IR THERMOGRAPHY IN FLUID MECHANICS AND HEAT TRANSFER

BY

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This Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) image of Mt. Vesuvius, Italy was acquired September 26, 2000. The full-size false-color image covers an area of 36 by 45 km. Vesuvius overlooks the city of Naples and the Bay of Naples in central Italy. (Popocatepetl and Mount Fuji are other volcanos surrounded by dense urban areas.) In 79 AD, Vesuvius erupted cataclysmically, burying all of the surrounding cites with up to 30 m of ash. The towns of Pompeii and Herculaneum were rediscovered in the 18th century, and excavated in the 20th century. They provide a snapshot of Roman life from 2000 years ago: perfectly preserved are wooden objects, food items, and the casts of hundreds of victims. Vesuvius is intensively monitored for potential signs of unrest that could signal the beginning of another eruption.
This lecture is in honor of
Giovanni Maria Carlomagno
for his many contributions to fluid Mechanics and Thermography
1. Methodology of thin film IR measurements.
2. Detection of coherent structures in single-phase flow.
3. Liquid-air flow. Thermal pattern on the heated wall.
6. Micro-channels. IR measurements of the heated wall and the fluid temperatures.
7. Conclusions.
The IR camera is placed in the vicinity of the heated foil. A very thin foil makes it possible to increase frequency response of the IR measurements.

Temperature measurements on the surface of capillary tubes

The method is based on compensating the background radiation by controlling its temperature to the same level of the temperature of the capillary tube. This is achieved by recording the infrared data against a background, whose temperature was maintained at a given value by a thermostat.

The purpose of this study was to connect the coherent structures, at the location of their formation at the boundary layer, to their appearance on the surface. There is also an additional physical insight which can be gleaned from the spots emergence on the water surface: the surface-renewal motions originate in the bursting motions which occur in the buffer region. That is, fluid which is strongly listed towards the outer layer almost always arrives by the bursting at the free surface and renews the free surface.

In the flow-visualization studies by Kline et al. (1967) it was shown that in the near-wall region of bounded turbulent flows, there are low-velocity streaks, and subsequent ejections of the low-velocity fluid to the outer region of the flow. There are several stages in the process by which low-velocity streaks are eventually ejected away from the wall. The total process was called a “burst”.

There is physical insight which can be gleaned from the spots emergence on the water surface. The surface-renewal motions originate in the bursting motions which occur in the buffer region. G. Hetsroni, A. Mosyak 1996 Bursting process in turbulent boundary layer at low Reynolds numbers. Chem.Eng. Comm. 148-150, 85-104
BURST DETECTING BY IR
Image analysis

Thermal spots on the water surface:
a single burst event,
b thermal spots from two ejections

From the video recording we counted the number of new spots $N_x$ as they appeared on the interface in the band $z^+=\pm50$ at the center of the flume. The spot frequency was $f_s=N_x/t_{sm}$, where $t_{sm}$ is the sampling interval. As the time between bursts in the present study was from 2 to 6 s a sampling frequency of 25 Hz was chosen, with a sampling time of 1,500 s. We also counted the number of spots, $N_{x,z}$, which appeared over the whole width of the interface. The spot frequency per unit of span was calculated as $F_s=N_{x,z}/(z\times t_{sm})$. 

http://dx.doi.org/10.21611/qirt.2012.390
BURST DETECTING BY IR Visualization

![IR Image](http://dx.doi.org/10.21611/qirt.2012.390)
**BURST DETECTING BY IR**

**Experimental results**

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Flow depth, $2h$ (m)</th>
<th>Reynolds number $Re$</th>
<th>Wall shear velocity $u^*$ (m/s)</th>
<th>Percent of drag reduction $Dr$, (%)</th>
<th>Bursting frequency $f^* = \frac{v}{tu^*^2}$</th>
<th>Bursting rate per meter, $F$ (bursts/ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.037</td>
<td>4,200</td>
<td>0.0070</td>
<td></td>
<td>0.0102</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>4,800</td>
<td></td>
<td>0.0077</td>
<td></td>
<td>0.0107</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>7,100</td>
<td></td>
<td>0.011</td>
<td></td>
<td>0.0103</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>12,000</td>
<td></td>
<td>0.017</td>
<td></td>
<td>0.0110</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>0.050</td>
<td>3,100</td>
<td>0.0042</td>
<td></td>
<td>0.0104</td>
<td>6.7</td>
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<tr>
<td></td>
<td>0.085</td>
<td>4,700</td>
<td>0.0035</td>
<td></td>
<td>0.0108</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>0.093</td>
<td>9,900</td>
<td>0.0060</td>
<td></td>
<td>0.0100</td>
<td>19</td>
</tr>
<tr>
<td>530 ppm by weight</td>
<td>0.037</td>
<td>3,700</td>
<td>0.0051</td>
<td>46</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Habon G solution</td>
<td>4,200</td>
<td>0.0054</td>
<td></td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6,200</td>
<td>0.0078</td>
<td></td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10,000</td>
<td>0.012</td>
<td></td>
<td></td>
<td>53</td>
<td></td>
</tr>
</tbody>
</table>

\[
Dr = \frac{\Delta P_{\text{water}} - \Delta P_{\text{surf}}}{\Delta P_{\text{water}}} \cdot 100
\]
EFFECT OF SURFACTANTS ON THERMAL STREAKS

Drag reduction solution

Water \hspace{1cm} \text{Re} = 5500 \hspace{1cm} \text{Habon G, C}=0.027\%
THERMAL PATTERN. SINGLE COARSE PARTICLE

\[ d^+ = 34, \quad C_v = 4 \cdot 10^{-4}, \quad Re = 2600 \]

experiment

DNS
## THERMAL PATTERN ON THE HEATED WALL IN AIR-WATER FLOW

### Inclined tube Experimental setup

| 1. tank; 2. pump; 3. flow regulator; 4. water flowmeter; 5. air regulator; 6. air flowmeter; 7. mixing section; 8. development section; 9. video camera; 10. IR camera; 11. pressure measurement section; 12. heated test section | ![Experimental setup diagram](http://dx.doi.org/10.21611/qirt.2012.390) | ![Experimental setup photo](http://dx.doi.org/10.21611/qirt.2012.390) |
THERMAL PATTERN ON THE HEATED WALL IN AIR-WATER FLOW

Thermal and flow visualization

Unclosed flow
Open annular flow with disturbance waves. Dryout on the upper part of the pipe may be associated with open annular flow with motionless or slowly moving droplets

Closed flow
Closed annular flow with air-water clusters and liquid film on the upper part of the tube. Time and space average heat transfer coefficient is about 3-8 times higher than that for unclosed flow
Vertical tube Experimental setup

The upper part of the vertical tube
Flow and thermal visualization

For the bubble flow, the streaky structure is destroyed. This phenomenon is accompanied by significant increase in the heat transfer coefficient.
The temperature distribution on the heated wall depends strongly on whether water containing small gas bubbles (slug) or water surrounding the Taylor bubbles passes the heated wall at any instant.
THERMAL PATTERN ON THE HEATED WALL IN AIR-WATER FLOW

Flow and thermal visualization. Still pictures

Taylor bubble

IR image

In the vicinity of Taylor bubble temperature of the heated wall increases
SATURATED BOILING ON THE HORIZONTAL HEATER MADE OF THIN FOIL. EXPERIMENTAL FACILITY

1 auxiliary heater
2 liquid
3 High Speed Video
4 IR Radiometer
5 electrical heater
50 µm foil
POOL BOILING

BBBLE DYNAMICS AND TEMPERATURE FIELD ON THE HEATER

Water, $q=100 \text{ kW/m}^2$

Habon G, 530 ppm
$q=100 \text{ kW/m}^2$
POOL BOLING

TEMPERATURE DISTRIBUTION ON THE HEATER

Water

q=100 kW/m²

Habon G

Area 1
Min Max Mean
106.6 115.1 124

Area 2
Min Max Mean
98.1 161.3 122

http://dx.doi.org/10.21611/qirt.2012.390
Temperature histograms

q=100 kW/m²

Water

Habon G

http://dx.doi.org/10.21611/qirt.2012.390
Habon G. Saturated boiling curves

$q$, kW/m$^2$ vs. $T_w - T_s$, K

- ▲ 1060 ppm Habon
- △ 530 ppm Habon
- × 260 ppm Habon
- □ 130 ppm Habon
- ● 65 ppm Habon
- ○ water

http://dx.doi.org/10.21611/qirt.2012.390
FLOW BOILING IN A CAPILLARY TUBE

\( d_{\text{in}} = 1.07 \text{ mm} \)

<table>
<thead>
<tr>
<th>QIRT 2012</th>
<th>27</th>
<th>39</th>
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</table>

**Experimental setup**

**Infrared image and temperature distribution**

[Diagram showing experimental setup and infrared image with temperature distribution graph]

http://dx.doi.org/10.21611/qirt.2012.390
FLOW BOILING IN A CAPILLARY TUBE
\( d_{in} = 1.07 \text{ mm} \)

Dryout
FLOW BOILING IN MICRO-CHANNELS
THERMAL FIELD ON THE HEATER

http://dx.doi.org/10.21611/qirt.2012.390
FLOW BOILING IN MICRO-CHANNELS
THERMAL FIELD ON THE HEATER

Test module

Schematic of the flow in the inlet manifold
Experimental apparatus

Diagram showing the experimental apparatus with components such as a high-speed video camera, microscope, synchronizer, and video tape recorder.
\[ \dot{m} = 95 \text{ kg/m}^2\text{s}, \ q = 160 \text{ kW/m}^2, \ d_h = 160 \mu\text{m} \]

1- The area of the heater

2- The area of the heater, where saturated flow boiling occurs at mean wall temperature of \( T_w = 107.9 \) °C

Measurements by non contact infrared thermography cover the whole temperature field
IR MEASUREMENTS IN THE LIQUID AND ON THE HEATER

Flow and thermal visualization

[Diagram of experimental setup]

Polycarbonate or Sapphire cover

http://dx.doi.org/10.21611/qirt.2012.390
Direct measurement of the liquid temperature through IR transmitted face layer.


The liquid is circulated in micro-channels (2) etched in the wafer (3). The heater (4) is attached to the top surface of the wafer (3). The micro-channel system is sealed by IR transparent window (1). The liquid temperature is measured by the IR camera (5) through this window.

Temperature oscillations on a heated wall

Serpentine heater 1×1 cm

Temperature

http://dx.doi.org/10.21611/qirt.2012.390
Measurements by IR camera inside the micro-channels
Fluid temperature changes in the spanwise direction due to effect of channel walls temperature
CONCLUSIONS

Infrared thermography was used to detect the coherent structures, which originate in the buffer region of turbulent flow.

The thermal pattern on the heated wall for the single-phase flow has a streaky structure.

For air-liquid flow the streaky structure is destroyed. This phenomenon is accompanied by a significant increase in the heat transfer coefficient and sharp decrease in the temperature fluctuation values, whereas the level of pressure fluctuations almost did not change.

Flow boiling in parallel micro-channels is accompanied by quasi-periodical rewetting and refilling. Boiling of surfactant solutions in micro-channels may be used to provide a nearly isothermal heat sink.
There is a reason to believe that using IR technique in ancient Rome could have saved the lives of many Pompeii citizens.

*The Last Day of Pompeii* is a large painting by the Russian artist Karl Briullov (1830-33).

The painting is classical, with the use of chiaroscuro.

Karl Briullov was born on 12.12.1799 in St. Petersburg and buried 11.6.1852 near Rome.

He could not resist putting his image in the painting and even depicted his mistress in a somewhat compromising position.
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molti ringraziamenti per l'attenzione