varying time constant based on the instantaneous velocity. However, Heitor *et al* reported that the correlation between the velocity and temperature was sensitive to their instantaneous time-constant compensation procedure. They attributed errors in their temperature compensation technique to inaccuracies in the time constant especially near the higher frequencies.

3. Cold-wire construction and testing

The development and testing of the simultaneous temperature and velocity measurement technique discussed in this paper took place in the Turbulence and Turbine Cooling Research Laboratory at the University of Texas at Austin. Since the difficulty of these measurements is primarily in measuring the temperature fluctuations, much time was invested in constructing and testing several micometre-sized diameter cold-wires. The first step was to acquire the capability of constructing these small diameter cold-wires. In order to avoid time delays and high costs, an in-house procedure for constructing these probes was developed based on a technique used by Haritonidis (1989). For specific details on the construction process refer to Thole (1992).

The platinum-10% rhodium wire material was manufactured by the Sigmund-Cohn Corporation with diameters of 2.5, 1.5 and 0.64 μm. These Wollaston wires were coated with a 30 μm diameter silver jacket which was removed using a 50% nitric acid and 50% distilled water mixture. After the silver coating was removed during the cold-wire construction, the bare wire was soldered to a TSI-1218 boundary layer hot-wire probe.

Because the resistance of a wire is inversely proportional to the square of the wire diameter, these micrometre-sized wires had very high resistances.

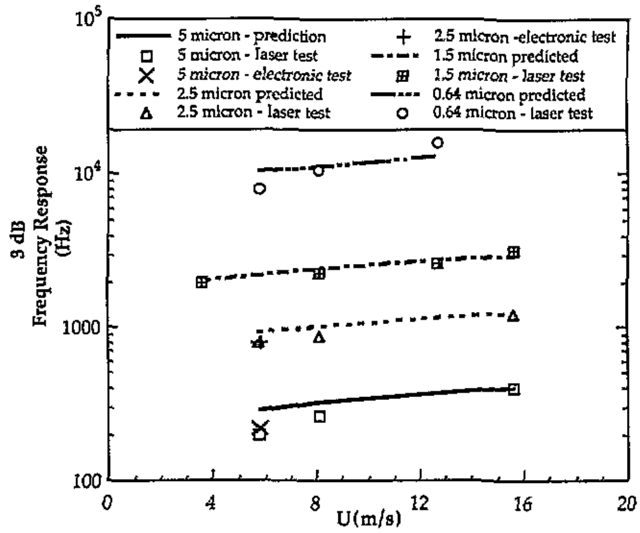

Figure 1. Measured frequency response for several different wire diameters and freestream velocities.

For example, the 0.64 μm diameter wire had a resistance/length of 580 Ω mm^{-1} and, hence, the total wire resistance for the 1.5 mm long sensor was 870 Ω. The TSI-1054A anemometer system had to be configured with an external resistor added to make up the difference. The cold-wire sensitivity to temperature for the 0.64 μm diameter wire was nominally $\mathrm{d}V/\mathrm{d}T = 5$ mV °C^{-1}.

Since the critical issue of the sensor was whether the frequency response was adequate, the response of four different diameter sensors (d_w = 5, 2.5, 1.5 and 0.64 μm) were measured and compared to the predicted frequency responses. For this first-order system, the predicted time constant, τ, was based on a balance between the thermal capacitance of the wire and the convective heat flux. The time constant is a function of the properties of the wire material (ρ_w, $C_{p,w}$ and d_w), the type of fluid (k_{air}), and the convection coefficient (non-dimensionalized as Nusselt number, Nu). The time constant is given by:

$$\tau = \frac{\rho_w d_w^2 C_{p,w}}{4 Nu k_{\text{air}}} \tag{1}$$

Two different tests were used to measure the responses. All of the wires were tested using a square-wave energy flux input imposed on the cold-wire. The energy flux was achieved by using a laser beam focused onto the wire and interrupted with a rotating chopper blade. The cold-wire response to the square-wave input was observed on an oscilloscope, and the frequency response was deduced from the measured relaxation time. In addition to this test, the frequency responses of the 5 μm and 2.5 μm diameter cold-wires were measured by using an external electronic sine wave input to the anemometer (Paranthoen *et al* 1983). Figure 1 shows good agreement between the measured and predicted responses for the four different diameter wires over a range of freestream velocities. There is a large gain in frequency response as the wire size decreases with only a slight increase in frequency response with increasing convective velocity.

The decision as to what wire diameter to use, for a specific application, must be based on the particular flow field and the minimum time scale of interest. For example, the application desired for this sensor was in a heated turbulent boundary layer having a freestream velocity of nominally 8 m s^{-1} and a momentum thickness Reynolds number as high as $Re_\theta = 1600$. To assess the required frequency response, the temperature fluctuation spectra was measured in the log-region of the heated turbulent boundary layer using a 0.64 μm diameter cold-wire. The spectrum showed a 60 dB decrease in the amplitude of temperature fluctuations at a frequency of 2600 Hz. As indicated by figure 1, the required sensor must have a wire diameter smaller than 1.5 μm and, hence, the 0.64 μm diameter wire was chosen to measure the temperature fluctuations.

4. Development of the simultaneous measurement technique

The simultaneous measurement technique involved using a two-component LDV system in conjunction with the 0.64 μm diameter cold-wire. Mean and rms velocities were measured using an LDV from TSI Inc which was used in the backscatter mode and included frequency shifting. A 10 μs conincidence window was set. The LDV probe volume length was 470 μm and the diameter was 70 μm. Since the LDV controlled the temperature acquisition (as will be discussed below), both the velocity and temperature data were corrected for velocity bias errors using residence time weighting. Bias errors typically occur in LDV measurements because there are a larger number of high velocity measurements relative to low velocity measurements. Since the LDV controls the temperature acquisition and the temperature–velocity correlation is significant, there would similarly be a bias in the temperature measurement. Hence, residence time weighting of both the velocity and temperature was required.

Seeding the flow, necessary for the LDV, required a special process because conventional seeding particles would tend to stick to the cold-wire sensor and reduce the frequency response. Several different solid particle seeding materials, ranging in diameters from 1 to 3 μm, were tested. The solid particle materials tested included titanium dioxide, alumina and silicon carbide, but none of these proved to be successful. A special incense smoke generator, which duplicated that of Wallace (1990), was constructed, tested and proven to be acceptable for seeding the flow. The incense smoke was generated by burning incense sticks and injected into the wind tunnel using compressed air. Although the smoke was filtered to remove tar particles, inherent in the incense smoke, not all of the tar particles could be removed. To remove these tar particles from the cold-wire, the wire was raised to an overheat ratio of 1.6 which vaporized the tar particles. This vaporizing process was required nominally every 5 min depending on the seeding rate.

There was a slight velocity sensitivity of the temperature probe which was detected only because the probes were used in a highly turbulent flowfield in conjunction with the LDV. Even though the operating current was reduced from 1.5 mA to 0.75 mA in order to decrease the velocity sensitivity, large temperature–velocity correlations were measured in a highly turbulent isothermal flowfield generated downstream of an unheated cylinder in crossflow. The velocity sensitivity was also confirmed by varying the freestream velocity of the wind tunnel while maintaining the air temperature at a constant temperature. Instantaneous measured temperatures, T_{meas}, were corrected for this velocity sensitivity using a velocity sensitivity coefficient, $\mathrm{d}T/\mathrm{d}U$, and the following relation,

$$T_{\mathrm{true}} = T_{\mathrm{meas}} + \frac{\mathrm{d}T}{\mathrm{d}U}(U_{\mathrm{cal}} - U_{\mathrm{meas}}) \qquad (2)$$

where U_{cal} is the velocity at which the cold-wire was calibrated to determine the temperature/voltage relationship and U_{meas} is the instantaneous measured velocity. The procedure would be to first calibrate the wire to determine the voltage-temperature sensitivity at a constant calibration velocity, U_{cal}. The next step would be to determine the temperature–velocity sensitivity coefficient, $\mathrm{d}T/\mathrm{d}U$. This was done by placing the LDV and cold-wire probes in a highly turbulent but isothermal flow. For this flow the actual temperature fluctuations were zero, but large temperature–velocity correlations were indicated because of the velocity sensitivity of the cold-wire. The temperature–velocity sensitivity coefficient was determined as the value which minimized the temperature–velocity correlation for the corrected temperature data. This nulling out process was done in a highly turbulent flowfield ($Tu \sim 20\%$) generated by an adiabatic cylinder in crossflow which was at the same temperature as the cylinder. This technique was much more precise than varying the wind tunnel speed while trying to maintain a constant freestream temperature. As this correlation coefficient was minimized, so was the rms of the output voltage since there were no temperature fluctuations present for the isothermal flow. The rms levels were reduced from $t_{\mathrm{rms}} = 0.50$ °C to 0.18 °C. A typical velocity sensitivity coefficient was $\mathrm{d}T/\mathrm{d}U = 0.06$ °C m^{-1} s.

Estimates of the effect of temperature fluctuations on the LDV measurements, due to fluctuations in the refractive index, showed that these would cause insignificant errors ($< 10^{-2}\%$). This is primarily due to the very small fluctuations in the refractive index expected for the 10 °C temperature differential between the freestream and test plate. Comparisons of experimental measurements of the rms velocty profiles for heated and unheated turbulent boundary layers also showed no effects of temperature fluctuations on the LDV measurements.

A major concern in using this technique was whether the LDV probe volume and cold-wire could be placed close enough. The simultaneous temperature and velocity measurements were made by placing the LDV probe volume immediately upstream of the cold-wire sensor at a distance small enough such that there would be negligible loss in correlation between the sensors. To ensure that the minimum possible separation could be achieved, the cold-wire sensor was placed at the tip of the probe tines during construction. The minimum separation distance between the LDV and cold-wire was 0.3 mm. Distances any closer than that could not be achieved because one of the laser beams would be partially blocked by the probe tine. Assessment of whether the separation distance was not too large, was based on a two-point velocity cross-correlation measurement using a hot-wire, in place of the cold-wire, in conjunction with the LDV.

Software controlled the simultaneous data acquisition system (Gan 1991). The LDV counter output was input directly into a National Instruments NB-DIO-32 digital input board. Also, a trigger pulse from the counter was sent to a National Instruments NB-MIO-16X 16-bit analogue-to-digital board. The trigger initiated the acquisition of the analogue (cold-wire) signal. Both boards were resident in a Macintosh II computer. There was a 30 μs time delay between the LDV input and the acquisition of the analogue (cold-wire) input. However, given a separation distance of 0.3 mm and a nominal convection velocity of 10 m s^{-1}, the data acquisition lag time corresponds to the convection time from the LDV probe volume to the hot-wire sensor which results in the maximum expected correlation.

The maximum allowable distance between the LDV and the cold-wire was based on the cross-correlation measured using the LDV and a hot-wire. The two-point velocity cross-correlation coefficient between the LDV and the hot-wire, positioned 0.3 mm apart, was measured to be $(R_{uu})_{12} = 0.95$ which is reasonably close to the ideal level of $(R_{uu})_{12} = 1.0$. The 5% decrease in the measured level is likely due to the hot-wire's sensitivity to the v-component. The 0.3 mm spacing, in terms of the common wall units used earlier in this paper, is $\Delta x^+ = 9$ which is considerably less than Chen and Blackwelder's (1978) and Subramanian and Antonia's (1981) multi-sensor elements.

5. Simultaneous measurements

Correlation coefficients, R_{ut} and R_{vt}, were measured across a heated turbulent boundary layer with minimal freestream turbulence level ($Tu < 1\%$) at a $Re_\theta = 1640$ and $Re_{\Delta 2} = 790$. Figure 2 compares the measured data with the measurements reported by Subramanian and Antonia (1981) and Chen and Blackwelder (1978). The R_{ut} coefficients were similar to those of Chen and Blackwelder, but the R_{ut} values of Subramanian and Antonia were significantly higher across most of the boundary layer. The R_{vt} coefficients were in agreement with both Chen and Blackwelder as well as Subramanian and Antonia.

Figures 3(a) and 3(b) compare the non-dimensional streamwise and normal heat flux distributions with

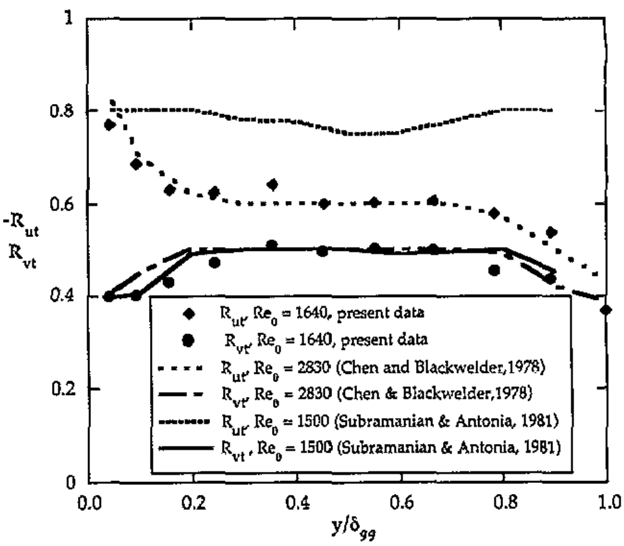

Figure 2. Comparison of velocity/temperature correlations with those given in the literature.

the data given in the literature. Again, Subramanian and Antonia (1981) report larger values of normalized streamwise heat flux distributions as shown in figure 3(a). The present data is in better agreement with that given by Fulachier (1972).

The data given in figure 3(b) indicate that the present data agree fairly well with that of Fulachier (1972), but the values are somewhat higher throughout most of the boundary layer compared with Subramanian and Antonia (1981) at nominally the same enthalpy thickness Reynolds number, $Re_{\Delta 2}$. Subramanian and Antonia found that the peak value of the measured normal heat flux was dependent on Reynolds number. At a $y/\delta_{99} = 0.1$, which was the closest measurement they made near the wall, the normalized heat flux values increased from $\rho C_p \bar{vt}/q''_w = 0.58$ to 0.85 as Reynolds number increased from $Re_{\Delta 2} = 990$ to 4750. For the present data, the peak values, which occurred at approximately $y/\delta_{99} = 0.1$, were $\rho C_p \bar{vt}/q''_w = 0.75$ and 0.8 as the Reynolds number increased from $Re_{\Delta 2} = 560$ to 940.

If all of the surface heat flux is transported by the normal turbulent heat flux, one would expect $\rho C_p \bar{vt}/q_w = 1$ near the wall. However, in the case of a constant heat flux test plate there is also streamwise convection, due to the streamwise variation of the wall temperature, and molecular conduction at the surface. Since the turbulent heat flux measurements near the wall are only 75–80% of the total wall heat flux, estimates of the convection term, $\rho C_p(\mathrm{d}T/\mathrm{d}x)\int u\mathrm{d}y$, were made to check the total energy balance. Estimates of the convection term were between 10–20% of the total wall heat flux. The molecular conduction term would also reduce the direct measurement of the normal heat flux.

6. Conclusions

The two-component LDV and 0.64 μm cold-wire technique, used to simultaneously measure temperature and velocity fluctuations in this work, has significant

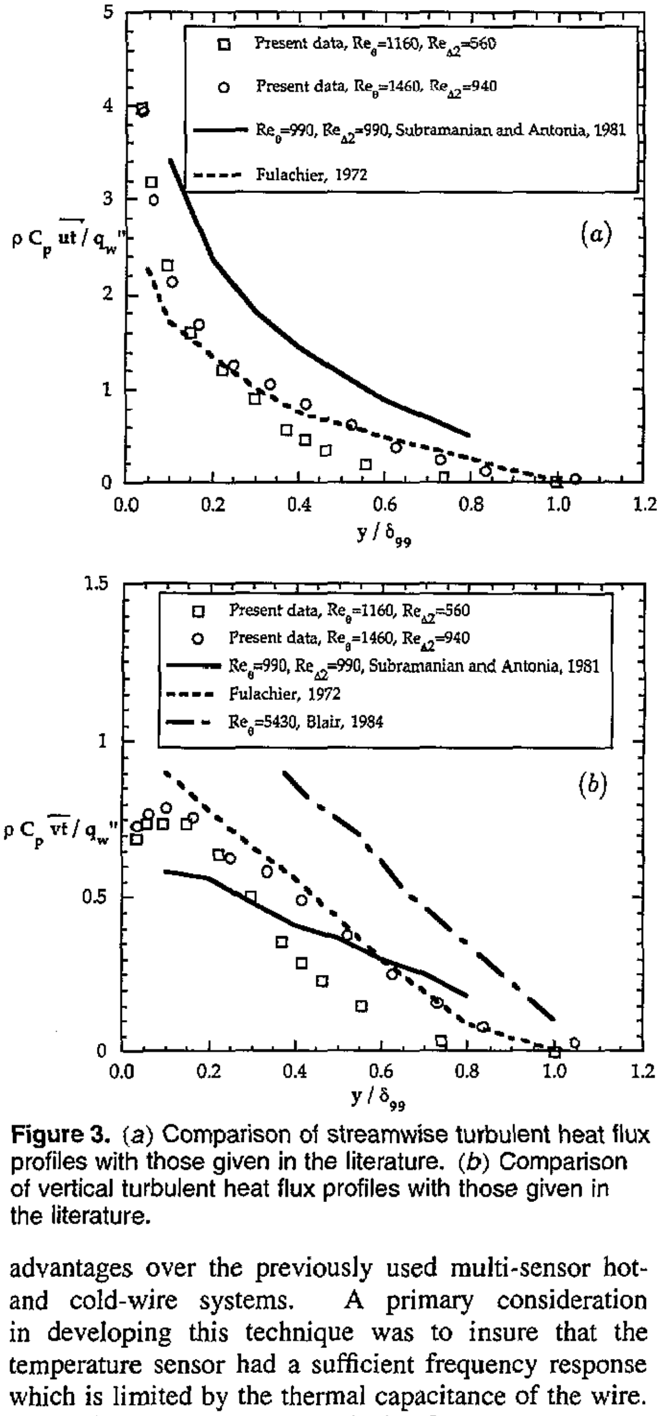

Figure 3. (*a*) Comparison of streamwise turbulent heat flux profiles with those given in the literature. (*b*) Comparison of vertical turbulent heat flux profiles with those given in the literature.

advantages over the previously used multi-sensor hot- and cold-wire systems. A primary consideration in developing this technique was to insure that the temperature sensor had a sufficient frequency response which is limited by the thermal capacitance of the wire. The 0.64 μm diameter wire had a frequency response of nominally 10 kHz which was more than adequate for the required application.

As indicated by the two-point velocity cross-correlation measurements, the spacing between the LDV probe volume and the cold-wire, which was 0.3 mm, was adequate for this particular application. Advantages in using the LDV and cold-wire combination as opposed to multi-sensor probes are that small spatial distances could be achieved with no danger of sensor interference, and no correction to velocity measurements are required.

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