Gravity Effects in Microgap Flow Boiling

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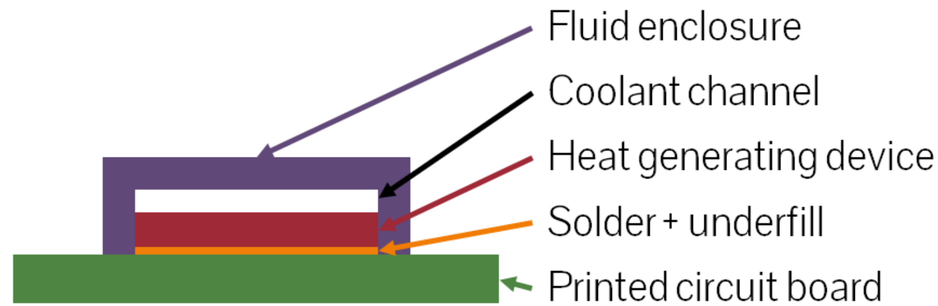
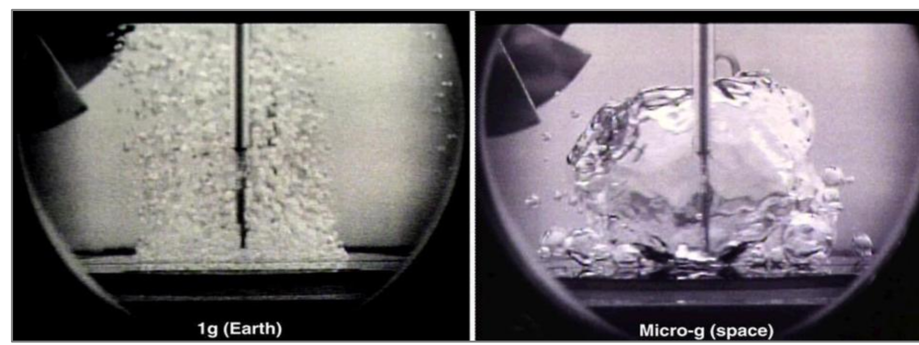
Session TI-3: Microgap Cooling & Evaporation/Condensation
ITherm – May 31, 2017

Motivation

- Electronic devices thermally-limited by remote cooling
- Embedded cooling facilitates contact between device and two-phase coolant flow
- Gravity can dominate two-phase system behavior
- Limited, conflicting data on flow boiling in reduced gravity



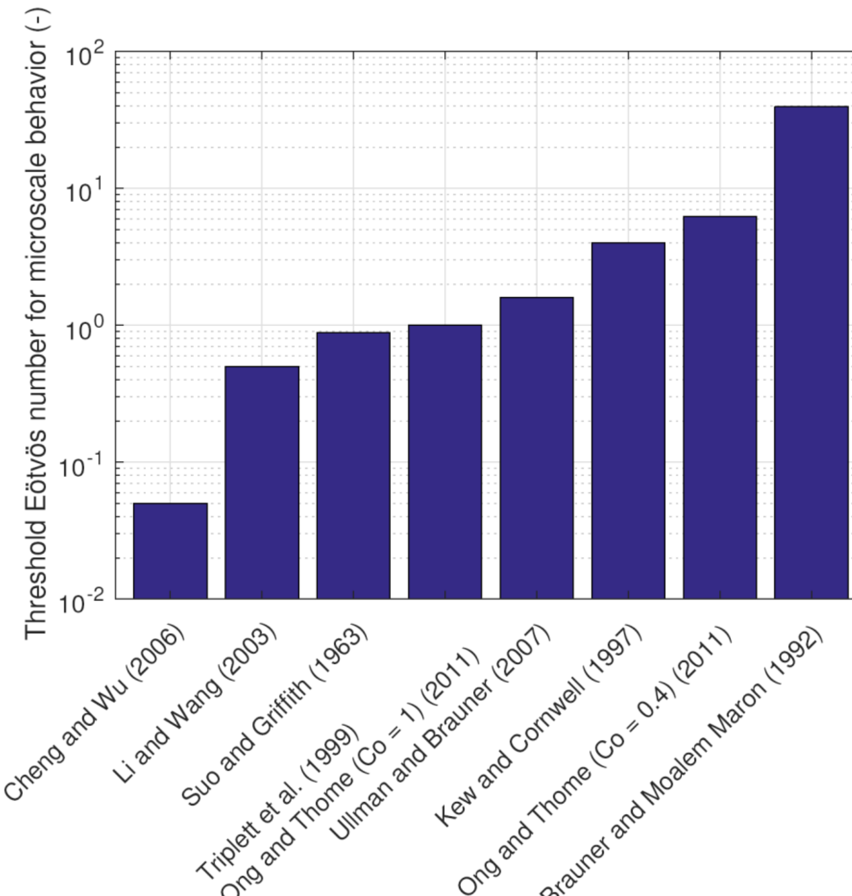


Microscale Eötvös Number

- Microscale → g-insensitive
- Most microscale criteria simplify to the Eötvös number

$$Eo = \frac{\Delta\rho \cdot g \cdot D^2}{\sigma}$$

- Criteria based on absence of stratification or uniformity of film thickness
- Possible regime-dependence

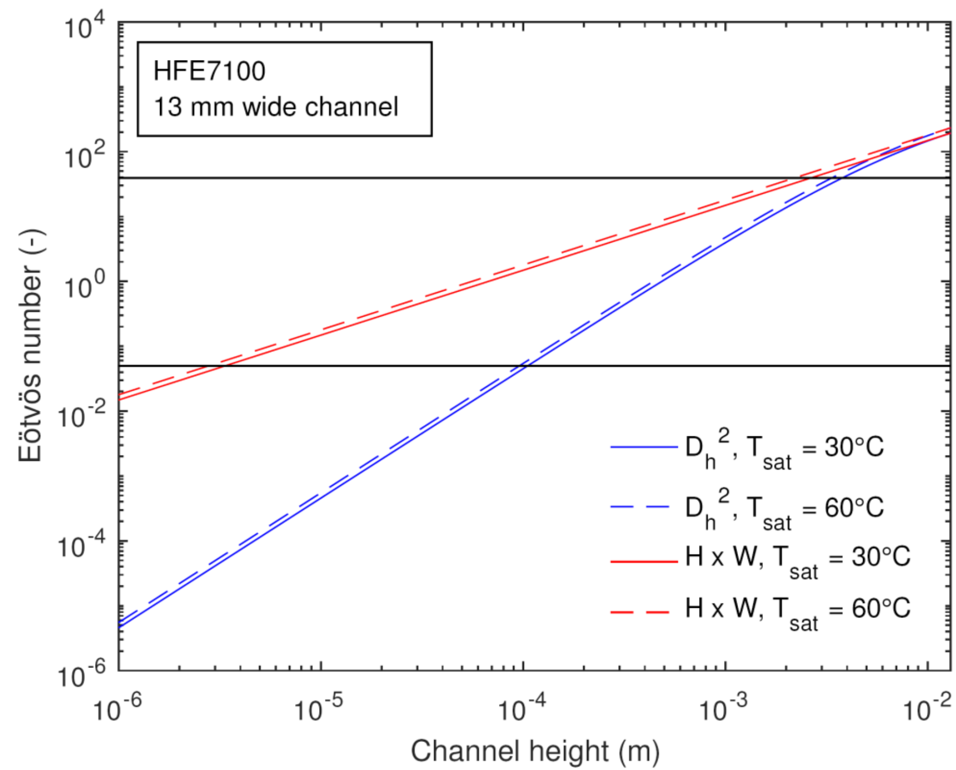


Eötvös Number Considerations

- Different formulation may be required for rectangular ducts
  - Gravity term scales with height
  - Surface tension scales with width

$$Eo = \frac{\Delta\rho \cdot g \cdot H \cdot W}{\sigma}$$

- Uncertainty in microscale height based on Eötvös number criteria, formulation



Convective Confinement Number

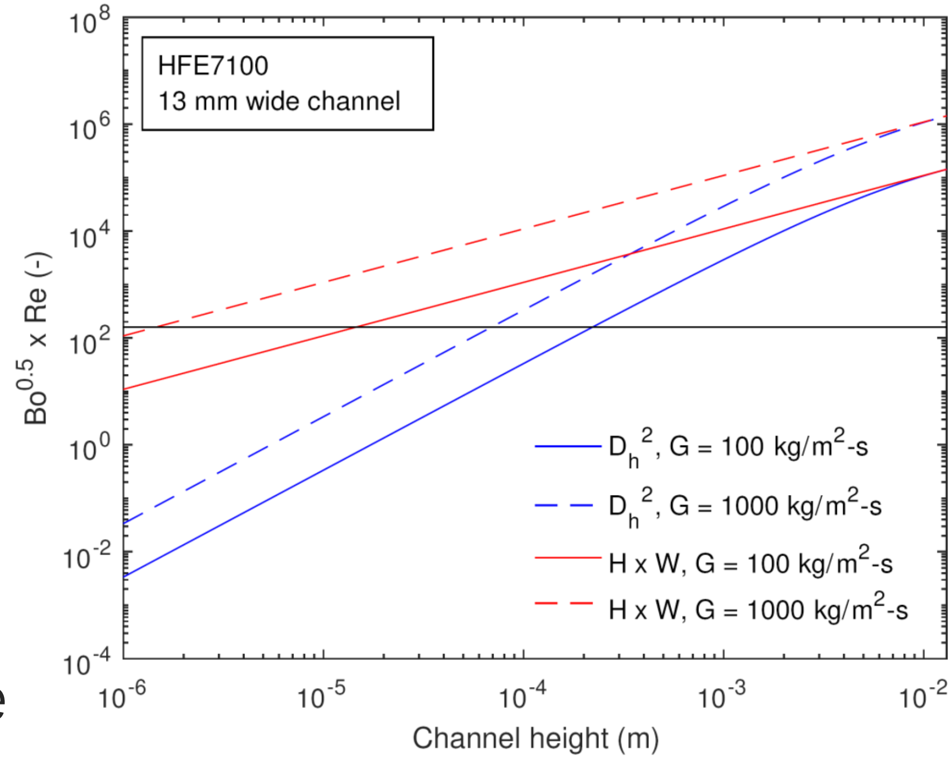
- Convective confinement number accounts for velocity

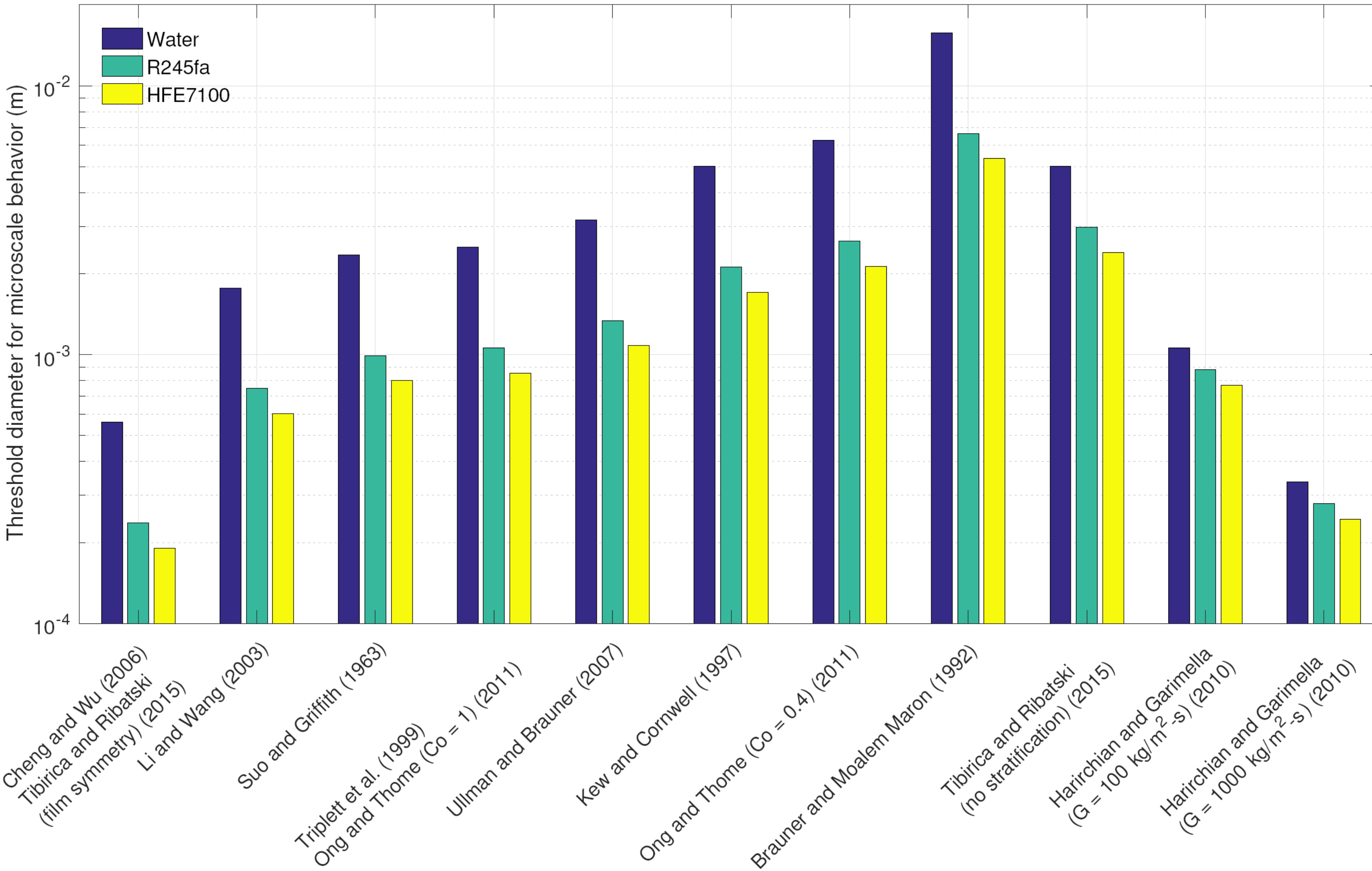
$$Bo^{0.5} \cdot Re < 160$$

$$Bo = \frac{\Delta\rho \cdot g \cdot D^2}{\sigma}$$

$$Re = \frac{G \cdot D}{\mu_l} \qquad D = \sqrt{A_c}$$

- All channels exhibit microscale behavior at low velocities



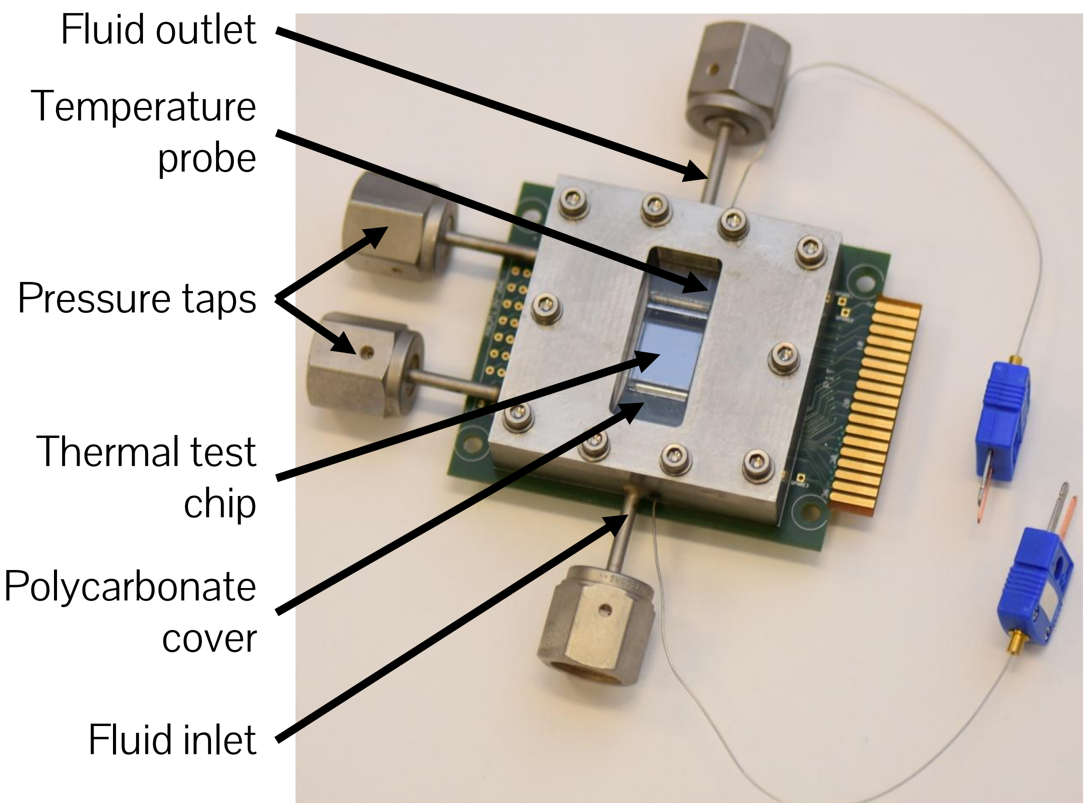

Water
R245fa
HFE7100
Threshold diameter for microscale behavior (m)
10^{-2}
10^{-3}
10^{-4}
Cheng and Wu (2006)
Tibirica and Ribatski (film symmetry) (2015)
Li and Wang (2003)
Suo and Griffith (1963)
Triplett et al. (1999)
Ong and Thome (Co = 1) (2011)
Ullman and Brauner (2007)
Kew and Cornwell (1997)
Ong and Thome (Co = 0.4) (2011)
Brauner and Moalem Maron (1992)
Tibirica and Ribatski (no stratification) (2015)
Harirchian and Garimella (G = 100 kg/m^2-s) (2010)
Harirchian and Garimella (G = 1000 kg/m^2-s) (2010)

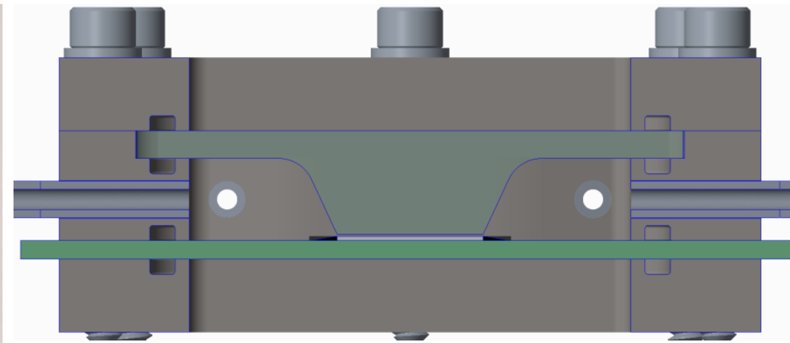
Objectives

Variation in microscale criteria + unresolved issue of appropriate length scales for rectangular ducts creates need for a research program to:

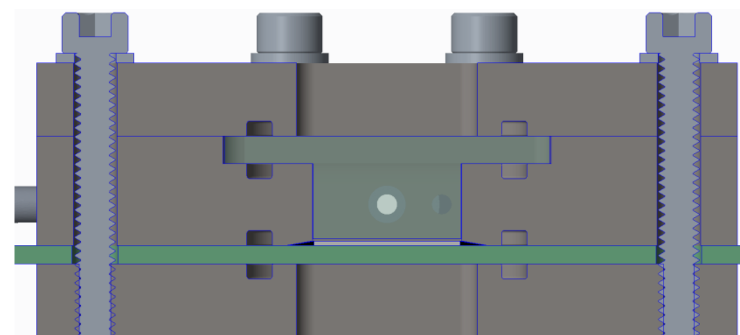
1. Characterize the parameters (channel size, velocity, fluid properties, heat flux, flow regime) that provide gravity-independent flow boiling performance
2. Determine the appropriate metric for assessing gravity-independence (flow regimes, measurements, instabilities)

Microgap Cooler Assembly

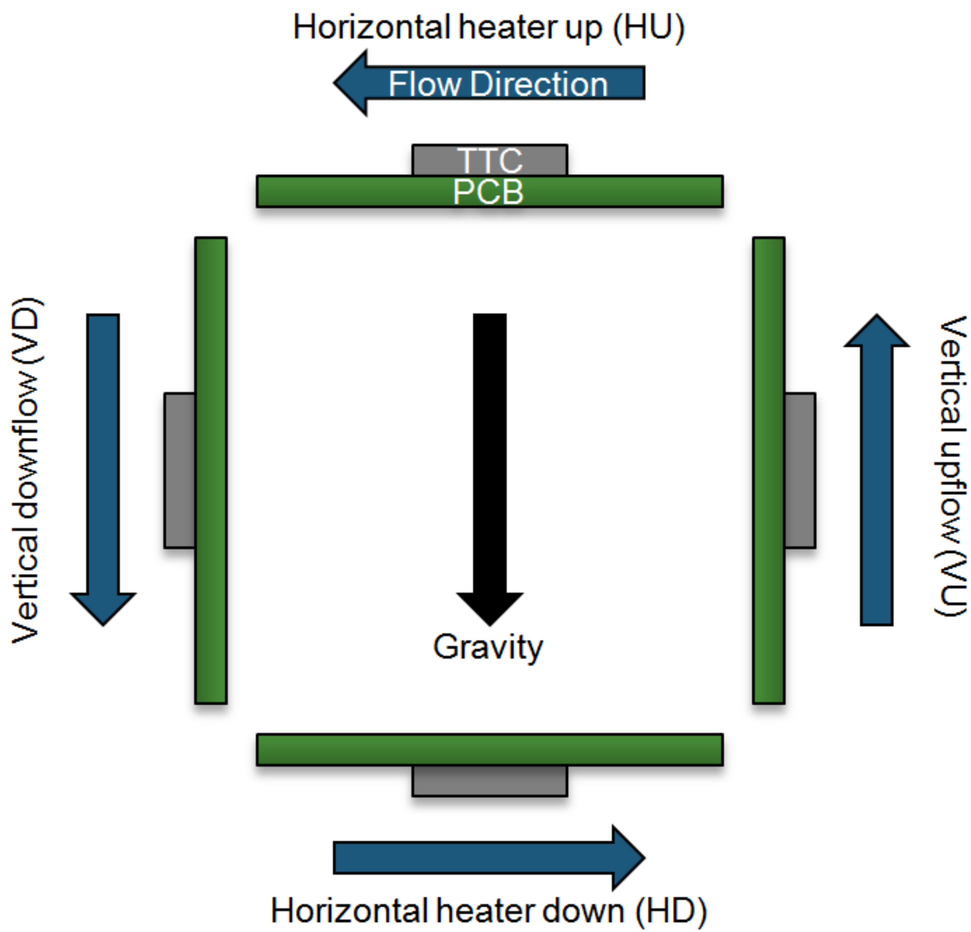




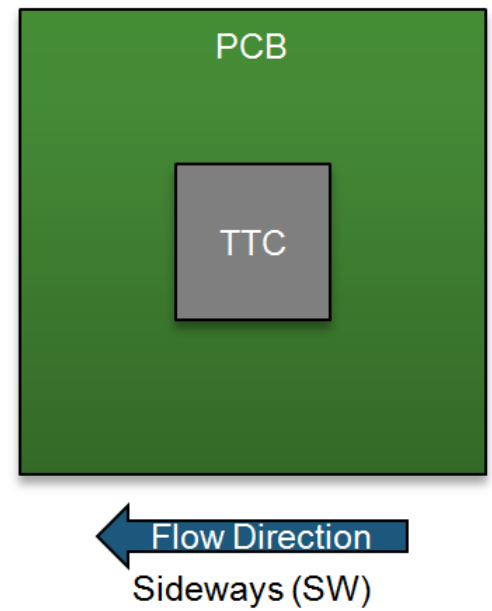
Axial Cross Section



Transverse Cross Section



Horizontal heater up (HU)
Flow Direction
TTC
PCB
Vertical downflow (VD)
Gravity
Vertical upflow (VU)
Horizontal heater down (HD)

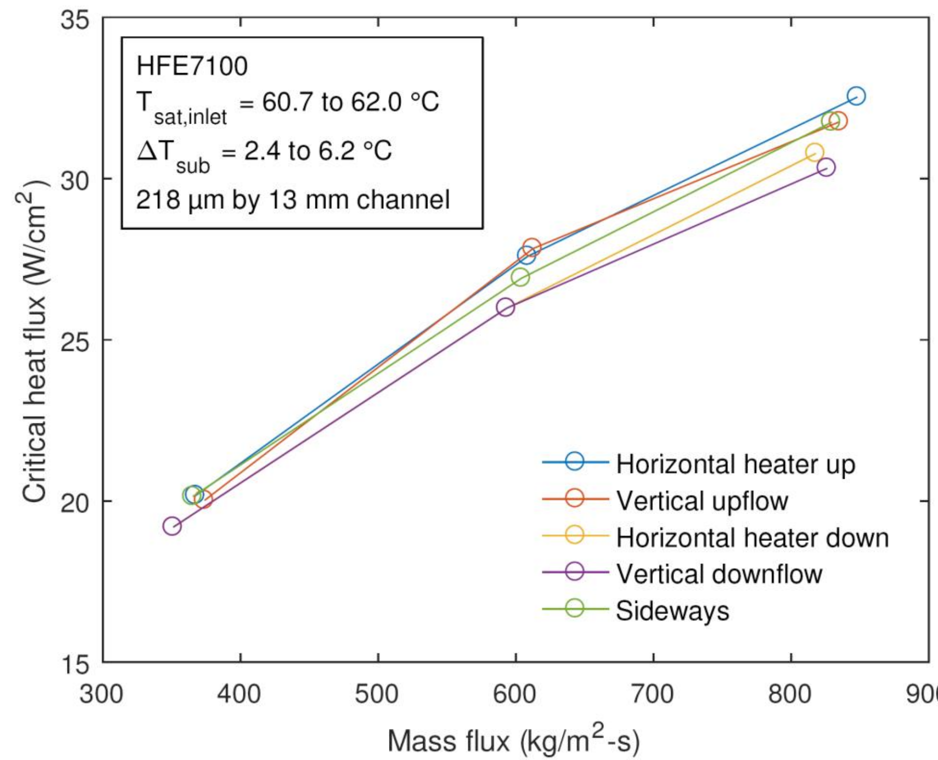


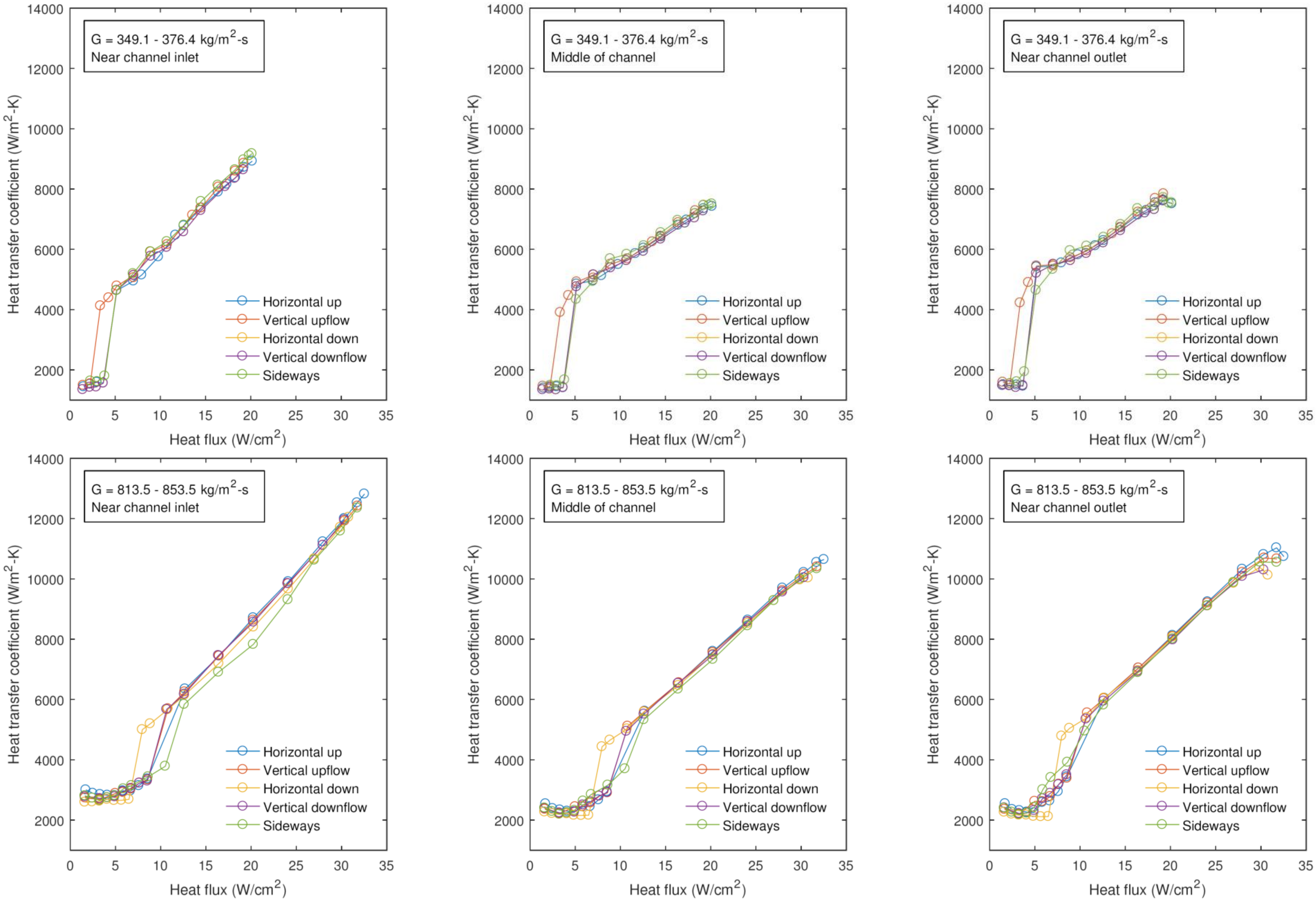
PCB
TTC
Flow Direction
Sideways (SW)

<table>
<tr><th>Orientation</th><th colspan="3">Eötvös Number</th></tr>
<tr><td>HU</td><td rowspan="5">$\frac{\Delta\rho \cdot g \cdot {D_h}^2}{\sigma} = 0.25$</td><td rowspan="5">$\frac{\Delta\rho \cdot g \cdot H \cdot W}{\sigma} = 3.9$</td><td rowspan="2">$\frac{\Delta\rho \cdot g \cdot H \cdot W}{\sigma} = 3.9$</td></tr>
<tr><td>HD</td></tr>
<tr><td>VU</td><td rowspan="2">$\frac{\Delta\rho \cdot g \cdot L \cdot W}{\sigma} = 227$</td></tr>
<tr><td>VD</td></tr>
<tr><td>SW</td><td>$\frac{\Delta\rho \cdot g \cdot W \cdot W}{\sigma} = 233$</td></tr>
</table>

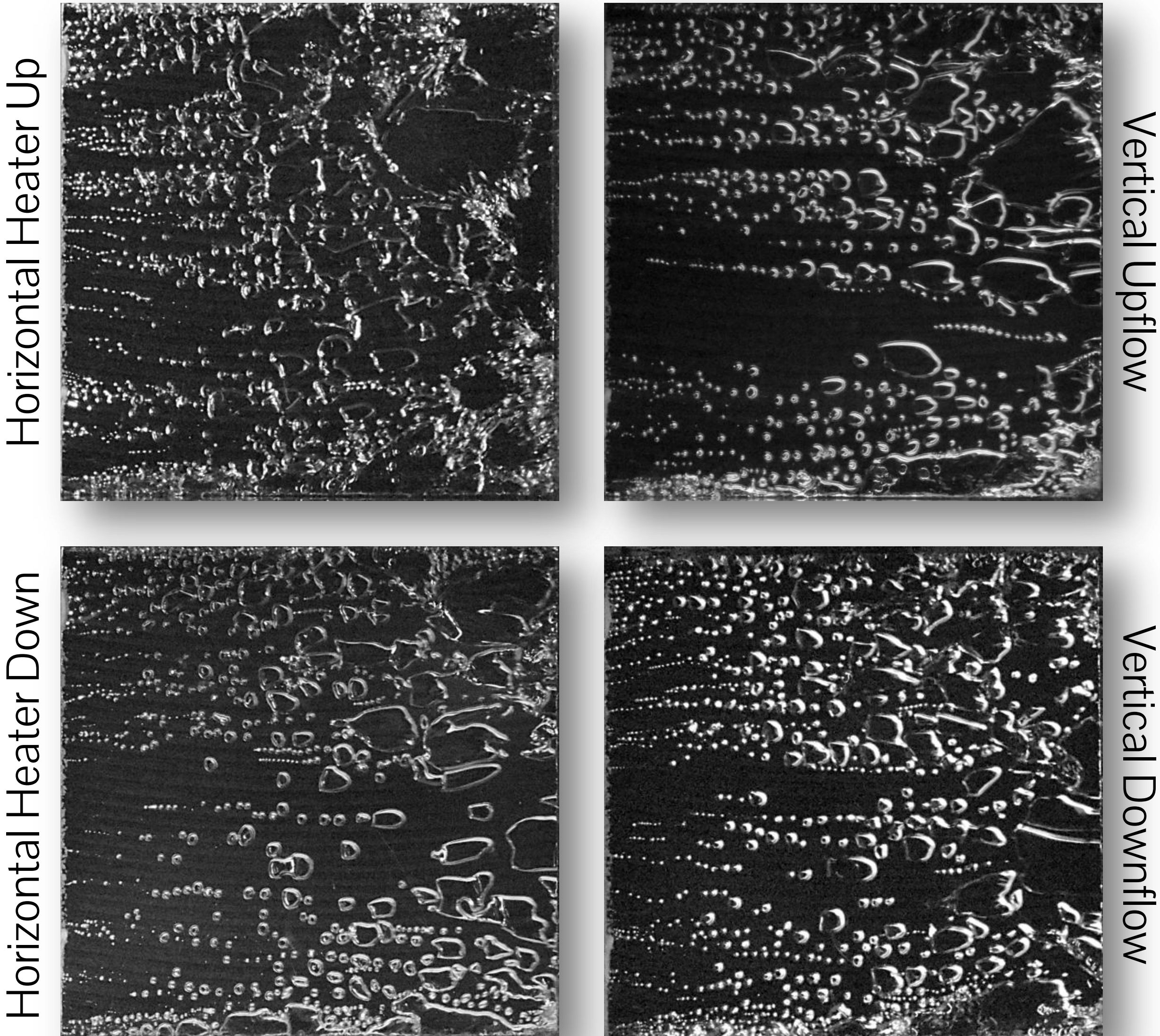
Critical Heat Flux

- CHF variation of < 6% at each mass flux across five evaporator orientations
- Some CHF variation attributable to mass flux variation (up to 6%)
- Tighter control of mass flux, inlet fluid condition desired in future experiments




G = 349.1 - 376.4 kg/m2-s
Near channel inlet
G = 349.1 - 376.4 kg/m2-s
Middle of channel
G = 349.1 - 376.4 kg/m2-s
Near channel outlet
G = 813.5 - 853.5 kg/m2-s
Near channel inlet
G = 813.5 - 853.5 kg/m2-s
Middle of channel
G = 813.5 - 853.5 kg/m2-s
Near channel outlet
Heat transfer coefficient (W/m2-K)
Heat flux (W/cm2)
Horizontal up
Vertical upflow
Horizontal down
Vertical downflow
Sideways

218 μm
23 W/cm^2
830 kg/m^2-s



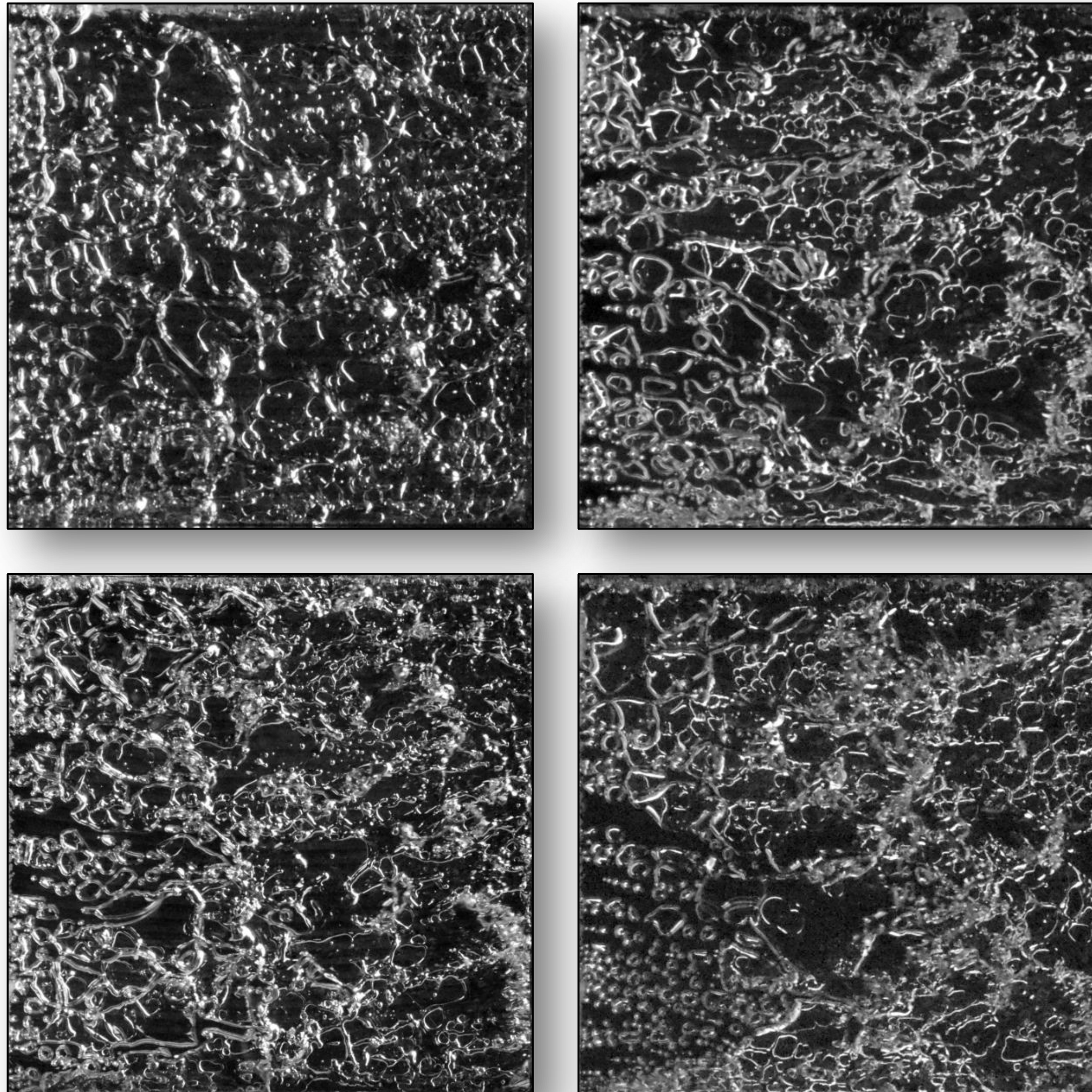
218 μm
20 W/cm^2
360 kg/m^2-s

Horizontal Heater Up

Vertical Upflow

Horizontal Heater Down

Vertical Downflow



Concluding Remarks

- Previous efforts to determine microscale transition have focused on ratio of gravitational forces to surface tension forces
  - Other parameters may be important (e.g., velocity, flow regime, heat flux)
- In present study, five orientations resulted in range of Eötvös numbers from 0.25 to 233 for a 218 μm by 13 mm channel
- Orientation change had minimal effect on CHF and HTCs
- Ongoing studies with range of channel heights will help identify additional parameters relevant to gravity effects discussion
- Validation in microgravity environment is planned

Acknowledgements

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Questions?

Thank you for your attention!

Slide (first use)	Reference
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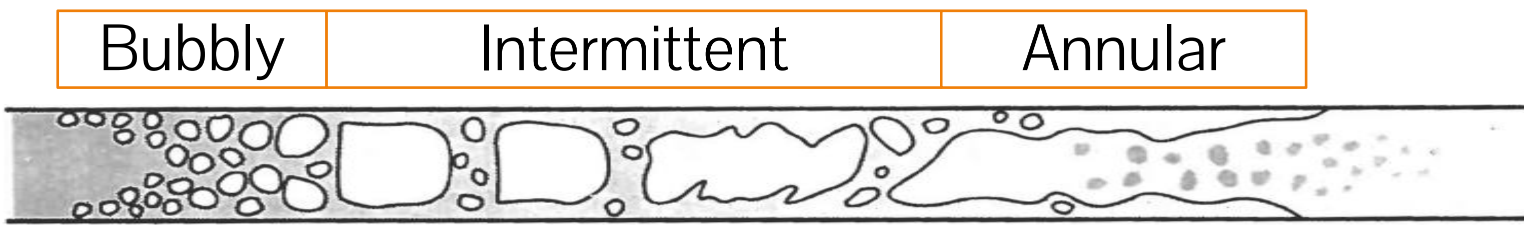
Supplemental Information

NASA Technology Roadmap

Number	Technology	Description	Performance Goals
14.2.1.2	High flux heat acquisition with constant temperature	Acquisition and removal of high heat fluxes over small areas with tight temperature control	Heat fluxes > 100 W/cm^2 Temperature control to ± 1 °C
14.2.2.10	Micro- and nano-scale heat transfer surfaces	Heat transfer surfaces and flow channels with micro- and nano-features to enhance two-phase heat transfer with higher heat fluxes and enhanced flow stability	Heat fluxes up to 1000 W/cm^2 Temperature differentials < 20 K Pressure drops < 20 kPa
14.2.3.2	Two-phase pumped loop systems	High-capacity, two-phase heat transport systems for thermal control of large heat loads (e.g., Rankine cycle power plants)	Two orders of magnitude improvement in heat transfer per unit of system mass

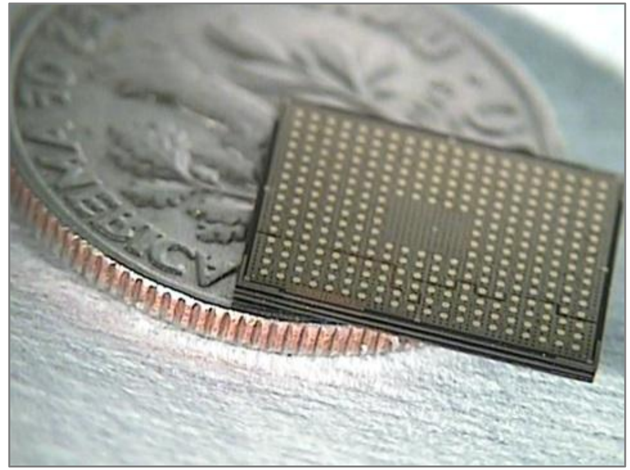
Two-Phase Flow Regimes

- Flow regimes describe distribution and extent of agglomeration of liquid and vapor phases

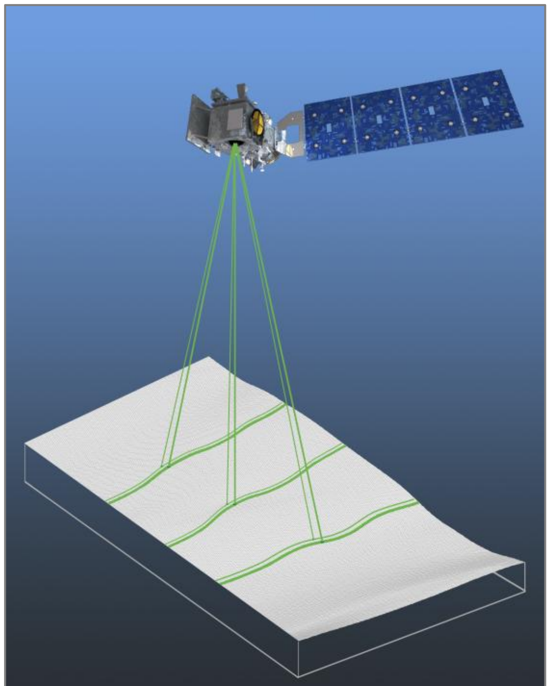


- Annular flow prevalent in small channels
- Knowledge of flow regime can inform correlation selection and improve predictive accuracy

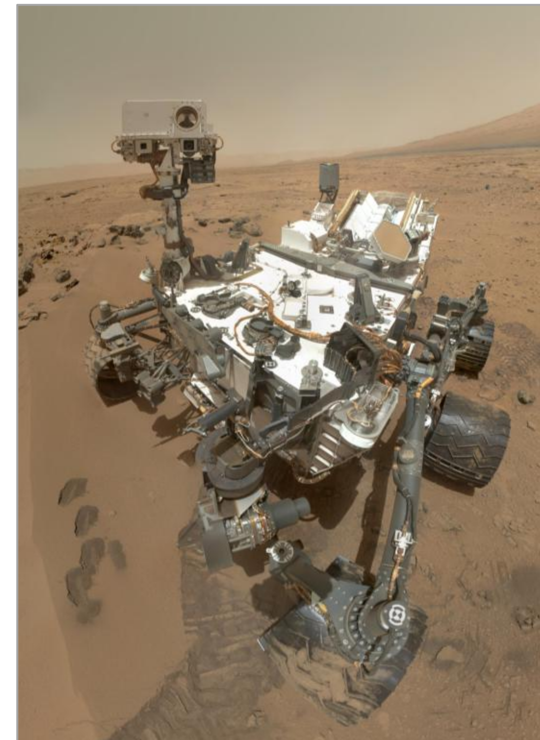
3D Integrated Circuits



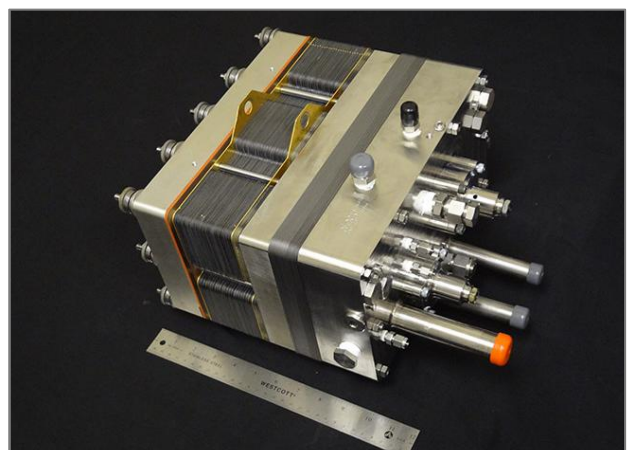
Lidar and Radar Instruments



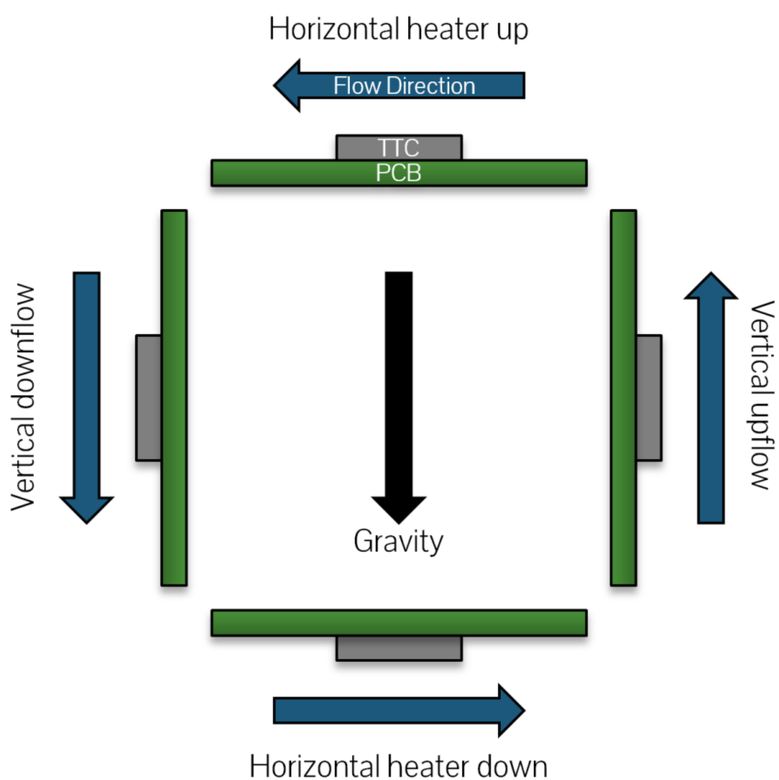
Rovers (RITEGs)

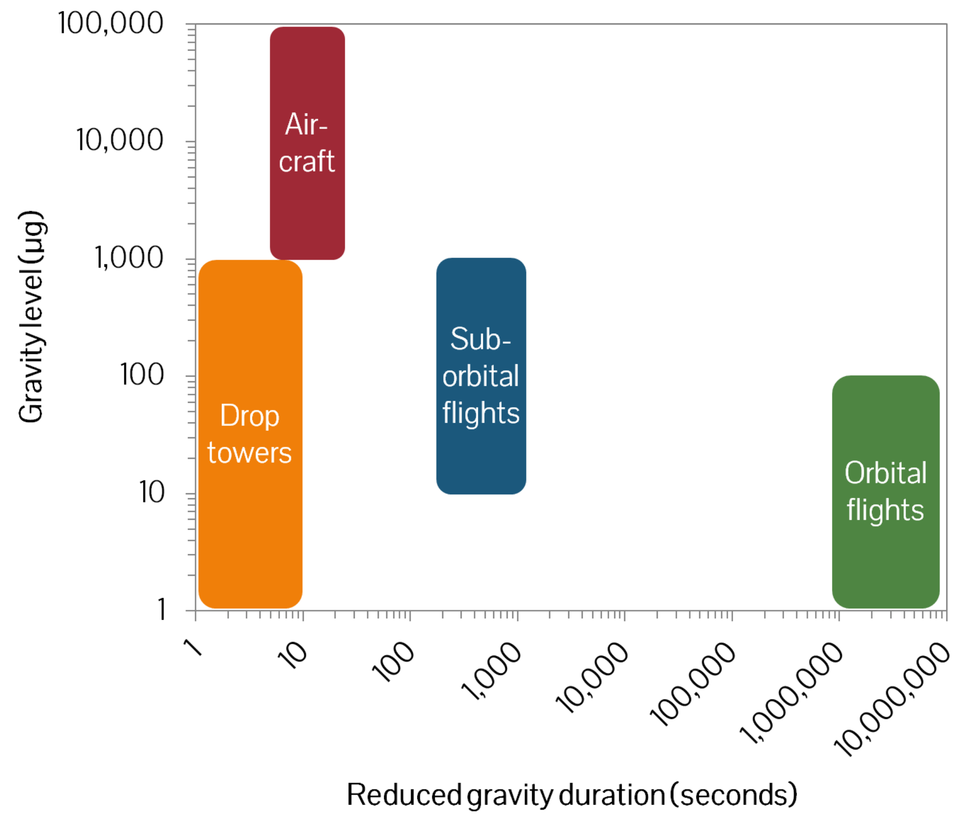


Fuel Cells



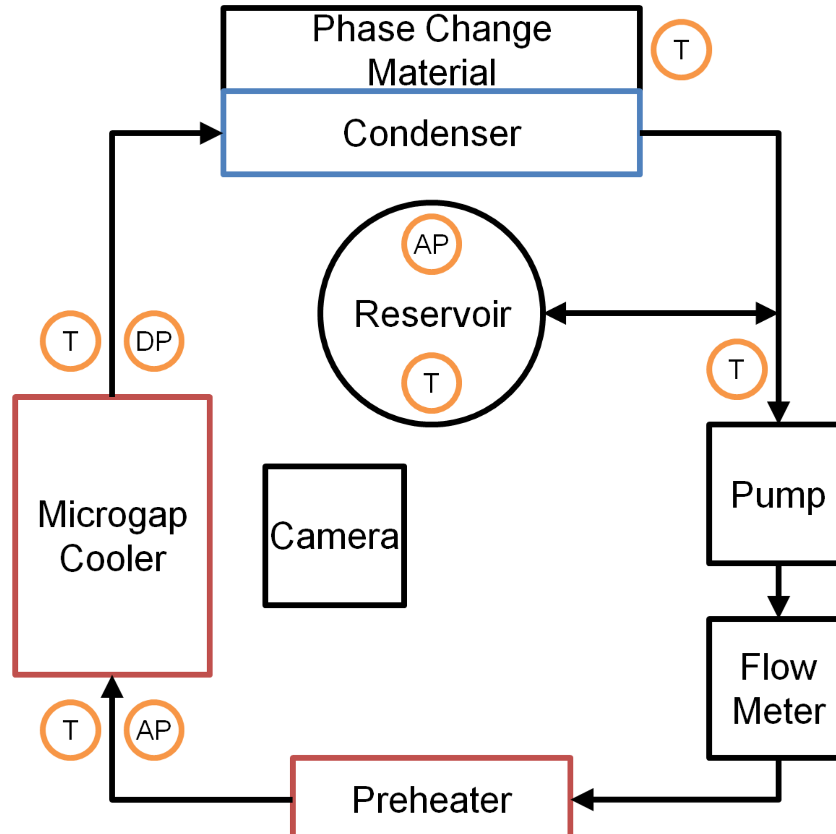
Methods for Assessing Gravity Effects





Flight Test

- Suborbital flight
  - 100 km apogee
  - 3+ minutes of < 0.001g
  - Launch loads of 3-4g
- Compact flow loop due to constraints on payload
  - 11 kg
  - 50 by 40 by 20 cm^3
  - 200 W



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