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Wall-shear stress measurement with quantitative IR-thermography

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Abstract

Forces are acting on an object immersed in a fluid flow. Next to normal forces, the tangential forces caused by viscous effects in the fluid play a major role in the aerodynamic design of aircraft. The viscous effects generate wall-shear stresses in the fluid flowing over the surface. These wall-shear stresses determine the viscous drag of an aircraft and thus partly determine the fuel consumption.
The most common measurement technique for wall-shear stresses is the hot-film technique. To achieve a more flexible measurement technique it is necessary to provide a fully external heating and temperature measurement. The present paper deals with the development of a measurement technique for local wall-shear stresses using quantitative IR-thermography. After giving a short overview of the theoretical aspects, the experimental setup and the data processing procedure is described. Finally the results of the performed experiments and conclusions are given.

Nomenclature

a	thermal diffusity
c	specific heat
c_f	dimensionless wall-shear stress
C	constant = 0.5384
k	thermal conductivity
L	length of the hot spot
q_c	heat transfer from the surface
T	temperature
u, v	velocity components
x, y	directions
δ_T, δ_U	thermal, velocity boundary layer thickness
ΔT	temperature reference scale
Θ	dimensionless temperature, $(T_w - T_e)/\Delta T$
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
τ_w	wall-shear stress
ξ	dimensionless x-direction, x/L
	subscripts
e	boundary layer edge
s	solid
w	wall

1. Introduction

For the aerodynamic design of aircraft it is important to know the wall-shear stress caused by viscous effects within the boundary layer, which develops along the surface. Basically the wall-shear stress can be measured with quantitative IR-thermography, which is based on the theory of the hot-film. Since there is an analogy between the momentum exchange and the energy exchange (see also [1]) the wall-shear stress can be determined by measuring the heat transfer from a hot surface to the flow and by measuring the surface temperature. In the case of hot-films the heating is supplied by an electrical heating foil inside the hot-film and thermocouples measure the temperature. These hot-films are usually glued onto the surface, where they might intrude the flow, or they are set flush into the object, which leads to a higher manufacturing effort. In any case the measurement is limited to a single position.

In contrast to the hot-film technique the heating in the present IR-technique is provided by a laser, which generates a hot spot on the surface and the measurement of the temperature is performed by an IR-camera. This technique has three main advantages. First the measurement is non-intrusive, second the position of the measurement point can be easily changed and third this technique can be used in flight tests of airplanes.

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2. Theory

To simplify the development of this new measurement technique the flow is assumed to be incompressible, two-dimensional and steady. Also the temperature is assumed to be steady and constant in z-direction (perpendicular to the flow), which means the hot spot is actually a hot band in z-direction. However, the locally increased surface temperature in x-direction (flow-direction) will be referred to as hot spot.

The relation between local heat transfer from a heated surface to the flow and the local wall-shear stress is derived from the continuity equation and the thermal boundary layer equation.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \qquad u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = a\frac{\partial^2 T}{\partial y^2} \tag{1}$$

with

$$y = 0 \Rightarrow u = v = 0,\ T = T_w, \qquad y = \delta_U \Rightarrow u = U_e,\ T = T_e$$

Since the hot spot is small nearby the wall, it can be assumed that (see *figure 1*):

$$\boxed{\begin{array}{llllll} - & \partial u/\partial x \to 0 & \Rightarrow & \partial v/\partial y \to 0 & \Rightarrow & v(y) \to 0 \\ - & \delta_T \ll \delta_U & & & & \\ - & y < \delta_T & \Rightarrow & u(y) = y\ \tau_w/\mu & & \end{array}}$$

Thus the thermal boundary layer equation (1) in the hot spot can be simplified to

$$\frac{\tau_w}{\mu}\, y\, \frac{\partial T}{\partial x} = a\frac{\partial^2 T}{\partial y^2} \quad . \tag{2}$$

Equation (2) can be solved by means of a similarity procedure [2]. This leads to the following relation for arbitrary wall temperatures T_w

$$\frac{q_c L}{k \Delta T} = C\left(\frac{\tau_w L^2}{\mu a}\right)^{1/3}\left[\Theta(0)\,\xi^{-1/3} + \int_0^{\xi}(\xi - \xi_0)^{-1/3}\frac{d\Theta}{d\xi_0}\,d\xi_0\right] \quad . \tag{3}$$

The dimensionless surface temperatures Θ are measured by the IR-camera.

Next to the wall-shear stress τ_w, the heat transfer q_c is the only unknown in equation (3), which needs to be determine q_c by solving the two-dimensional heat transfer equation for the solid (Poisson equation).

$$k_s\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) = 0 \quad . \tag{4}$$

The thermal boundary conditions for the solid are sketched in *figure 2*.

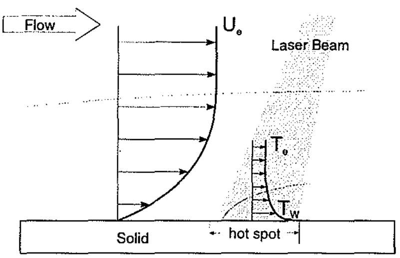

Figure 1: Velocity and thermal boundary layer for local heating

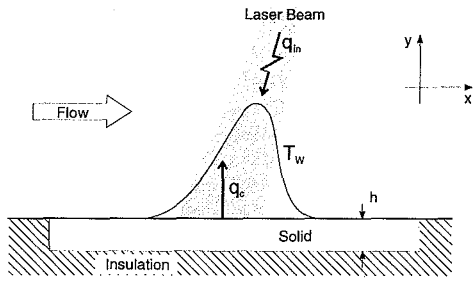

Figure 2: Boundary conditions for an externally heated flat plate

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Assuming a perfect insulation on each side of the solid, except for the side facing the flow, two different methods can be introduced. In the steady method the hot spot is continuously heated by a laser, while the IR-camera measures the temperature in steady state conditions. Since it is rather difficult to measure the irradiated heating power distribution q_{in} along the hot spot, the unsteady method has been chosen in this investigation, in which the temperature decay, after turning off the laser, is monitored. For the unsteady method the term $\rho_s c_s \frac{\partial T}{\partial t}$ needs to be added to the Poisson equation (4). But although the surface temperature T_w varies, the thermal boundary layer can still be considered as quasi steady, because the heat capacity of the thermal boundary layer $\rho c \delta_T$ is much smaller than the heat capacity of the solid $\rho_s c_s h$ and the fluid almost immediately adjusts to the temperature changes on the surface of the solid.

With the given boundary conditions the temperatures inside the solid can be determined by solving the unsteady Poisson equation (4) numerically. The heat transfer transfer q_c can be calculated with the given temperatures by

$$q_c = -k_s \left. \frac{\partial T}{\partial y} \right|_{y=h} \tag{5}$$

Next to the numerical solution of the Poisson equation additional software has been written to calculate the temperature in the fluid. With the help of this numerical method the complete experiment can be simulated. A typical temperature calculation for the solid and the fluid is presented in *figure 3*. The dashed line represents the boundary layer thickness δ_U.

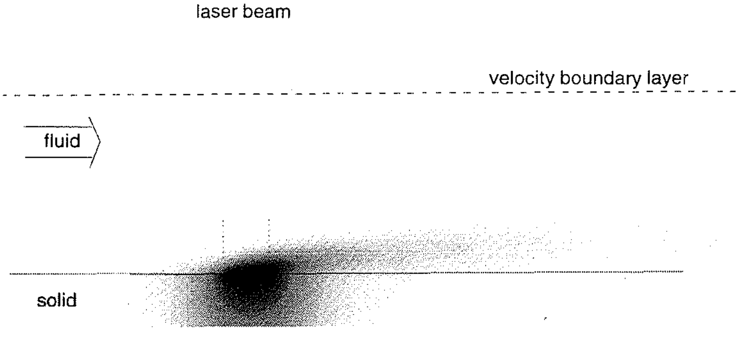

Figure 3: Numerical calculation of the temperature in the fluid and in the solid (black=warm, white=cold)

3. Experimental setup

The performance and the accuracy of the present measurement technique has first been tested in a laminar flow along a flat plate without pressure gradients (Blasius flow). The flat plate has been set vertically in a closed wind tunnel with a cross-section of 40 cm x 40 cm. The complete experimental setup is sketched in *figure 4*.

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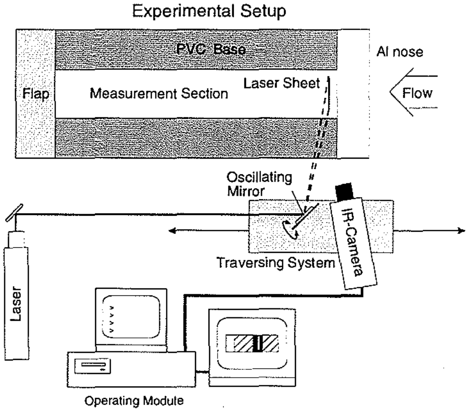

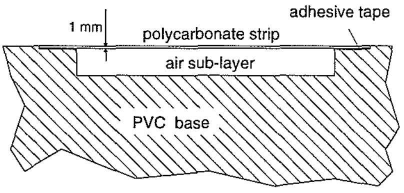

Figure 4: Experimental setup

Figure 5: Cross-section of the measurement strip

A 5W Argon laser provides the required heating. To reduce the heat transfer problem by one dimension, a laser sheet perpendicular to the flow is generated by an oscillating mirror. The mirror and the AGEMA 880 LWB IR-camera are fixed on a traversing system to position the measurement point. The output signal of the camera is transmitted to the operating module, where the data can be stored. A common problem in IR-thermography in closed wind tunnel tests is the low transmissivity of the wind tunnel walls. To achieve a sufficiently strong signal a slit has been cut in the wall and covered with a very thin plastic foil, which only reduces the signal by approximately 2%.
The properties of the solid material have strong influence on the performance of the temperature measurement with an IR-camera. In these experiments various demands on the size of the hot spot and the time scale of the temperature decay have to match the capabilities of the camera and have to fulfill the assumptions of local heating used in the derivation of equation (3).

spot size

Due to the limited spatial resolution of the IR-camera the hot spot should be sufficiently large to obtain an accurate temperature measurement [3]. On the other hand the assumption of local heating requires a tiny hot spot.

temperature decay

Next to the spatial resolution the time response of the camera is also limited. Thus a larger time scale of the temperature decay should be preferred.

The spot size and the time scale can be adjusted by controlling the power and the diameter of the laser beam and by changing the thickness, the specific heat capacity and the heat conductivity of the surface materials. With the help of the numerical simulation the optimum material for the expected velocity range (5 m/s — 25 m/s) has been found. In these experiments a 1 mm polycarbonate strip has been inserted in the measurement section. A cross section of the measurement section of the plate is shown in *figure 5*. The air sub-layer beneath the surface material provides a sufficient insulation. To increase the emissivity of the surface the transparent polycarbonate strip is covered by a 0.1 mm thin dull black PVC foil.

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4. Data processing

To calculate the wall-shear stress a series of data processing steps have to be passed through. For these purposes several software routines have been developed. The following list presents the complete series for one wall-shear stress measurement:

- create a steady hot spot with a laser
- start camera measurement
- turn off the laser
- stop camera measurement
- determine the laser turn off time
- derive the temperatures in the hot spot from the measured signal for equidistant time steps after turning off the laser (= boundary conditions for the Poisson equation)
- reduce the signal noise by averaging and Fourier analysis
- solve the Poisson equation in the solid for each time step
- calculate q_c
- calculate τ_w with equation (3)

5. Results

As already mentioned this measurement technique has been tested in a Blasius flow. To check the accuracy of the measured wall-shear stress $c_{fx} = \tau_w/\frac{1}{2}\,\rho\, U_e^2$, the result is compared with the numerical simulation. *Figure 6* presents the relative error

$$\Delta c_f = \frac{c_{fx} - c_{f\,num.\,sim.}}{c_{fx}} \tag{6}$$

of the measurement after turning off the laser for filtered and not filtered temperature data.

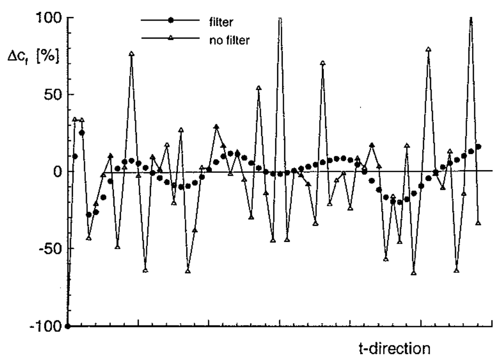

Figure 6: Δc_f for each time step

It can be seen that this measurement technique gives large fluctuations for the calculated wall-shear stress. These fluctuations are caused by scatter in the temperature measurement due to signal noise. This scatter leads to huge errors in the temperature derivatives and thus in the heat transfer q_c. Since τ_w is proportional to the third power of q_c, the error in the wall-shear stress is approximately amplified with a factor 3. These errors of about $\pm 100\%$ can be reduced significantly by extensive filtering. The remaining fluctuations can be eliminated by averaging c_f in time, as long as the flow conditions are constant.

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With the help of this final procedure the wall-shear stress has been measured on three different x-positions and for different free stream velocities U_e. These measurements are compared with the theoretical relation between the local dimensionless wall-shear stress c_{fx} and the local Reynolds number $Re_x = U_e\, x/\nu$ (see also [1])

$$c_{fx} = 0.664\ Re_x^{-0.5} \quad . \tag{7}$$

The results of this comparison are presented in *figure 7.*

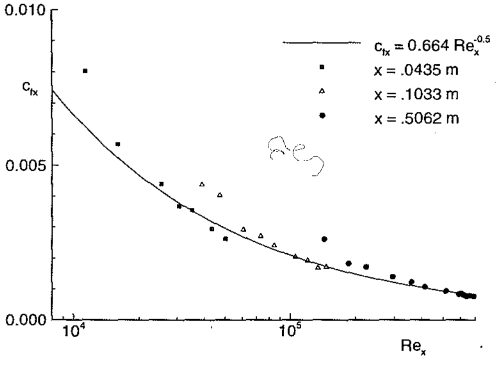

Figure 7: c_{fx} on a flat plate

The relative error is less than 11% for free stream velocities U_e higher than 10 m/s. For lower velocities the error rapidly increases due to natural convection effects along the hot spot. Natural convection produces an upwards velocity component in z-direction and thus gives additional heat transfer to the flow. With increasing U_e the influence of the natural convection can be more and more neglected compared with the heat transfer caused by the free stream velocity. To achieve a better accuracy for low flow velocities the effects of natural convection have to be compensated for.

6. Conclusions

The results show that it is possible to quantitatively measure the local-wall shear stress with IR-thermography. In contrast to the hot-film technique with electrical heating, where the heat transfer to the flow is given by the electrical power, the determination of the external heating power (laser) is much more difficult. Since the heat transfer to the flow has to be calculated out of surface temperatures and the local wall-shear stress is proportional to the third power of the heat transfer, the accuracy of the measurements mainly depends on the averaging and filter methods.

But with improving capabilities of the IR-cameras like spatial resolution, time response and signal to noise ratio this measurement technique can be extended to flows with pressure gradients, higher velocities and turbulence.

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