SHORT PAPER

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Temperature correction for oil film interferometry with infrared camera in skin friction measurements

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1 Introduction

Because drag reduction directly reduces fuel consumption, research on drag reduction techniques has become increasingly important in transport aircraft development as environmental issues have gained weight. Since skin friction contributes over half of the total aerodynamic drag on a thin airfoil at high speeds (Szodruch 2011), reducing it will obviously have a significant impact on fuel efficiency. There are many techniques for skin friction measurement, such as global luminescent oil-film method (Liu 2008; Lee et al. 2018, 2020), oil-film interferometry method (Zilliac et al. 2011; Driver et al. 2008; Bottini et al. 2015; Kurita et al. 2016), MEMS-based sensors (Ho et al. 1998), liquid crystal coatings (Kheireddine 1997), balance sensors (Allen 2012), and conventional shear-stress measurement techniques [Preston tube (Patel 1965), Clauser plot, Pitot tube (Ludwig et al. 1950; Schoenherr 1932)]. However, it is very difficult to measure skin friction with high accuracy, because skin friction depends on boundary layer condition, and the measured values are very small. The global luminescent oil-film method utilizing luminescent intensity was developed by Liu et al. (2008) and the absolute skin friction can be globally determined with calibration, using a point-based sensor at several locations. Lee et al. (2020) indicated that the values of skin friction by the luminescent oil-film method depend on the oil-film thickness and the values agreed well with those determined using the Clauser chart method (Clauser 1956) when the oil-thickness is close to the viscous sublayer thickness (less than five wall unit). The oil film interferometry method has been widely used and has received much attention over the past 20 years because it has greater accuracy and is easier to use compared to other techniques (Naughton et al. 2002), but the oil used has a temperature dependency that reduces the skin friction measurement accuracy and it requires smooth, reflective surfaces. Therefore, surface temperature measurement simultaneously with the skin friction measurements is quite important to correct the temperature dependency (Zilliac et al. 2011). According to the Zilliac G's uncertainty analysis, temperature variations of 5°F lead to 5.5% uncertainty in the total uncertainty is 14.9%. Although temperature sensitive paint (TSP) can be used for oil temperature correction (Bottini et al. 2015), spraying TSP on the model surface is very time-consuming. One study used an infrared point sensor to measure oil temperature (Kurita et al. 2016), but the sensor could measure at only one surface point during a wind tunnel run.

In this study, the accuracy of the oil film interferometry method for measuring skin friction is improved by correcting the temperature dependency of the oil using temperature measurements from an infrared camera. This technique is particularly effective when the temperature correction is applied to a surface with a non-uniform temperature distribution. The skin friction coefficients estimated by this temperature-

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corrected oil film interferometry were compared with those estimated from velocity profiles and shear stress in addition to theoretical values.

Skin friction measurements were carried out on an aluminum flat plate mounted in an open-type low speed wind tunnel with 0.2×0.3 m cross section at $U_e = 22.8, 34.2$, and 46.2 m/sec. The measurement points on the flat plate in this test are shown in Fig. 1. The measurements with shear stress sensor and Pitot rake were implemented at $x = 570$ mm downstream from leading edge. Measurements by the oil film interferometry method were carried out at eight points (four points with heater area, and the other points with no heater area). Each measurement value was averaged over approximately 10 mm range in the stream wise. These representative locations are 555, 565, 575, and 585 mm from the leading edge. A roughness element was attached 30 mm downstream from the leading edge to induce a boundary layer transition. The measurement system is shown in Fig. 2. The test section of the wind tunnel was covered by side walls and was only accessible from above when setting up instruments. The oil-film interferometry measurement system consists of a CCD camera (Allied Vision Prosilica GX 6600), a sodium lamp, a reflector, and an infrared (IR) camera (InfReC R500EX). The resolutions of the CCD camera and IR camera are 6576×4384 and 640×480 pixels, respectively. In addition, the spatial resolutions per pixel of the CCD camera and IR camera in this study are approximately 0.023 mm and 0.3 mm, respectively. The peak of wave length of the sodium lamp is 590 nm. The silicon oil with 50 cS (mm^2/s) was used in this study. A heater was embedded into the plate to change the surface oil temperature to validate the temperature correction. Since the oil film is very thin (under 1 μm) when the fringes appear, it is assumed that the oil temperature is the same as temperature of the plate surface. Therefore, surface temperature measurement is equivalent to oil temperature measurement. However, because the flat plate was made of aluminum and had a mirror finish, its surface emissivity was very low, making temperature measurement by the IR camera very difficult. In this study, polyimide Kapton® tape, which has been widely used in oil film interferometry, was applied to the surface to increase the emissivity. The thickness of the Kapton is 50 μm . The Kapton can improve the accuracy of temperature measurement, because the surface of the Kapton can emit only the infrared radiation by itself and do not reflect the infrared radiation originated from outside. The temperature of the tape was measured by the IR camera. For correct temperature measurement, the value of the IR camera's emissivity parameter needs to be set to the emissivity of the measured surface. We set the emissivity parameter before the wind tunnel runs by comparing IR camera temperature measurements of the tape surface with temperatures from a thermocouple on the surface of the tape, and adjusting the parameter until they agreed. The parameter value that gave correct temperature readings was found to be 0.96.

A Pitot rake with 31 pipes was set up to measure the total pressure to estimate the velocity profile in the boundary layer, and the skin friction is calculated using Eq. (1) (Schoenherr 1932)

$$\frac{1}{C_f} = 17.08(\log_{10} R_\theta)^2 + 25.11 \log_{10} R_\theta + 6.012, R_\theta = \frac{U_e \delta}{\nu} \quad (1)$$

where C_f is the skin friction coefficient, R_θ is Reynolds number based on momentum thickness, ν is kinematic viscosity, U_e is free stream velocity, and δ is the boundary layer thickness. The skin friction is also calculated using Eq. (2) (Ludwig et al. 1950)

$$C_f = 0.246 \times 10^{-0.678H} R_\theta^{-0.268}, H = \frac{\delta^*}{\theta} \quad (2)$$

where H , θ , and δ^* is a shape factor, momentum thickness, and displacement thickness, respectively.

A shear stress sensor with a 10-mm diameter movable disk was flush-mounted on the flat plate so as not to disturb the flow. Figure 3 shows a schematic of the shear stress sensor. Skin friction due to air flowing over the disk deflects the shaft attached to the disk, and the deflection is detected by a strain gauge. The sensor is very sensitive, and its capacity is only 0.1 gf.

The oil film interferometry technique works on the principle that oil placed to an aerodynamic surface will flow and thin due to shear stress (skin friction). As time goes on, the oil film thickness decreases to the point that interference fringe patterns will be spaced far enough apart to be visible as shown in Fig. 4. The experimental procedure in this study is showed as follows. At first, the oil is put on the two places (the heater area and no heater area in the measurement point) at $x = 550$ mm before the tunnel starts (see Fig. 1). Two images of the fringes at regular intervals are used for determining the skin friction. Brightness value data of the fringes in the stream wise are extracted from the images. Each of fringe spacings Δs_n at t_n (s), Δs_{n+1} at t_{n+1} (s) are determined using averaged peak-to-peak values from the wave of brightness. For example, the averaged fringe-spacing difference, $\Delta s_{n+1} - \Delta s_n$, in the heater area at 34.2 m/s is approximately 1.5 mm.

Fig. 1 Schematic diagram of the measurement points (eight points) on the flat plate (Plan view)

Fig. 2 Measurement system used in the tests: (a) Side view, (b) Top view

The spatial resolution per pixel of the CCD camera (0.023 mm) is much smaller than this fringe-spacing difference. Temperatures on the fringe measurement points T_{wall} are extracted from the images with IR camera, and kinematic viscosity μ_{oil} , oil density ρ_{oil} are determined from Eq. (3). The values of temperatures at t_n (s) were employed for the correction, because two values of temperatures at t_n (s) and t_{n+1} (s) are almost the same. Total temperatures of this flow were used for determining skin frictions without temperature correction. Finally, skin friction coefficients are determined from Eq. (4) by the fringe-spacing difference ($\Delta s_{n+1} - \Delta s_n$), the kinematic viscosity (μ_{oil}), the refractive index of the oil (n_0), the wavelength of light from the illuminating sodium lamp (λ), the light refraction angle through the oil (θ_r), the tunnel

Fig. 3 Shear stress sensor

dynamic pressure (q_∞). The integral, containing μ_0 and the tunnel dynamic pressure q_∞ , is integrated from time t_n through t_{n+1} .

$$\log\left(\frac{\mu_{\text{oil}}}{\rho_{\text{oil}}}\right)_T = \frac{763.1}{273 + T_{\text{wall}}} + \log\left(\frac{\mu_{\text{oil}}}{\rho_{\text{oil}}}\right)_{298\text{K}} \quad (3)$$

$$C_f = \frac{\tau_w}{q_\infty} = \frac{(2n_0/\lambda) \cos(\theta_r)(\Delta s_{n+1} - \Delta s_n)}{\int_{t_n}^{t_{n+1}} (q_\infty/\mu_{\text{oil}}) dt} \quad (4)$$

Figure 5 shows the measured boundary-layer velocity profile at $U_e = 22.8$ m/s, $x = 570$ mm with the laminar Blasius profile and the fully turbulent power-law profile. In Fig. 5, the height and the velocity are nondimensionalized by boundary layer thickness, δ and free stream velocity, U_e , respectively. The value of the shape factor ($H = \delta^*/\theta$ = displacement thickness/momentum thickness) of the measured profile is 1.33. As an indicator, conventionally typical of laminar flows are at $H = 2.59$, while typical of turbulent flows are at $H = 1.3$ – 1.4 (Schlichting 1979). In addition, the measured profile agrees much more the power-law curve than the Blasius profile. Therefore, the measured profile is considered to be closer to turbulent flow. In addition, it appears from the boundary-layer velocity profile that there is not a boundary layer separation by a disturbance caused by the Kapton tape. Figure 6 shows images of interference fringe patterns at $t = 360$ and $t = 520$ s. in the oil film on the Kapton during a wind tunnel run at $U_e = 34.2$ m/sec. The fringe spacings increase with time regardless of whether the heater is on or off. Oil temperature distributions obtained $t = 360$ s during the same wind tunnel run as Fig. 6 using the infrared camera are shown in Fig. 7. The values of surface temperatures for correction obtained at the skin-friction measurement points (eight points) with the total temperature of the flow are shown in Table 1. Since the spatial resolutions per pixel of the IR camera (0.3 mm) is much smaller than spacings between measurement points, temperature corrections for the measurement points are possible. In any flow velocities, the temperatures in the heater area are approximately 3 °C higher than those in the no heater area, and are approximately 6 °C higher than the total

Fig. 4 Schematic diagram of the skin friction measurements using interference fringes of oil

Table 1 Oil temperature used for the correction on the measurement points (No heater area and Heater area) with total temperature ($t = 360$ s.)

U_e [m/s]	x [m]	y [m]	Oil temperature in no heater area by IR camera [°C]	x [m]	y [m]	Oil temperature in heater area by IR camera [°C]	Temperature of free stream [°C]
22.8	0.555	0.030	21.8	0.555	0.082	24.6	19.9
			22.0			25.6	
			22.1			26.1	
			22.0			25.9	
34.2	0.555	0.030	24.0	0.555	0.082	26.3	21.7
			24.1			27.3	
			24.2			27.8	
			24.2			27.5	
46.2	0.555	0.030	25.9	0.555	0.082	28.2	24.1
			26.2			29.2	
			26.2			29.8	
			26.2			29.5	

Table 2 Skin friction coefficient by shear stress sensor

Re_{x_ave}	C_{f_ave}	$C_{f_1\sigma}$
8.10.E+05	0.00359	0.00004
1.21.E+06	0.00318	0.00002
1.62.E+06	0.00284	0.00005

Fig. 5 Boundary layer profile at $U_e = 22.8$ m/s, $x = 570$ mm

temperatures. Figure 8a, b shows results of skin friction coefficients, C_f , with and without oil temperature correction in the heater area and in no heater area. In the no heater area, values of C_f with and without the temperature correction lie between the theoretical values as shown in Fig. 8a. On the other hand, in the heater area, values of C_f without the temperature correction does not lie between the theoretical values as shown in Fig. 8b. Since the total temperature is lower than the oil temperature, the kinematic viscosity estimated from the total temperature is higher than oil kinematic viscosity. Therefore, values of C_f using total temperature are overestimated compared to the actual C_f values. After the correction, the values of C_f are almost within the theoretical values. The mean in four times of measurement values by shear stress sensor and the standard deviation (1σ) are shown in Table 2 and the random error is much smaller than the mean values. Figure 9 shows values of C_f from oil film interferometry after correction compared to those obtained by the shear stress sensor and velocity profile with Pitot rake. Here, the corrected results in the no heater area are also included in the results of oil film interferometry. Measurements obtained by all the approaches are within the range of the theoretical values. Particularly, the measured C_f values and C_f

Fig. 6 Images of interference fringe patterns ($U_e = 34.2$ m/s, $t = 360$ s. and $t = 520$ s.)

Fig. 7 Oil temperature distribution on Kapton with infrared camera ($U_e = 34.2$ m/s, $t = 360$ s.)

Fig. 8 Skin friction results with and without oil temperature correction

Fig. 9 C_f from oil film interferometry after the correction compared with values from other approaches: shear stress sensor and Pitot rake

gradient to Re_x in the oil film interferometry method are closer to the measurement values by shear stress sensor than the measurement values by Pitot rake. The accuracy of the shear stress sensor is quite high, and its measurements are very reliable, since it directly measures skin friction. Thus, the oil temperature was successfully corrected, and skin friction measurements with higher accuracy are expected using this method.

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