Quantifying the Effects of Transient Heating Conditions on Microchannel Flow Boiling Instabilities

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Next-Generation Thermal Management

AESA Radar in a Fighter Aircraft

Air-cooled Copper Heat Sink

Sudhakar and Weibel, JEP, 2017

Two-Phase Microchannel Heat Sink

Sudhakar and Weibel, JEP, 2017

Source

- Junction/Chip (<10^-3 m)
- Package/Case (10^-2 m)
- PCB/Heat Sink (10^-2 - 10^-1 m)
- Room/Ambient (>10^-1 m)

Sink

- 10000 kW/m^2
- 1000 kW/m^2
- 100 kW/m^2
- 10 kW/m^2
- 0.1 kW/m^2

‘Remote’ Cooling

‘Embedded’ Two-Phase Cooling

Bar-Cohen, JNEM, 2013

http://www.northropgrumman.com/Capabilities/ANAPG81AESAARadar/Pages/default.aspx
https://www.navsea.navy.mil/Home/Warfare-Centers/NSWC-Crane/
https://www.navsea.navy.mil/Home/Warfare-Centers/Partnerships/NEEC/
Experimental Facility

- 500 μm-diameter borosilicate glass microchannel
- Constant or transient heating
  - ITO coating provides heat flux to channel via Joule heating
  - Solid-state switch enables heat flux switching during transient heating experiments
- Working fluid: Degassed HFE-7100
- High-frequency measurement of heat flux, wall temperature, pressure drop, and mass flux
- Synchronized high-speed flow visualizations enable time-resolved characterization

Experimentally measured thermal time constant of the microchannel during single-phase flow: \( \tau = 0.43 \) s

Selection of Transient Heating Conditions

Selected three heat fluxes which result in highly contrasting flow conditions under *constant* heating conditions:

- **15 kW/m²**: single-phase flow
- **75 kW/m²**: continuous two-phase flow
- **150 kW/m²**: exceeds critical heat flux

### Design of Experiments: Single Heat Flux Pulse

<table>
<thead>
<tr>
<th>Low Heating Level [kW/m²]</th>
<th>High Heating Level [kW/m²]</th>
<th>Duty Cycle [%]</th>
<th>Heating Pulse Frequency, <em>f</em> [Hz]</th>
<th>Initial Heat Flux [kW/m²]</th>
<th>Pulsed Heat Flux [kW/m²]</th>
<th>Pulse Durations [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>75</td>
<td>50</td>
<td>0.1, 0.2, 0.5, 1, 2, 5, 10, 15, 20, 25, 50, 100</td>
<td>15</td>
<td>75</td>
<td>0 - 0.50*, 0.75, 1, 2, 4, 6, 8, <strong>10</strong></td>
</tr>
<tr>
<td>15</td>
<td>150</td>
<td>50</td>
<td>0.8, 1, 2, 3, 4, 5, 10, 15, 20, 25, 50, 100</td>
<td>75</td>
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</tbody>
</table>

*Increments of 0.05 s
Single Heat Flux Pulse (10 s) from 15 kW/m² to 75 kW/m²

- Explosive-like growth at the onset of boiling due to the rapid-bubble-growth instability

- Dynamic response to boiling resembles that of an underdamped mass-spring-damper system subjected to a unit step input

Single Heat Flux Pulse (10 s) from 15 kW/m$^2$ to 75 kW/m$^2$

During the transition, the wall temperature overshoots the eventual steady wall temperature by approximately 20 °C.
Time-periodic Heat Flux Pulses: 15/75 kW/m² at 5 Hz

- Flow regime transitions and pressure drop oscillations occurring simultaneously
- Pressure drop oscillations induced at exactly the heating pulse frequency (5 Hz)

Conclusions

• Single heat flux pulse
  – Step up/down in heat flux that induces/ceases boiling causes the wall temperature to temporarily over/under-shoot the eventual steady wall temperature
  – At onset of boiling, dynamic response resembles that of an underdamped mass-spring-damper system subjected to a unit step input

• Time-periodic heat flux pulses
  – For $f > 10$ Hz: transient heat flux is attenuated and effectively becomes a constant heat flux
  – For $1$ Hz $< f < 10$ Hz: flow boiling is heavily coupled to transient heating conditions
  – For $f < 1$ Hz: acts as a step change between different heat flux levels

• Next-generation cooling strategies will need to consider increased coupling between device operation and cooling performance
Acknowledgments

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https://www.navsea.navy.mil/Home/Warfare-Centers/Partnerships/NEEC/