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Letter

An improved wall shear stress measurement technique using sandwiched hot-film sensors

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ABSTRACT

In this letter we present a novel wall shear stress measurement technique for a turbulent boundary layer using sandwiched hot-film sensors. Under certain conditions, satisfactory results can be obtained using only the heat generated by one of the hot-film and a calibration of the sensors is not required. Two thin Nickel films with the same size were used in this study, separated by an electrical insulating layer. The upper film served as a sensor and the bottom one served as a guard heater. The two Nickel films were operated at a same temperature, so that the Joule heat flux generated by the sensor film transferred to the air with a minimum loss or gain depending on the uncertainties in the film temperature measurements. Analytical solution of the shear stress based on the aforementioned heat flux was obtained. The preliminary results were promising and the estimated wall shear stresses agreed reasonably well with the directly measured values (with errors less than 20%) in a fully developed turbulent pipe flow. The proposed technique can be improved to further increase precisions.

Wall shear stress is an important parameter in turbulent wall bound flows; it not only determines the viscous drag force but is also used to scale the near wall velocity profiles. There are different existing techniques to measure the wall shear stress, e.g. direct measurements on or near the wall, optical methods such as the oil-film interferometry [1–4] and the microelectromechanical systems (MEMS) sensors such as surface flush-mount hot-film sensors, reviewed in Refs. [5–7]. Among these techniques, MEMS thermal sensor is of great practical importance and was used in many aerospace applications such as aircraft wing and compressor blade in gas turbine. Recent development of thermal sensor technique was discussed in Refs. [8, 9]. Analysis of heat and momentum balance over the hot-film sensor [10–13] suggested that the total Joule heating Q from the sensor film and the time average shear stress $\bar{\tau}_w$ over the sensor satisfy

$$Q = A\bar{\tau}_w^{1/3} + B. \tag{1}$$

Here, $Q = Q_a + Q_s$, Q_a is the heat flux transfers to the cold air and Q_s is the heat transfers to the cold wall by conduction as illustrated in Fig. 1; constants A and B varies with Q_a and Q_s, and both can be determined by a calibration [10]. In a typical calibration process, the sensor was positioned at a location where the mean wall shear stress could be adjusted and measured directly using a more reliable method, usually on the wall of a fully developed pipe or channel flow. An *in-situ* calibration is preferred to remove some of the effects such as alignment, temperature, electrical resistance of cables and connectors, etc. However, an *in-situ* calibration is not always practical. Performance of the pre-calibrated sensors deteriorated as the ambient temperature, surface condition might change with time. Therefore, it is highly desirable to develop a wall shear stress measurement technique with reasonable accuracy and does not require a calibration.

Inspired by the heat shield used in Refs. [14–16], a guard heater film with the same size and operated at a same temperature to the sensor film was positioned between the sensor film and the wall, as shown in Fig. 2(a). A non-electrical conductive thin membrane with a thickness of d and thermal conductivity of k_f was used to separate the two metal films, in this way the con-

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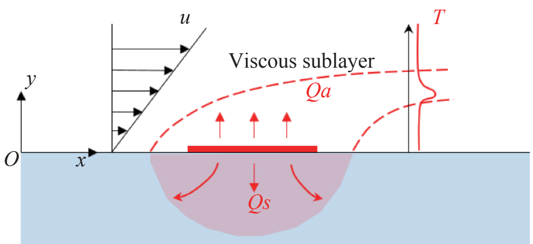

Fig. 1. Schematic of a single hot-film sensor.

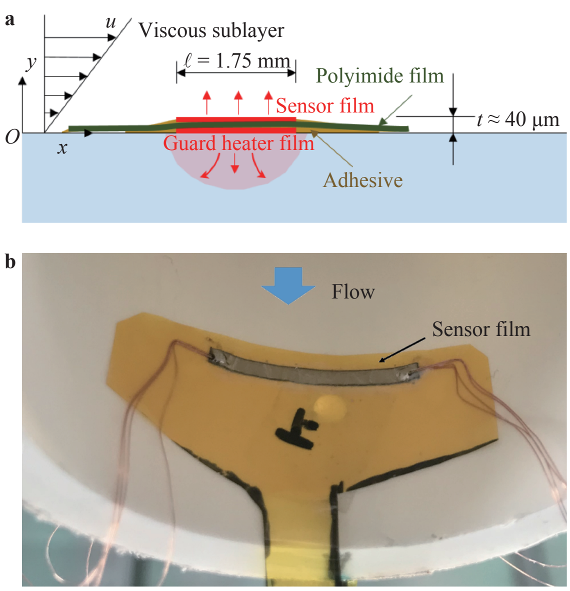

Fig. 2. **a** Schematic and **b** Picture of the sandwiched hot-film sensors.

duction heat transfer from sensor film through the membrane

$$Q_s = k_f \frac{T_f - T_g}{d} lw \approx 0, \tag{2}$$

as the guard heater film temperature T_g was set to equal to the sensor film temperature T_f. Here, l and w are the length and width of the metal films, respectively. Therefore, $Q \approx Q_a$ and the constant B in Eq. (1) vanishes as Hanratty and Campbell [5] found that B linked to heat loss Q_s, and Eq. (1) becomes

$$Q = A\bar{\tau}_w^{1/3}. \tag{3}$$

Following an approach based on the integral momentum and energy balances in the thermal boundary layer outlined in Bellhouse and Schultz [10], an analytical solution of A in Eq. (3) for air as the medium is found to be

$$A = 3\frac{k^{2/3}\rho^{1/3}C_p^{1/3}wl^{2/3}}{(36\mu)^{1/3}}(T_f - T_o) \tag{4}$$

assuming the thermal boundary layer is within the viscous sublayer of a turbulent boundary layer; and the temperature profile is parabolic inside the thermal boundary layer. Here, T_f is the film temperature for both sensor and heater films; T_o is the air temperature; k, ρ, C_p, and μ are the thermal conductivity, density, specific heat and absolute viscosity of air, respectively, which are weakly temperature dependent and were evaluated using the average of sensor film and air temperatures, $(T_f - T_o)/2$. In this way, $\bar{\tau}_w$ can be estimated using Eqs. (3) and (4) without a requirement of calibration as long as the assumption of thickness of thermal boundary layer (δ_T) is located within 5 wall units ($y^+ \lesssim 5$). The analytical solution of the thermal boundary layer thickness at the downstream edge of the film is

$$\delta_T = \left(\frac{36k\mu l}{\rho c_p \bar{\tau}_w}\right)^{1/3}. \tag{5}$$

The sensor assembly is made of two 2 μm thick, 22 mm wide (w), and 1.75 mm long (l) films made of Nickel (GOODFELLOW NI000120), as shown in Fig. 2(b). The length and width of both Nickel films were measured under a microscope at 40 × magnification. The uncertainty was less than 0.01 mm (0.6% of film length). The two thin films formed a sandwich structure separated by a 40 mm long, 40 mm wide, and 25 μm thick polyimide membrane (DUPONT KAPTON 10 with a thermal conductivity of $k_f = 0.12\ \mathrm{W/(m \cdot K)}$). The metal films were attached to the membrane using adhesive. The total thickness of the sensor assembly t was less than 40 μm. The thickness was $t^+ \approx 0.6$ and 2.0 in terms of wall unit in the cases of $\bar{\tau}_w \approx 0.05$ Pa and 0.45 Pa, respectively, and can be regarded as weakly intrusive in this wall shear stress range.

Two edges of each film were connected to fine gauge copper wires by soldering. Both films were kept at a temperature 50°C above the air temperature by supplying DC current to the films using a multi-channel DC power supply (KEITHLEY 2231A-30-3) and monitoring their electrical resistances R. The total heat flux generated by the sensor film was the product of the voltage and current across the film $Q = EI$. Both voltage and current were measured using a multi-meter on the power supply with uncertainties of ±1 mV (0.2% of typical voltage) and ±1 mA (0.1% of typical current), respectively. The relations between resistance R and the average film temperature T_f is

$$T_f = T_o + \frac{R - R_o}{\alpha R_o}. \tag{6}$$

Here, R_o is the cold film resistance at the room temperature T_o, the temperature coefficient of resistance of Nickel is $\alpha = 0.0068\ {}^\circ\mathrm{C}^{-1}$ according to the manufacturer's data. The ambient temperature T_o was measured using a PT100 temperature sensor with a uncertainty of ±0.1 °C. The resistance of each film was evaluated using $R = E/I$. Following Coleman and Steele [17], the uncertainty of film resistance was found to be 0.3% of typical value (±1.5 mΩ); the uncertainty of the temperature difference $T_f - T_g$ was 0.4% of typical value (±0.2 °C). The mean wall shear stress was then estimated using Eq. (3) with A given in Eq. (4). The largest uncertainty in the estimated $\bar{\tau}_w$ arises from the heat conduction through the membrane due to the uncertainty in $T_f - T_g$, which can be as large as 12.0% of Q. It is noted that the wall will be heated by the guard heater film as indicated in the red shaded area in Fig. 2; the pre-heating leads to an error as the air arrives at the sensor film with a temperature larger than the freestream temperature. This error could be minimized by limiting the operating time.