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

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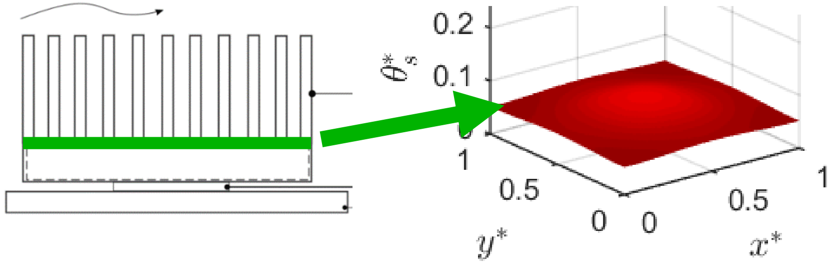
Next-Generation Thermal Management

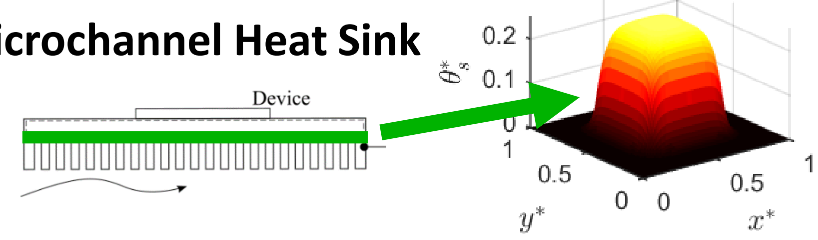
AESA Radar in a Fighter Aircraft

Air-cooled Copper Heat Sink



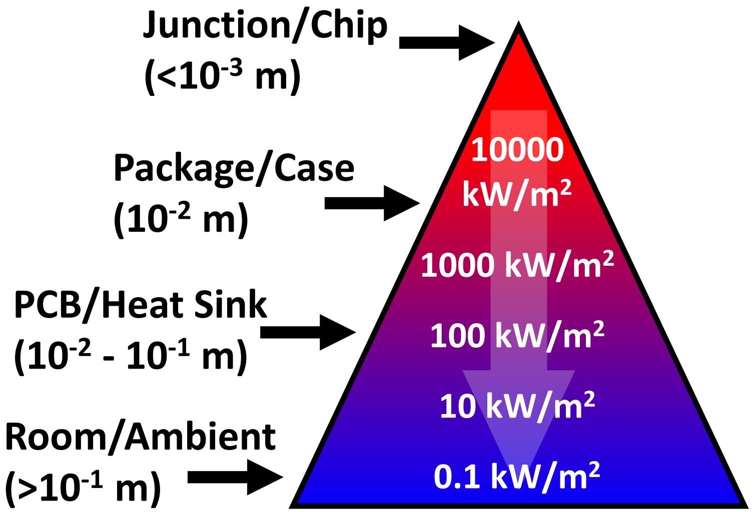
Sudhakar and Weibel, *JEP*, 2017

Two-Phase Microchannel Heat Sink



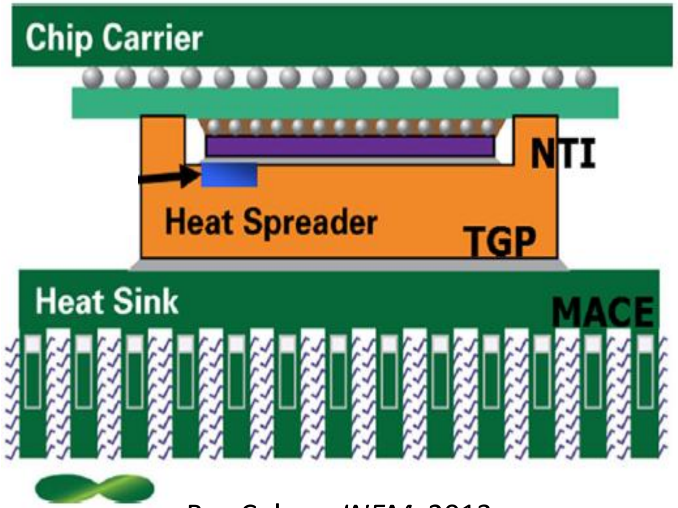
Sudhakar and Weibel, *JEP*, 2017

Source



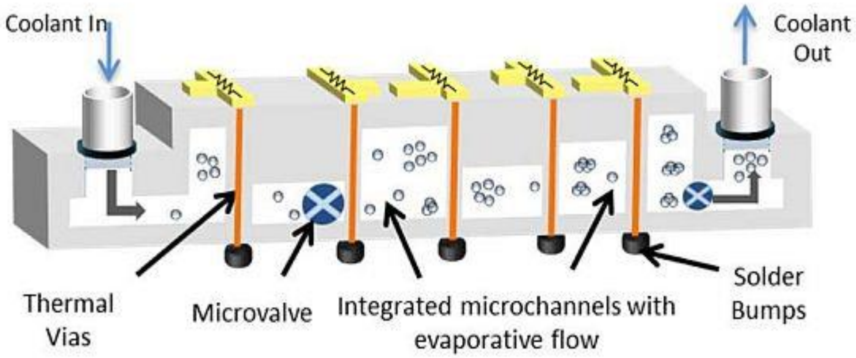
Sink

'Remote' Cooling



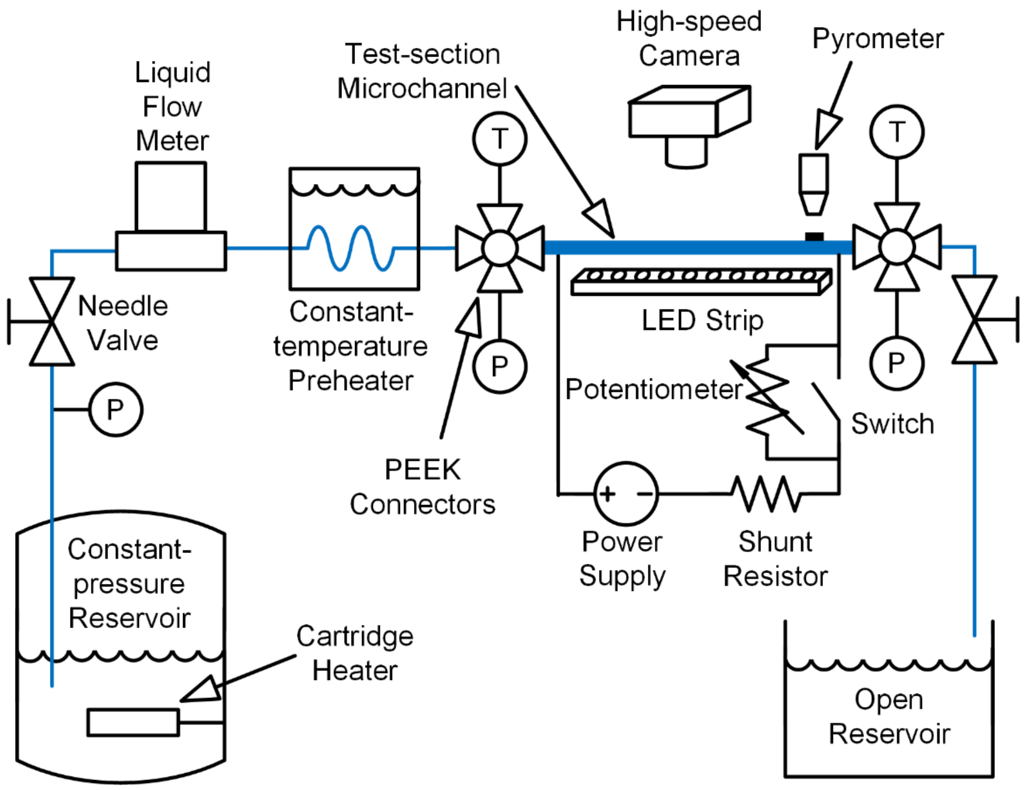
Bar-Cohen, *JNEM*, 2013

'Embedded' Two-Phase Cooling



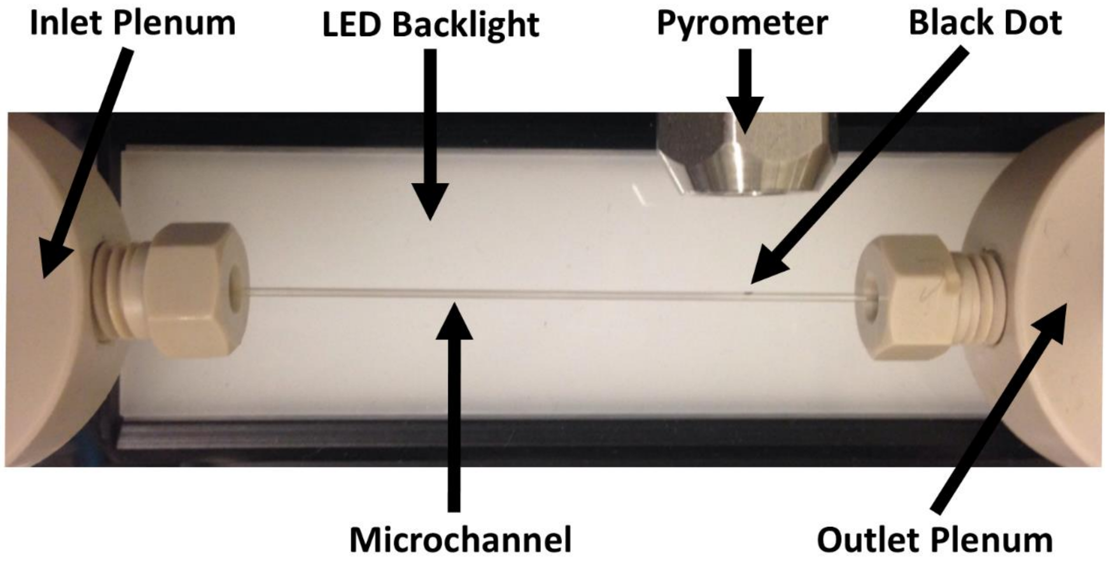
Bar-Cohen, *JNEM*, 2013

Experimental Facility



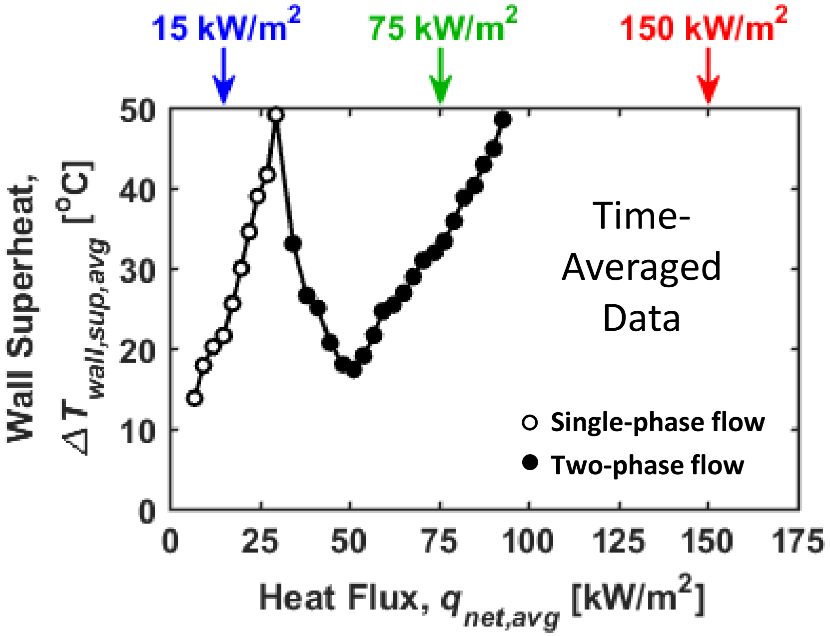
Experimentally measured thermal time constant of the microchannel during single-phase flow: τ = 0.43 s

- 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



Kingston, Weibel, & Garimella, *International Journal of Heat and Mass Transfer*, 2020, 154, 119643.
Kingston, Weibel, & Garimella, *International Journal of Heat and Mass Transfer*, 2020, 154, 119686.

Selection of Transient Heating Conditions



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

- 15 kW/m^2: single-phase flow
- 75 kW/m^2: continuous two-phase flow
- 150 kW/m^2: exceeds critical heat flux

Design of Experiments: Time-periodic Heat Flux Pulses

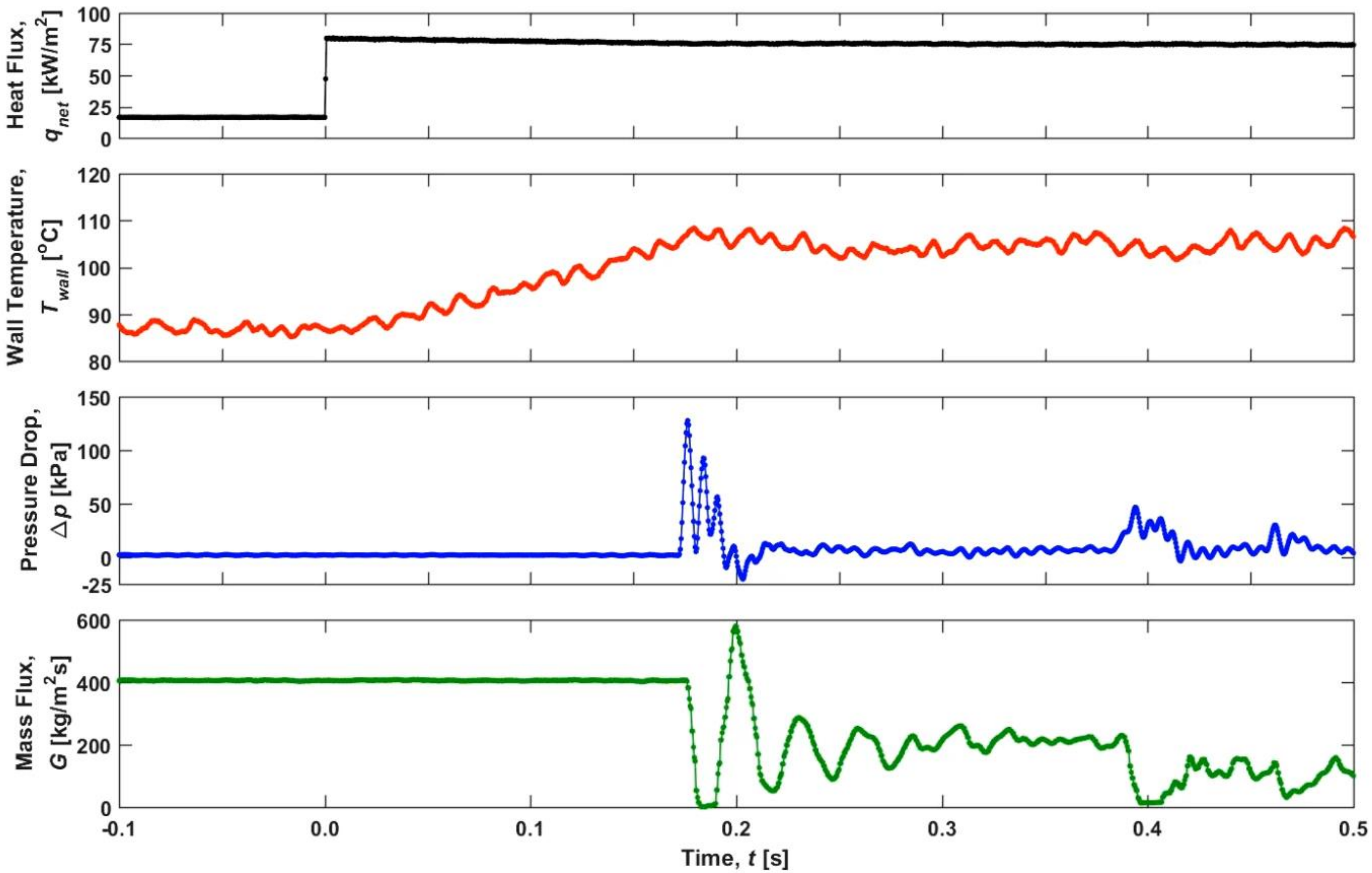
Low Heating Level [kW/m^2]	High Heating Level [kW/m^2]	Duty Cycle [%]	Heating Pulse Frequency, *f* [Hz]
15	**75**	**50**	0.1, 0.2, 0.5, 1, 2, **5**, 10, 15, 20, 25, 50, 100
15	150	50	0.8, 1, 2, 3, 4, 5, 10, 15, 20, 25, 50, 100
75	150	25	0.8, 1, 2, 3, 4, 5, 10, 15, 20, 25, 50, 100

Design of Experiments: Single Heat Flux Pulse

Initial Heat Flux [kW/m^2]	Pulsed Heat Flux [kW/m^2]	Pulse Durations [s]
15	**75**	0 - 0.50*, 0.75, 1, 2, 4, 6, 8, **10**
75	15	0 - 0.50*, 0.75, 1, 2, 4, 6, 8, 10
15	150	0 - 0.35*
75	150	0 - 0.50*

* Increments of 0.05 s

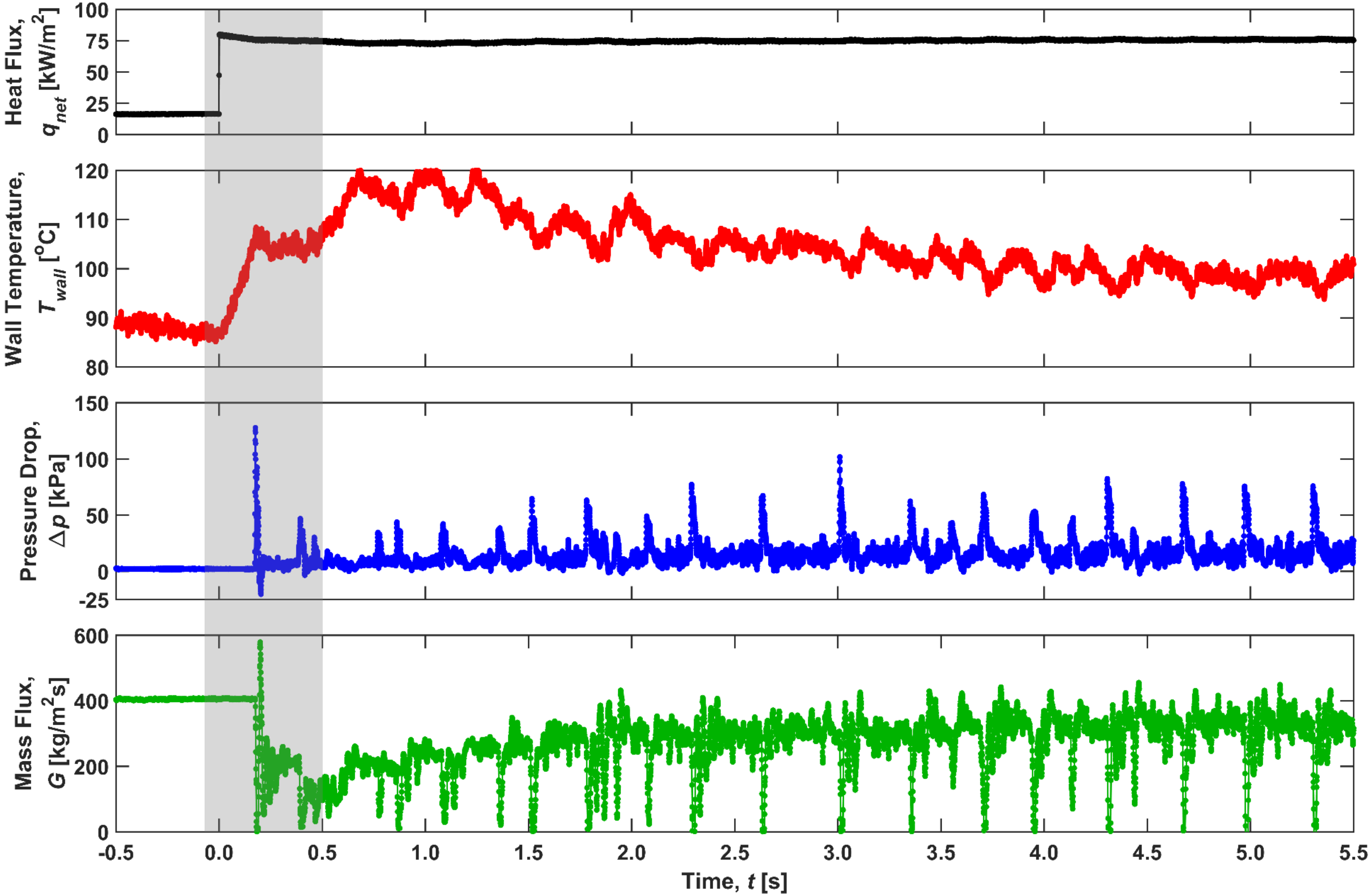
Single Heat Flux Pulse (10 s) from 15 kW/m^2 to 75 kW/m^2



- 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

Kingston, Weibel, & Garimella, Time-resolved characterization of microchannel flow boiling during transient heating: Part 1 - Dynamic response to a single heat flux pulse, *International Journal of Heat and Mass Transfer*, 2020, 154, 119643.

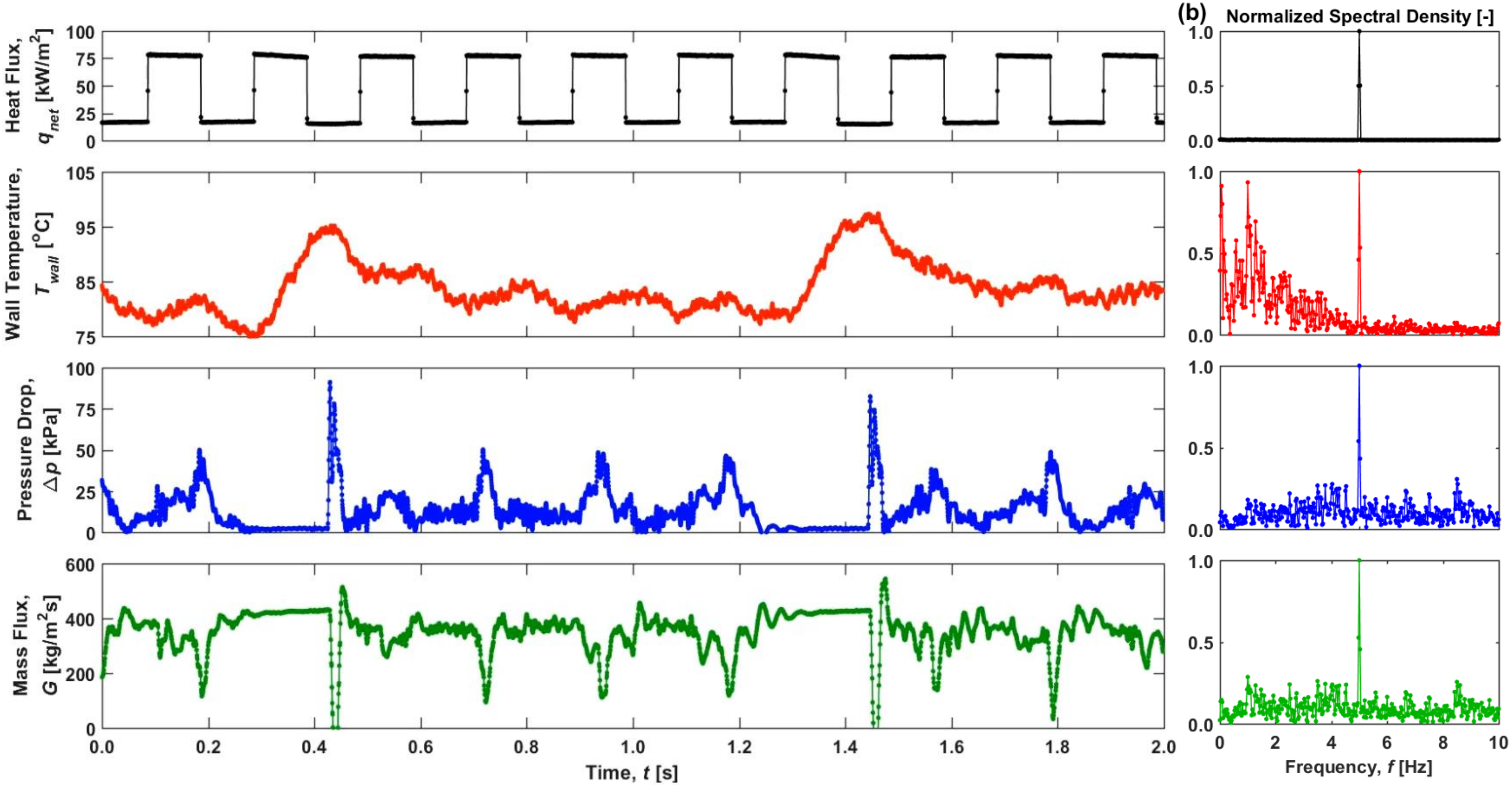
Single Heat Flux Pulse (10 s) from 15 kW/m^2 to 75 kW/m^2



During the transition, the wall temperature overshoots the eventual steady wall temperature by approximately 20 °C

Kingston, Weibel, & Garimella, Time-resolved characterization of microchannel flow boiling during transient heating: Part 1 - Dynamic response to a single heat flux pulse, *International Journal of Heat and Mass Transfer*, 2020, 154, 119643.

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)

Kingston, Weibel, & Garimella, Time-resolved characterization of microchannel flow boiling during transient heating: Part 2 - Dynamic response to time-periodic heat flux pulses, *International Journal of Heat and Mass Transfer*, 2020, 154, 119686.

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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Time-resolved characterization of microchannel flow boiling during transient heating: Part 1 – Dynamic response to a single heat flux pulse

Todd A. Kingston[1], Justin A. Weibel*, Suresh V. Garimella[2,*]

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