Thermography Applied to Anti-Icing Systems

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= Chemical Engineering Laboratory for Finely Divided Solids, Energy & Environment

- South West of France
- Ministère de l’Économie, des Finances, et de l’Industrie
- Civil Engineers  (Major in Chemical Engineering)
OUTLINE

1. An overview of Infrared Thermography (IRTh)
2. IRTh applied to anti-icing systems
3. IRTh applied to Fluid flow thermal characterization
4. Conclusion
An overview of IR Thermography = Thermal Images…

- Microcomponent analysis
- Skin & Fever
- Art restoration
- Vascular

…or Temperature fields?
IRTh: measurement of infrared radiation by a radiometer

Radiative Heat Transfer

- **Surface of bodies**
- « Instantaneous »
- No need for a material medium for propagation

IRTh: usually within 1 – 15 μm

Energy ➔ Signal / Noise

Sensitivity ➔ thermal Resolution
Typical modern IR cameras… fast, sensitive, friendly…

- Sensor: InSb, InGaAs, MCT, microbolometric…
- Focal plane Array: 640x512 pixels or 320x256 pixels
- Thermal sensitivity 30 °C: < 20 mK InSb, MCT
  < 85 mK μbolometric
- Spectral Sens. : 1 - 5 µm or 3 - 5 µm (InSb), 8 - 12 µm
- Typical: 150 – 400 Hz !!!
- Integration time: about 10 µs
- One pixel Sensor = 15 µm
Calibration: Black body

Emissivity

\[ \varepsilon = \frac{E_{\text{object}}(T)}{E_{\text{Black body}}(T)} \]
Infrared measurement: typical situation

1 = Object of interest
2 = Thermal influence of surrounding parts, such as walls, other objects…
3 = Surrounding part reflect on the object
4 = Object emissive power
5 = Partial transmission of the intermediate medium
6 = Signal arriving to the IR camera
7 = Output signal
Optical properties and spectral range impact on the thermal signal

Combustion

Methane - Air

CO₂ spectral emissivity

Glass bottle process

Bottle Cooling / Surface Temperature
Two different approaches for Quantitative IRTh

1/ Qualitative = thermal imaging ????

2/ Quantitative IRTh = Measurements

Temperature measurements

Calibration
known Emissivities
Radiometric equations ; control of meas. conditions

Temperature fields

2’/ Relative variations of the thermal signal + image processing

Uniform Emissivity
Minimize surrounding effects
Process temperature or even DL signal

Images processing for NDT or Parameter maps
Which difference between visible range CCD cameras and IRTh?

*Lighting*

**CCD**

Received 2D signal only depending on surface information

**IRTh**

Thermal non-equilibrium: Passive or Active Heat Excitation

Received 2D signal dependent of full thermal 3D information

Some subwall information is available!

*(here = fluid flow in the subwall micromixer)*
What for?

Temperature measurements

Retrieve some local properties or parameters

Correlate these parameters to some magnitudes of interest

*image processing*

*Inverse methods*

*Compression*

*Reduction 3D / 2D*
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IRTh applied to anti-icing systems

Numerous works devoted to thermo-fluid dynamics

- Temperature field measurements
  - Boundary layers analysis
  - Impinging jets
  - Interaction of fluid flow with the surface of a body

- Heat transfer coefficient measurements
  - High enthalpy flows (supersonic)
  - Coupling Shear stress and heat transfer (Reynolds analogy)


IRTh applied to anti-icing systems

Multi jets thermal anti-icing systems (wing, tails, engine inlet)

Convective heat transfer coefficient mapping

Academic bench results

Von Karman Institute for Fluid Dynamics (VKI, Belgium)

Real wing bench results

IRTh applied to anti-icing systems

IRTh and Icing wind tunnel (ONERA)

Temperature measurements for validation of a thermal simulation code for an anti-icing systems on helicopter rotor blades

\[ S' = \tau \epsilon S_{\theta_0} + \tau (1 - \epsilon) S_{\theta_a} + (1 - \tau) S_{\theta_{atm}} \]  

Using Radiometric equation  Determine radiative properties

Black paint emissivity  Ice emissivity  …number and size of droplets

IRTh applied to anti-icing systems

IRTh and Icing wind tunnel (ONERA)

Fig. 11 Température mesurée en conditions givrantes

Fig. 8 Cycles de chauffage

IRTh applied to anti-icing systems

Airfoil Leading Edge

Convective heat transfer coefficient mapping

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Velocity and heat transfer parameter mapping

Thermal Surface Measurements

Self-emission phenomenon and Variations in emissivity

\[
\frac{\partial T}{\partial t} + V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} = \frac{1}{\rho c} \left( \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) \right) + g
\]

Velocity Conduction and interfaces Heat source

In-depth heat transfer
IRTh applied to Fluid flow thermal characterization

Fluid flow troubleshooting

\[ \frac{\partial T}{\partial t} + V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} = \frac{1}{\rho c} \left( \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) \right) + g \]

IRTh can be used to detect:
- Change in velocity
- Change in global heat capacity
- Change in heat transfer coefficients
- Change in global thermal resistance
- Change in mass flow rates
- Heat source term

External bodies
Fouling
Inclusions
Phase change enthalpy
Velocity and diffusion mapping for a moving solid

“Flash” excitation

Diffusing pattern after 2D displacement, non-uniform field $V(x,y)$

$\frac{\partial T(x,y,z,t)}{\partial t} + V_x \frac{\partial T(x,y,z,t)}{\partial x} + V_y \frac{\partial T(x,y,z,t)}{\partial y} = a \left( \frac{\partial^2 T(x,y,z,t)}{\partial x^2} + \frac{\partial^2 T(x,y,z,t)}{\partial y^2} + \frac{\partial^2 T(x,y,z,t)}{\partial z^2} \right)$
Velocity and diffusion mapping for a moving solid

Infrared sequence showing a moving and diffusing pattern

Diffusivity and velocity mapping from previous image sequence sampled at 25 Hz

Fluid flow in microchannels

With Flow rate measurement

Active
With Laser diode

Passive

Cristalization of nanoparticles

Laser diode

μchannel

Serynge pump
Fluid flow in microchannels

Cristalization of nanoparticules
Peclet field $Pe_{i,j}$ estimation

$$Pe_{i,j} = \frac{\Delta(T_{i,j} - T_{i,j}^0)}{\delta(T_{i,j})}$$

$$\text{var} \left( Pe_{i,j} \right) = 40 \sigma^2 \delta T_{i,j}^{-2}$$

Application to a chemical reaction characterization

Temperature field $T_c$, at $Q = 1000 \, \mu l h$

Chemical source term at $Q = 1000 \, \mu l h$

Reactive Droplets

Acid injection (HCl)  Base injection (NaOH)

Oil Injection

Quasi instantaneous mixing
1 droplet = 1 microreactor
Intensification of the experiments!
Infrared tracking

Freezing of biological cells: Phase change and thermal diffusivity

Freezing of biological cells: Phase change and thermal diffusivity

\[ F_{O_{i,j}} \Delta T_{i,j}^k + \Phi_{i,j}^k = \delta T_{i,j}^k \]

Analysis of correlations

\[ \rho_{i,j}^F = \frac{\sum_{F_i} \Delta T_{i,j}^k \delta T_{i,j}^k}{\| \Delta T_{i,j}^k \|_{F_i} \| \delta T_{i,j}^k \|_{F_i}} = \langle \Delta T, \delta T \rangle \rightarrow \pm 1 \]

Freezing of biological cells: Phase change and thermal diffusivity

Fourier Number versus time for three pixels.

Heat source versus time for three pixels.

Field of Fourier number at the end of the processing.

Field of heat source at the end of the processing.
Conclusion and perspectives

Many open problems: icing and fluid flow parameters control

IRTh = Temperature field measurements

… But also for thermal parameters mapping

… Benefit of image processing tools and inverse methods

… Also inverse technics with single sensors!