Orientation Effects in Two-Phase Microgap Flow

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IPACK2018-8383

August 29, 2018

Motivation

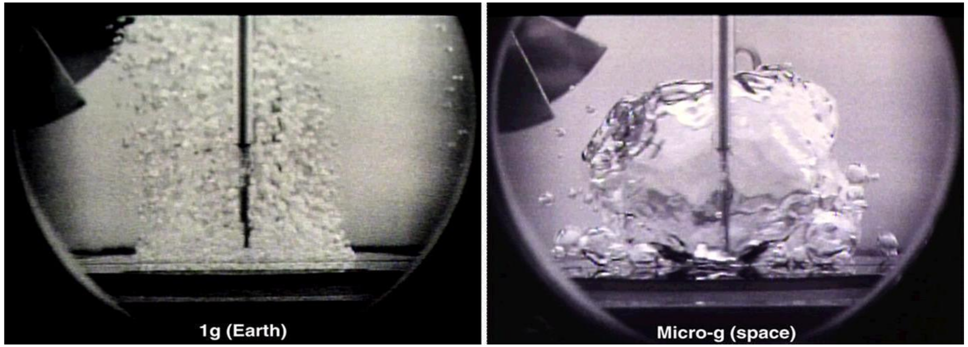
- Increasing power density of electronic devices necessitates better cooling
- Two-phase coolers can provide high flux heat removal and high efficiency
- Pumped loops offer longer transport distances and precise flow rate control

NASA Thermal Technology Roadmap	
Area	**Needs**
High Flux Heat Acquisition with Constant Temperature	• High flux heat removal (100 W/cm^2) • Tight temperature control (± 1 °C)
Micro-and Nano-scale Heat Transfer Surfaces	• Very high heat flux removal (1000 W/cm^2) • Small temperature gradients (< 20 °C)
Two-Phase Pumped Loop Systems	• Two-phase heat transport systems for large heat loads, such power plants

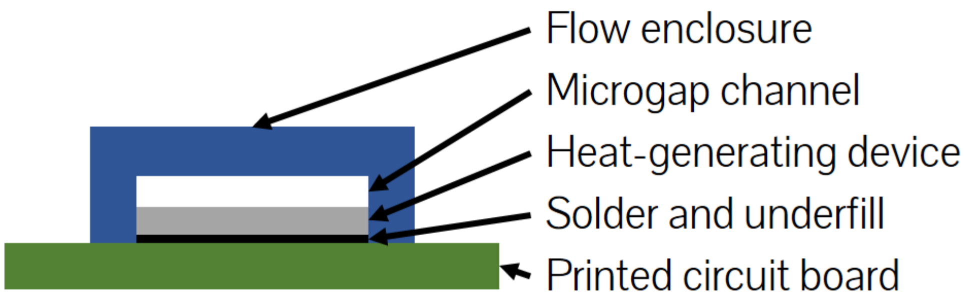
Swanson, Theodore and Motil, Brian. "NASA Technology Roadmaps TA 14: Thermal Management Systems." (2015). https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_14_thermal_management_final.pdf.

Motivation

- Versatile coolers must work reliably in all orientations, microgravity, and high-g
- Two-phase microgap coolers balance performance and simplicity
  - Absence of criteria for orientation- and gravity-independent performance



Dhir, Vijay and Warier, Gopinath. "Nucleate Pool Boiling eXperiment (NPBX)." (2018). https://www.nasa.gov/mission_pages/station/research/experiments/229.html.

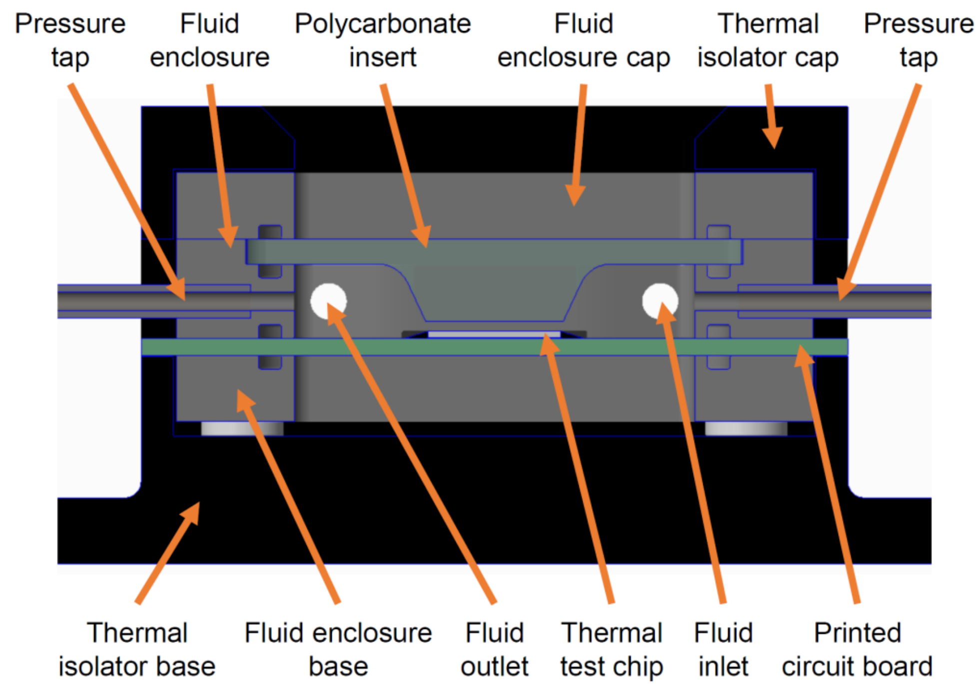


Objectives

1. Characterize orientation effects on flow boiling flow regimes, heat transfer coefficients (HTCs), and critical heat flux (CHF) in microgap channels
2. Assess the efficacy of using the Bond, Weber, and Froude numbers for establishing orientation-independent behavior in microgap channels
3. Establish the magnitude of appropriate non-dimensional numbers for orientation-independent behavior

Approach – Microgap Cooler

- 12.7 mm by 12.7 mm by 0.6 mm silicon thermal test chip
- 1.01 mm tall by 13.0 mm wide by 12.7 mm long channel
- Flow boiling of HFE7100
  - Saturation temperature: 62 ℃
  - Inlet subcooling: 1 - 5 ℃
  - Mass fluxes: 100 - 700 kg/m^2-s
  - Differential pressure: 0.1 - 1.4 kPa



Approach – Non-Dimensional Numbers

$$Bo = \frac{(\rho_l - \rho_v) \cdot g \cdot L_g \cdot L_\sigma}{\sigma}$$

$$We = \frac{\rho_m \cdot {u_m}^2 \cdot L_\sigma}{\sigma} = \frac{G^2 \cdot L_\sigma}{\rho_m \cdot \sigma}$$

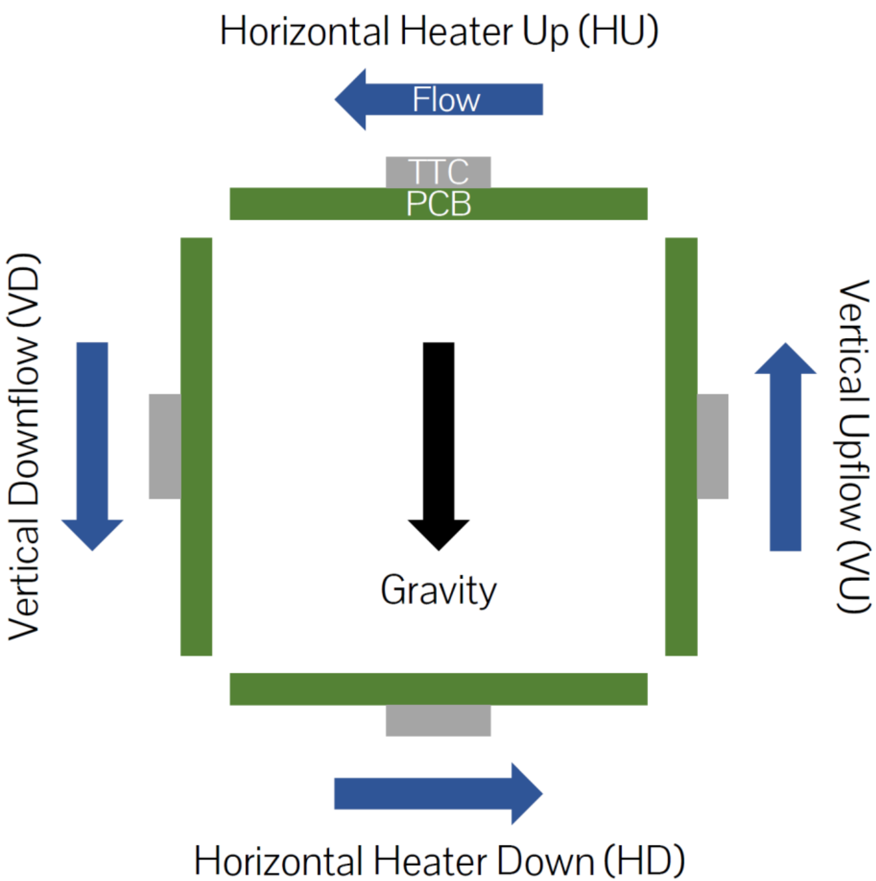
$$Fr = \sqrt{\frac{We}{Bo}} = \frac{G}{\sqrt{\rho_m \cdot (\rho_l - \rho_v) \cdot g \cdot L_g}}$$

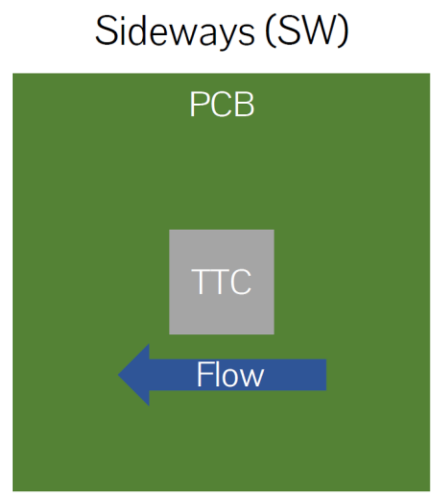
- D_h often used for both length scales in the Bond Number
- L_g should be length parallel to gravity vector
- L_σ should be based on liquid-vapor interface
  - W used in present study

Reynolds, William, Saad, Michel, and Satterlee, Hugh. "Capillary Hydrostatics and Hydrodynamics at Low g." Technical Report No. LG-3. Stanford University, Stanford, CA. 1964.

Baba, Soumei, Ohtani, Nobuo, Kawanami, Osamu, Inoue, Koichi, and Ohta, Haruhiko. "Experiments on Dominant Force Regimes in Flow Boiling using Mini-Tubes." *Frontiers in Heat and Mass Transfer* Vol. 3 (2012): pp. 1-8. DOI 10.5098/hmt.v3.4.3002. http://thermalfluidscentral.org/journals/index.php/Heat_Mass_Transfer/article/view/259.

Approach – Evaporator Orientations





TTC: Thermal test chip
PCB: Printed circuit board

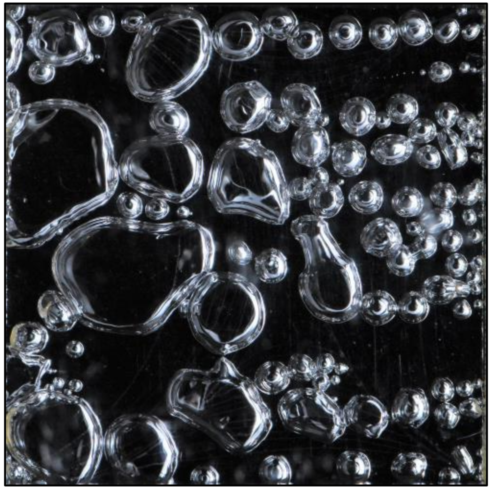
Results – Flow Visualization

1.01 channel height

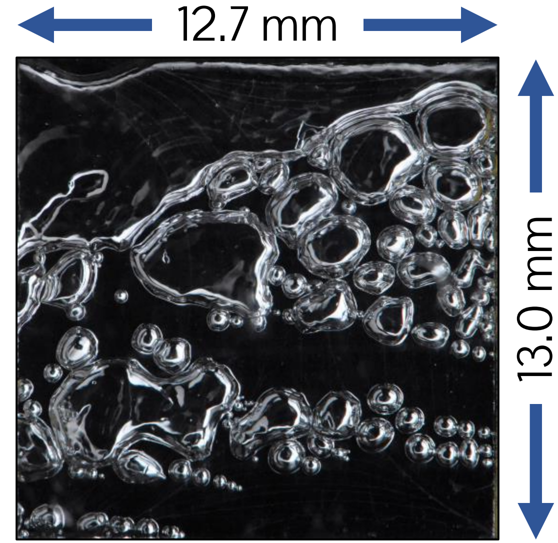
100 kg/m^2-s

52.5 to 54.4 kW/m^2

Horizontal Heater Up

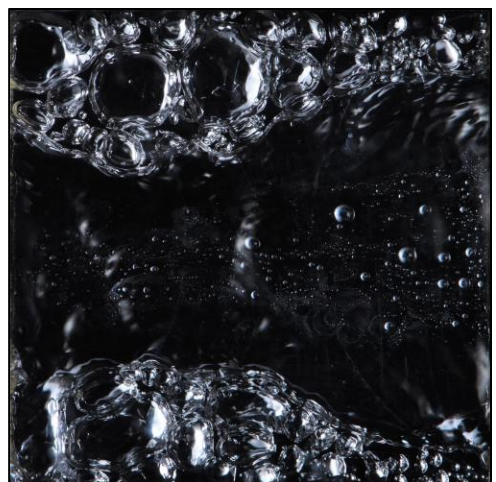


Vertical Upflow



Sideways

Horizontal Heater Down



Vertical Downflow

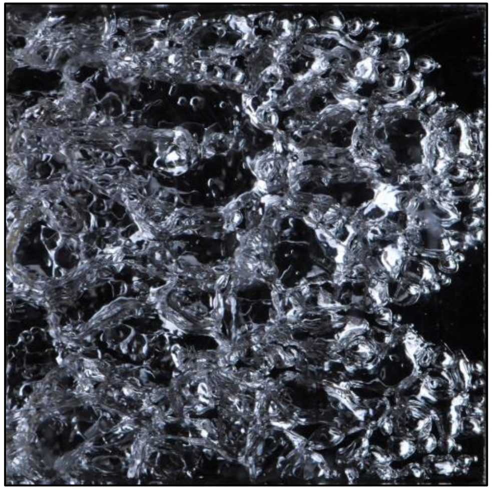
Results – Flow Visualization

1.01 channel height

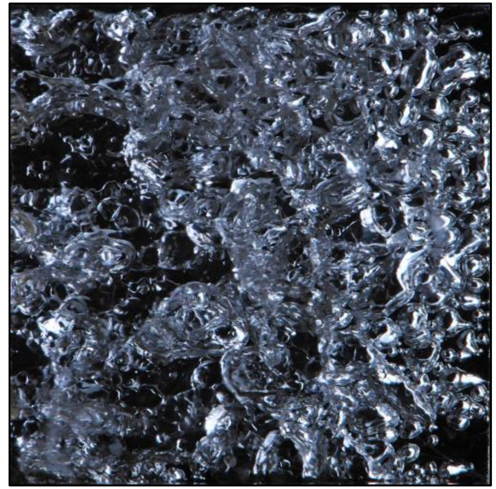
300 kg/m^2-s

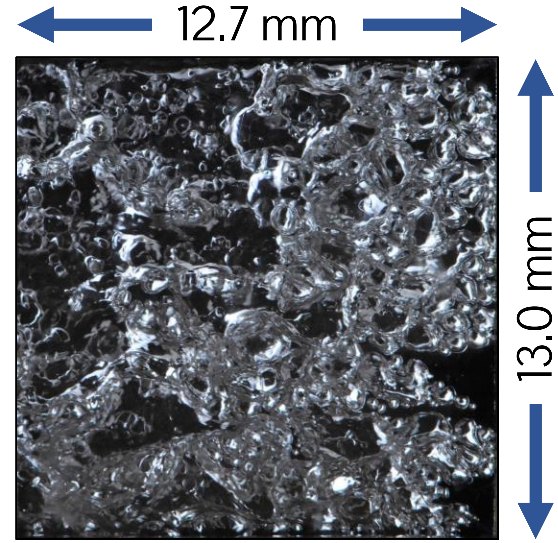
171.2 to 172.1 kW/m^2

Horizontal Heater Up

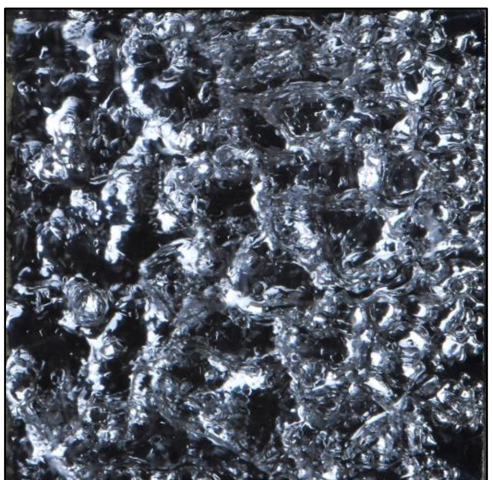


Vertical Upflow

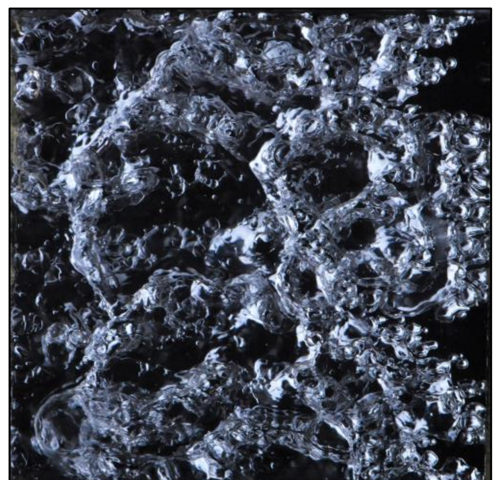




Sideways

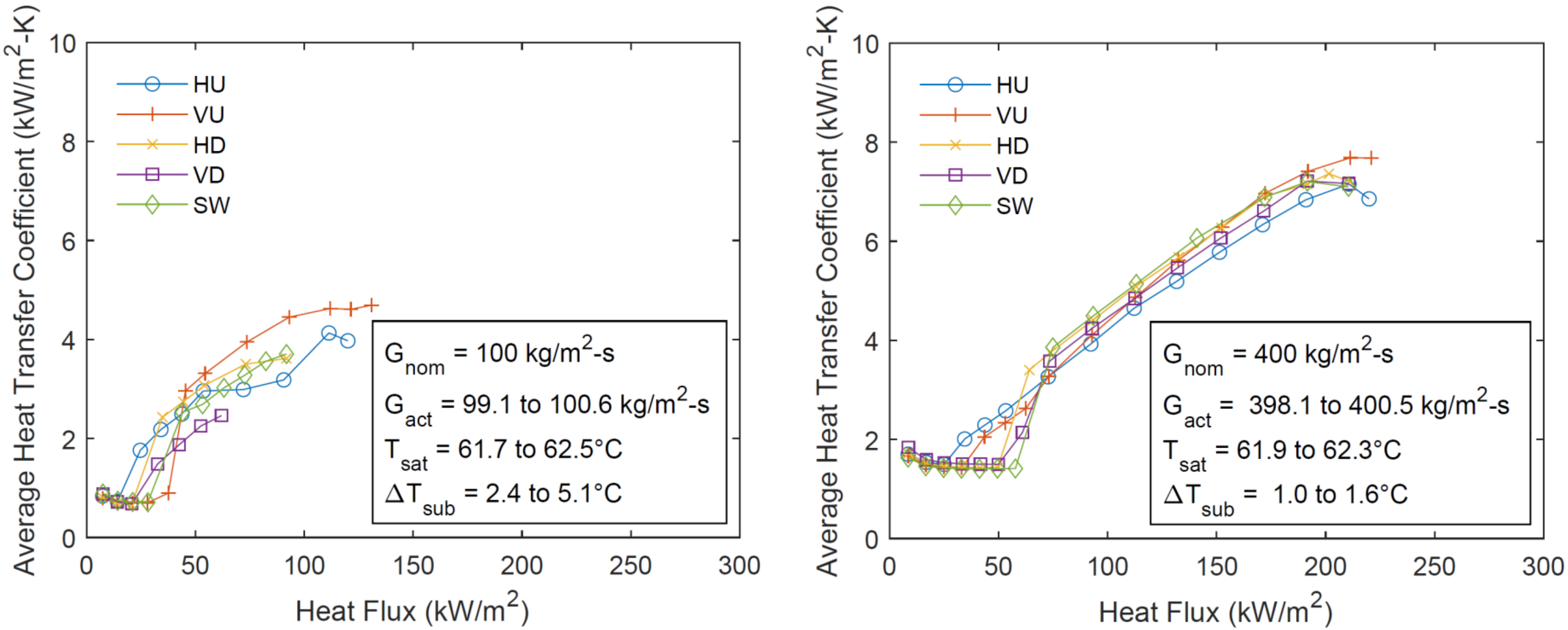


Horizontal Heater Down



Vertical Downflow

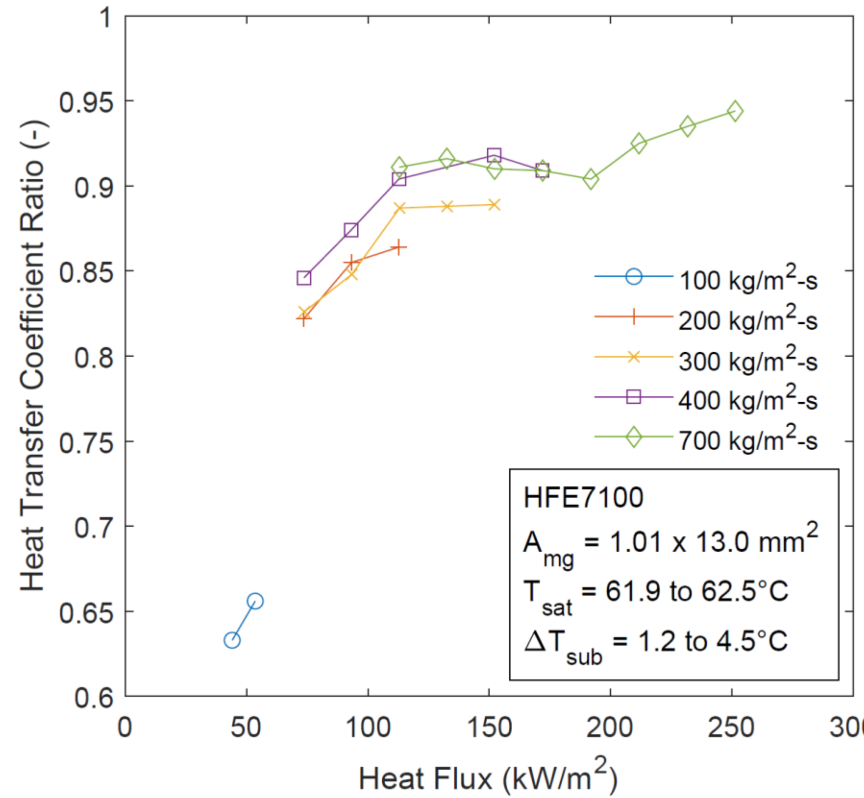
Results – Heat Transfer Coefficients



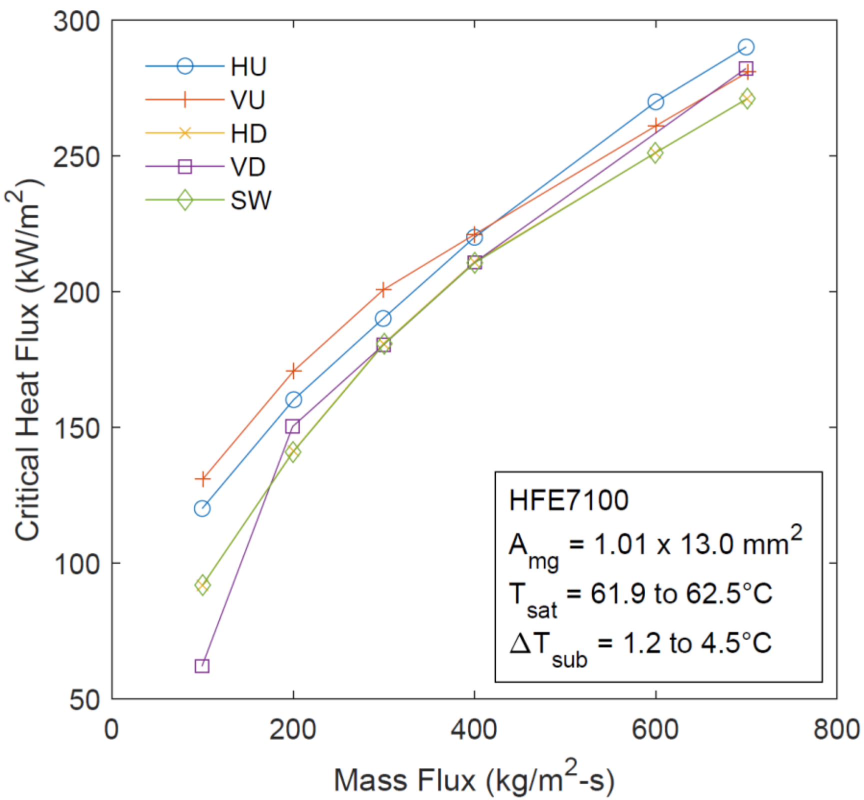
- No clear trend between the onset of nucleate boiling (ONB) and orientation
- Higher mass fluxes delay ONB to higher heat fluxes
- Above 100 kg/m^2-s, two-phase HTCs increase linearly with heat flux

Results – Heat Transfer Coefficients

- $HTC\ Ratio = \frac{HTC_{min}}{HTC_{max}}$
  - Among orientations
- HTC ratio approaches unity with increasing mass flux and heat flux
- Small variation persists at highest mass and heat fluxes
  - Variation exceeds uncertainty

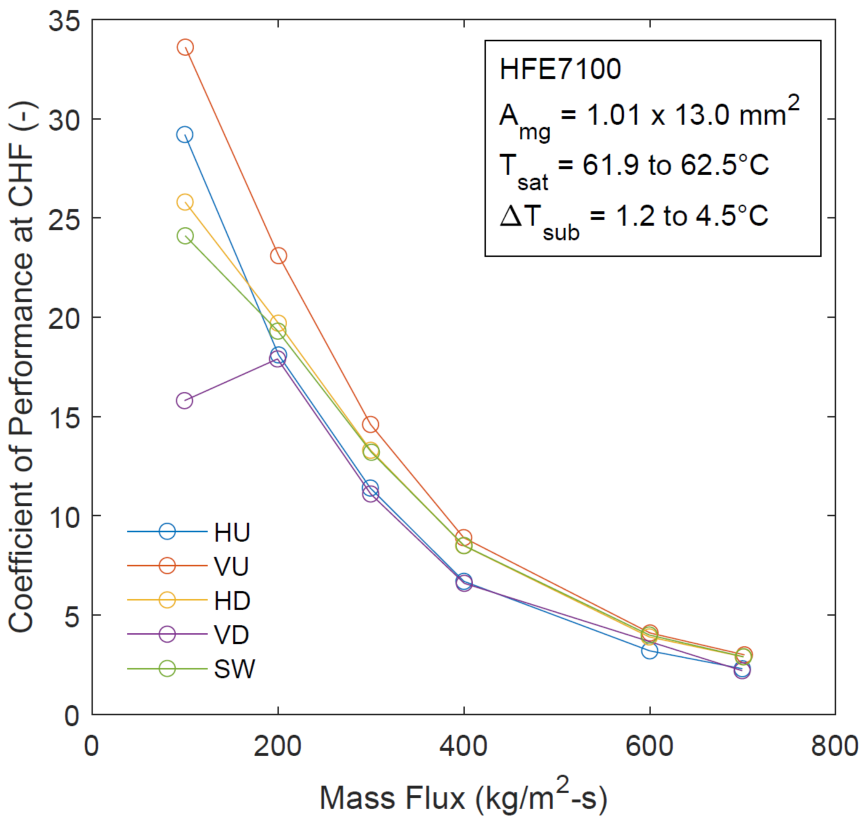


Results – Critical Heat Flux



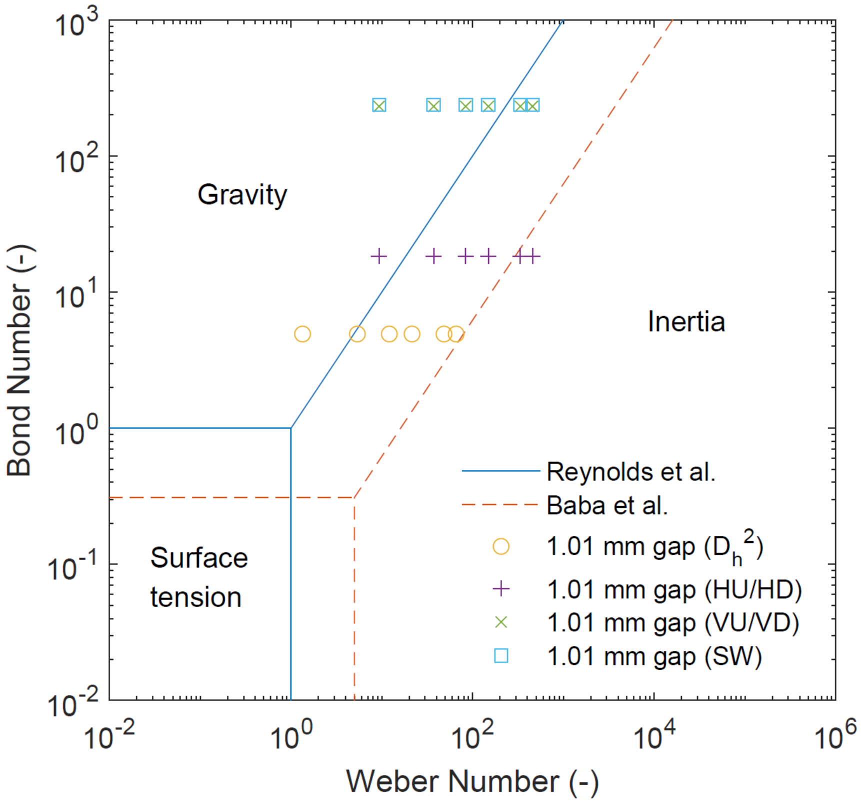
- CHF increases with increasing mass flux for all orientations
- At low mass fluxes, higher CHF observed in VU and HU orientations
- < 10% variation across all orientations at and above 400 kg/m^2-s

Results – Coefficient of Performance



- $\text{COP} = \dfrac{\dot{q}}{P_{pump}}$
- Order-of-magnitude decrease in COP from 100 to 700 kg/m²-s
- Very high mass fluxes mitigate g-effects at expense of system efficiency

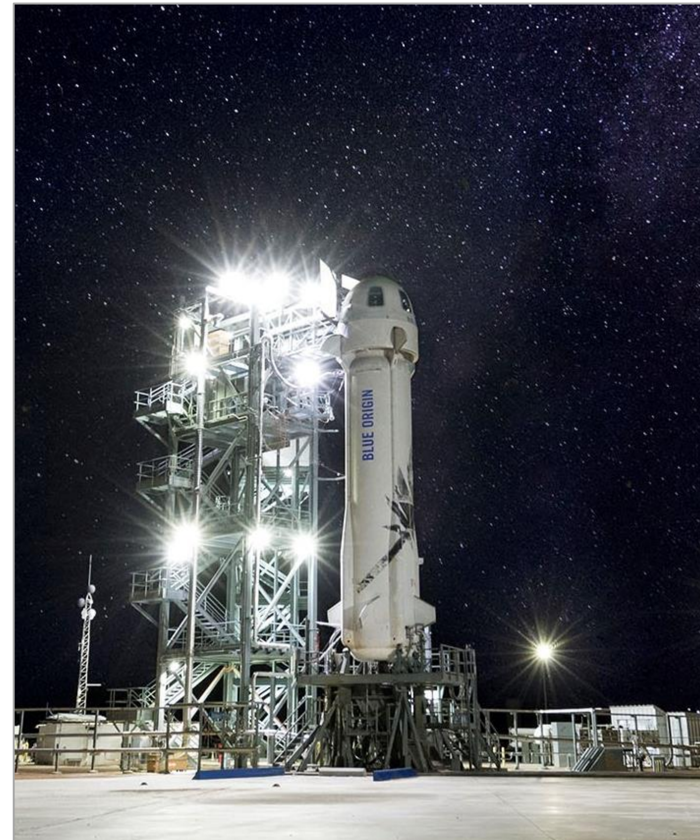
Results – Force Regime Map



- Classical boundaries predict correct regime using proposed formulation of non-dimensional numbers
  - Length parallel to gravity vector as L_g
  - Channel width as L_σ
- Additional data needed to assess boundaries of surface tension dominated regime

Ongoing and Future Work

- Non-dimensional analysis of previous research
- Orientation testing of microgap coolers with smaller channel heights and different fluids
- Suborbital flight experiment



Blue Origin. "Blue Origin New Shepard M9 Pad." (2018).
https://www.nasa.gov/sites/default/files/thumbnails/image/bo_new_shepard-m9_pad.jpg.

Summary and Conclusions

- Effect of evaporator orientation on flow boiling of near-saturated HFE-7100 in a 1.01 mm by 13.0 mm wide channel was studied
  - Despite short height and length, gravity affected flow regimes, HTCs, and CHF at low mass fluxes
  - Good agreement among orientations observed at higher mass fluxes (< 10% variation in HTCs + CHF above 400 kg/m^2-s) and higher heat fluxes
  - Some variation in HTCs + CHF persisted at highest mass and heat fluxes
  - Dominant force regime was accurately predicted using proper length for gravity term in Bond number formulation and classical regime boundaries

Acknowledgements

- NASA Center Innovation Fund and Flight Opportunities Program
- NASA GSFC Thermal Technology Development Facility
  - Colleagues: Mario Martins, Alfred Wong
  - Summer Interns: Keith Coulson, Lucia House, Daniel Laudien, Annie Miles

Questions?

Thank you for your attention!