HIGH RESOLUTION INFRARED THERMOGRAPHY FOR AIRFOILS BOUNDARY LAYER INSPECTION IN PASSIVE MODE

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ABSTRACT
In thermo-fluid-dynamics, the important role played by the boundary layer phenomena is well known. In order to set up an experimental tool, able to measure fluid dynamic magnitudes in the boundary layer, many efforts have been made and some advanced measurements have been developed. Since the mid-sixties, infrared thermography has been applied as a measurement technique. Primarily, this technique was used in space missions where the protection of space vehicles in the re-entry phase was of prime importance. Nowadays, thermography is one of the most advanced non-intrusive measurement techniques and presents many advantages such as no-needs for particular settings of system under analysis. Therefore, considering that boundary layer continues to be a fundamental aspect in fluid-dynamics studies, the present work wants to dwell on the possibility to enlarge the application of the infrared measurement technique, in particular for subsonic flows in passive mode. These conditions point out important problems of measurement for the low energy content and for the type of thermal exchange that can not be simplified as it is traditionally made in supersonic flows. Either the possibility to operate with modern infrared cameras or the improvements of new theoretical models in the data reduction process will be described in this paper and an application to an airfoil will be presented. The measurement technique used in this paper can be applied to any aerodynamic profile and can be easily used as a non intrusive technique to characterize the flow fields of blade cascades for gas turbines and turbomachinery in general.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>c</td>
<td>thermal capacity of the body material</td>
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<td>c_f</td>
<td>fluid specific heat</td>
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<td>C_f</td>
<td>skin friction coefficient between fluid and airfoil</td>
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<tr>
<td>erf</td>
<td>Gauss error function</td>
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<tr>
<td>erfc</td>
<td>complementary Gauss error function</td>
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<td>Fo</td>
<td>Fourier number</td>
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<td>h</td>
<td>heat transfer coefficient between fluid and body</td>
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<td>h</td>
<td>conduction heat transfer coefficient</td>
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<td>L</td>
<td>characteristic length,</td>
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<tr>
<td>Nua</td>
<td>Nusselt number</td>
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<td>Pr</td>
<td>Prandtl number</td>
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<td>Re</td>
<td>Reynolds number</td>
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<td>St</td>
<td>Stanton number</td>
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<tr>
<td>t</td>
<td>time</td>
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<tr>
<td>T</td>
<td>temperature</td>
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<tr>
<td>V</td>
<td>fluid velocity</td>
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<tr>
<td>f</td>
<td>fluid</td>
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<tr>
<td>sup</td>
<td>surface</td>
</tr>
<tr>
<td>x</td>
<td>coordinate linked to a characteristic length of the profile</td>
</tr>
<tr>
<td>0</td>
<td>initial time step</td>
</tr>
<tr>
<td>∞</td>
<td>undisturbed fluid</td>
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INTRODUCTION
As it is well known, boundary layers play a fundamental role for the analysis of fluid-dynamic phenomena and for the interaction between fluid flows and solid bodies. This explain the continuous research efforts in order to identify experimental and measurement techniques able to give suitable information about this kind of phenomena.
Therefore, when the first thermographic measurement systems became available in the mid '60, they were soon applied to get information from fluid flows, in order to try to have solutions, based on the well known Reynolds analogy, for many open problems of the fluid-dynamic theory.

This analogy defines a fundamental relation between the temperature distribution, over a body immersed in a flow, and the information concerning the heat flow and the distribution of the friction coefficient over the same body. This correlation can be expressed by the following relation [Kreith, 1988]:

\[ St_x = \frac{Nu_x}{Re_x \cdot Pr} = \frac{C_{fc}}{2} \]  

(1)

where, \( Nu_x = (h \cdot x) / k_f \),

\[ Re_x = (\rho_f \cdot V \cdot \delta_x) / \mu \]

and \( Pr = e_f \cdot \mu / k_f \).

ACTIVE AND PASSIVE TECHNIQUES

One of the main parameters to take into account to choose the implementation method of a thermographic measurement system for the analysis of fluid flows is the Mach number [Astarita, et al., 2001, Carlomagno and De Luca, 1993].

Until recently, the energy transferred from subsonic flows to solid bodies was not sufficient to create detectable temperature differences with the available thermographic systems. In order to overcome this problem the so called “active technique” was used. This substantially means that the solid body is artificially heated in order to obtain temperature differences that can be detected with the available thermographic systems. The other possibility, when the body could not be heated, because of its shape or for other reasons, is to heat the flow. In this case the implementation of the measurement technique is called “passive technique”.

In any case, heating the body or the flow, can cause modification of the fluid phenomena, such as fluid flow detachment or laminar-turbulent transitions that do not occur normally in the flow and are significant disturbing effects.

In any case the passive techniques is preferred to the active because of its minimal needs of solid body surface conditioning and changes. It normally needs only surface paintings in order to have uniform emissivity.

PRINCIPLE OF OPERATION

When a solid body is located in a flow, heat is transferred by means of convection, conduction and radiation. In this case, it is possible to disregard the conduction heat transfer, even if it will be considered later for the data reduction technique.

Radiation heat transfer represents the main heat transfer mode, because it is directly measured by a thermographic system. In steady state conditions, the contribution of radiation is balanced by the convection heat transfer between the body and the fluid.

At each point where there is a temperature difference between the fluid and the body, convective heat transfer takes place according to the relation:

\[ \Phi = h \cdot (T_{sup} - T_{\infty}) \]  

(2)

Since the heat transfer coefficient changes in laminar or turbulent flow, a different temperature will be measured after the flow transition from laminar to turbulent [Balageas and Bouchardy, 1993, Gartnberg, et al., 1989]. This is the fundamental key point that suggest the use of infrared thermography for fluid flows experimental studies; in fact, as a consequence of the laminar-turbulent transition on the surface of solid body, it is possible to observe a detectable temperature gradient on the transition borders, with different temperatures corresponding to the area where turbulent or laminar conditions are present.

It can be observed experimentally with the passive technique, that the laminar to turbulent transition zone is located where the solid body has a higher temperature, which is caused by a higher heat transfer coefficient. A zone with a lower temperature can be caused by the same transition phenomena when the active technique is used: i.e. the fluid flow is cooler than the solid body.

THE THERMOCAMERA DELTATHERM 1550

The measurement system used in this paper is a Deltatherm 1550 differential thermographic camera manufactured by Stressphotonics Inc. The thermographic sensor is a 320x256 pixel InSb focal plane array, sensible in the wavelength range 3÷5 [μm].

Figure 1: Thermocamera Deltatherm 1550.

Sensor is cooled by a Stirling cycle inside the camera. Thermal resolution of the detectable mean temperature difference is 1 mK with a mean time of at least 30s.

DATA REDUCTION TECHNIQUE

One of the main reasons that makes difficult the use of measurement techniques based on thermography for fluid flow studies, is the very complex data reduction techniques that are needed to obtain the heat transfer coefficient distribution from temperature maps. This is mainly because the complex shape of the body of interest does not allow to use simple formulas but requires specific models for each body. In any case, the method for data reduction is based on modelling the main heat transfer mechanism that occurs between the body and the flow.

The technique here proposed is the so called “skin technique”, that uses the assumption of a body with a low thermal resistance and capacity. With this assumption, it is possible to consider that an instantaneous heat transfer take place inside the body and it is thus possible to disregard the conductive heat transfer. Therefore, the general form of the heat transfer equation reduces to:
Combining Eqs. (3) and (2), we can write:

\[ h = \left( \frac{c \cdot \rho \cdot e \cdot \partial T}{(T_\infty - T)} \right) \]  

(4)

It is thus possible, by using equation (4), to measure the time history of the surface temperature and calculate the heat transfer coefficient. The accuracy of the approximation can be estimated by using the Biot number [Carbonaro, et al., 2002], that assure an acceptable approximation for Biot numbers lower than 0.1.

The Fourier number must be also be considered:

\[ F_0 = \frac{a \cdot t}{L^2} \]  

(5)

in order to have an estimate of the temporal delay of the system when thermal changes occur.

Typically \( F_0 > 0.5 \) [Aymer de la Chevalerie, et al., 1997] is used to estimate the minimum elapsed time for data acquisition, from the instant of body immersion in the fluid stream [Gartenberg, et al., 1989].

When the above conditions are satisfied, it is possible to use Eq (4) for data reduction, with evident advantages from the technical point of view.

Another fundamental key point is the temporal characterization of \( h \) because of the thermal gradient is not constant and this means that a function \( h(t) \) must be considered.

If thermal energy is transferred in short periods of time, \( h \) can be assumed constant. If we also assume the temperature of the flow constant, Eq. (4) can be solved analytically obtaining:

\[ \frac{\left[ T(t) - T_\infty \right]}{(T_\infty - T)} = \exp \left[ -\left( \frac{h}{\rho \cdot e \cdot c} \right) \right] \]  

(6)

The thermographic system used in this paper allows to obtain a very high resolution in the measurement of temperature differences because an average with respect to time is calculated. This improves the signal to noise ratio considerably but it needs to solve the heat transfer equation with the time period used by the camera for mean data acquisition. The situation is illustrated in Figure 2, where the step is the time period of the mean temperature distribution acquired by the thermocamera.

\[ T_i - T_\text{amb} = (T_{f,i+1} - T_{\text{amb}}) - (T_{f,i-1} - T_{\text{amb}}) \cdot e^{\left( \frac{h}{a} \right)^2 \cdot \text{erfc} \left( 1 + \frac{h}{k} \cdot \sqrt{a T_i} \right) - (T_{f,i+1} - T_{f,i-1})} \cdot \text{erfc} \left( 1 + \frac{h}{k} \cdot \sqrt{a(T_i - \Delta T)} \right) \]  

(8)

Eq. (8) was obtained by assuming an infinite length body which was calculated as a solution of the following equation:

\[ \frac{\partial^2 [T(t) - T_\text{amb}]}{\partial x^2} - \frac{1}{a} \cdot \frac{\partial [T(t) - T_\text{amb}]}{\partial t} = 0 \]  

(9)

Eq. (8) has been solved to obtain the values for \( h \).

**EXPERIMENTAL SET UP**

Some tests using thermography have been performed in the wind tunnel of the University of Perugia. The wind tunnel is a closed circuit type with an available test section of 2200x2200 mm, at atmospheric pressure.

The fan generated heat increases the air temperature, with a linear trend that can be expressed by the equation (Figure 2):

\[ T_i = T_0 \cdot \left( \frac{t}{20} \right) \]  

(10)

where \( T \) is the temperature of the air flow, in [°C], and \( t \) is the time in [s].

This temperature increase allows to do measurements with a passive technique without any heating of the measured body.

The body used inside the flow for testing is a classical Fokker airfoil, realized in wood, with a cord of 162 mm and a length of 300 mm.
The airfoil has a copper support on a side, and pressure tappings in the central section of its upper surface. Tests have been performed using thermal transient of 30 s with integration steps of 10 s.

Figures 4 and 5 show typical results obtained as thermal maps with zero incidence and 20 s after the fan starts.

In Figure 4, it is possible to see the effect of pressure tappings, located in the middle of the airfoil, on the heat transfer coefficient. This phenomena is caused by the shape of the taps which disturb the boundary layer and, consequently, the convective heat transfer between the airfoil and the flow. Similar considerations can be drawn on the border effect (Figure 5): in fact the flow near the ends of the airfoil is deviated by the copper supports over the upper side of the airfoil, changing the flow field and, in accordance with the Reynolds analogy, the distribution of the convective coefficient and, consequently, of the temperature.

Analysing the temperature profile along a line parallel to the chordwise (Figure 6), it is possible to see that after a first gradual reduction of the temperature, a strong decrease occurs and a subsequent temperature increase is present on the final part, towards the trailing edge.

This temperature profile can be justified only with the strong relationship between the thermal map and the flow and heat transfer conditions. The thermal map shows on the first part a laminar flow and after a velocity increase a transition between laminar and turbulent flow where the relative minimum of temperature profile take places.

After that, the temperature increases a second time, in the turbulent region because here the heat transfer is more efficient.
Using the data processing technique previously illustrated, it is possible to obtain the heat transfer coefficient distribution illustrated in Figure 7. Taking from this distribution a profile along a chord parallel to the lateral border of the airfoil, as it is possible to see in Figure 8, there is an agreement with classical bibliographic results, presented in Figure 9 [Goldstein, 1983]. The figure shows the non-dimensional parameter, defined in the same figure linked to the shear stress, obtained by experimental measurements over an airfoil, using Stanton tubes.

Since there is an evident link between the shear stress and the skin friction and between the skin friction and the convection heat transfer coefficient (Reynolds analogy), the results of the data processing can be easily compared to those obtained with classical measurement techniques.

CONCLUSIONS

The thermographic technique described in this paper has shown how it is possible to determine the heat transfer coefficient along an airfoil.

This techniques, although it is applied in this paper to low speed flows, can be used to calculate the heat transfer coefficients for any type of turbomachinery blades and cascades where an optical access is possible.

The technique is also very useful in the determination of the point of transition from laminar to turbulent flow and can be used for comparison with CFD calculations of turbomachinery.

It can also be used in determining the flow characteristics and interactions in cooled turbine blades and nozzle.

Finally, it can be a suitable technique to show the effects induced by secondary flows on the cascades.

REFERENCES


