EXTENDED THEORY OF OIL FILM INTERFEROMETRY FOR SKIN FRICTION MEASUREMENT

Antonio Segalini[1], Peter A. Monkewitz [2] & Jean-Daniel Rüedi [2]
[1] *Linné FLOW Centre, KTH Mechanics, S-100 44, Stockholm, Sweden*
[2] *Faculty of Engineering Science, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015, Lausanne, Switzerland*

Abstract In recent years, the independent measurement of wall shear stress with oil film interferometry has led to a step increase in the understanding of turbulent boundary layers. However, while many arguments depend critically on a precise knowledge of the skin friction, the systematic errors of the oil film technique are not well known. In particular the basic theory underlying the technique has essentially not evolved since it was first proposed by Tanner & Blows (J. Phys. E: Sci. Instrum., vol. 9, 1976, p. 194). The purpose of this study is to elucidate the dominant systematic error of the classical oil film method. We derive the corrections to the basic Tanner & Blows similarity solution for the film development in zero pressure gradient boundary layers and validate the analysis experimentally. This allows to formulate best practice guidelines for the oil film technique that help push uncertainties below 1%.

Since [7] introduced the oil film and oil drop technique to measure wall shear stress of air flows it has slowly gained ground relative to other methods, as documented by Janke [2] and Rüedi *et al.* [5] for instance. The oil drop method, where small individual oil drops are deposited on the wall, has become the method of choice for the *independent* determination of wall shear stress over the last decade. As such it is a cornerstone of recent experimental turbulent boundary layer research by Chauhan *et al.* [1] and Österlund [4], for instance, and its accuracy is a central issue in the ongoing debate on turbulent boundary layer scalings [3].

According to the basic similarity solution [7], the thickness of a two-dimensional oil film entrained by a zero-pressure-gradient boundary layer is

$$h^*(x^*,t^*) \;=\; \frac{\hat{\mu}^* x^*}{\tau_{\mathrm{w}}^* t^*} \quad , \tag{1}$$

and the observed fringe spacing Δx^* is proportional to the inverse slope of h^*, i. e.

$$\Delta x^* \;=\; \frac{\tau_{\mathrm{w}}^*\, t^*}{\hat{\mu}^*} \frac{\lambda^*}{2(\hat{n}^2 - \sin^2\varphi)^{1/2}} \quad , \tag{2}$$

where τ_{w}^* is the wall shear stress of the air boundary layer entraining the oil, $\hat{\mu}^*$ is the dynamic viscosity of oil, λ^* the wave length of the illuminating light in air $\hat{n}$ the refraction index of oil relative to air and φ the viewing angle. As seen from equation (2), the classic theory predicts, at any given time, the same Δx^* everywhere on the oil drop.

An example of the fringe spacing distribution Δx^* along the centerline of the drop is reported in figure 1 for different times. A systematic variation of Δx^* along x^* is evident, even at large times. The variation is quite small but it is not clear from the classic theory what is causing it and if it can lead to a systematic error in the estimation of τ_{w}^*.

A possible explanation for this (small) variation is the velocity discontinuity at the oil-air interface in the basic similarity solution (1) of Tanner & Blows [7] which only satisfies continuity of shear stress. Close to the wall the velocity profile of the air boundary layer can be approximated by $u^* = (\tau_{\mathrm{w}}^*/\mu^*)y^*$. In the oil the shear stress τ_{w}^* induces a Couette flow with velocity $\hat{u}^* = (\tau_{\mathrm{w}}^*/\hat{\mu}^*)y^*$. Hence the velocity jump at the interface is $[u^* - \hat{u}^*](y^* = h^*) = [(\hat{\mu}^*/\mu^*) - 1](x^*/t^*)$ which is generally non negligible. This velocity discontinuity must be compensated by an internal boundary layer developing above the oil drop which in turn modifies the shear stress seen by the oil. In order to simplify the analysis, a two-dimensional four-layer flow structure is proposed where each layer is identified by the dominant physical phenomena, allowing a simplified analysis similar to the simplifications of triple-deck theory [6]. Our analysis shows that the internal boundary layer generated by the "oil hill" is able to explain a part of the discrepancy between the classic theory and the observed fringe spacing. Another reason for the observed non-uniform fringe spacing is the slightly non-planar oil-air interface which depends on how the oil has been deposited, i.e. on its initial shape. By taking these two effects into account in the processing of measured fringe spacings, the uncertainty of the wall shear stress is significantly reduced and an uncertainty below 1% appears feasible in well controlled settings. Furthermore, the present analysis allows to formulate guidelines pertaining to the best time (early or late in the drop evolution) and to the best place (front or rear of the drop) to acquire fringe images.

References

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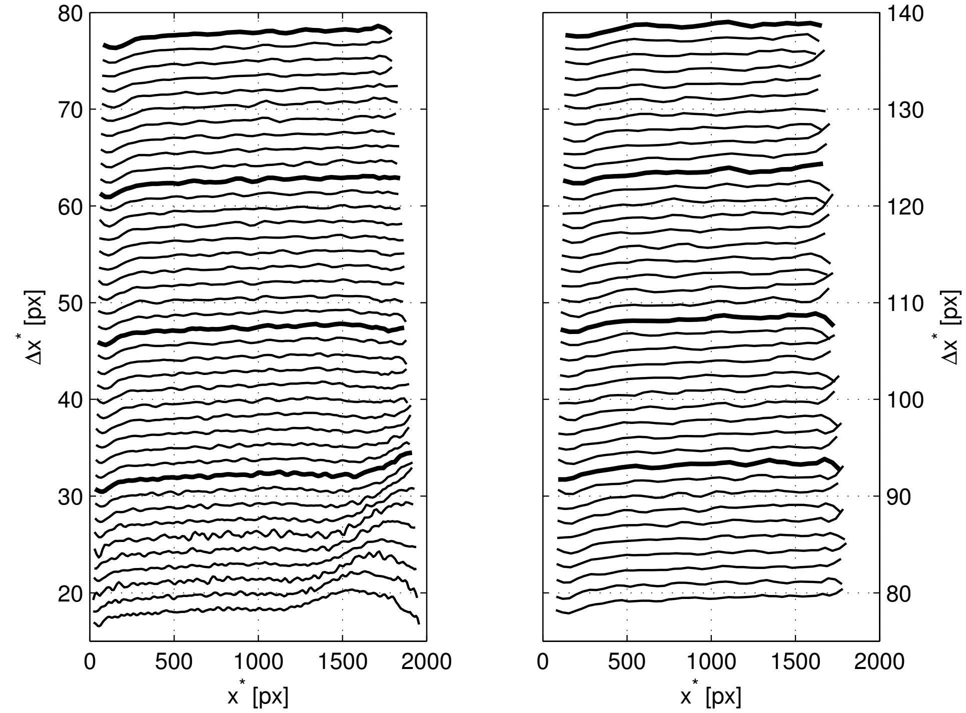

Figure 1. Observed fringe spacing in pixels (with 281 pixels/mm) versus x at different times $t^* = \mathrm{n}\delta t^*$ with steps of $\delta t^* = 10$ s. Left: n=0-39, right: n=40-79. The origin corresponds to the visual leading edge of the drop.

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