Infrared Thermography for Flow Visualization and Heat Transfer Measurements

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Abstract- *The paper intends to discuss the use of IR thermography as a new technology tool in various heat transfer and fluid dynamics problems. Different operating modes and their implementation are presented. Particular emphasis is given to the measurement of convective heat transfer coefficients. The development of appropriate software is also presented.*

Basic Principles of Infrared Thermography

Thermography is a measurement technique of thermal maps. Accurate quantitative analysis of thermal images acquired in real time is an essential performance requirement of a thermographic system. The technology of modern infrared (IR) thermography can currently attain this goal to a considerable extent.

Basically an IR thermal imager is a camera which detects the electromagnetic energy radiated in the IR spectral band from an object (whose temperature has to be measured) and converts it into an electronic video signal. In particular, starting from the object, IR energy is first radiated through a medium (typically the atmosphere). It then enters the sensing system, passing through a lens, an aperture (or a filter), and finally impinges on a single IR detector or a focal plane array (FPA) sensor, which transduces the radiation into an electrical signal. The IR systems of the first generation, which are typically are equipped with a single detector, need also a scanning mechanism (see later) ; for this reason they are termed conventionally IR scanning radiometers (IRSRs). IR (staring) cameras based on FPA sensing elements do not generally require any scanning device; nevertheless, since the image may be still thought of as the output from an electronic scanning, hereafter they will be also referred to as IRSRs.

The standard instantaneous output is represented generally by a matrix of data having a number of elements typically of the order of 20-60k or more. Consequently, it is necessary to treat the data by means of numerical techniques. As a result, the procedures and the algorithms generally referred to as digital image processing may be conveniently applied; in particular, image enhancement and image restoration.

Monochromatic radiation intensity E_l, emitted by a surface having an absolute temperature T, is given by Planck's law:

$$E_l = e_l E_{l0} = \frac{e_l C_1}{l^5 (e^{C_2 / lT} - 1)} \qquad (1)$$

where e_l is the spectral hemispherical emittance, C_1 and C_2 are the first and second radiation constants respectively; λ is the wavelength of the radiation being considered, and $E_{\lambda 0}$ is the blackbody monochromatic radiation intensity.

By integrating Planck's law over the entire spectrum the total radiation intensity E is obtained (Stefan-Boltzmann law):

$$E = esT^4 \qquad (2)$$

where ε is the total hemispherical emittance (or emissivity coefficient) and σ is the Stefan-Boltzmann constant.

Measurements made by means of spectral radiometers or pyrometers are generally based on Eq. (1). Infrared cameras are often classed as total-radiation radiometers, although Eq. (2) does not apply, since their detectors sense radiation in a limited band width (window) of the IR spectrum.

In fact, IRSRs typically perform measurements in two different windows of the IR band: the short-wave (SW) window and the long-wave (LW) one. The choice of an appropriate spectral band (SW or LW) depends on different factors. Some surfaces have a higher emissivity factor in the SW window; moreover, low-cost detectors and/or thermoelectrically cooled detectors are also available in this band. However, in spite of the relatively high atmospheric transmission coefficient, usually the SW region requires some compensation while performing high-accuracy measurements at viewing distances greater than *1m.* On the other hand, the LW region exhibits a very low coefficient of atmospheric absorption, except in the case of very high water vapor content. Due to a higher thermal contrast or sensitivity in this window, higher overall system performances can be achieved.

The detector is the core of the IR thermographic system. The most frequently used detectors are the so-called photon detectors, in which the release or transfer of electrons is directly associated with photon absorption. The main characteristic of photon detectors is that they have a very short response time (of the order of microseconds) but they require cooling well below the ambient temperature to allow for high sensitivity and rapid scanning (if needed). Therefore, the sensor is frequently located in the wall of a Dewar chamber, which is cooled by liquid nitrogen (LN2). To increase the operating time of the radiometer, a demand-flow Joule-Thompson cryostat using high-pressure nitrogen (or argon) gas or a Stirling closed-cycle cryogenic refrigerator can also be employed. An alternative method, based on a thermoelectrical (Peltier) cooling effect, eliminates the use of detector cooling agents. This, however, generally results in a sensitivity loss of the radiometer.

When the sensing element is a single detector or point detector, in order to have it receive energy from different parts of the field of view (i.e., to scan the object), a proper electromechanical scanning mechanism must be used. This scanning mechanism may consist of moving mirrors, refractive elements (such as prisms), or a combination of the two. For two-dimensional imaging, such a mechanism allows object scanning in both vertical and horizontal directions. Infrared scanning radiometers that scan the object in only one direction (one-dimensional IRSRs) are also available. They are convenient when measuring temperatures of objects moving in a direction perpendicular to the scanning one or to have very high scanning speed in the study of fast transient phenomena (e.g., heat transfer in shock tunnels).

More recently, the focal plane array (FPA) sensor has been introduced. The FPA technology avoids the need for scanning mechanisms employing a highly reliable, very simple two-dimensional matrix of sensors, which may range from 120 x 120 elements up to 1040 x 1040 elements. In addition to detectors and cryocooler assembly, generally the sensor unit also contains all of the electronics associated with operation and control of FPA, and provides the mechanical and electrical interface to a variety of optic assemblies. In contrast to the traditional dewar/cooler combination, an Integrated Detector Cooler Assembly is utilized, which eliminates significantly thermal losses and mass of a dewar inner stem so that is thermodynamically more efficient. The result is lower input power and faster cool down time for a given cooler.

Before reaching the detector, IR energy passes through specially designed lenses. Only IR-transmitting glasses such as germanium, silicon, or sapphire can be used. Moreover, lenses must be coated with a proper material to allow for maximum IR transmission. The use of filters also allows one to see through certain atmospheres or to measure the surface temperature of objects, such as glass or plastic, or even of flames. Low-pass, high-pass, band-pass/reject, and attenuating filters are available.

The overall performance of an IR imaging system is conventionally measured by the amount of useful and accurate information that can be acquired per unit of time. This can be expressed by means of the following parameters: thermal sensitivity, or equivalent random noise level; frame frequency, or update rate of the thermal image; image resolution, or number of independent measurement data points that compose the image; digital intensity resolution, or number of intensity levels that allow one to resolve fine temperature differences.

The sensitivity of an IRSR system is generally expressed by the noise equivalent temperature difference (NETD), the temperature difference between two images resulting in a signal equal to the random background noise of the camera. The frame frequency is usually expressed through two parameters: the scan rate per line and the scan rate per field. Depending on the line interlace used to update the whole imaging frame, the rate at which completely interlaced picture frames are updated is finally obtained (frame frequency). Image resolution is the capability of a thermal imaging system to detect and accurately measure the temperature of small portions (slits of reduced width) of the object surface, with the term *small* referring to the size of the total image. Resolution is generally determined by characteristics of the detector such as size and, for scanning systems, response time.

From a rigorous point of view, the spatial resolution of an optical system in the physical domain is defined in terms of local impulse response. The impulse response is defined as the system output to a radiation input represented by a point source. When the image is recorded by means of a line-scan mechanism, the impulse response is defined rigorously along the scanning direction only. It depends on the sensor (dimensions, response time), the scanning frequency, and the phenomena related to optical diffraction and aberration.

Experience shows that, due to the influence of such effects, the impulse response of a line-scan imaging system is of Gaussian type:

$$D(x) = \exp[-(x/s)^2] \qquad (3)$$

where σ is the shape parameter and the source is located at x=0.

The impulse response of an IRSR can be measured by means of the thermal contrast produced by a window with a variable width placed in between two knife edges held at a temperature lower or higher than that of background. The input signal may be represented in dimensionless form by the function *rect(x/w)*, where *w* is the window aperture. The system response, i.e. the window image, is given by the convolution product of the window itself by the impulse response *D(x)* of the system:

$$I(w,x) = rect(x/w) * D(x) \qquad (4)$$

From Eq. (4) in principle one can determine the function D.

The system peak response, which is reached at the origin x=0, can be normalized over the value Im obtained with a window having an infinite aperture, and plotted as a function of the window width. This function is generally referred to as Slit Response Function, SRF, and is defined by the equation:

$$SRF(w) = \frac{I(w,0)}{I(\infty,0)} \qquad (5)$$

SRF constitutes a way to characterize the spatial resolution. Under the assumption that the impulse response is of gaussian type, SRF is:

$$SRF(w) = \frac{\int_0^{w/2s} \exp(-x^2)dx}{\int_0^{\infty} \exp(-x^2)dx} = erf(\frac{w}{2s}) \qquad (6)$$

where $x = x / s$. Then it is possible to evaluate the shape parameter σ from the relationship:

$$s = w_0 / 0.96 \qquad (7)$$

where w_0 is the slit aperture corresponding to 50% SRF.

The spatial resolution of an optical system may be, in an alternative way, defined in the frequency domain by the Optical Transfer Function, OTF, which is the normalized value of the Fourier transform of the impulse response. It results:

$$OTF(n) = \exp(-p^2 s^2 n^2) \qquad (8)$$

where ν is the spatial frequency. The normalized magnitude of OTF is defined as Modulation Transfer Function, MTF. This may be also defined as the amplitude response of the system to sinusoids of different spatial frequencies. A linear optical system images a sinusoid as another sinusoid. The effect of the limited resolution of the system is given by the MTF which is the modulation depth in the image, as a function of the spatial frequency, for a constant amplitude of the input object. Usually MTF is a decreasing function of spatial frequency.

The intensity resolution (commercially referred to as dynamic range) defines the ability of a thermographic system to resolve temperature differences with respect to the temperature-measuring range. Dynamic range can be expressed by means of the number of gray shades (or digital levels of intensity) used to encode the thermal image.

Typical temperature ranges of IRSRs span from about -20 to 800°C, and can be extended up to 1500-2000°C by using filters.

The Computerized IR Imaging System

Infrared radiation emitted by the model is amplified and converted into an electronic video signal that is displayed on the monitor of the driving unit. This houses all the operational controls of the IR camera. Thermal images can be continuously recorded by a videotape analog or digital recorder. After the test, the recorded data can be replayed in playback mode and, if necessary, digitized by the analog-digital converter. Fully computerized IR imaging technology also allows on-line automated direct-digitizing and recording processing. Viewing and processing images in real time permit scanner adjustments during the test, thus ensuring the accuracy of the posttest analysis. After analog-digital conversion, thermal data are fed into a computer for more sophisticated quantitative analysis.

In relating the radiation detected by IRSR to the radiation emitted by the three main sources (object, surroundings, and atmosphere), image-processing software typically takes into account, among others, the following parameters: thermal level, thermal range, surface emissivity coefficient, lens type, viewing distance, and air and ambient temperatures. The basic computer display mode is generally a colored image where each color is related to a temperature interval and the isotherm is visualized as the boundary line between two colors. Standard image-processing software usually can provide thermal profiles and gradients across the surface, temperature frequency histograms in a given area, temperature differences from different images, and image filtering and zooming. Dedicated software can be developed to reduce data in final form for specific applications.

The problem of restoring (in a general sense) the thermal images, both from the imaging and the measurement points of view, has been addressed by present authors. The requirement of the image restoration is stressed in heat transfer phenomena where relatively high spatial temperature gradients are present.

For a linear system, a simple relationship linking the Fourier transform of the (degraded) image *G* to that of the input (true) image *F*, may be:

$$G(n,m) = F(n,m)H(n,m) \qquad (9)$$

where ν and μ are the spatial frequencies. *H*(ν, μ) is referred to as the Optical Transfer Function (OTF) which expresses the degradation originated by the system.

In principle, restoring thermal images may be performed by means of the relationship (inverse filter method):

$$\tilde{f}(x,y) = \Im^{-1}\{F(n,m)\} = \Im^{-1}\{G(n,m) / H(n,m)\}$$

where $\tilde{f}(x,y)$ denotes the restored image as a function of the spatial co-ordinates x and y. This is an approximation of the true image because, besides the errors introduced by the numerical algorithm, the degradation process symbolized by eq. (9) does not include the noise term, the knowledge of which is usually limited to an information of statistical nature. Attention has to be focused on modeling of two degradation effects: the first one due to the imaging and sampling systems and the other one caused by the tangential thermal conduction inside the model.

The Use of IRSR to Visualize Flow Fields and to Measure Convective Heat Fluxes

The capability of the IR thermography to measure convective heat flux rates and visualize flow fields was already analysed in various applications by Carlomagno and de Luca. Before discussing some relevant aspects of the IRSR implementation for convective heat flux sensors, it is useful to make some remarks about the different experimental procedures to be followed according to if the flow Mach number is relatively low or not.

In the case of iposonic flow regime, since the aerodynamic heating is not adequate to the sensitivity of IRSR, it is necessary to artificially create a temperature difference between the model surface and the flow, i.e. it is necessary to heat the model in the so-called active mode. This may be performed either by varying the flow temperature (i.e., by heating it, or, more simply, by turning off the cooling device of the wind tunnel facility), or by heating the model in steady state or transient ways. A very convenient procedure to steadily heat the model in simple geometries is the so-called heated thin foil technique, which consists of coating the model surface with a very thin metallic foil, heating it by Joule effect and measuring the heat transfer coefficient from the foil to the flowing stream . Carlomagno, de Luca applied this technique to study the heat transfer from a plate to impinging jets and to characterize the boundary layer development over a model wing, so as to detect transition and separation regions. They also used the heated thin foil technique to analyse the transient natural convection over a vertical plate.

Another active technique consists of heating the model, at least for short periods of time, by means of a radiative source whose effects match the convective ones. For the sake of detecting the laminar-turbulent transition over a wing section, some authors applied this method in a line-scan utilization of IRSR where the surface of an airfoil was radiatively heated by a CO2 laser and then the temperature decay was monitored when the heating ceased. Some other authors proposed two methods for inferring the heat transfer coefficient from the measured temperature, one based on the zero order time moment of temperature, the other one using the temperature Laplace trasform.

At high Mach numbers, because of the stream high enthalpy content, the detection of the thermal image by the IR thermography may be relatively simpler. In fact, the strong aerodynamic heating makes possible the use of the IR camera in the so-called passive mode. Generally the model, which is initially at uniform ambient temperature, is suddenly exposed to the air stream. According to the properly selected thermal model, the thin skin techniques are used to obtain the convective heat transfer coefficients and/or to make a diagnostics of the boundary layer.

The applications listed below have been or are currently developed at DETEC of Università di Napoli “FedericoII”.

Convective heat transfer measurements

- single jet and array of jets
- hypersonic flows around linear and shaped bodies (within HERMES space program)
- detection of Gortler vortices in hypersonic flow
- transients in natural convection

Characterization of boundary layer on airfoils

- 2D and 3D flows
- detection of laminar or turbulent separation
- transition to turbulence

Non-destructive testing in composite materials

- rockets containers
- thermal properties of composites

Thermal analysis of aeronautical components

- efficiency of anti-icing devices for airfoils and engine intakes
- hot components of turbojets

Temperature measurements of glass sheets

- evaluation of rheological properties of glasssheets

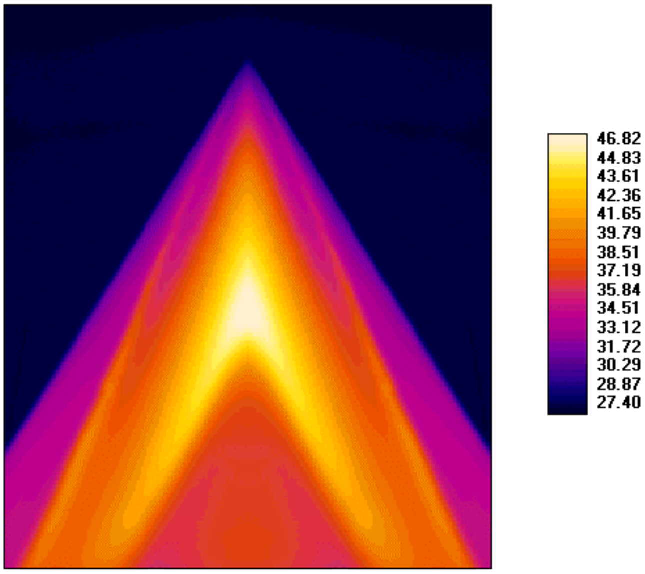

Figure 1. Thermogram of the leeward side of a delta wing

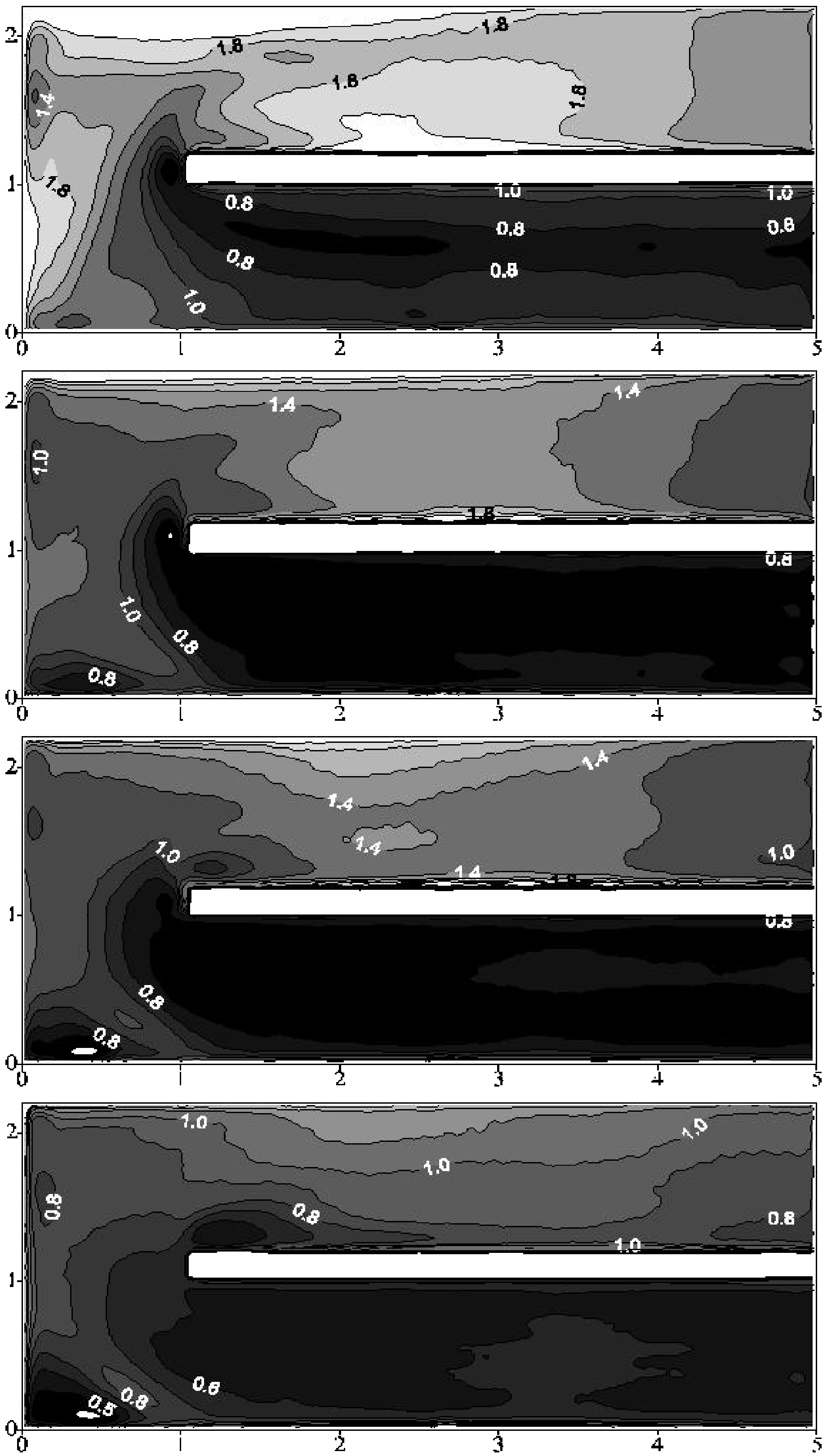

Figure 2. Non-dimensional Nusselt number for a 180 deg turn channel flow

Conclusions

The capability of the IR scanning radiometer to measure convective heat fluxes and to visualize flow fields has been analyzed; the different experimental procedures to be followed, according to if the flow Mach number is relatively low or not, have been addressed. The need of restoring (i.e. of removing the degradation effects) the recorded thermal images has been also discussed; attention has to be focused on modeling of two degradation effects, caused by the imaging and sampling systems and by the tangential thermal conduction inside the model.

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