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

Author(s):
Iijima, H.; Uchiyama, T.; Kato, H.

Publication date:
2018-10-05

Permanent link:
https://doi.org/https://doi.org/10.3929/ethz-b-000279215

TEMPERATURE CORRECTION FOR OIL FILM INTERFEROMETRY WITH INFRARED CAMERA IN SKIN FRICTION MEASUREMENTS

H. IIJIMA[1,c], T. UCHIYAMA[1], H. KATO[1]

[1]Aeronautical Technology Directorate, Japan Aerospace Exploration Agency, Chofu, Tokyo 182-8522, Japan
[c]Corresponding author: Tel.: +81-50-3362-7488; Fax: +81- 422 – 40 - 3234; Email: iijima.hidetoshi@jaxa.jp

KEYWORDS:
Main subjects: skin friction, oil film interferometry, temperature correction
Fluid: incompressible flows
Visualization method(s): Infrared camera
Other keywords: shear stress sensor, pitot rakes

ABSTRACT: *The skin friction on an aluminum flat plate with a turbulent boundary layer was measured in a low speed wind tunnel using oil film interferometry with temperature correction by an infrared camera. Polyimide tape was applied to the surface of the plate in order to enhance its emissivity. A heater embedded in the plate was used to change the temperature of the oil on the plate to evaluate the temperature correction. As a result, the skin friction coefficients estimated by the oil film interferometry with temperature correction agreed well with those estimated from velocity profiles measured with a Pitot rake and from shear stress measured by a strain gauge sensor.*

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 [1], reducing it will obviously have a significant impact on fuel efficiency. There are many techniques for skin friction measurement, such as oil film interferometry, MEMS-based sensors, liquid crystal coatings, balance sensors, and conventional shear-stress measurement techniques (Preston tube, Clauser plot, Pitot tube, etc.) [2]. However, it is very difficult to measure skin friction with high accuracy, because the measured values are very small. 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, but the oil used has a temperature dependency that reduces the skin friction measurement accuracy [3] and it requires smooth, reflective surfaces. Although temperature sensitive paint (TSP) can be used for oil temperature correction [4], spraying TSP on the model surface is very time-consuming. One study used an infrared point sensor to measure oil temperature [5], 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-corrected oil film interferometry were compared with those estimated from velocity profiles and shear stress in addition to theoretical values.

2 Experimental Setup

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 the Japan Aerospace Exploration Agency (JAXA). To validate the method of oil film interferometry temperature correction using an infrared camera, skin friction coefficients were also simultaneously measured using two methods: using velocity profile measured by a Pitot rake, and using shear stress measured by a strain gauge. The measurements were implemented 570 mm downstream from leading edge. A roughness element was attached to induce a boundary layer transition, and it was found that the boundary layer condition at the measurement point is turbulent from the velocity profile.

The measurement system is shown in Fig. 1. 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 was very simple and consisted of a CCD (charge-coupled device) camera, a sodium lamp, a reflector, and an infrared (IR) camera. 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, it is assumed that the temperature of oil is the same as that of the plate surface. 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® [6] tape, which has been widely used in oil film interferometry, was applied to the surface to increase the emissivity. The Kapton can improve the accuracy of temperature measurement, because the surface of the Kapton can emit only the infrared radiation by itself and don't 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.

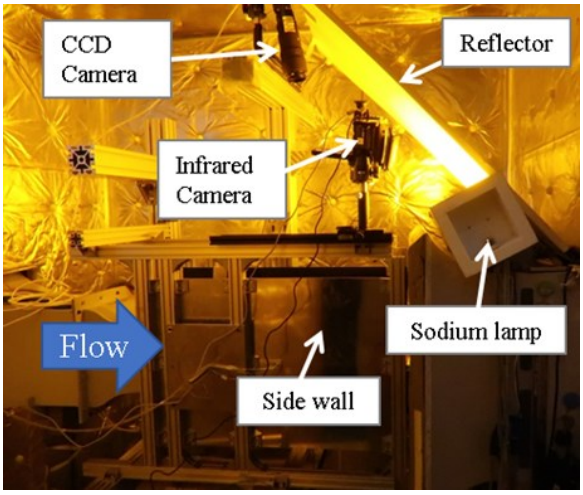
A Pitot rake with 31 pipes was set up to measure the total pressure to estimate the velocity profile in the boundary layer, and the skin friction was calculated using Eq. (1) (formula of Karman - Schoenherr)

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

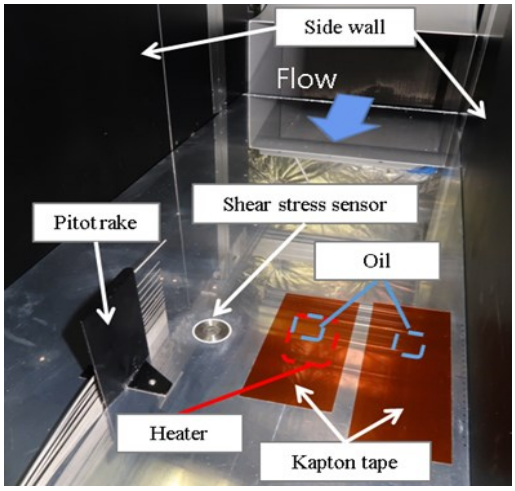
where C_f is the skin friction coefficient, R_θ is momentum thickness, ν is kinematic viscosity, U_e is free stream velocity, and δ is the boundary layer thickness. The skin friction was also calculated using Eq. (2) (the formula of Ludwieg - Tillmann)

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

where H is a shape factor, δ^* is displacement thickness.



(a)



(b)

Fig. 1. Measurement system used in the tests: (a) Side view, (b) Top view.

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 2 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. A purge pipe and a T-type thermocouple are attached to clean the inside of sensor and to monitor its temperature.

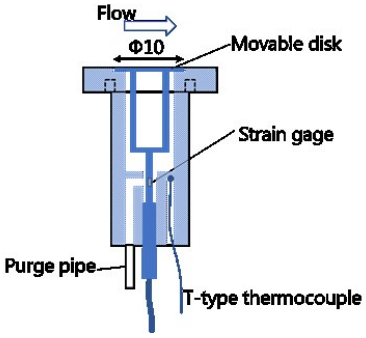


Fig. 2. Shear stress sensor

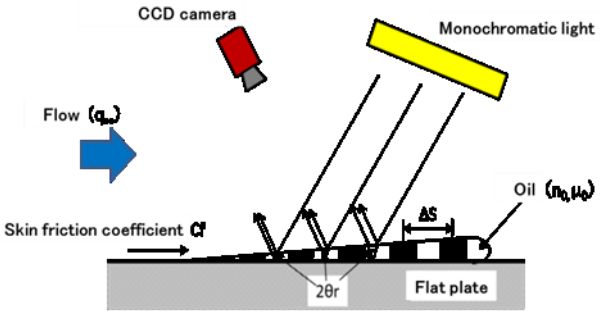


Fig. 3. Skin friction measurements using interference fringes of oil.

3 Oil film interferometry

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 patterns will be spaced far enough apart to be visible as shown in Fig. 3. Skin friction coefficients (C_f) are calculated using Eq. (3):

$$C_f = \frac{\tau_w}{q_\infty} = \frac{(2n_0/\lambda)\cos(\theta_r)(\Delta s_{n+1} - \Delta s_n)}{\int_{t_n}^{t_{n+1}} (q_\infty/\mu_0)\, dt} \quad (3)$$

where n_0 is the refractive index of the oil, λ is the wavelength of light from the illuminating sodium lamp, θ_r is the light refraction angle through the oil, and Δs is the spacing between the fringes. The integral, containing the hydraulic quantity of oil viscosity μ_0 and the tunnel dynamic pressure q_∞, is integrated from time t_n through t_{n+1}. The fringe spacings (Δs_n and Δs_{n+1}) are measured at those times. Eq. (4) is used for oil temperature correction [7]. The oil temperature was measured with the infrared camera (InfReC R500EX) shown in Fig. 4.

$$log\left(\frac{\mu_{oil}}{\rho_{oil}}\right)_T = \frac{763.1}{273 + T_{wall}} + log\left(\frac{\mu_{oil}}{\rho_{oil}}\right)_{298K} \quad (4)$$

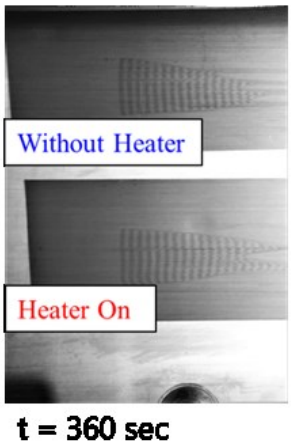
Fig. 4. Infrared camera (InfReC R500EX).

4 Results

Figure 5 shows images of interference fringe patterns in the oil film on the Kapton during a wind tunnel run at U_∞ = 34 m/sec. The fringe spacings increase with time regardless of whether the heater is on or off. Oil temperature distributions obtained during the same wind tunnel run as Fig. 5 using the infrared camera are shown in Fig. 6.

Figure 7 shows result of skin friction coefficients, C_f, with and without temperature correction by the oil temperature distributions. The corrected oil temperature value was the temperature measured by the infrared camera, while the uncorrected oil temperature was the temperature of the free stream in the wind tunnel. The difference between these values was about 6 ℃. As is evident from Fig. 7, the values of C_f after correction lie between the two theoretical values. Figure 8 shows values of C_f from oil film interferometry after correction compared to those obtained by the shear stress sensor and Pitot rake. Here, the results without the heater are also included in the results of oil film interferometry. Measurements obtained by all the approaches, including the corrected oil film interferometry, are within the range of the theoretical values. The accuracy of the shear stress sensor is quite high, and its

measurements are very reliable, since it directly measures skin friction. In Fig. 8, the shear stress sensor results agreed well with those of the corrected oil film interferometry. Thus, the oil temperature was successfully corrected, and skin friction measurements with higher accuracy are expected using this method.



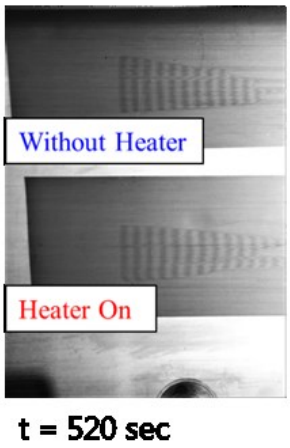


Fig. 5. Images of interference fringe patterns (U_∞ = 34 m/sec., t = 360sec. and t = 520sec.).

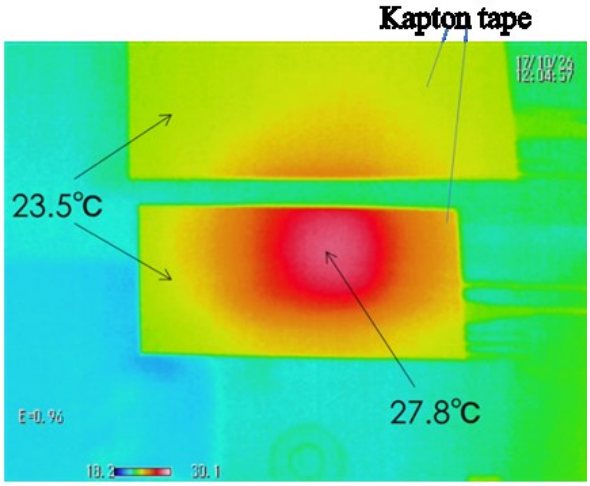


Fig. 6. Oil temperature distribution on Kapton with infrared camera.

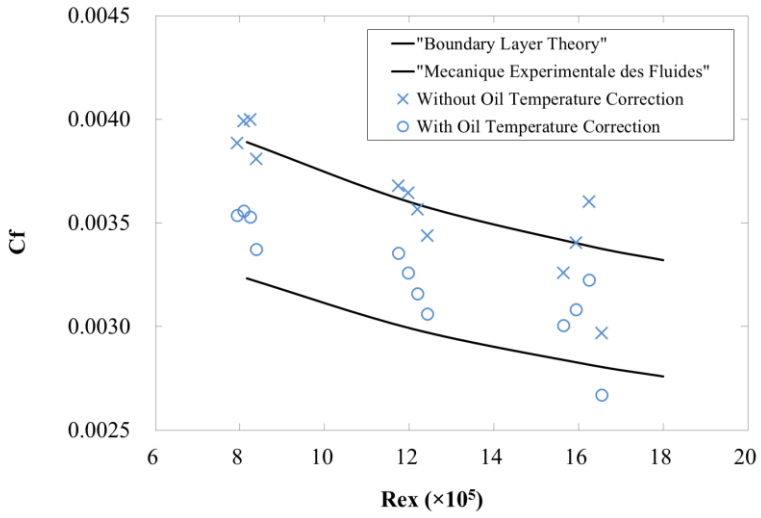


Fig. 7. Skin friction results with and without oil temperature correction with oil temperature distribution.

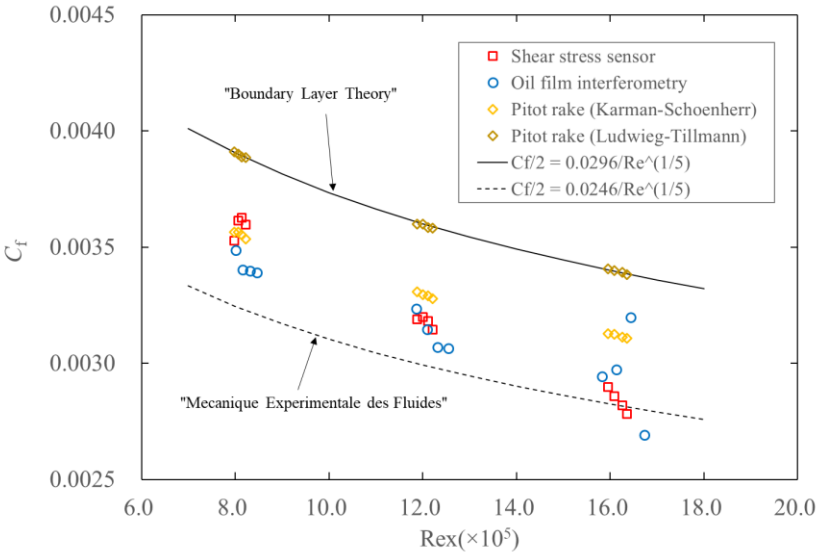


Fig. 8. C_f from oil film interferometry after the correction compared with values from other approaches: shear stress sensor and Pitot rake.

4 Conclusions

This paper describes a method for the temperature correction of oil film interferometry in skin friction measurements. Temperature measurements of the surface of an aluminum plate were successfully made using an infrared camera by applying polyimide tape (Kapton®[6] tape) to increase emissivity. The values of C_f from the corrected oil film interferometry agreed well with those from conventional approaches using a shear stress sensor and a Pitot rake, as well as two theoretical values. These results therefore suggest that the oil temperature in the skin friction measurement was successfully corrected.

References

[1] Szodruch, J., "Viscous Drag Reduction on Transport Aircraft", AIAA Paper 91 -0685.

[2] Jonathan, N., "Modern developments in shear-stress measurement", Progress in Aerospace Sciences 38 (2002) 515-570.

[3] Gregory, G., "A Comparison of the Measured and Computed Skin Friction Distribution on the Common Research Model", AIAA 2011-1129

[4] Bottini H.,"Effects of wall temperature on skin-friction measurements by oil-film interferometry", Meas. Sci. Technol. 26 (2015) 105301 (pp.).

[5] Kurita, M., Iijima, H., "Oil-film interferometry using correction for variation of oil-viscosity with temperature", JSASS-2016-2130. (In Japanese)

[6] DuPont, polyimide film.

[7] ShinEtsu Chemical Co. Ltd. Silicone Fluid KF-96, Performance Test Results