Flow Boiling and Condensation Experiment (FBCE) for the International Space Station

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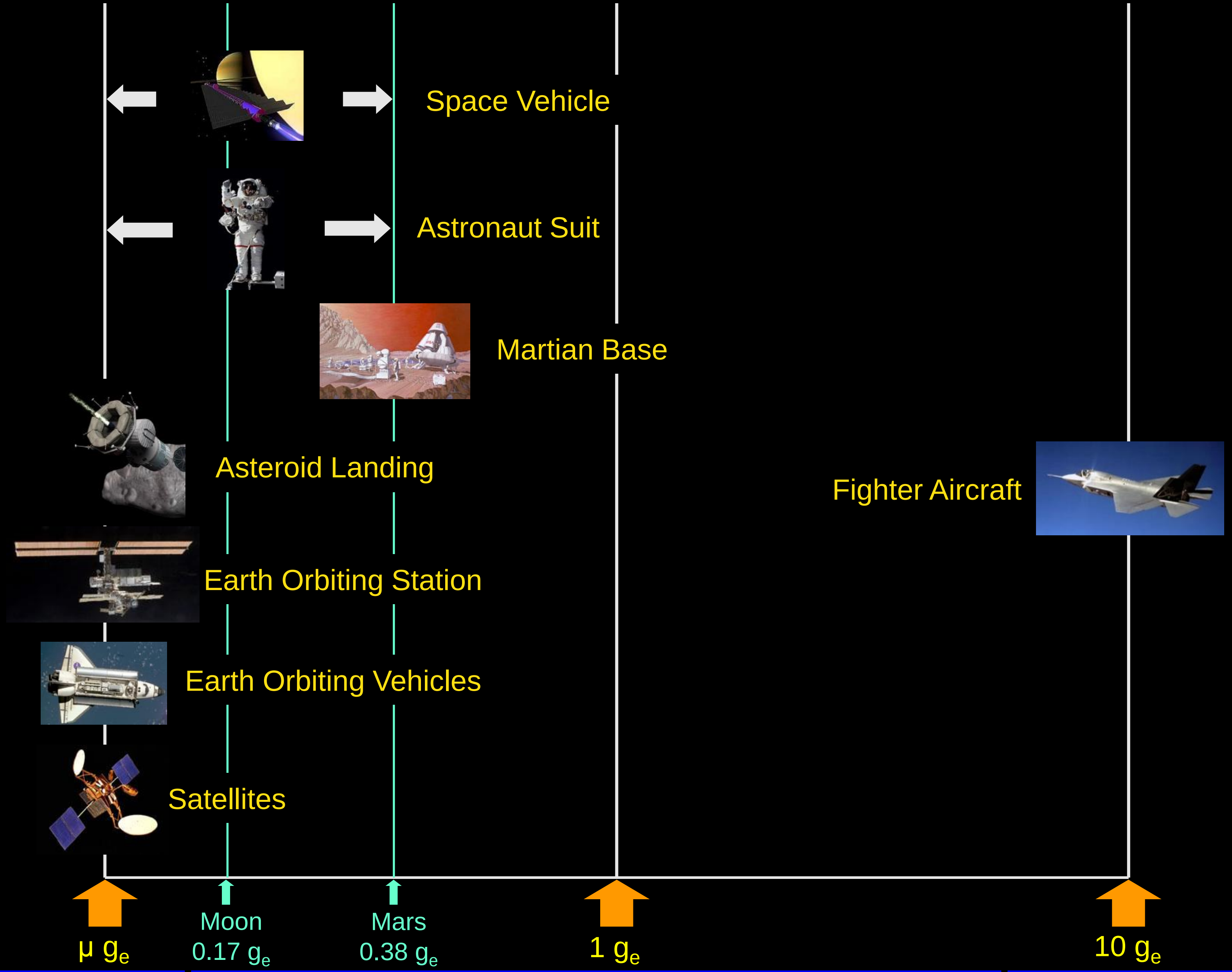
Examples of Systems Demanding Predictive Models of Effects of Gravity on Two-Phase Flow and Heat Transfer



Space Vehicle

Astronaut Suit

Martian Base

Asteroid Landing

Fighter Aircraft

Earth Orbiting Station

Earth Orbiting Vehicles

Satellites

$\mu\ g_e$

Moon $0.17\ g_e$

Mars $0.38\ g_e$

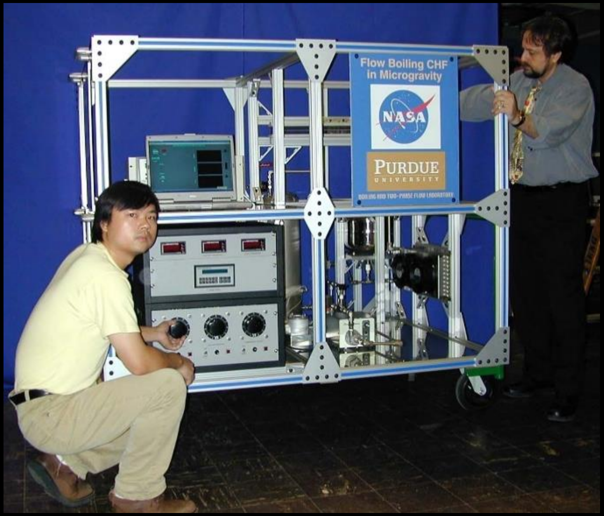
$1\ g_e$

$10\ g_e$

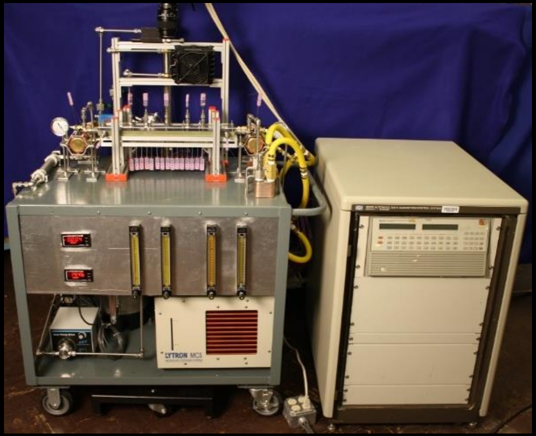
NASA-Supported Facilities at Boiling & Two-Phase Flow Laboratory

High-Capacity Condensation Facility

One-g Flow Boiling Facility

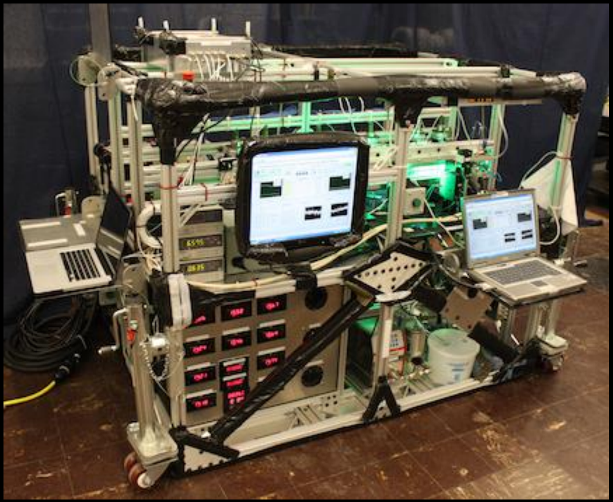


Parabolic Flight Flow Boiling Facility



Mini/micro-channel Condensation Facility

Falling-Film Heating/Evaporation Facility



Parabolic Flight Condensation Facility

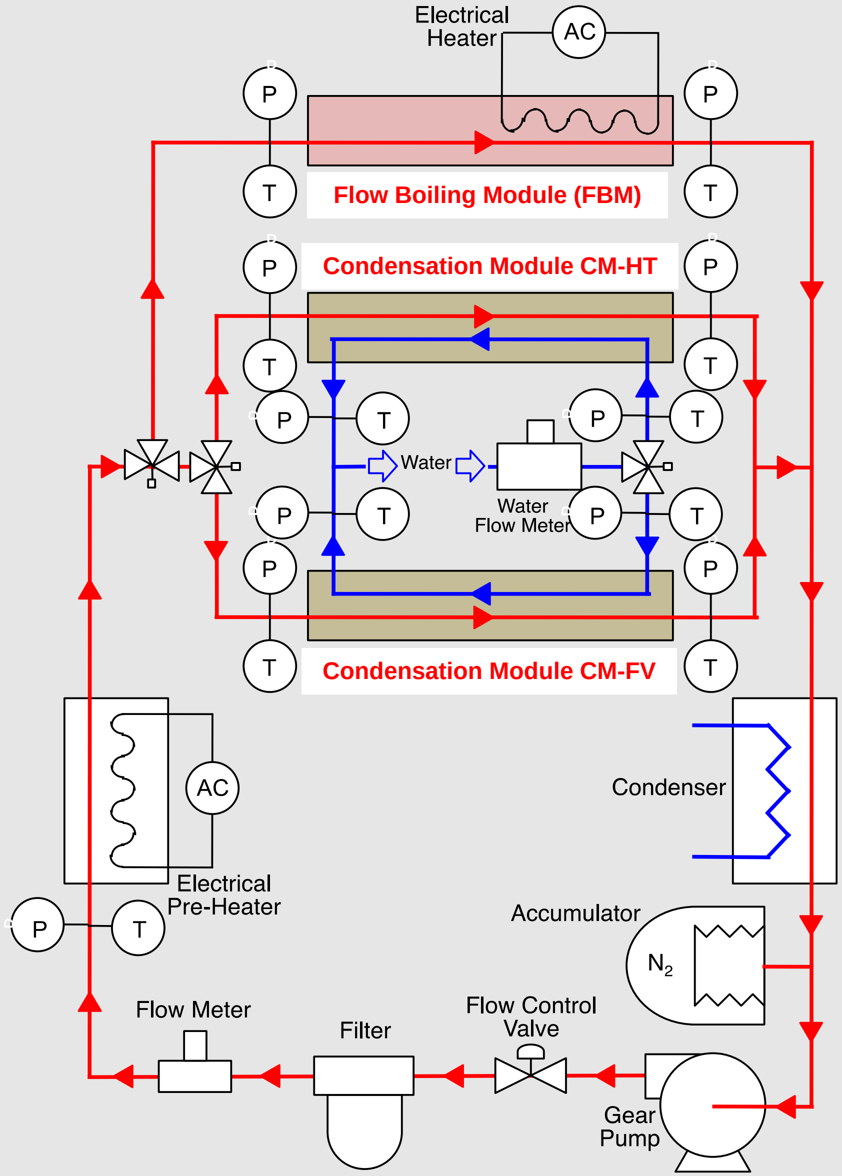
Overriding Objectives of FBCE

The proposed research aims to develop an integrated two-phase flow boiling/condensation facility for the International Space Station (ISS) to serve as primary platform for obtaining two-phase flow and heat transfer data in microgravity.

Overriding objectives are to:

1. **Obtain flow boiling database in long-duration microgravity environment**
2. **Obtain flow condensation database in long-duration microgravity environment**
3. **Develop experimentally validated, mechanistic model for microgravity flow boiling critical heat flux (CHF) and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent CHF**
4. **Develop experimentally validated, mechanistic model for microgravity annular condensation and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent annular condensation; also develop correlations for other condensation regimes in microgravity**

Layout of FBCE



Consists of:

- nPFH sub-loop
- Water sub-loop

Contains three test modules:

- Flow Boiling Module (FBM)
- Condensation Module CM-HT for heat transfer measurements
- Condensation Module CM-FV for flow visualization

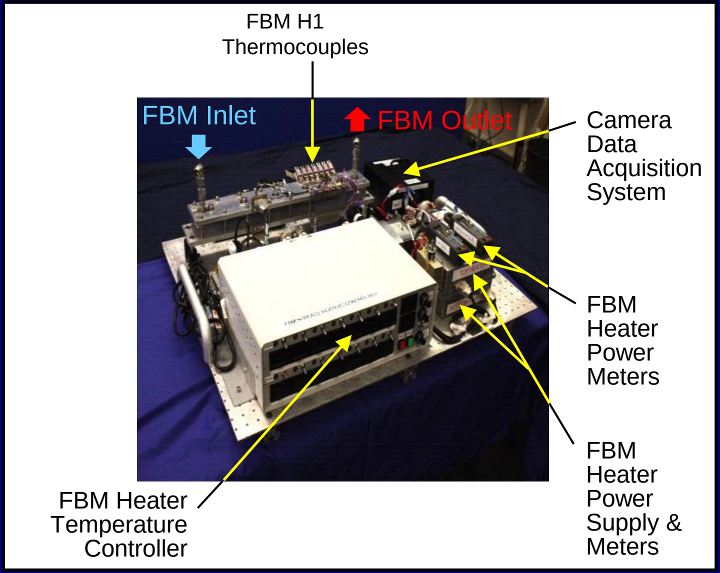
Primary 2014 – 2015 Research Topics

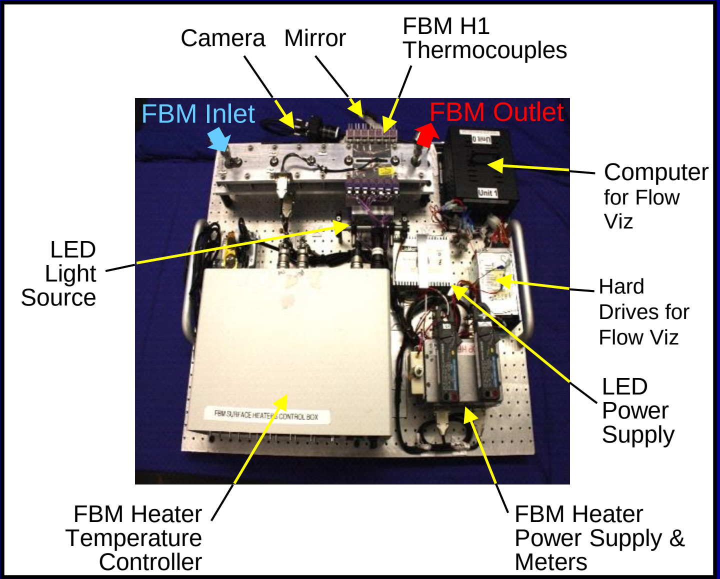
1. **Both One g_e and Parabolic flight flow boiling experiments using single-sided and double-sided heat walls**

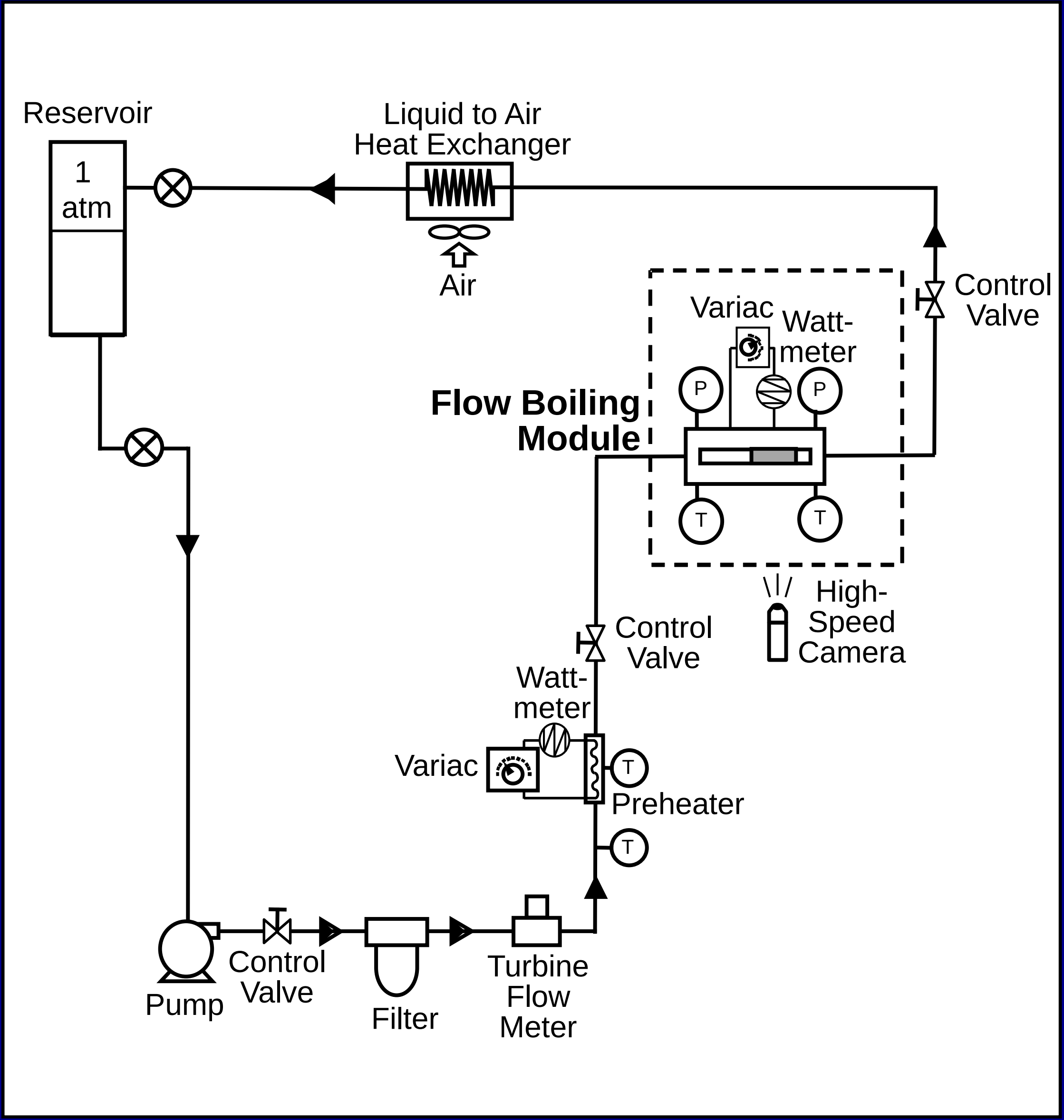
2. **Modeling of CHF for single-sided and double-sided heated walls at different orientations in Earth gravity and in microgravity**

3. **Computational modeling of condensing film**

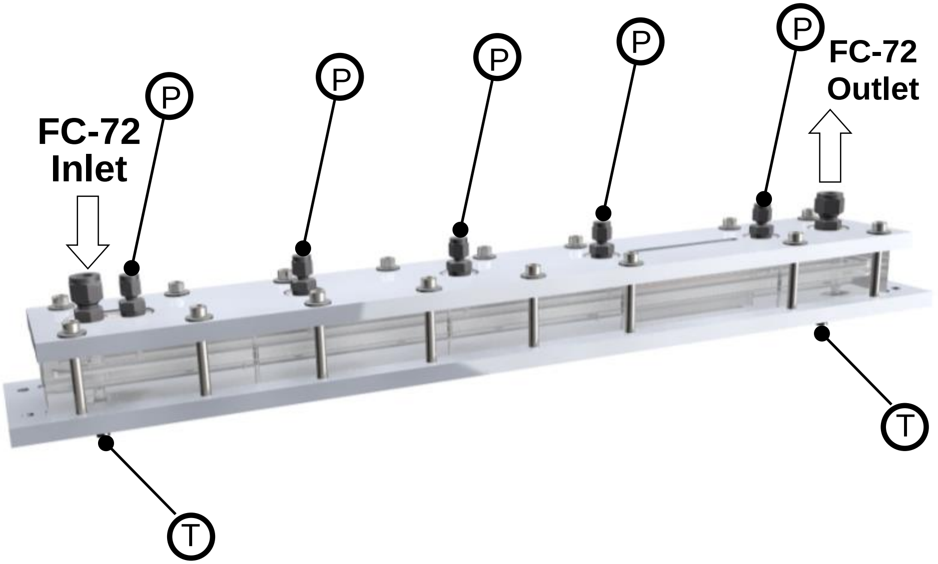
Flow Boiling Facility

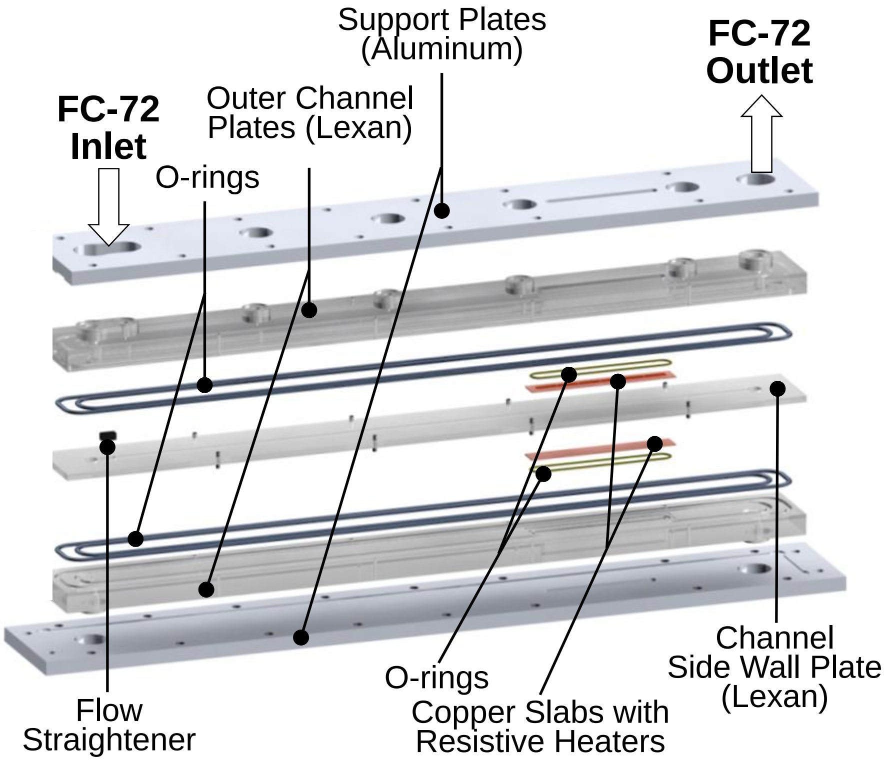


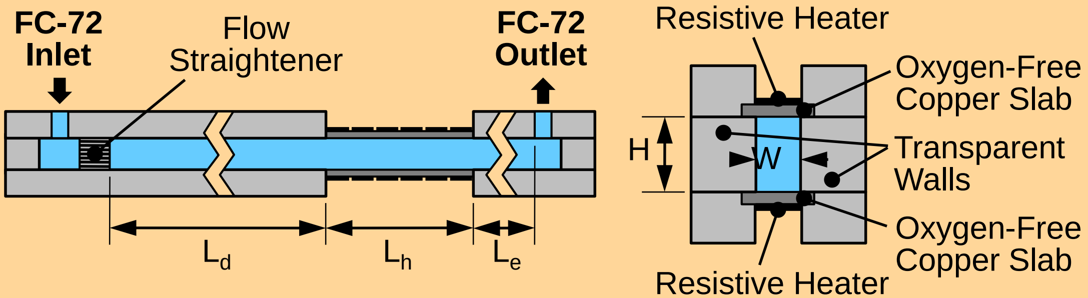




Flow Boiling Module



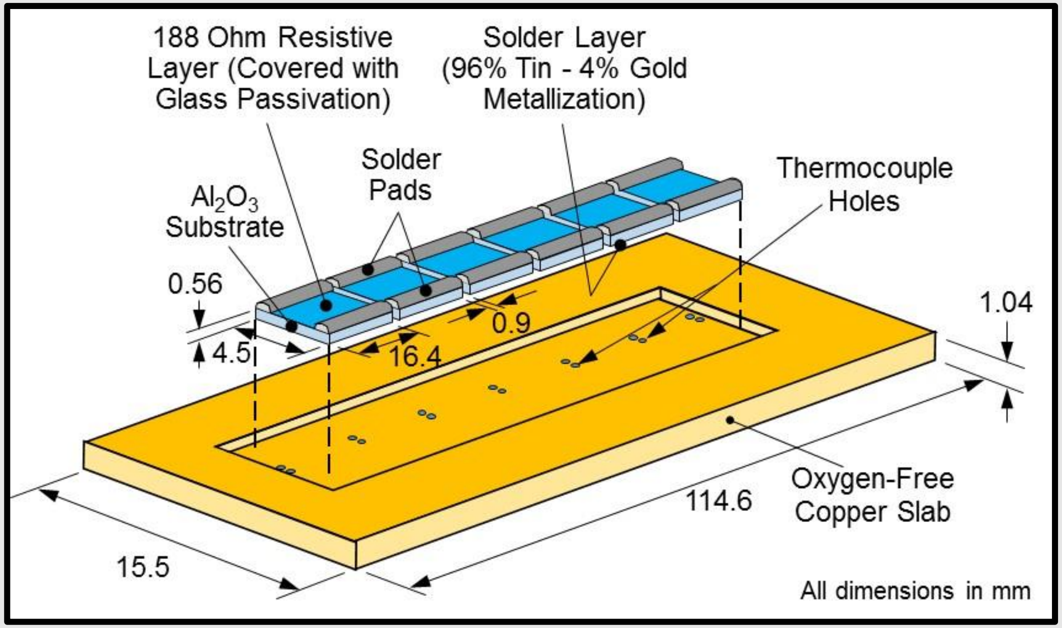


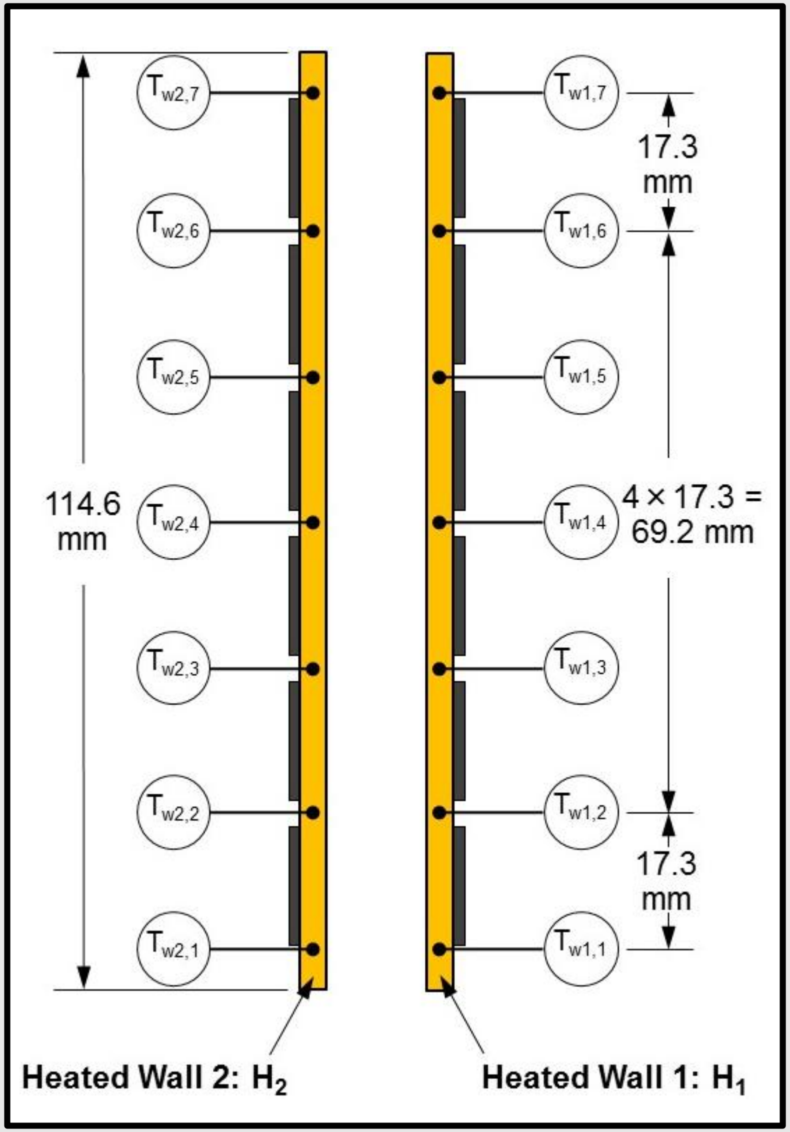


Development Length: $L_d = 327.9$ mm
Heated Length: $L_h = 114.6$ mm
Exit Length: $L_e = 60.9$ mm

Channel Height: H = 5.0 mm
Channel Width: W = 2.5 mm

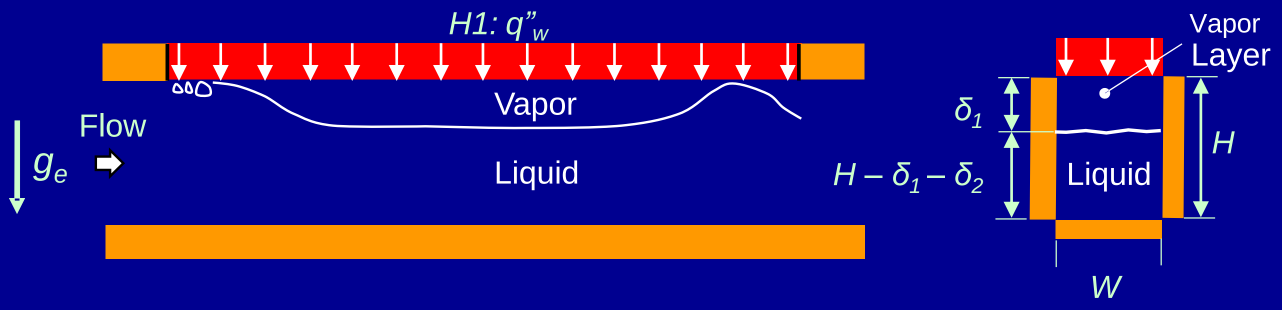
Heated Wall Design



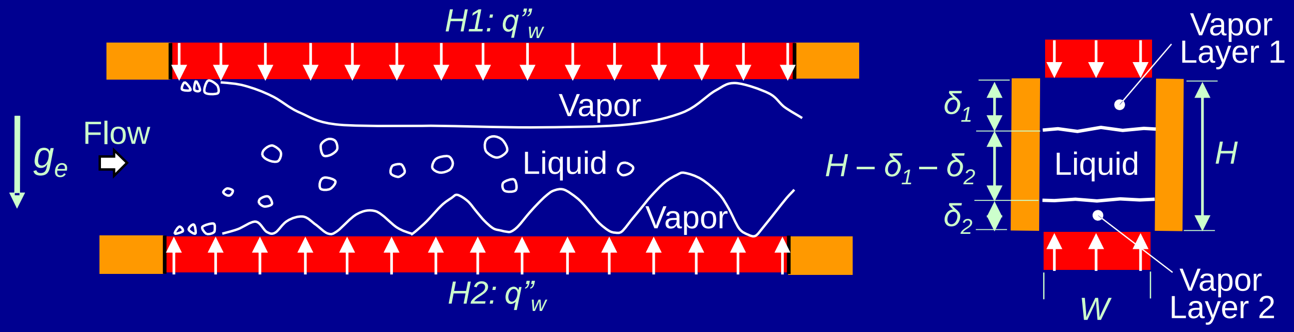


Horizontal Flow Boiling – Heated Wall Configurations

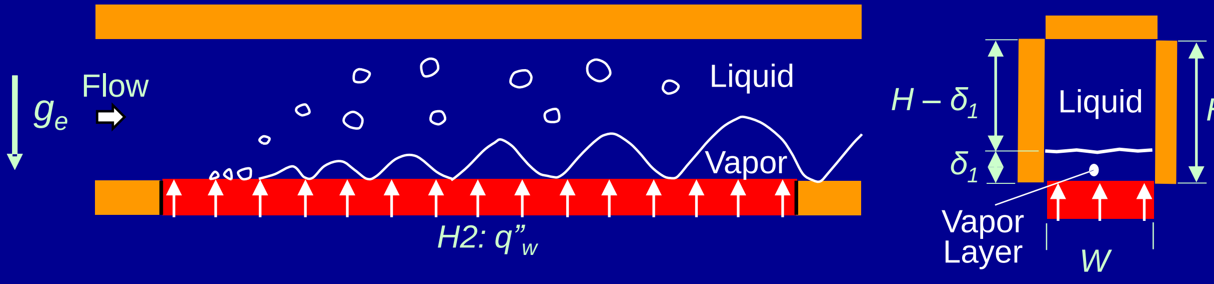
Top wall heating



Double-sided heating

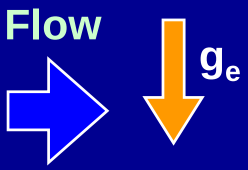


Bottom wall heating



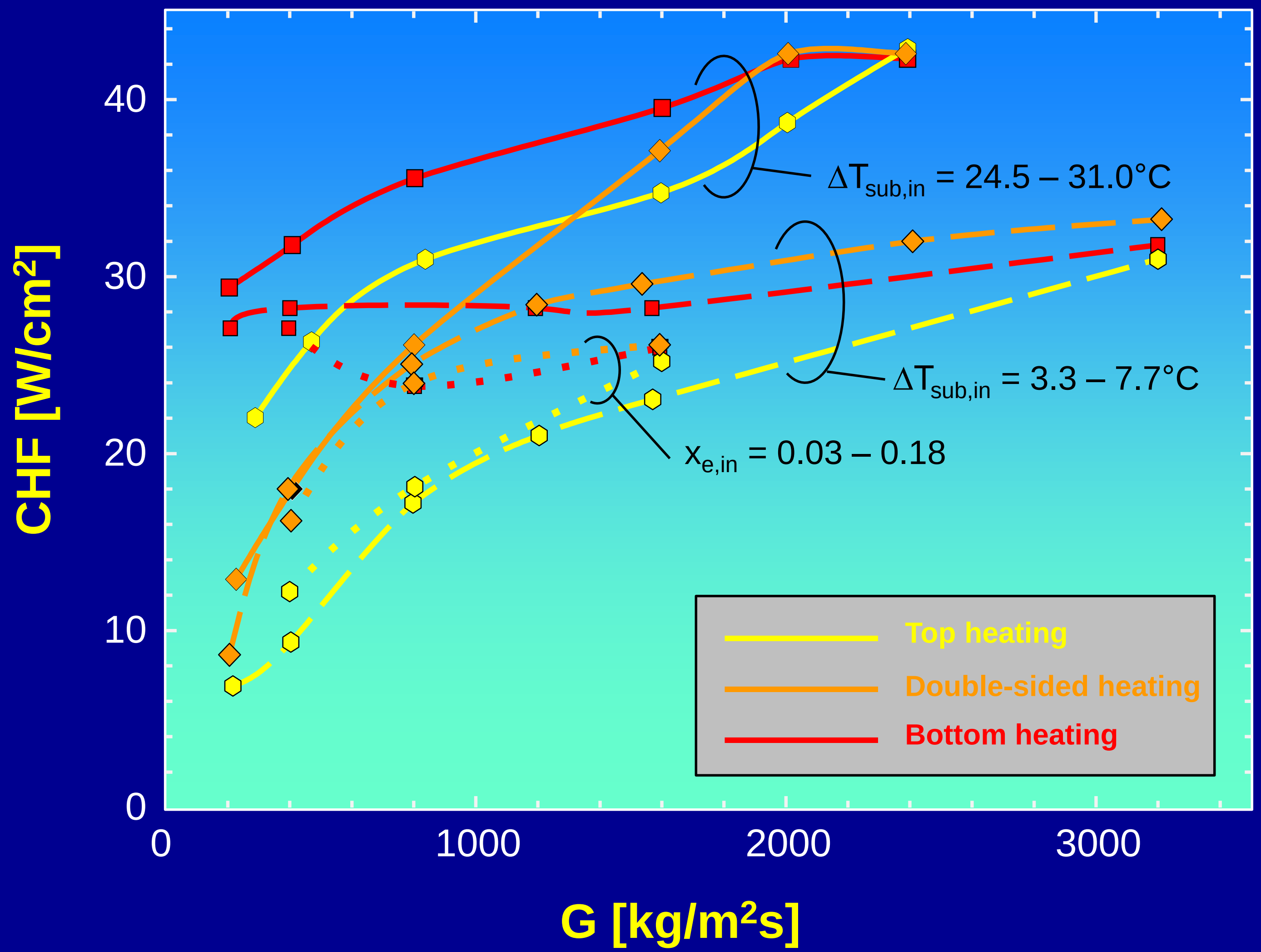
Horizontal Flow Boiling – Flow Visualization

Slightly subcooled flow at low velocity



$G = 394.8 – 403.4\ kg/m^2s$ ($U = 0.25\ m/s$)
$\Delta T_{sub,in} = 3.6 - 5.1°C$

Horizontal Flow Boiling – Experimental CHF Results



Separated Flow Model for Double-Sided Heating

Mass Balance:

Vapor layer 1:

$$U_{g1} = \frac{q''_w z}{\rho_g \delta_1 \left(c_{p,f} \Delta T_{sub,in} + h_{fg} \right)}$$

Vapor layer 2:

$$U_{g2} = \frac{q''_w z}{\rho_g \delta_2 \left(c_{p,f} \Delta T_{sub,in} + h_{fg} \right)}$$

Liquid layer:

$$U_f = \frac{U H}{H - \delta_1 - \delta_2} - \frac{2 q''_w z}{\rho_f \left(H - \delta_1 - \delta_2 \right) \left(c_{p,f} \Delta T_{sub,in} + h_{fg} \right)}$$

Momentum Balance:

Heated wall vapor layer 1:

$$G^2 \frac{d}{dz} \left[\frac{x_1^2}{\rho_g \alpha_1} \right] = -\alpha_1 \frac{dp}{dz} - \frac{\tau_{w,g1} P_{w,g1}}{A} \pm \frac{\tau_{i1} P_{i1}}{A} - \rho_g \alpha_1 g \sin\theta$$

Central Liquid layer:

$$G^2 \frac{d}{dz} \left[\frac{\left(1 - x_1 - x_2 \right)^2}{\rho_f \left(1 - \alpha_1 - \alpha_2 \right)} \right] = -\left(1 - \alpha_1 - \alpha_2 \right) \frac{dp}{dz} - \frac{\tau_{w,f} P_{w,f}}{A} \pm \frac{\tau_{i1} P_{i1}}{A} \pm \frac{\tau_{i2} P_{i2}}{A} - \rho_f \left(1 - \alpha_1 - \alpha_2 \right) g \sin\theta$$

Heated wall vapor layer 2:

$$G^2 \frac{d}{dz} \left[\frac{x_2^2}{\rho_g \alpha_2} \right] = -\alpha_2 \frac{dp}{dz} - \frac{\tau_{w,g2} P_{w,g2}}{A} \pm \frac{\tau_{i2} P_{i2}}{A} - \rho_g \alpha_2 g \sin\theta$$

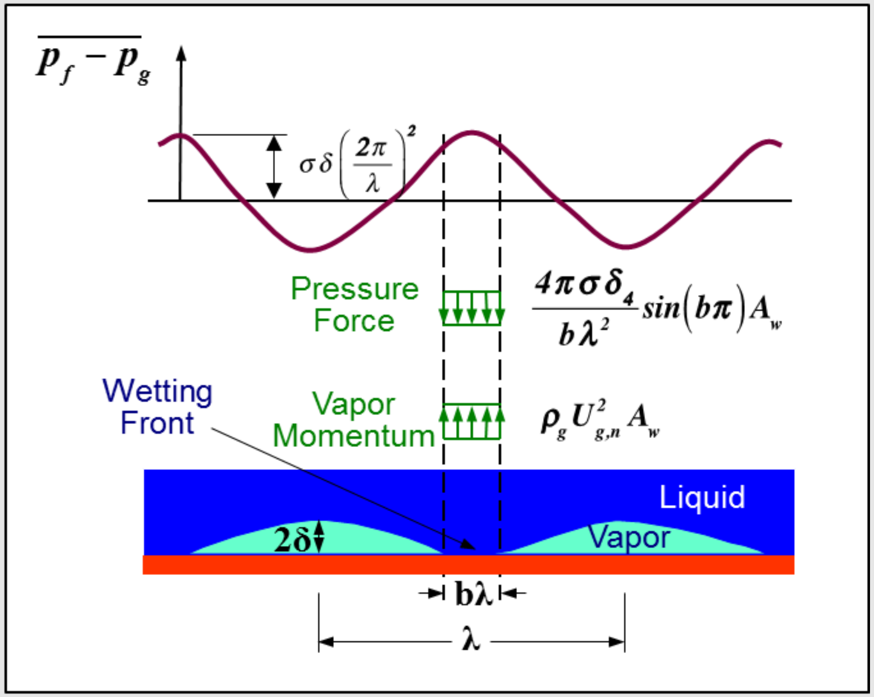
Energy Balance:

$$\frac{dx_1}{dz} = \frac{dx_2}{dz} = \frac{q''_w W}{\dot{m} \left(c_{p,f} \Delta T_{sub,in} + h_{fg} \right)}$$

Interfacial Lift-off CHF Model

Use separated flow model to determine axial variations of:

U_{g1}, U_{g2}	*Near-wall vapor layer velocities*
U_f	*Liquid layer velocity*
δ_1, δ_2	*Near-wall vapor layer thicknesses*



Critical interfacial wavelength

$$k_c = \frac{2\pi}{\lambda_c} = \frac{\rho_f'' \rho_g'' (U_g - U_f)^2}{2\sigma(\rho_f'' + \rho_g'')} + \sqrt{\left[\frac{\rho_f'' \rho_g'' (U_g - U_f)^2}{2\sigma(\rho_f'' + \rho_g'')}\right]^2 + \frac{(\rho_f - \rho_g) g_n}{\sigma}}$$

where $\rho_f'' = \rho_f \coth(2\pi H_f / \lambda_c)$ and $\rho_g'' = \rho_g \coth(2\pi H_g / \lambda_c)$

Earth Gravity: $g_{n,1} = g_e \cos\theta$ and $g_{n,2} = g_e \cos(\theta + \pi) = -g_e \cos\theta$

Microgravity: $g_{n,1} = g_{n,2} = \mu g_e \cong 0 \quad \Rightarrow \quad \lambda_c = \frac{2\pi\sigma(\rho_f'' + \rho_g'')}{\rho_f'' \rho_g'' (U_g - U_f)^2}$

Mean pressure difference across wetting front

$$\overline{p_f - p_g} = \frac{4\pi\sigma\delta}{b\lambda_c^2}\sin(b\pi)$$

where b = 0.20 is ratio of wetting front length to wavelength

Interfacial lift-off criterion

$$\overline{p_f - p_g} = \rho_g\left[\frac{q_w''}{\rho_g h_{fg}}\right]^2$$

Surface energy balance

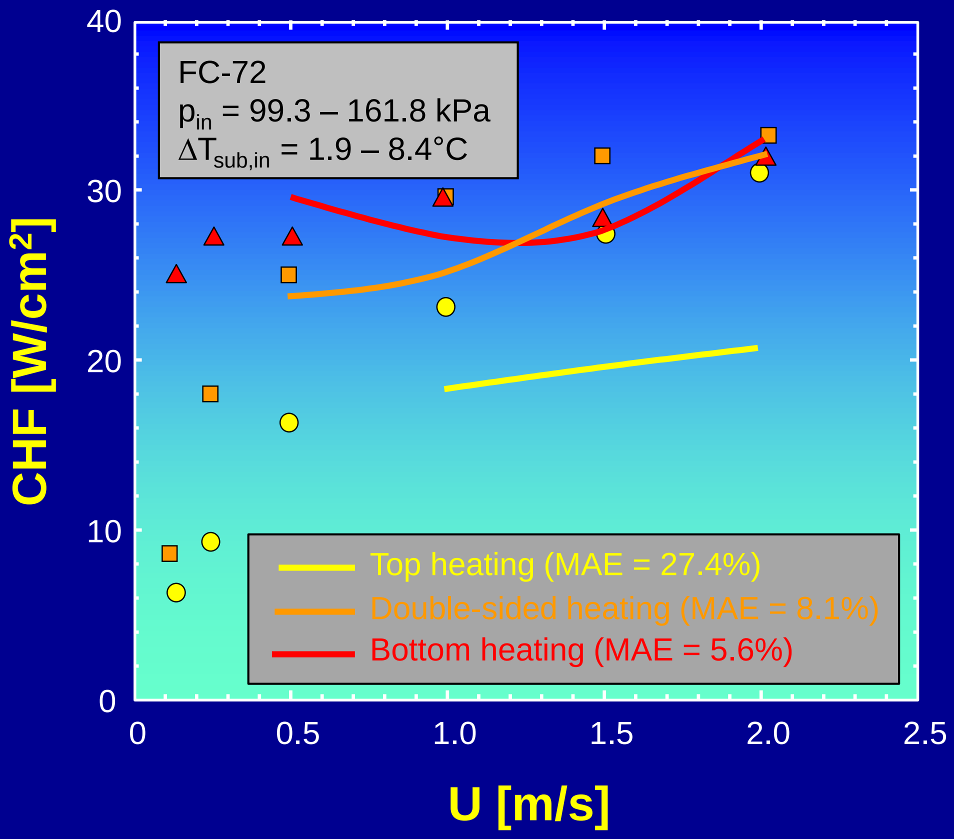
$$q_m'' = b q_w''$$

Critical heat flux

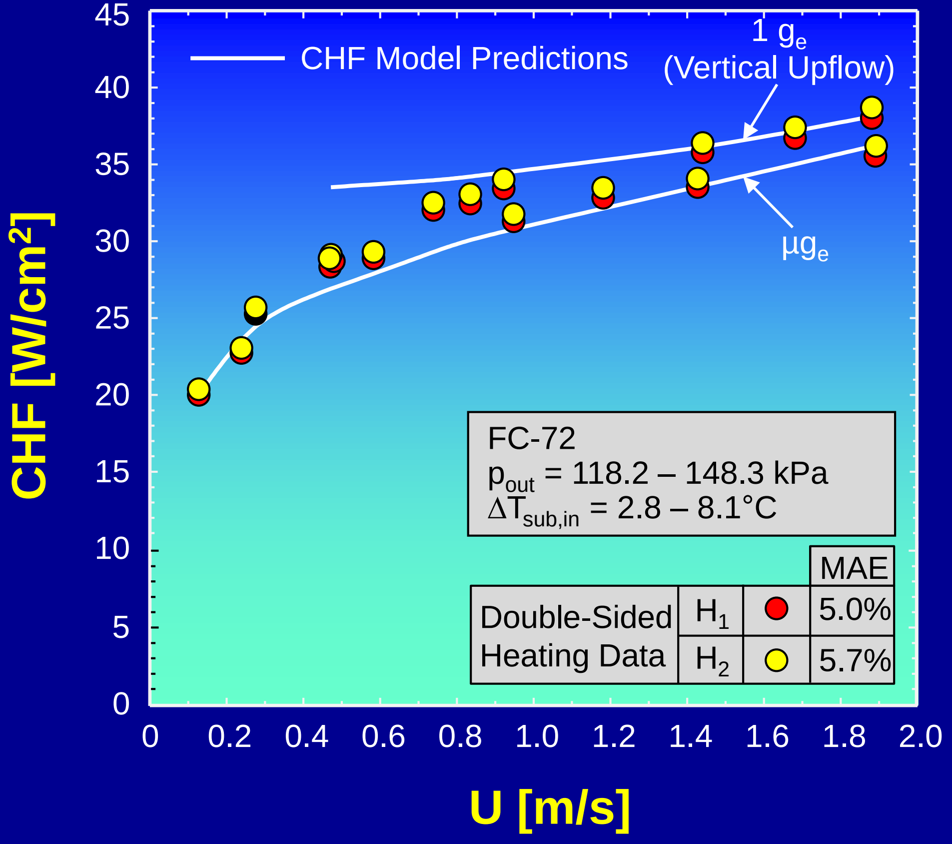
$$q_m'' = \rho_g\left(c_{p,f}\Delta T_{sub,in} + h_{fg}\right)\left[\frac{4\pi\sigma b \sin(b\pi)}{\rho_g}\right]^{1/2} \left.\frac{\delta^{1/2}}{\lambda_c}\right|_{z^*}$$

CHF Model Predictions

One g_e Horizontal Flow

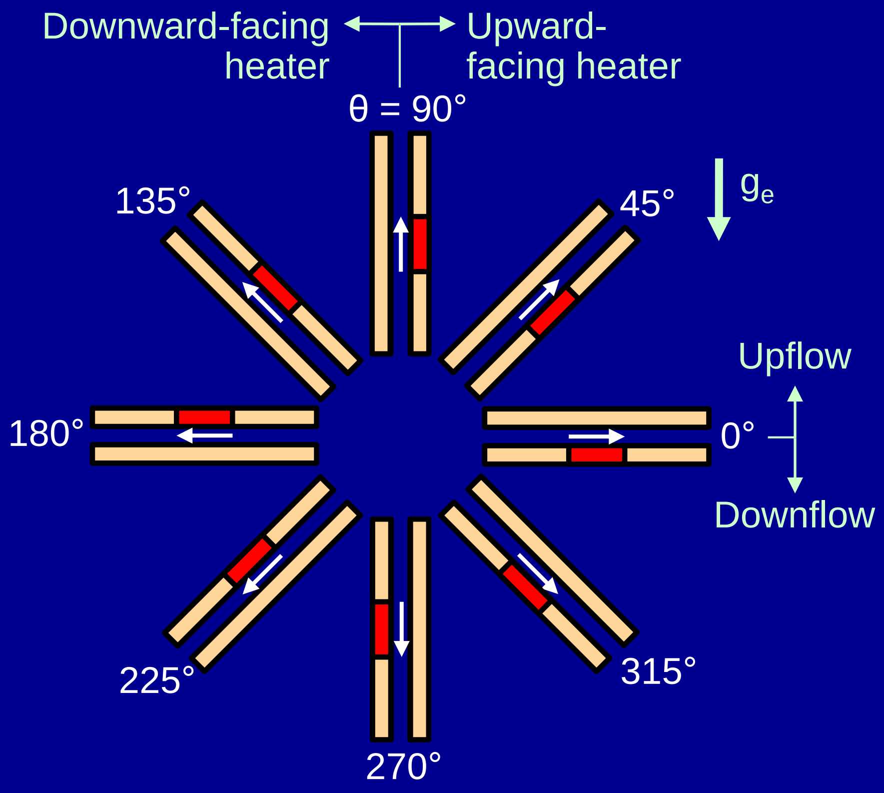


Microgravity & One g_e Vertical Upflow



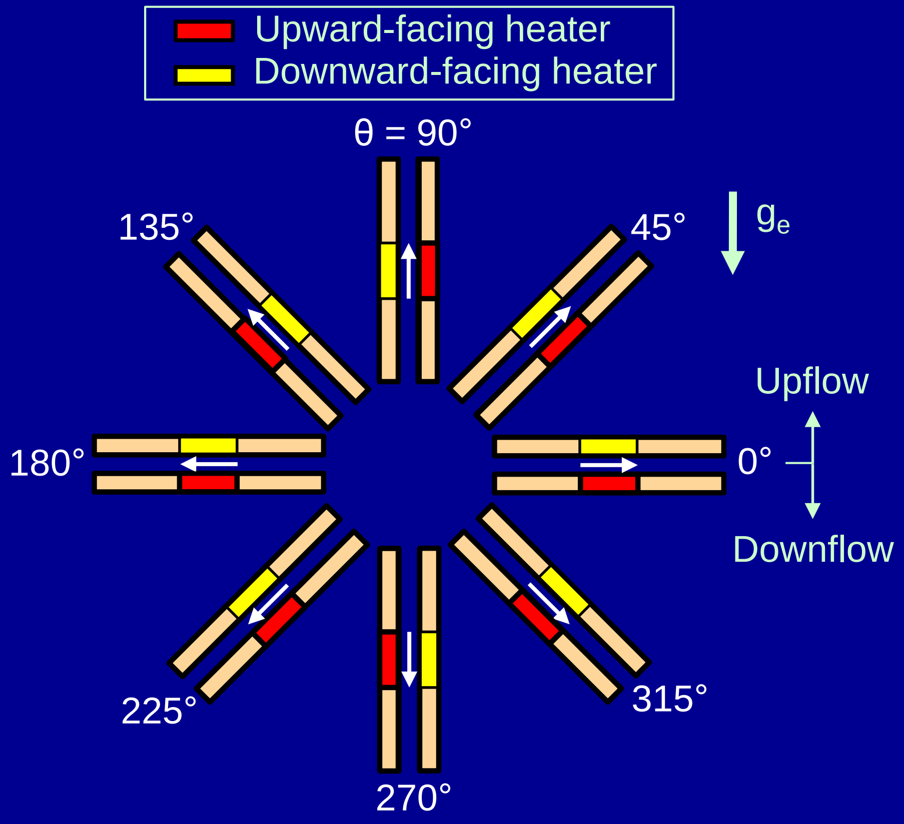
Single-sided versus Double-sided Heating in Earth Gravity

Single-sided Heating



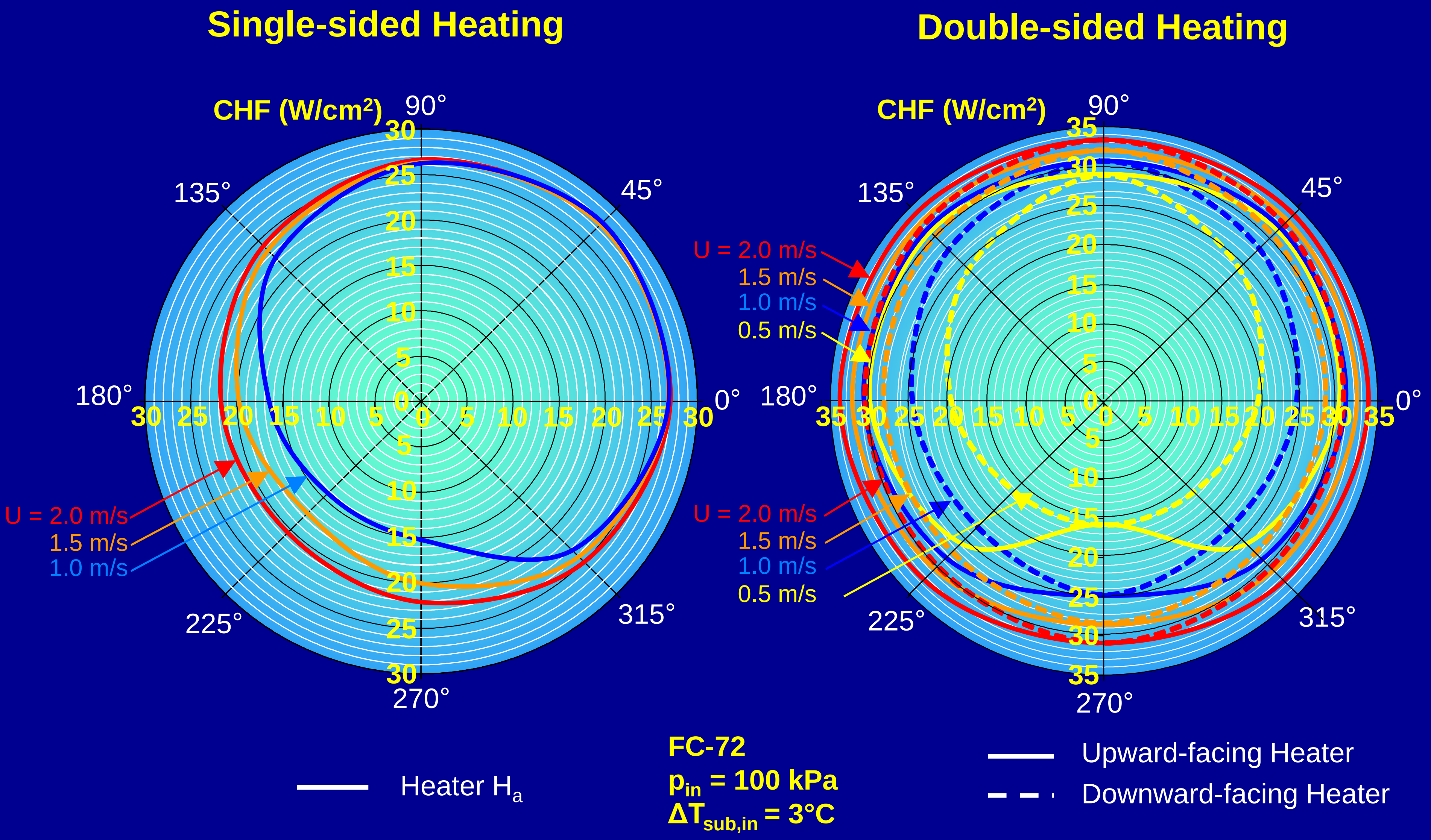
Downward-facing heater
Upward-facing heater
θ = 90°
135°
45°
g_e
Upflow
180°
0°
Downflow
225°
270°
315°

Double-sided Heating



🟥 Upward-facing heater
🟨 Downward-facing heater
θ = 90°
135°
45°
g_e
Upflow
180°
0°
Downflow
225°
270°
315°

CHF Predictions for Single-sided versus Double-sided Heating in Earth Gravity



FC-72
p_{in} = 100 kPa
$\Delta T_{sub,in}$ = 3°C

Data Sharing Plans

Impetus for Data Sharing

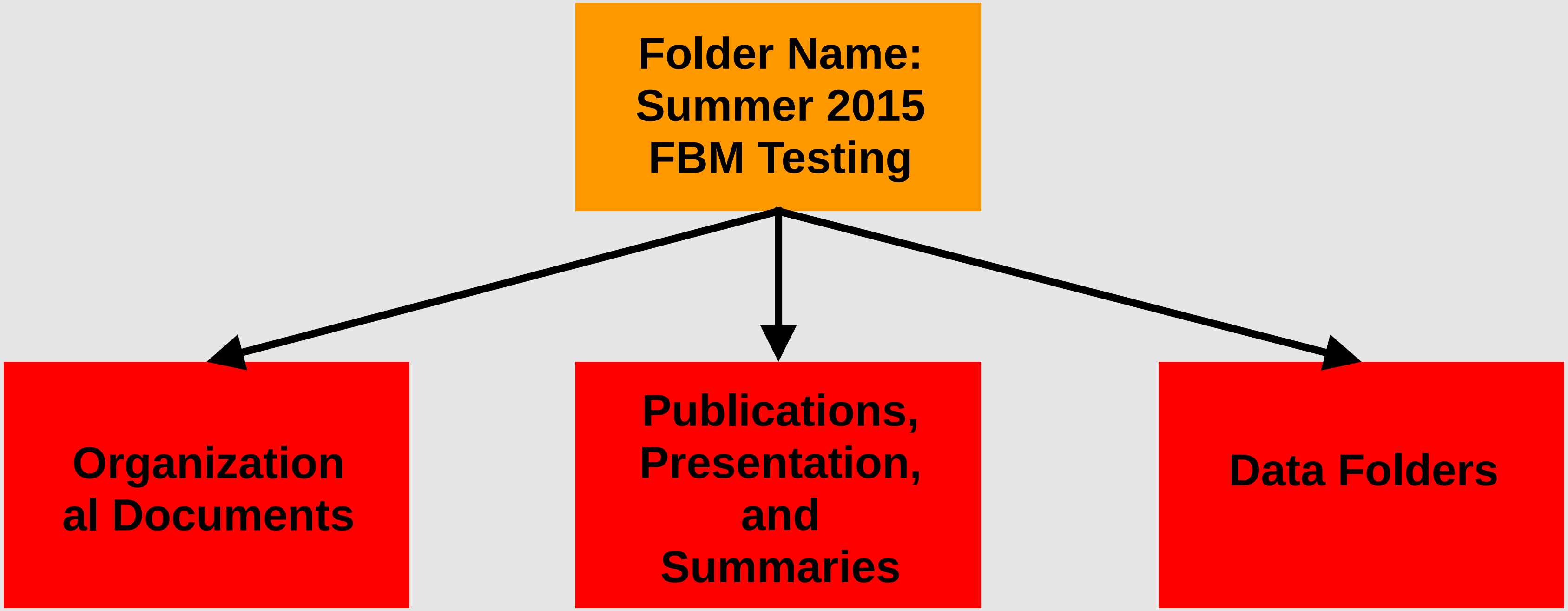
- **NASA Office of Physical Science Informatics (PSI) tasked with organizing and distributing databases to researchers in the field**

- **Large databases (terabytes of data) will be generated from FBCE ISS experiment**

- **Purdue-Glenn team will create organization structure for FBCE databases to be provided to (PSI)**

- **Purdue is presently exploring most effective means for packaging data for ease of use by other researchers using recent FBM Earth's gravity data as example**

Organizational Structure of FBM Database



Folder Name: Summer 2015 FBM Testing

Organizational Documents

Publications, Presentation, and Summaries

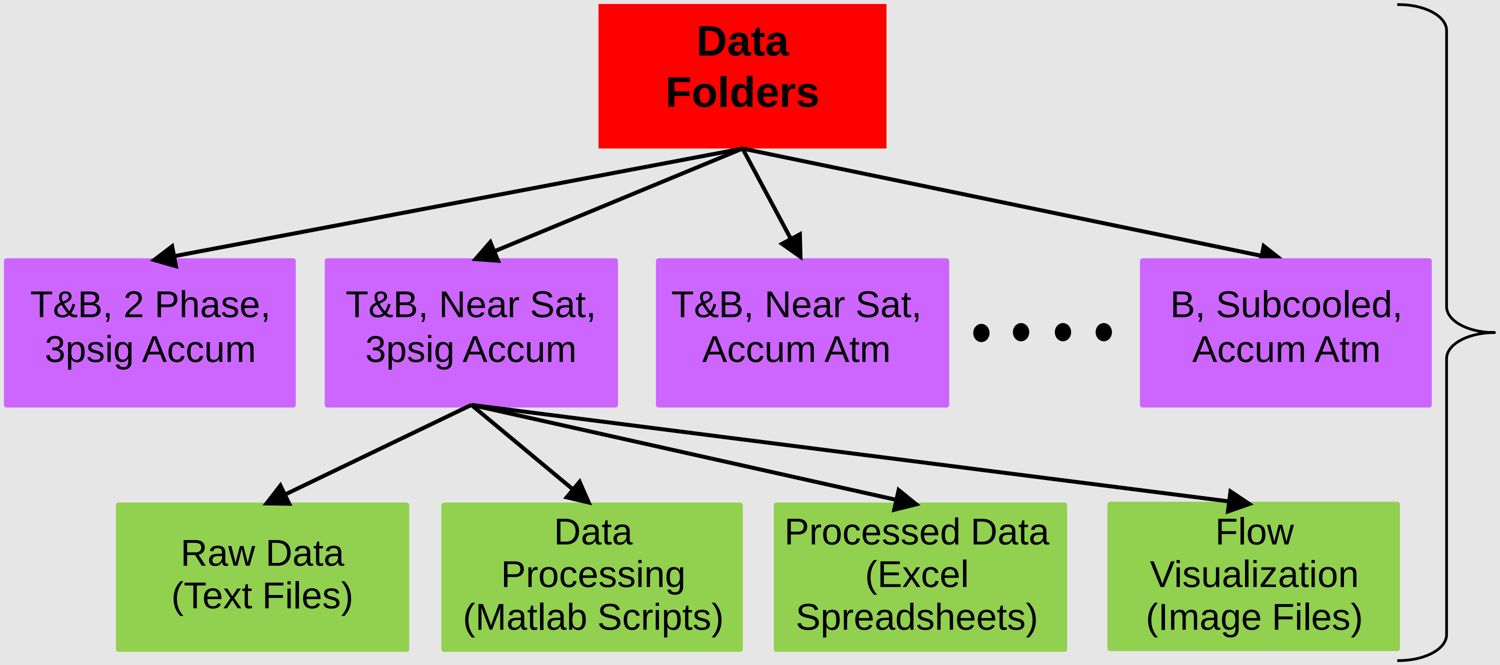
Data Folders

Data Folders

Contain four filetypes:

- ***Text Files*** **containing raw sensor data output by data acquisition system**
- ***Matlab Scripts*** **for processing raw data**
- ***Excel Spreadsheets*** **containing all relevant parameters (*e.g.*, pressure drop, heat transfer coefficient, CHF) output by processing script**
- ***Image Files*** **for flow visualization**

With subfolders used to group data by operating conditions



Full description of file paths and data file structures found in "Organizational Documents" folder

Computational Modeling

ANSYS Fluent Modeling

Objectives

- Study flow condensation using CFD solver Fluent
- Select an appropriate phase change model
- Study heat transfer and fluid flow characteristics over a broad range of Reynolds numbers
- Lay foundation for future computational modeling of complicated flow boiling processes

Condensation Test Facility

Numerical Approaches to Modeling Two-Phase Systems

- **Lagrangian**
  - **Smoothed-Particle Hydrodynamics (SPH) Method:** Gingold & Monaghan (1977), Lucy (1977)
  - **Multiphase Particle-in-Cell (MP-PIC) Method:** Harlow (1955)
- **Eulerian**
  - **Level-Set Method (LSM):** Osher & Sethian (1955)
  - **Volume-Of-Fluid (VOF) Method:** Hirt & Nichols (1981)
  - **Coupled Level-Set/Volume-Of-Fluid (CLSVOF) Method:** Sussman & Puckett (2000), Enright *et al.* (2002), Tomar *et al.* (2005)
- **Eulerian-Lagrangian**
  - **Front Tracking Method:** Unverdi & Tryggvason(1992), Tryggvason *et al.* (2001)

Phase Change Models

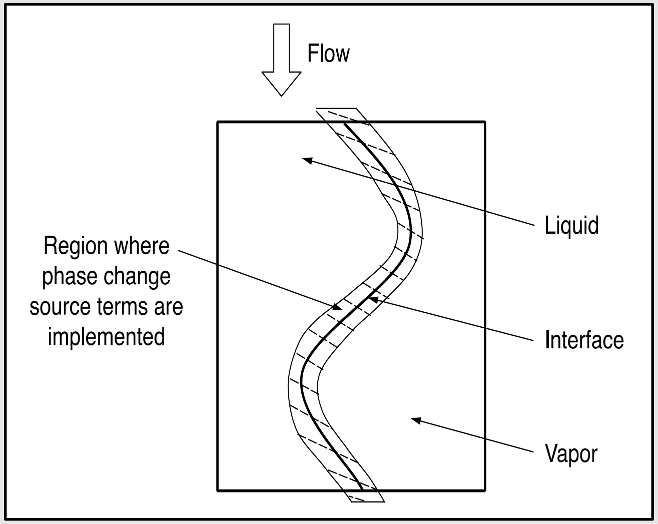
- **Rankine-Hugoniot jump condition**

Mao (2009). Michita & Thome(2010), Sun *et al.* (2012)

$$q_i'' = -k_{eff}\nabla T_i \times \vec{n} = \dot{m}'' h_{fg}$$

$$S_g = -S_f = \dot{m}''\left|\nabla\alpha_g\right| = \frac{k_{eff}\left(\nabla\alpha\times\nabla T\right)}{h_{fg}}$$

where $k_{eff} = a_g k_g + a_f k_f$



- **Schrage Model (1953)**

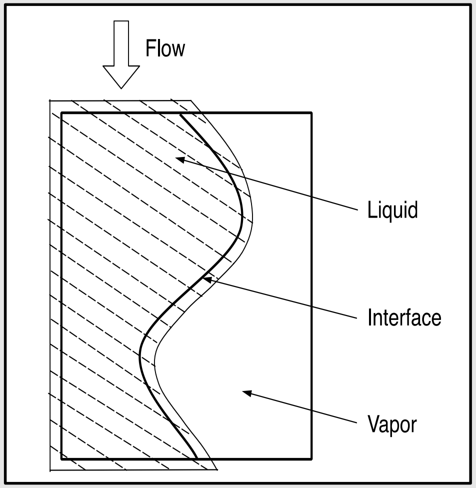
Kartuzova & Kassemi (2011), Magnini *et al.* (2013) …

$$S_g = -S_f = \dot{m}''\left|\nabla\alpha_g\right|$$

where $\dot{m}'' = \frac{2}{2-\gamma_c}\sqrt{\frac{M}{2\pi R}}\left[\gamma_c\frac{P_g}{\sqrt{T_g}} - \gamma_e\frac{P_f}{\sqrt{T_f}}\right]$

- **Lee Model (1980)**

Wu *et al.*(2007). Yang *et al.*(2008), Fang *et al.*(2010) …



$$S_g = -S_f = r_i a_g r_g \frac{\left(T - T_{sat}\right)}{T_{sat}}$$ for condensation ($T < T_{sat}$)

$$S_g = -S_f = r_i a_f r_f \frac{\left(T - T_{sat}\right)}{T_{sat}}$$ for evaporation ($T > T_{sat}$)

Phase Change Models

Rankine-Hugoniot jump condition

Mao (2009). Michita & Thome (2010), Sun *et al.* (2012) …

Pros:

1. Ease of implementation

Cons:

1. Allows for phase change only along interface
2. Cannot maintain saturation temperature

Schrage Model (1953)

Kartuzova & Kassemi (2011), Magnini *et al.* (2013)…

Pros:

1. Successfully used for evaporating & condensing films

Cons:

1. Requires use of empirical coefficient γ
2. Allows for phase change only along interface

Lee Model (1980)

Wu *et al.* (2007). Yang *et al.*(2008), Fang *et al.* (2010) …

Pros:

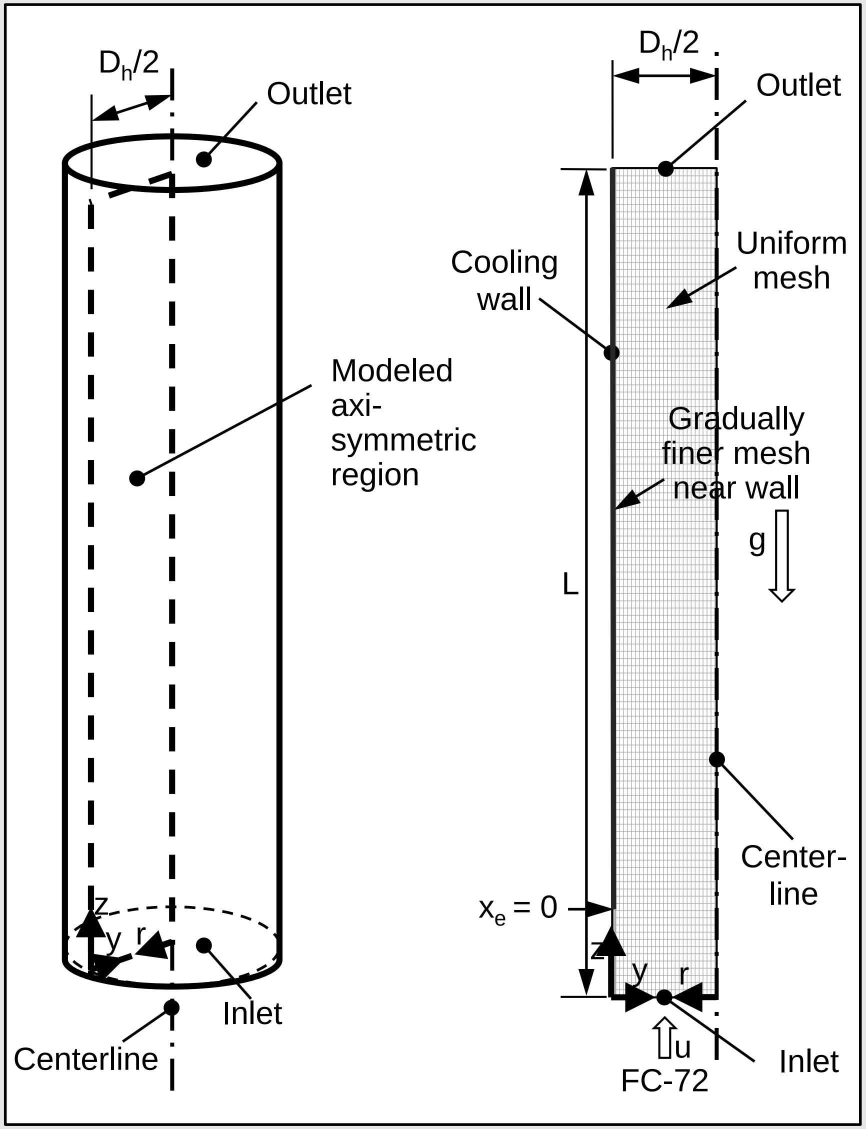
1. Ease of implementation
2. Successfully used for condensation processes

Cons:

1. Not applicable for subcooled boiling
2. Requires use of empirical coefficient r_i

Computational Domain, Governing Equations and Boundary Conditions

Computational Domain



Governing Equations

- **Continuity Equations**

- Liquid Phase:

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f\right) + \nabla \times \left(\alpha_f \rho_f \vec{u}_f\right) = \boxed{S_f}$$

- Vapor Phase:

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g\right) + \nabla \times \left(\alpha_g \rho_g \vec{u}_g\right) = \boxed{S_g}$$

Lee model (2008)

$$S_g = -S_f = r_i a_g r_g \frac{\left(T - T_{sat}\right)}{T_{sat}}$$

- **Momentum Equation**

$$\frac{\partial}{\partial t}\left(\rho \vec{u}\right) + \nabla \times \left(\rho \vec{u}\vec{u}\right) = -\nabla P + \nabla \times \left[\mu\left(\nabla\vec{u} + \nabla\vec{u}^T\right)\right] + \rho\vec{g} + \vec{F}$$

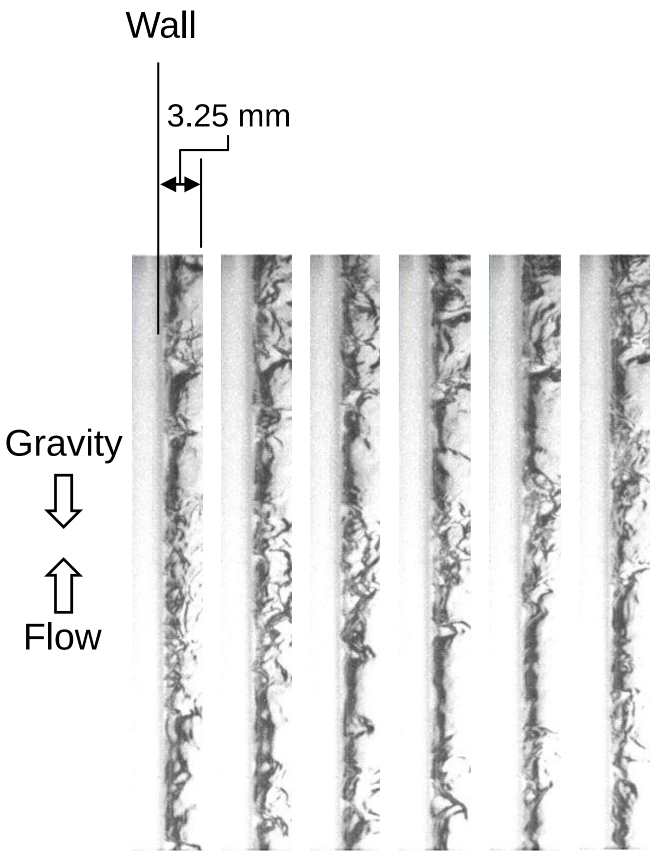
- **Energy Equation**

$$\frac{\partial}{\partial t}\left(\rho E\right) + \nabla \times \left(\vec{u}\left(\rho E + P\right)\right) = \nabla \times \left(k_{eff} \nabla T\right) + \boxed{Q} \Leftarrow Q = h_{fg} S_f$$

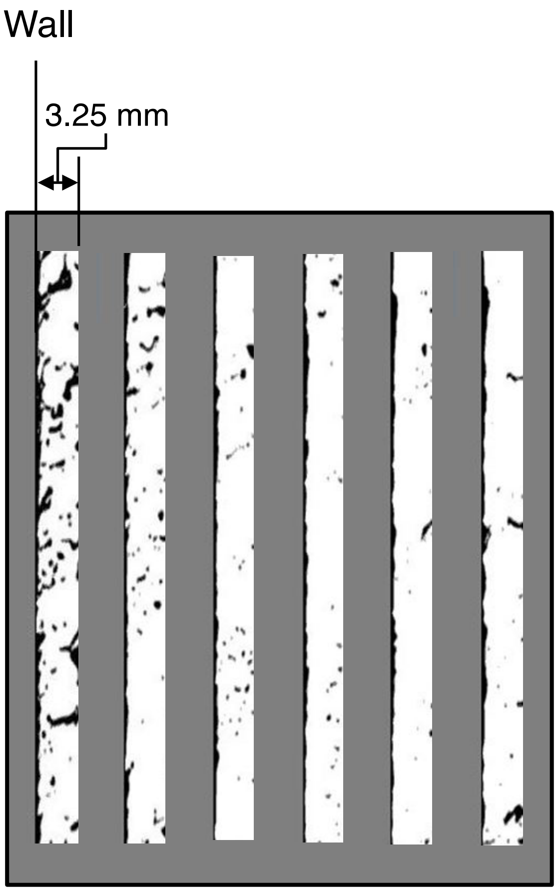
Boundary Condition

- **Axisymmetric centerline**
- ***k-ω SST* turbulence model**
- **Inlet uniform velocity from experimental data**
- **Wall heat flux from experimental data**

Void Fraction Results: Climbing Film Regime



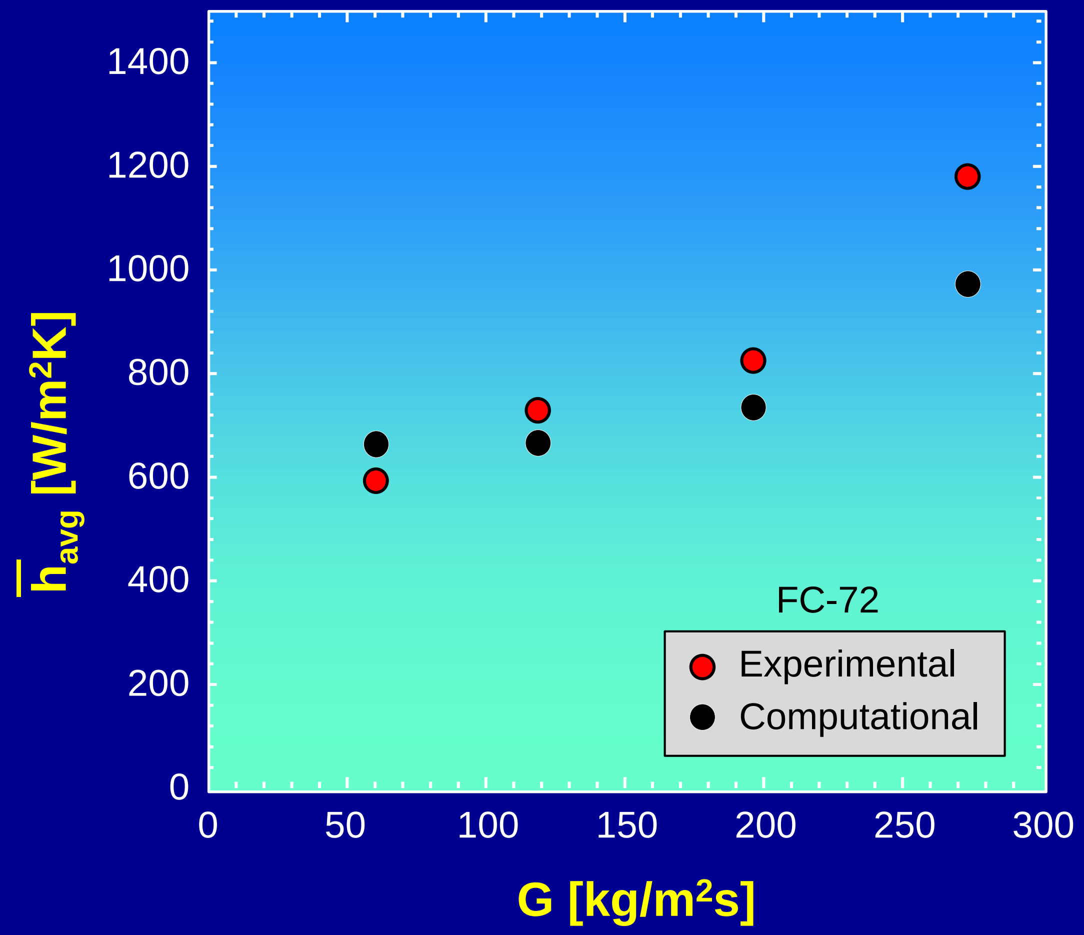
$G = 106.5$ kg/m^{2}s
$x_{e,in} = 1.16$



$G = 116.7$ kg/m^{2}s
$q''_{wall,avg} = -3.10$ W/cm^2
$x_{e,in} = 1.16$

Climbing film

Predictions of Average Heat Transfer Coefficient



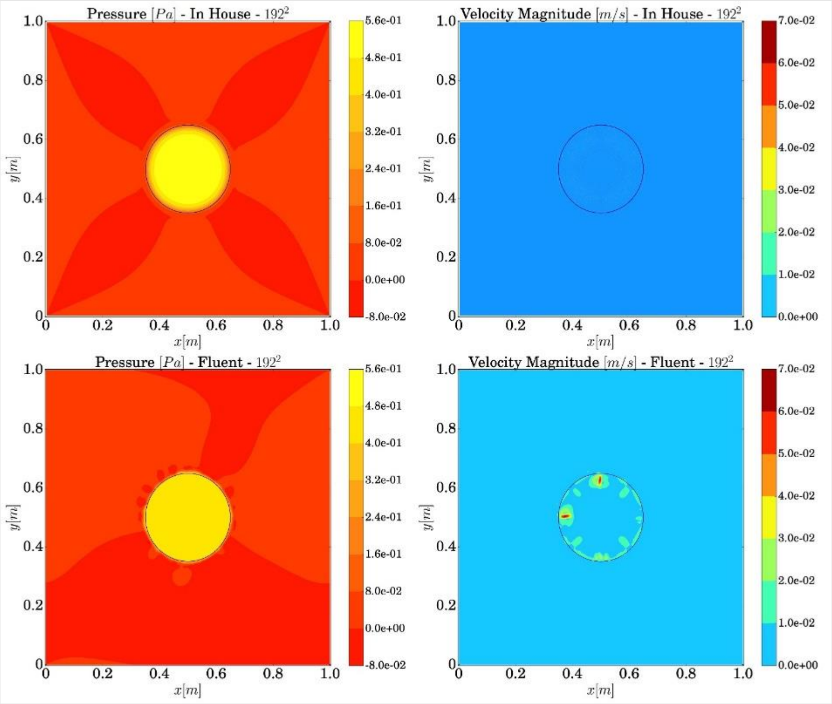
Future Computational Modeling

Need for Development of In-House Code

- Fluent is able to accurately replicate experimental results, but “tuning” necessary for phase change model means it is not a reliable predictive tool
- Difficult to work with Fluent because solver code is proprietary
- Fluent very robust and can tackle wide range of problems, making it slower than a dedicated research code
- Fluent does not utilize cutting edge multi-phase computational techniques

Current Work

Current Work



- **Working with Prof. Carlo Scalo's group at Purdue University to develop a 2-D code using best available computational techniques**
- **Performing comparisons with Fluent to quantify in-house solver performance**

Future Work

- **Use proposed 2-D code to run select cases which can be represented reasonably well by 2-D domains (e.g., axi-symmetric flow condensation, slug flow)**
- **Scale 2-D code up to 3-D, highly parallelized solver, which will include turbulence effects, to be run on Purdue supercomputing cluster**
- **Begin comparing data for transient cases with 3-D geometry to prior experimental studies**

Acknowledgements

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