An Excursus of Some Research Performed with Infrared Thermography at Federico II

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SCOPE OF THE PRESENTATION

This presentation reviews some of the experimental and theoretical work carried out, over the past several years, by the speaker and his research team, while applying infrared thermography to thermo-fluid-dynamics and NDT. Most of the work was performed at University of Naples Federico II and:

- Centre d’études aérodynamiques et thermiques (CEAT), Poitiers, France
- Università di Pisa, Pisa, Italy
- University of Tokyo, Tokyo, Japan
- Italian Centre for Aerospace Research (CIRA), Capua, Italy
- Centro Spazio (Space Centre), Pisa, Italy
- Politecnico di Torino, Torino, Italy
- Delft Technical University, Delft, The Netherlands (prof. Scarano group)
- Universidad Carlos III de Madrid, Madrid, Spain

The research team involved in the present work is composed by:

- Tommaso Astarita
- Piergiorgio Berardi
- Gennaro Cardone
- Giovanni Maria Carlomagno
- Stefano Discetti
- Luigi de Luca
- Carlo Salvatore Greco
- Andrea Ianiro
- Michele Imbriale
- Carosena Meola

Several Master and PhD students
(who, actually, performed most of the experiments)
At the beginning of the 70ties, our research group started with non-destructive testing.

The isothermal line in a steel slab having a cavity, initially at ambient temperature, suddenly exposed to steam on one side and viewed from the other one.

The present research was focused on the study of unsteady surface temperature fields to obtain information about the internal physical structure of a thermally loaded system, by discriminating among surface temperature differences and their time evolution; in other words, the idea was to adopt the time variable in the place of the depth variable (i.e. the coordinate normal to the observed surface) to recover knowledge about the "inside" of the system.

Most probably, this work introduced the lock-in concept.
NON-DESTRUCTIVE TESTING (Lockin)

Lockin thermography setup

- a periodic heat flux is incident on the surface of interest
- IR camera monitors the varying sample surface temperature and local differences of the phase, and/or of the amplitude, response are sought for.

Direct estimation of defect depth

Heat diffusion length

\[ \mu = \sqrt{\frac{\alpha}{\pi f}} \]

Thermal diffusivity

Heating frequency

For phase images, the thermal penetration depth is: \( p = 1.8 \mu \)

DETECTION OF RESIDUAL CERAMIC in serpentine cooling passages of turbine blades

Type A blade

**Internal core** (passages for blade cooling)

Blade surface viewed by the camera

Type A blade
Phase images for $f = 0.65$ Hz

The *phase angle discontinuities* (inside the white rectangles) in the first channel from the trailing edge (right side) testify the *presence of residual ceramic*. 
Type B blade

Serpentine cooling passages

residual ceramic
IMPACT EVENTS

(Thermographic on-line monitoring and Non-destructive testing after impact)


IMPACT WITH CHARPY PENDULUM

Front view

Infrared camera

Side view

Specimen

Hammer
DATA ANALYSIS

The *first image* $T(i, j, t =0)$ of the sequence (i.e. the specimen surface at ambient temperature, before the impact) *is subtracted* to each subsequent image so as to generate a map of temperature difference $\Delta T$ caused by the impact:

$$\Delta T = T(i,j,t) - T(i,j,0)$$

where: $i$ and $j$ represent lines and columns of the surface temperature matrix, respectively.

Then, a sequence of $\Delta T$ images is created.

Samples of GFRP and Glare® are tested.
HIGH SPEED ACQUISITION OF THERMAL IMAGES

**GFRP** with the SC3000

at **300Hz** images are composed of **48 lines**

at **900Hz** images are composed of **16 lines**
SEQUENCE OF ΔΤ IMAGES

**GFRP**, $E_i = 19J$, taken at 300Hz with SC3000

- Before impact
- $t = 0.0033s$
- $t = 0.01s$
- $t = 0.02s$
- $t = 0.40s$
- $t = 0.90s$
DAMAGED AREA IN GFRP

Raw *thermal* image taken *during impact*

Lockin *phase* image $f = 0.14\text{Hz}$ *after impact* to detect defects

Picture in the *visible* of a translucent GFRP, *after impact*
SEQUENCE OF $\Delta T$ IMAGES OF Glare®
taken with SC3000 at $900\text{Hz}$, specimen impacted at $2.7\text{J}$

But, at the time, we had to switch to:

**THERMO-FLUID-DYNAMICS**

*(that was our most proper business)*
**INFRARED THERMOGRAPHY IN THERMO-FLUID-DYNAMICS**

*Series: EXPERIMENTAL FLUID MECHANICS* - Springer

Astarita Tommaso and Carlomagno Giovanni Maria

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APPLIED & TECHNICAL PHYSICS, MECHANICS

**ABOUT THIS BOOK**

Information
- Introduction into this very accurate surface temperature measurement method
- Examines a significant number of examples and applications in detail
- Guides both, the experienced researcher and the young student

Infrared thermography is a measurement technique that enables to obtain non intrusive measurements of surface temperatures. One of the interesting features of this technique is its ability to measure a full two dimensional map of an object surface temperature and, for this reason, it has been widely used as a surface flow visualization technique. Since the temperature measurements can be extremely accurate, it is possible, by using a heat flux sensor, also to measure convective heat transfer coefficient distributions on a surface, making the technique *de facto* quantitative. This book, starting from the basic theory of radiation and heat flux sensors, guides, both the experienced researcher and the young student, in the correct application of this powerful technique to study convective heat transfer problems. A significant number of examples and applications are also examined in detail, often pointing out some relevant aspects.

Table of contents:

*Introduction and Historical Groundings - Physical Background - Infrared Scanner - Heat Flux Sensors - Restoration of Thermal Images - Some Practical Considerations - Applications.*
MEASUREMENTS OF HEAT FLUXES

Measuring heat fluxes from a stream to a surface is one of the main and difficult issues of *thermo-fluid-dynamics*. *Measuring heat fluxes involves measuring temperatures.*

The temperature has to be measured in *heat flux sensors* (generally slabs).

The appropriate equation for heat conduction in solids, applied to the *selected sensor model*, yields the relationship by which the measured temperature is correlated to the heat transfer rate.

The use of an infrared camera as *temperature detector* is beneficial when compared to standard detectors.

- Entirely *two-dimensional detector* (allows the evaluation of *heat flux variations* and of *errors due to tangential conduction* along the sensor).
- *Non intrusive* (avoids the errors due to *thermal conduction through thermocouples, or RTD’s connections*).
**UNSTEADY HEAT FLUX SENSORS**

**THIN SKIN** - The thin skin is based on the assumption that a thin slab constituting the sensor behaves as an *ideal calorimeter* which is *isothermal across its thickness*. Heat flux uniformly increases the slab temperature with time.

\[ Q_w = Q_c - Q_r \]

\[ Q_w = \rho cs \frac{dT}{dt} \]

**THIN FILM** - The thin film is based on the *theory of heat conduction in a semi-infinite wall*. Heat flux steadily increases the slab *surface* temperature \( T(t,0) \).

\[ Q_w = \text{const} \]

\[ T(t,0) - T_i = \frac{Q_w}{2} \sqrt{\frac{t}{\pi \rho c k}} \]
HEATED THIN FOIL (STEADY)

It consists of heating a thin metallic foil (AISI 40µm thick), or a printed circuit board, by Joule effect and, by measuring the foil temperature, computing the heat transfer coefficient $h$ between the foil and the stream.

$T_{aw}, V$

flowing stream

$\dot{q}_j, h(T_w - T_{aw}), \dot{q}_k$

$\dot{q}_r$

the foil back can be thermally insulated

- $\dot{q}_j$ is the known Joule heating
- $\dot{q}_r$ are the losses due to radiation
- $\dot{q}_k$ are due to tangential conduction
- $\dot{q}_c$ is convection at sensor back side
- $h(T_w - T_{aw})$ is the convective flux to be measured

If the Biot number is:

$$Bi = \frac{hs}{\lambda} \ll 1$$

the heated foil can be assumed isothermal across thickness and measurements performed on either foil side.

The heat transfer coefficient $h$ is inferred from the energy conservation equation:

$$h = \frac{\dot{q}_j - \dot{q}_r - \dot{q}_k - \dot{q}_c}{T_w - T_{aw}}$$
IMPINGING JETS (*heated thin foil*)

EXPERIMENTAL ARRANGEMENT FOR IMPINGING JETS

*The heated foil consisted of a 40μm AISI 304 foil*
Jet impinging on a plate, contours of constant temperature; $z/d=6$, $Re=28000$ (1986).

To my knowledge, shows the first thermographic image of an impinging jet.
RECOVERY FACTOR

\[ r = \frac{T_{aw} - T_\infty}{T_o - T_\infty} \]

RELIEF MAP OF THE RECOVERY FACTOR OF A JET IMPINGING ON A FLAT PLATE FOR \( D = 10\text{mm}, \ z/d = 2 \) AND \( M = 0.52 \) (1991)

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RELIEF MAP OF THE NUSSELT NUMBER OF A SINGLE JET IMPINGING ON A FLAT PLATE FOR $D = 10\text{mm}$, $z/d = 2$ AND $Re_D = 28,000$ (1991)

In a 1990 technical meeting in Kozubnik (Bielsko-Biała, prof. Fisdom), I was asked if these plots originated from numerical computations !!!
SHEAR LAYER INSTABILITY

In the meantime, Meola et al. (1995), through measurements of *adiabatic wall temperature*, observed instability developing for high $M$ values.

E.g., for $z/d = 4$, as the Mach number $M$ increases, the vortex ring, which is located in the shear layer at $r = 1.2d$ ($r$ indicates the radial coordinate), strengthens and breaks up (*Widnall instability*), entailing entrainment of warmer ambient air and giving rise to the formation of azimuthal structures.


Variation of adiabatic wall temperature with the Mach number for $d = 5 \text{ mm}$, $z/d = 4$; (a) $M = 0.3$; (b) $M = 0.4$; (c) $M = 0.5$; (d) $M = 0.56$; (e) $M = 0.67$; (f) $M = 0.71$
HYPERSONIC FLOW
The model is suddenly exposed to a high enthalpy hypersonic stream at $M = 8.15$ (CEAT, Poitiers) and thermal images of the windward (bottom) side are recorded as a function of time.

Several trip cylindrical wires (0.5mm high, 0.22mm in diameter and placed at 5mm steps) are implanted 30mm away from the ellipsoid nose.
Temperature map of the windward side of a double ellipsoid model at $M = 8.15$, $\alpha = 30^\circ$, $0.48s$ after model injection. Wires wakes are clearly visible.

HYPERSONIC FLOW OVER A FLAT PLATE FOLLOWED BY A RAMP
(e.g., heat transfer in re-entry problems; thin film)

**HEAT FACILITY**

*High Enthalpy Arc-heated Tunnel, Centro Spazio (PISA), Italy*

Main characteristics are:

- Blow-down tunnel
- Test duration: 20 - 300 ms
- Mach number: 6
- Total Temperature: 300 - 4000 K
- Total Entalpy: 0.3 - 6 MJ/kg
- Reynolds Number: $10^4$-$10^6/m$
- Fluids: air, helium, argon, CO2
FLAT PLATE WITH 15° RAMP IN A $M = 6$ HYPERSONIC FLOW
FLAT PLATE WITH 15° RAMP

Flow from left to right

Leading edge

Hinge line

\( M = 6 \)
FLAT PLATE WITH 15° RAMP
Nominal conditions $H_o = 1.8MJ/kg$ ; $P_o = 6bar$

Centerline data

MODIFIED STANTON NUMBER
(based on $H_o$)

Flat plate

Hinge line

x [mm]

0 40 80 120
Images of Goertler vortices (fluiddynamic instability) on a 30° ramp in a hypersonic flow at $M = 8.15$ (thin-film sensor; AGA 780):

a) coarse (acquired) image;
b) sensor and camera restoration.
PICCOLO TUBE
(DE-ICING OF A WING LEADING EDGE)
(heated thin foil)

No ice

Ice formation and accretion

With ice

Wing with de-icing piccolo tube
EXPERIMENTAL APPARATUS

The test article includes the leading edge of a NACA 0012 wing profile (1.5m chord), stopped at about 1/10 of the chord, with inside a spray (piccolo) tube at 4% of the chord to simulate the de-icing device.

The profile is 0.2m span-wise, made of an AISI foil (40µm thick) and lodged inside two ad-hoc fixtures to apply voltage difference.

The infrared camera (CEDIP Jade III, cooled FPA 320x240 InSb pixels, 3.8-5.3µm band, sensitivity 20mK at 300K) views the foil side opposite to the jet impingement one, both from the front and the back.
Since we are looking at a three-dimensional device, a **geometrical camera calibration procedure**, with the thermal images of the calibration target, is necessary.

The target calibration plate is made of an Al plate, 120x120mm², with 17x17 (289) holes, 2.2mm diameter and 10mm deep, so to behave almost as black bodies.

The plate is moved back and forth, within measurement domain, to perform geometrical calibration.

A thermal 3D image can, therefore, be fully reconstructed.
3D TEMPERATURE RECONSTRUCTION FOR $d = 4\text{mm}$, $\phi = 30^\circ$, $M = 1.0$ AND $p/d = 15$:

(a) Wall temperature $T_w$ (with foil heating);
(b) Adiabatic wall temperature $T_{aw}$ (without foil heating).

\[ \dot{q}_j = h(T_w - T_{aw}) \]

\[ Nu = \frac{hd}{\lambda} \]
INFLUENCE OF JETS PITCH ON $Nu$, $M = 1.0$ AND $\phi = 50^\circ$

(a) $p/d = 5$;
FLOW IN A ROTATING U CHANNEL
(e.g., internal cooling of turbine blades; heated thin foil)

FLOW IN A ROTATING CHANNEL

The effects of rotation, as in *turbine blades*, change strongly the thermo-fluid-dynamic behavior of the flow in a channel. This happens because *in a rotating channel with an U turn* there is interaction between the following forces:

- **Pressure gradients causing the flow in the main direction**
- **Coriolis forces**
- **Centrifugal forces**

The resulting flow field is highly three-dimensional (especially in the turns) and this affects the heat transfer coefficient distribution. This is why the problem has been studied with both *Particle Image Velocimetry (PIV)* and *InfraRed Thermography (IRT)*.
COMPARISONS OF $Nu/Nu^*$ DISTRIBUTIONS

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$Nu = \frac{hD}{k}$; $Nu^* = 0.024 Re^{0.8} Pr^{0.4}$
IMPINGING JETS
(e.g., for cooling purposes; heated thin foil)

TOMOGRAPHIC PIV (3D-3C)

Tomographic PIV is a very powerful research tool. TomoPIV is an innovative experimental technique, based on a *multiple camera system*, *three-dimensional volume lighting* and 3D reconstruction of particles velocity field within the *whole measurement volume*.

**Tomographic PIV experimental apparatus for impinging jets**
TOMOGRAPHIC PIV (3D-3C)

Tomographic PIV is a time-resolved research tool. Besides what is encountered in standard nozzles, chevron nozzles generate azimuthal instabilities, already in the jet shear layer, which induce an increase of the heat transfer in the impingement region. The noise they produce is much lower.

ONSET OF HORIZONTAL NATURAL CONVECTION

Main dimensionless parameters:

- Prandtl number \( \text{Pr} = \frac{\nu}{\alpha} \);
- Rayleigh number \( \text{Ra}_L = \text{Pr} \cdot \text{Gr}_L = \frac{\beta \Delta T g L^3}{\nu \alpha} \);
- Aspect ratio \( A = \frac{D}{L} \).

\[
q_c = \lambda \frac{\partial T}{\partial y} \approx \alpha \rho c_p \frac{\Delta T}{L}
\]

\[
\text{Ra}_L = \frac{g \beta q_c L^4}{\rho \nu \alpha^2 c_p}
\]
ONSET OF HORIZONTAL CONVECTION

Schematic of the experimental apparatus
$t/\tau_{bl_0} = 0.25$

$Ra = 1.3 \times 10^6$

$t/\tau_{bl_0} = 0.7$

$N_u$

$N_u$

$y/L$

$T/L$

$x/L$

$x/L$

$y/L$

$y/L$
ELECTRONIC COOLING

Classical devices to cool:
• Fan
• Heat Sink
• High conductivity materials
NEW PERSPECTIVES: **SYNTHETIC JETS**

- Zero net mass flow rate.
- Are generated by means of loudspeaker or a diaphragm movement in a cavity.
- Can be used in electronic cooling and flow control applications.

SYNTHETIC JETS (FLUID DYNAMICS)


The formation criterion for synthetic jets is:

\[
\frac{Re}{S^2} > K
\]

where \( K \) is a number whose value is 1 and 0.16 for plane two-dimensional and axisymmetric jets, respectively, \( Re \) the **Reynolds number** and \( S \) the **Strouhal number** \((S = \frac{V_m}{2\pi f D})\).


**Phase averaged velocity**

![Phase averaged velocity](image)
SYNTHETIC JETS (HEAT TRANSFER)

The synthetic jet heat transfer is found to be comparable with the continuous axisymmetric jet and expected to be better at high Reynolds number. (Chaudhari M, Puranik B and Agrawal A, Heat transfer characteristics of synthetic jet impingement cooling, *Int. J. Heat Mass Transfer*, 53 (2010) 1057-1069)

Further understanding of the heat transfer mechanisms could be achieved exploiting time-resolved heat flux measurements, which is the objective of ongoing research. (Valiorgue P, Persoons T, McGuinn A and Murray DB, Heat transfer mechanisms in an impinging synthetic jet for small jet-to-surface spacing, *Exp. Therm Fluid Sci*, 33 (2009) 597-603)

METHODS FOR HEAT TRANSFER ENHANCEMENT

- Acoustic excitation (Liu & Sullivan 1996);
- Application of swirl (Ianiro & Cardone 2012);
- **Introduction of mesh screens within the nozzle** (in particular *fractal grids*);
- Introduction of perforated plates between nozzle and target plane (Lee et al 2002).

*Carlamagno & Ianiro, ETFS (2014)*

*Popiel, ETFS (1991)*

*El Hassan et al, POF (2013)*

*Violato et al, IJHFF (2012)*
HOW TO OBTAIN A FRACTAL GRID?

Repeat the same pattern several times by scaling its dimensions.
Infrared camera FLIR SC6000 (640x512 pixels, 3.2 pixels/mm).
**EXPERIMENTAL DETAILS**

**Effective meshlength**

\[ M = \frac{\pi d^2}{P} \sqrt{1 - \sigma} \]

**Grid solidity**

\[ \sigma = \frac{b}{M} \left( 2 - \frac{b}{M} \right) = 0.32 \]

from Hurst & Vassilicos, POF (2007)

<table>
<thead>
<tr>
<th>FRACTAL GRID</th>
<th>REGULAR GRID</th>
</tr>
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<tbody>
<tr>
<td>L₀</td>
<td>10mm</td>
</tr>
<tr>
<td>t₀</td>
<td>1mm</td>
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<tr>
<td>M</td>
<td>2.4mm</td>
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<tr>
<td>b</td>
<td>0.4mm</td>
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JWT Jet **Without** Turbulators  
RG Regular Grid  
FG Fractal Grid
Strong HT enhancement in the stagnation region.

Cross-shaped Nu map.

Double peak due to ring vortices; Stagnation point heat transfer decreases as the distance increases.

Multi-channel behaviour, with several local maxima in the $Nu$ distribution.

Strong HT enhancement in the stagnation region. Cross-shaped Nu map.

$Re = 28,700$
CONCLUDING REMARKS

Infrared Thermography represents an innovative methodology for heat transfer studies, that we can use to either perform non-destructive testing as well as to measure convective heat fluxes, its mean features being:

- provides a full two-dimensional information
- is a non-contact technique
- allows a computerized elaboration of the images

The presented results were concerned with some significant experiments carried out during the past several years by the research group the presenter belongs to.

Through these results, it is proved that infrared thermography is able to yield valuable information about:

- non-destructive evaluation of materials, markedly composites,
- accurate heat transfer measurements in complex fluid flows, especially if coupled with PIV.