Cryogenic Flow Boiling Parabolic Flight Experiment and Universal Correlations for Cryogens

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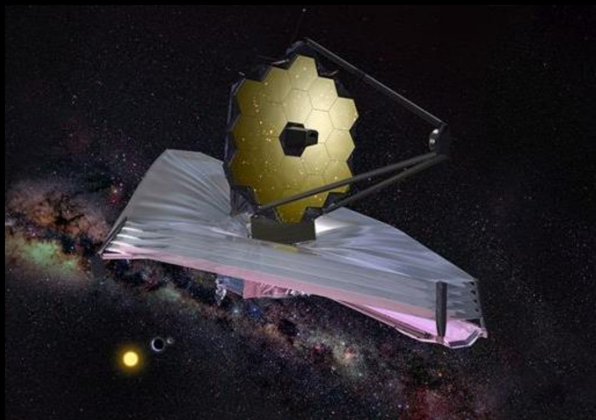
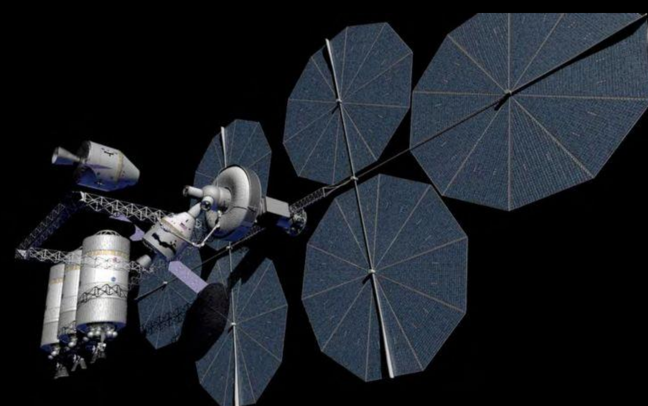
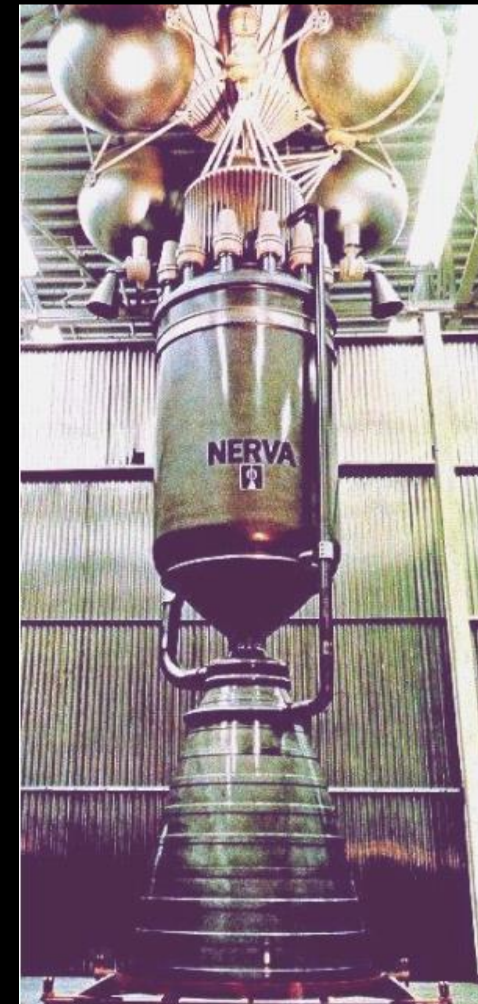
Space Applications of Cryogens



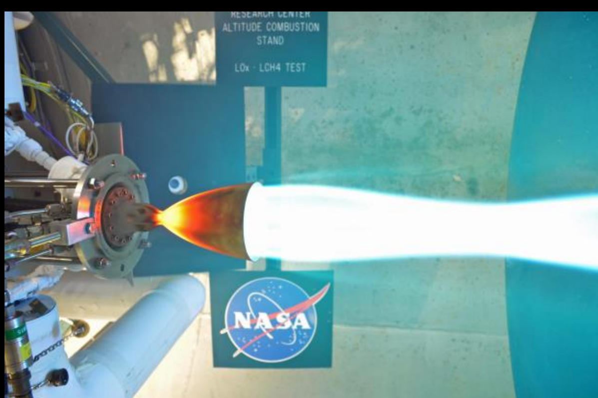
James Webb
Space Telescope
(LHe)



Orbital Refueling



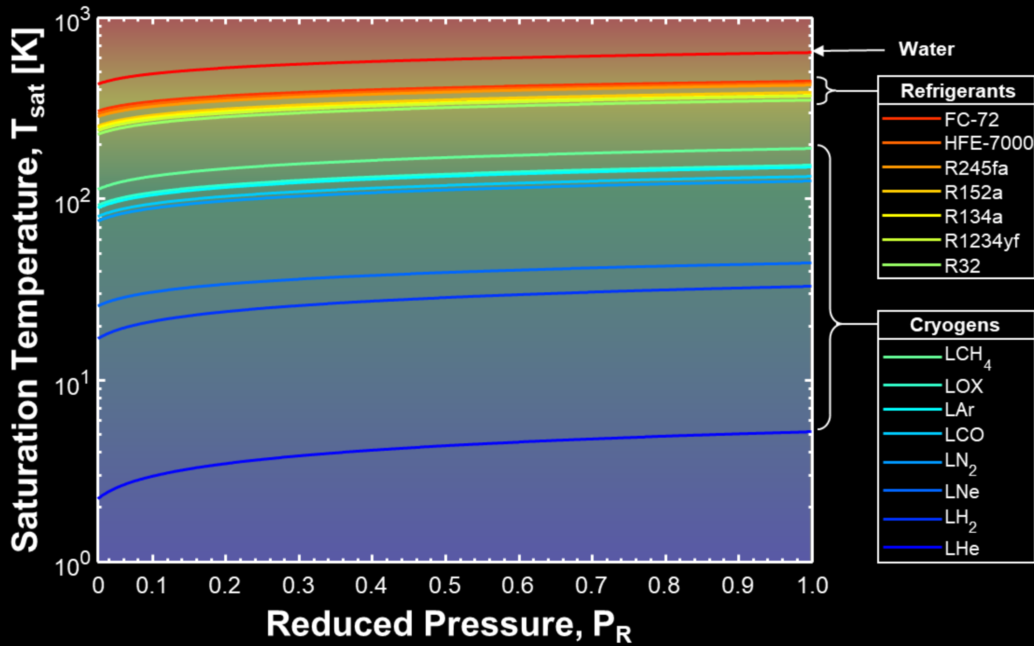
Nuclear Thermal
Propulsion Systems
(LH_2)



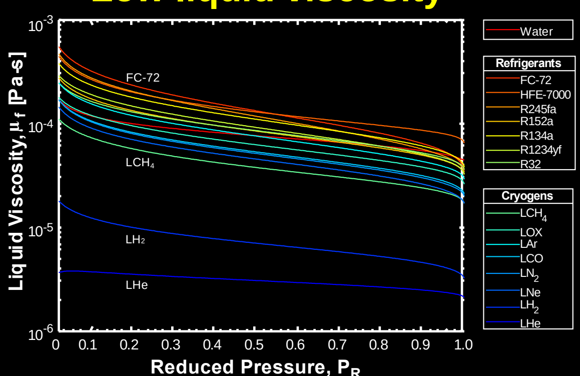
Propulsion and Cryogenics
Advanced Development
(PCAD) Project
(LOX/LCH_4)

Unique Characteristics of Cryogens

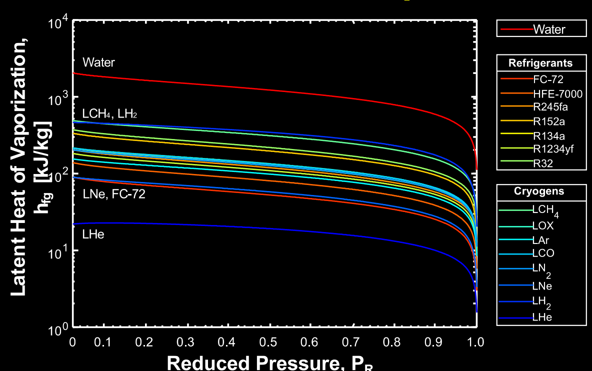
Very low saturation temperature



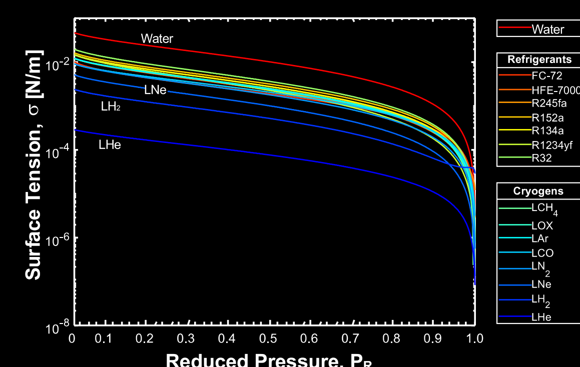
Low liquid viscosity



Low latent heat of vaporization



Low surface tension

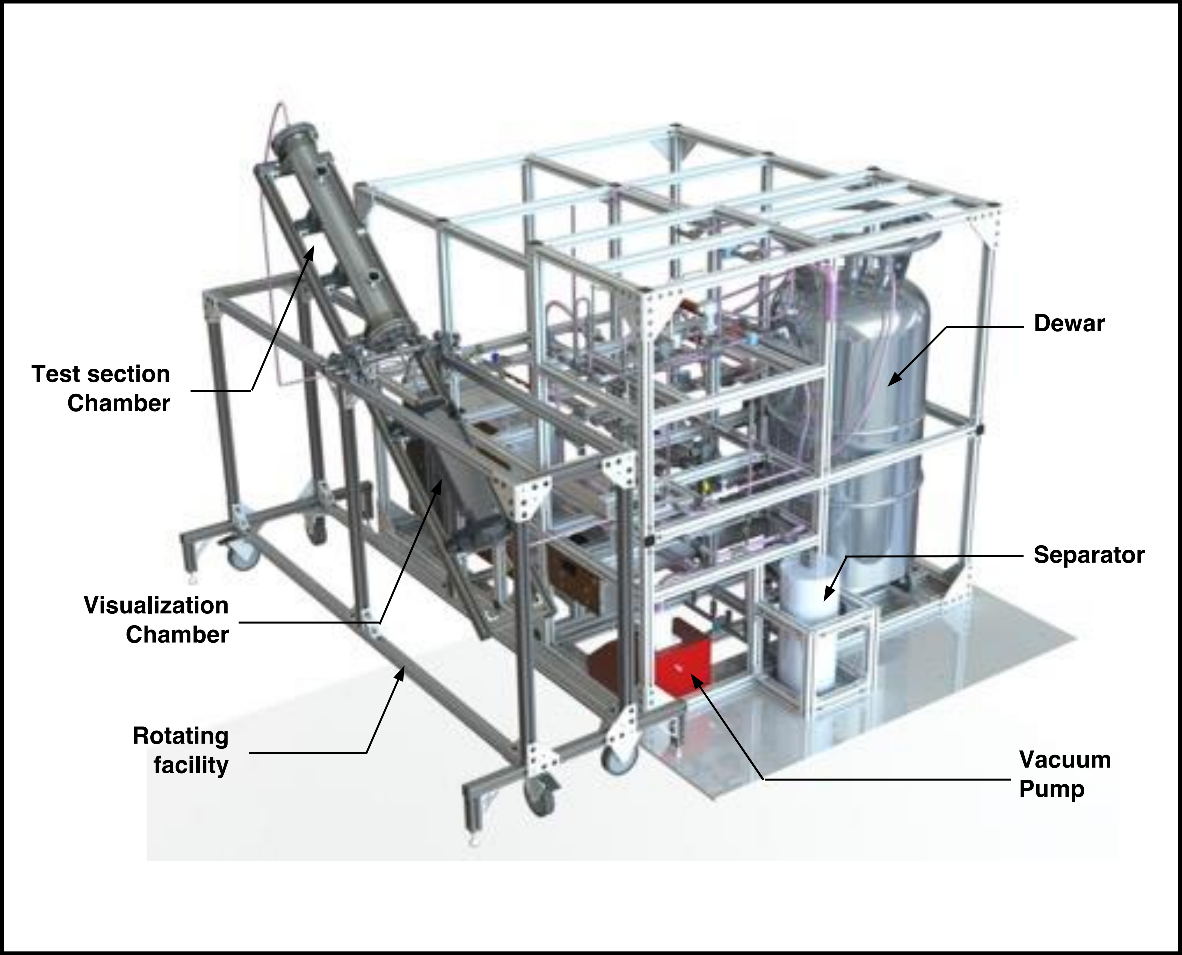


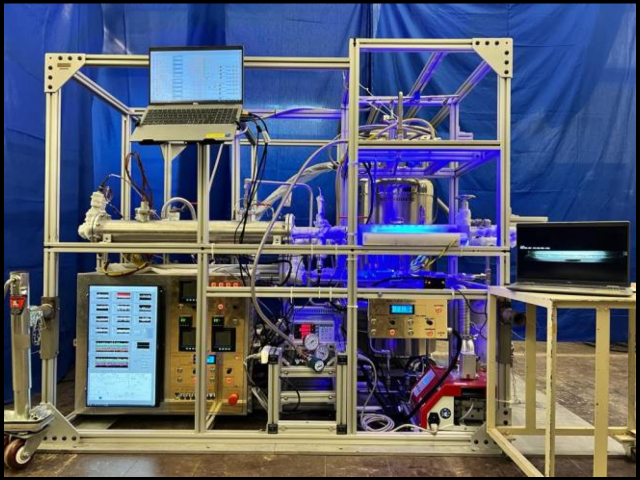
PU-BTPFL Cryo Projects

PU-BTPFL CRYO Projects

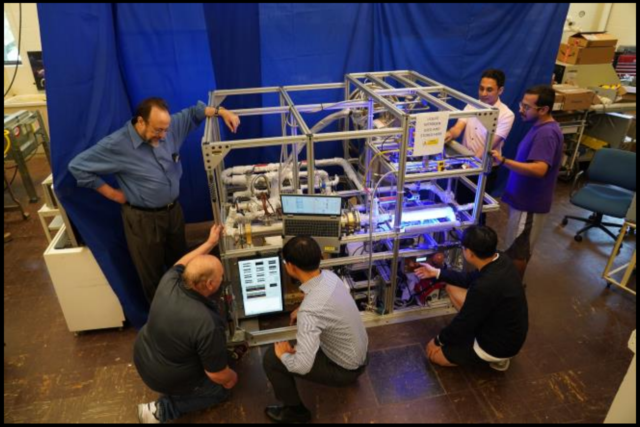
#	Project Title	Project Duration
1.	Cryo Heated tube flow boiling I → Parabolic flight (5 flight days)	Jan. 2021 – Jan. 2023
2.	Cryo Heated tube flow boiling II → Flight Extension (4 flight days)	Oct. 2023 – Oct. 2024
3.	Cryo Pool boiling → Ground Exp.	June. 2023 – Nov. 2023
4.	Cryo Spray cooling → Ground Exp.	Mar. 2023 – Mar. 2025
5.	Cryo Spray cooling – Flight Exp → Parabolic flight (5 flight days)	Mar. 2023 – Mar. 2025

CAD of Test Rig with Rotating Platform

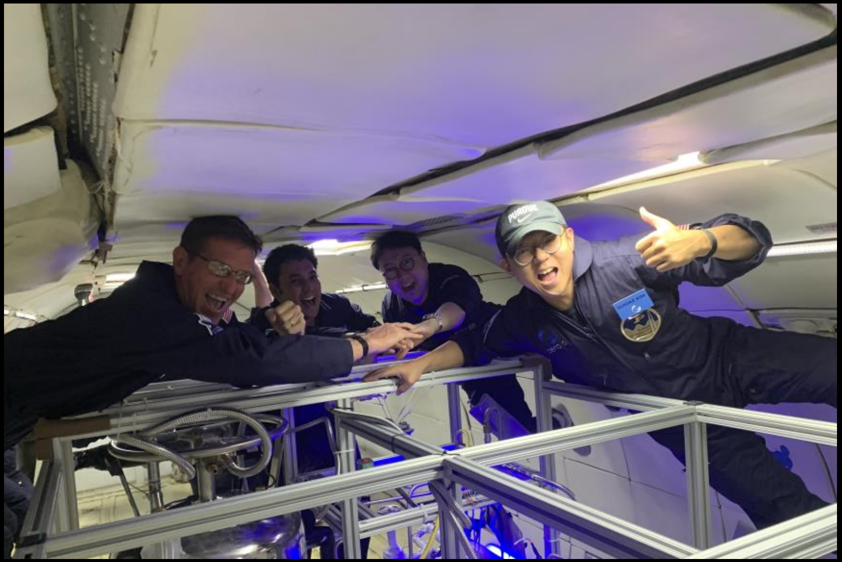




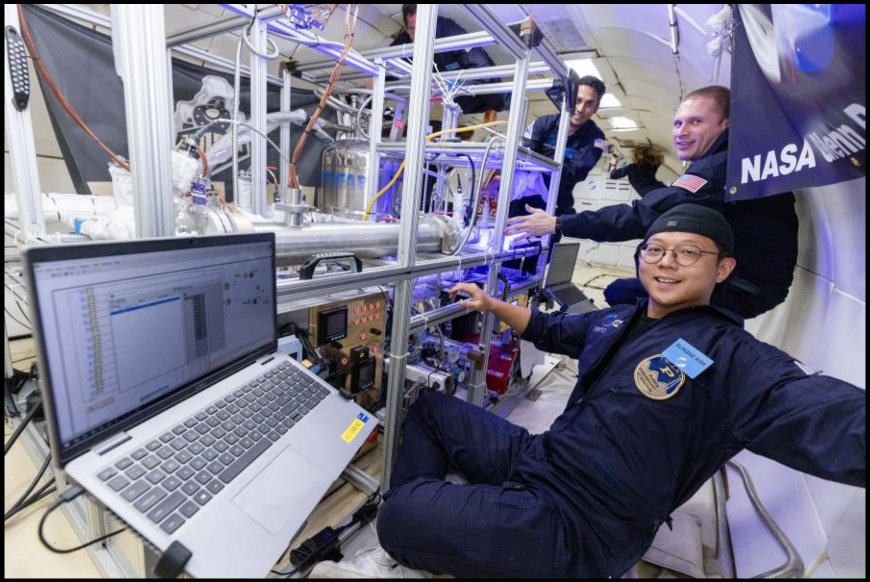
Constructed Flight Rig

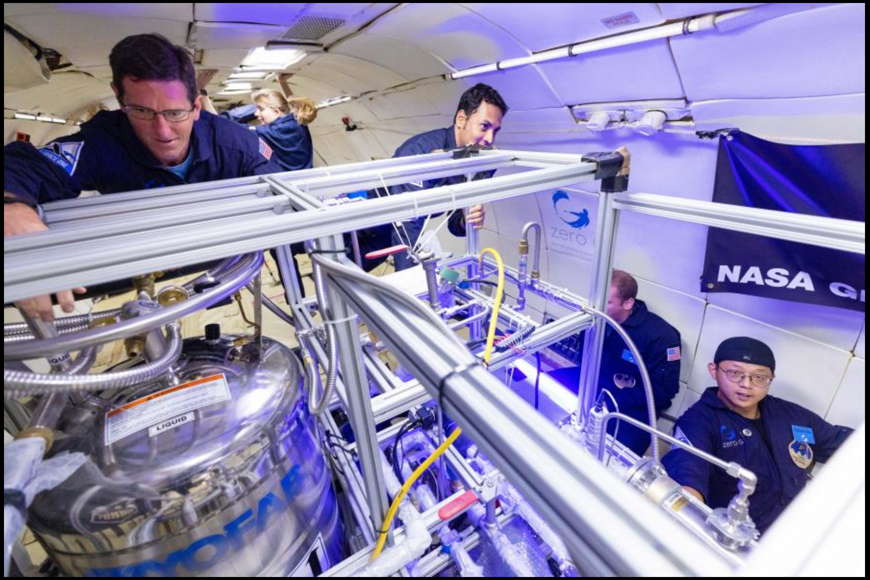


June 2022 Flight Experiments

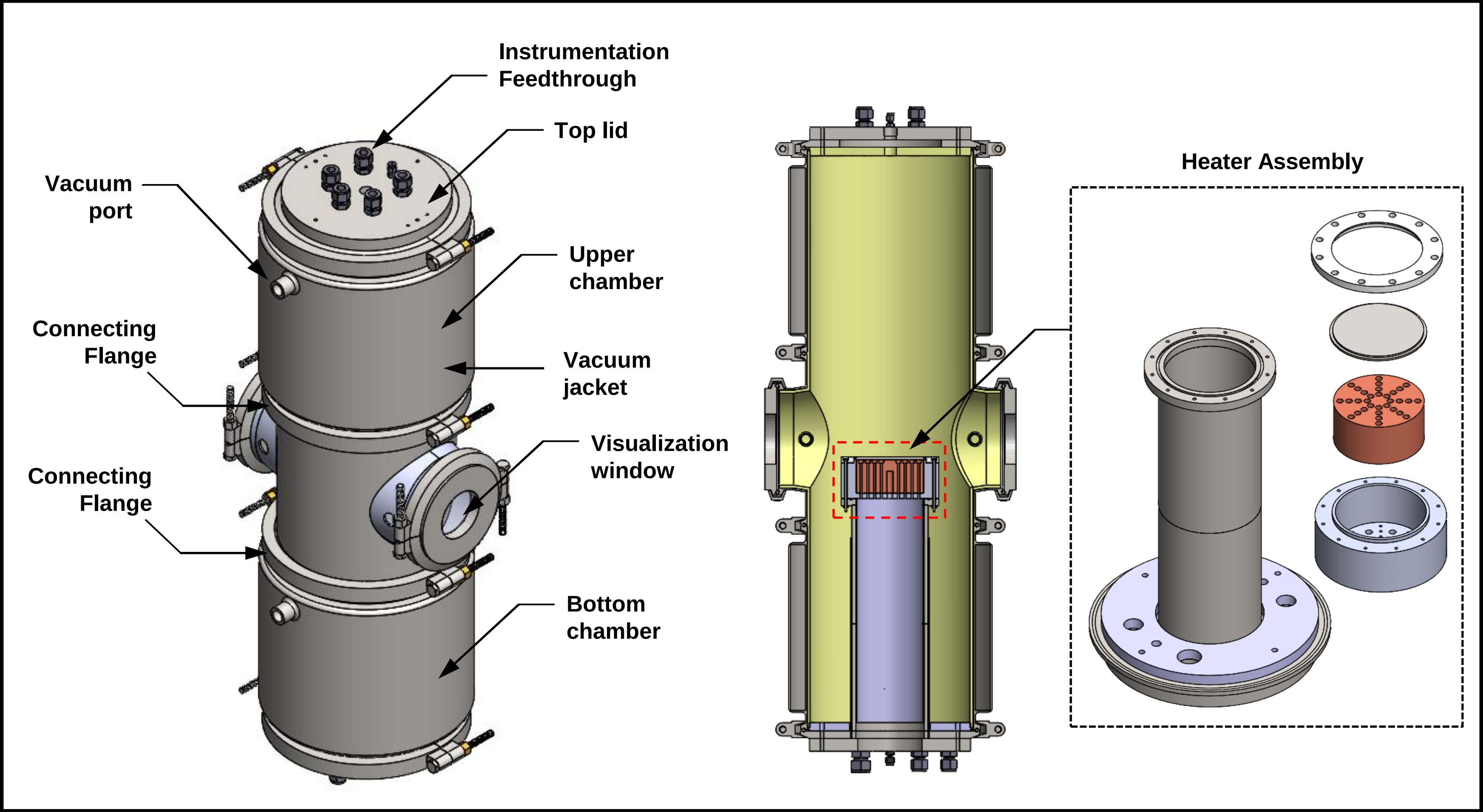


Nov. 2022 Flight Experiments





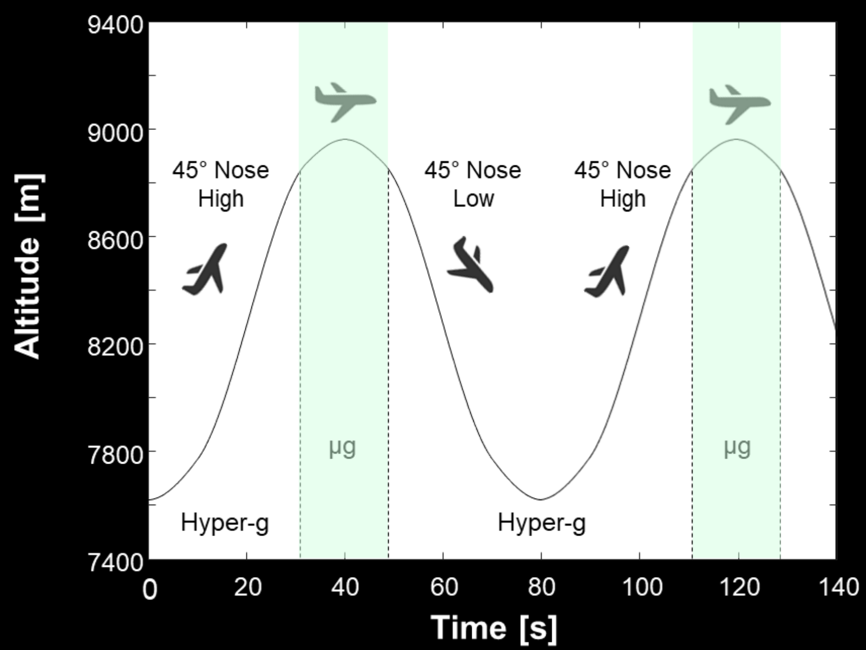
Pressure Chamber Design



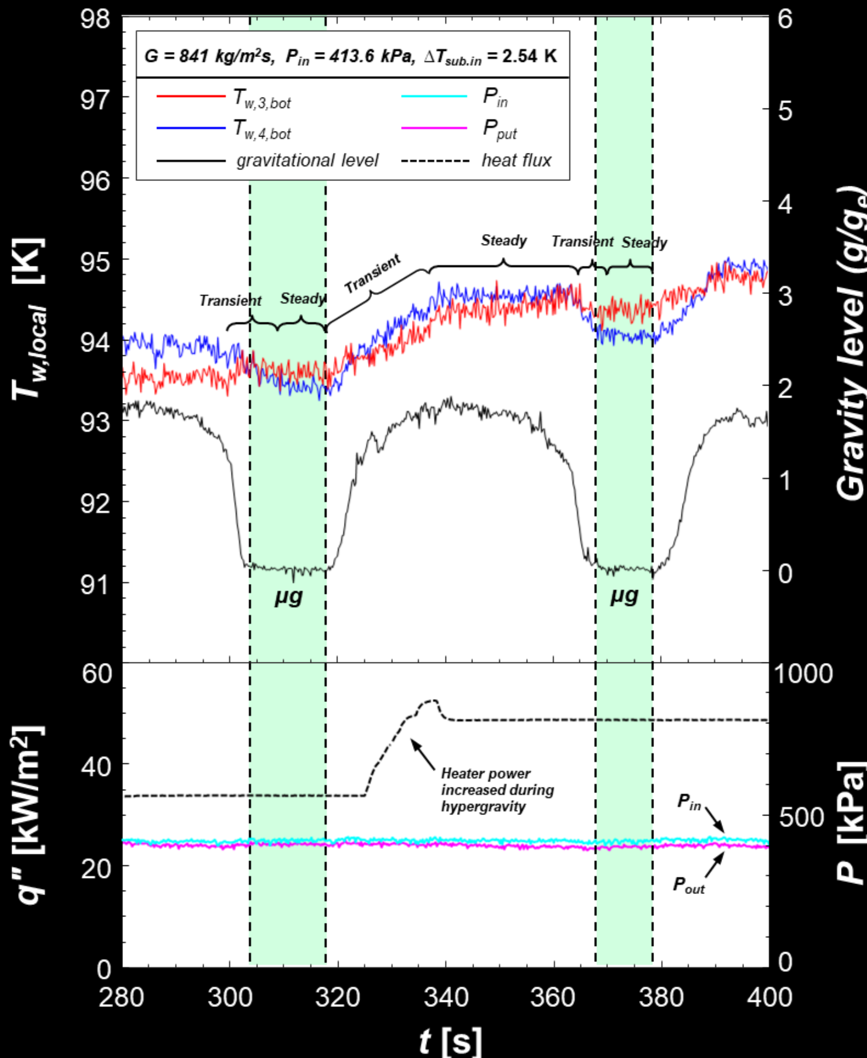
Experimental Results

1. Microgravity LN_2 Flow Boiling

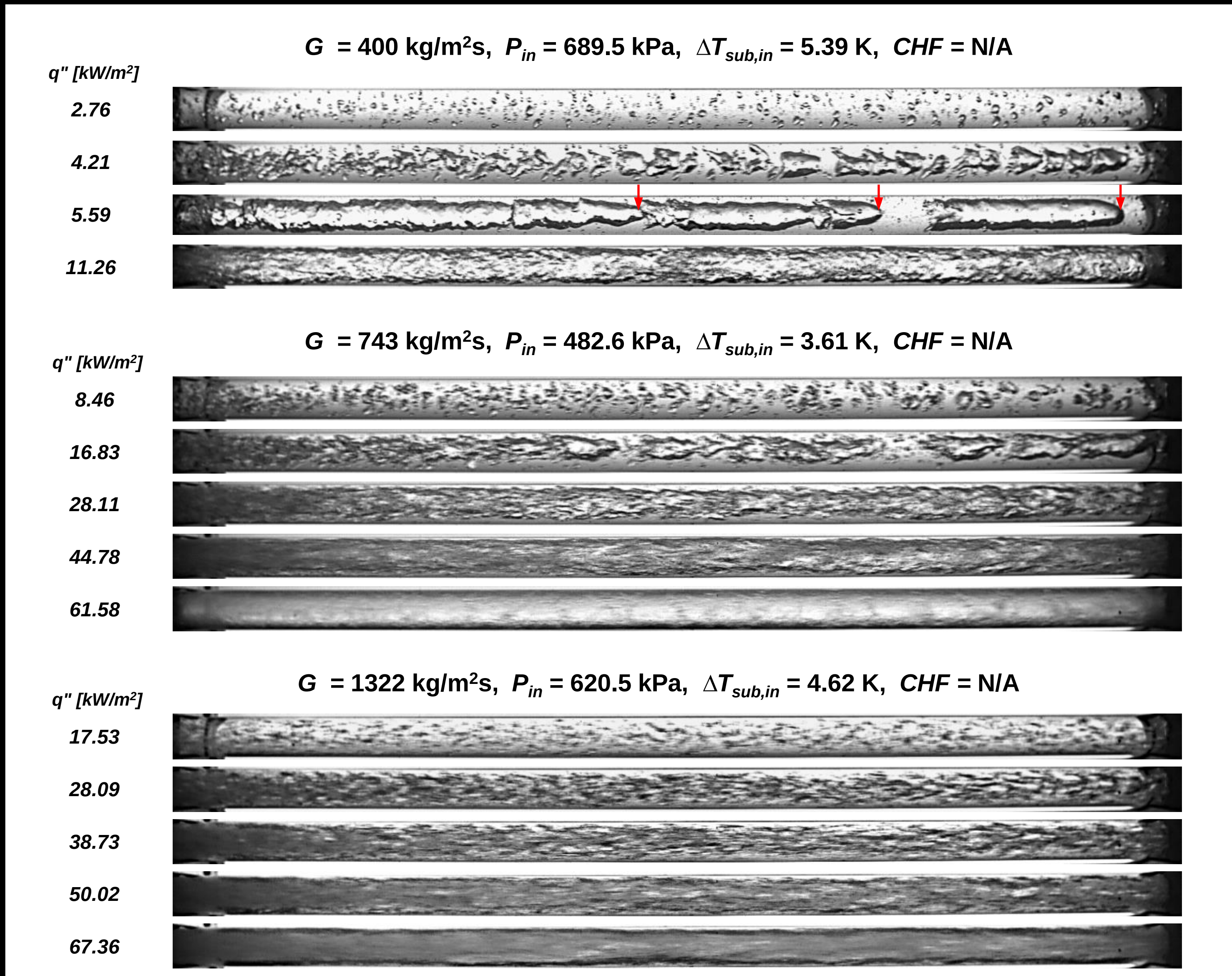
Parabolic flight projectile



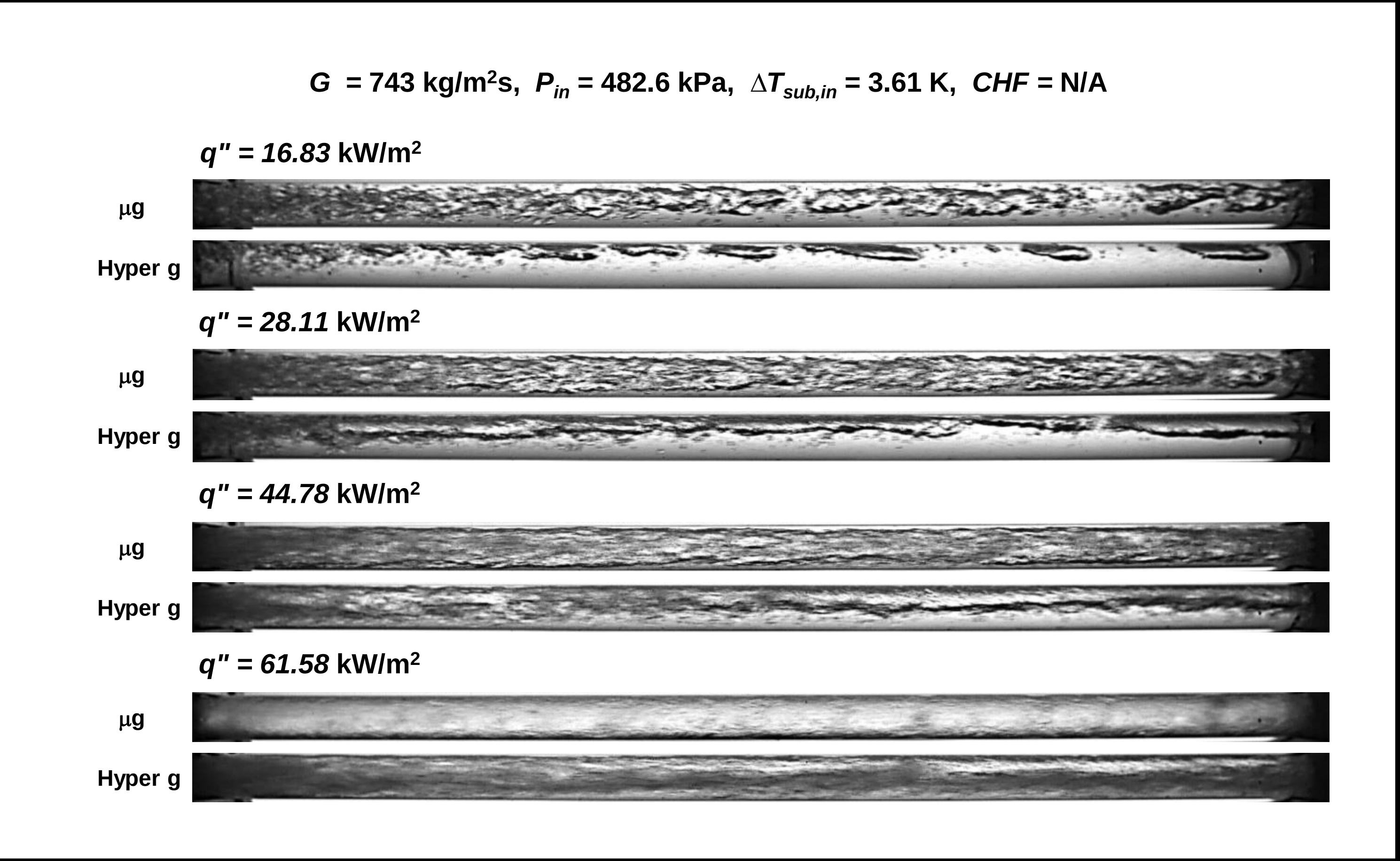
Transient dynamics of measured parameters



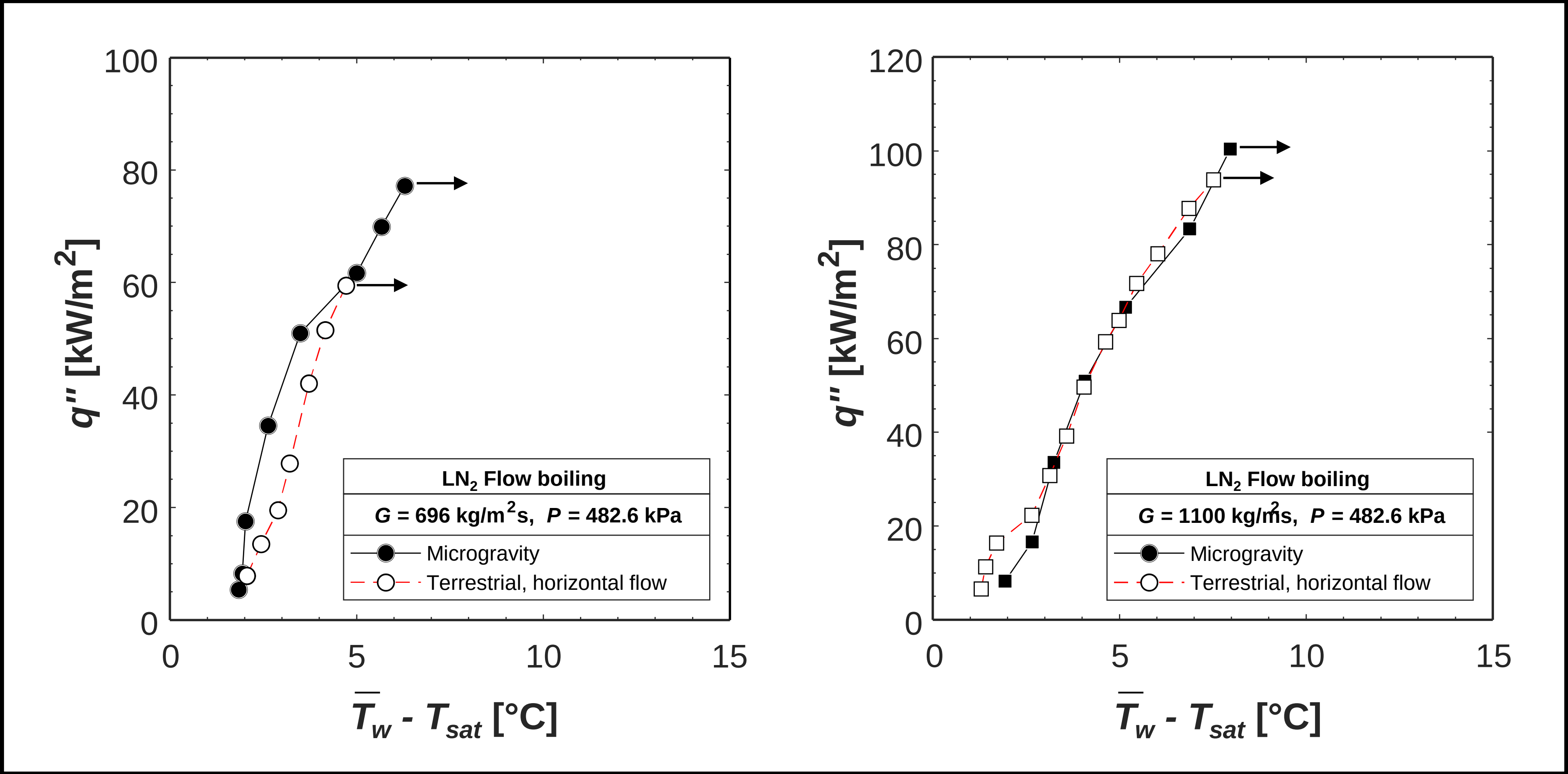
Flow Visualization Results : Microgravity



Effect of gravity on interfacial flow pattern

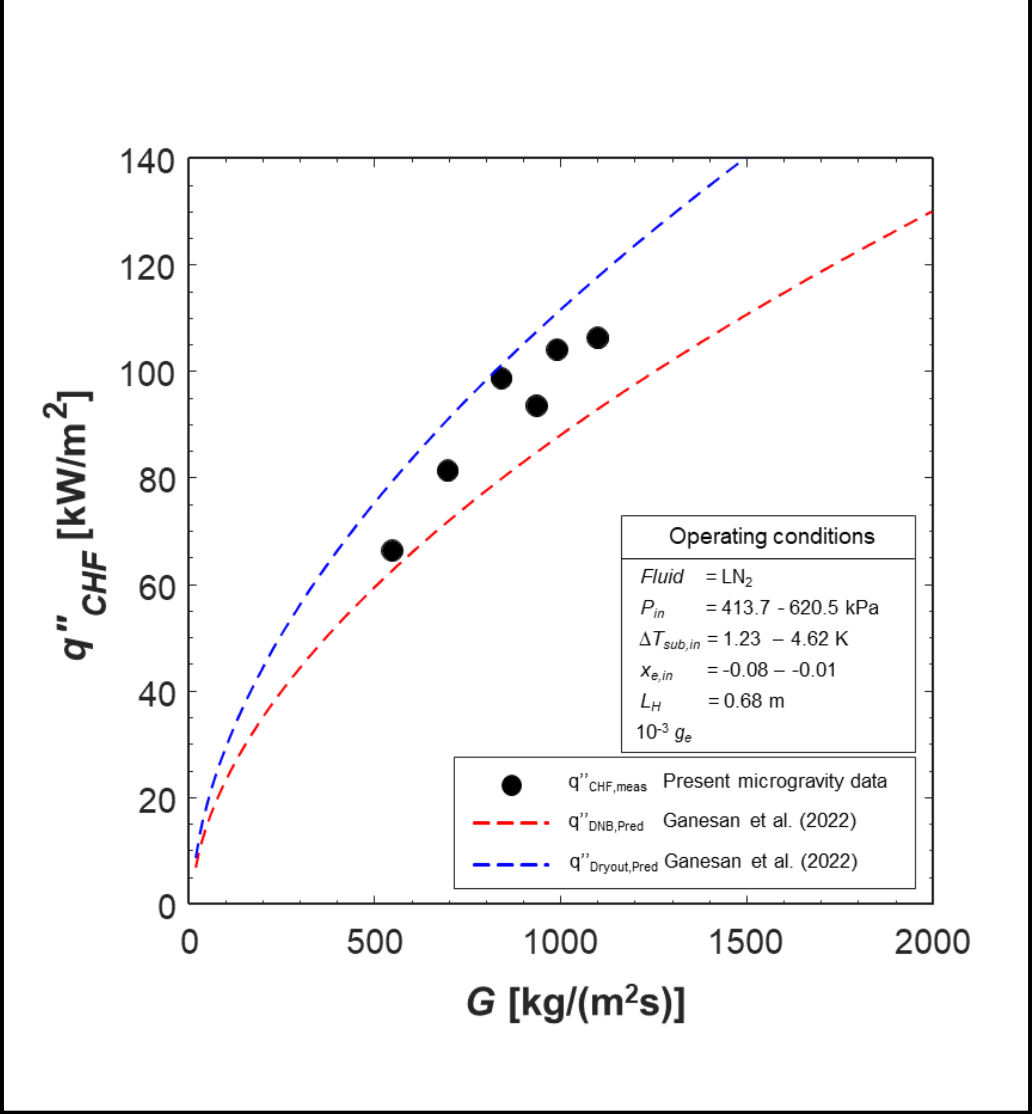


Effect of gravity on boiling curve



- Lower wall superheat in low heat flux range in microgravity due to flow symmetry
- Merging of boiling curves at high mass velocity due to dominating effect of flow inertia over gravity
- Larger CHF in microgravity compared to 1-g_e horizontal flow; due to symmetrical flow pattern in *μg*

Microgravity CHF



Measured μg CHF

- CHF Mechanism : annular liquid dryout
- CHF increases with *G*
- CHF tend to level-off as *G increases*
- Requires more *μg* CHF for high G

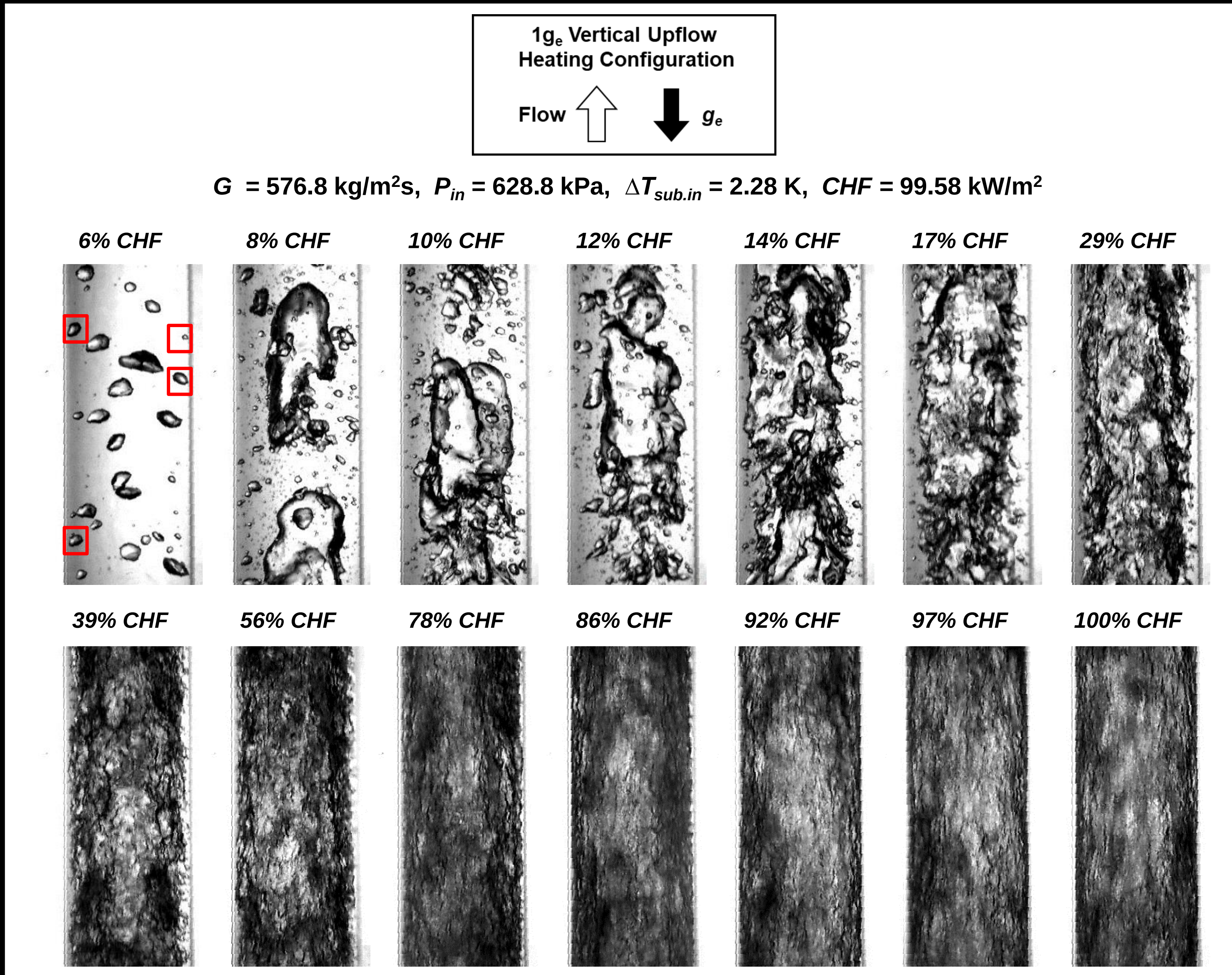
Predictions by CHF correlations

- CHF correlation by Ganesan et al. (2022)
- Dryout & DNB correlations
- *μg* CHF is predicted with decent accuracy

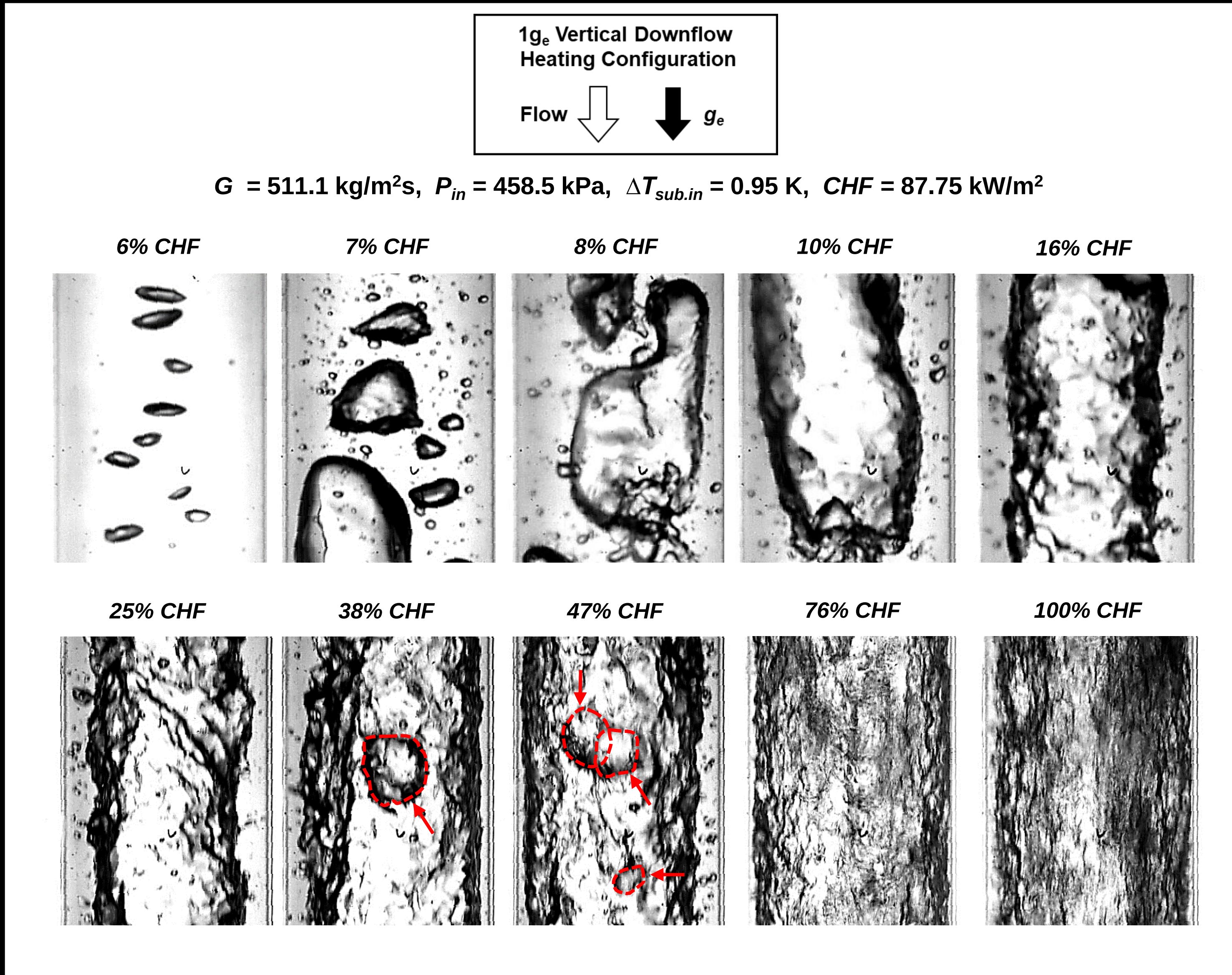
Experimental Results

2. Terrestrial LN_2 Flow Boiling

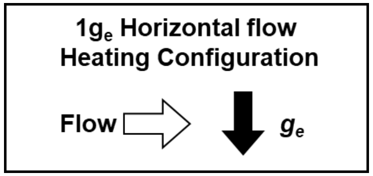
Flow Visualization Results : 1-g_e Vertical Upflow



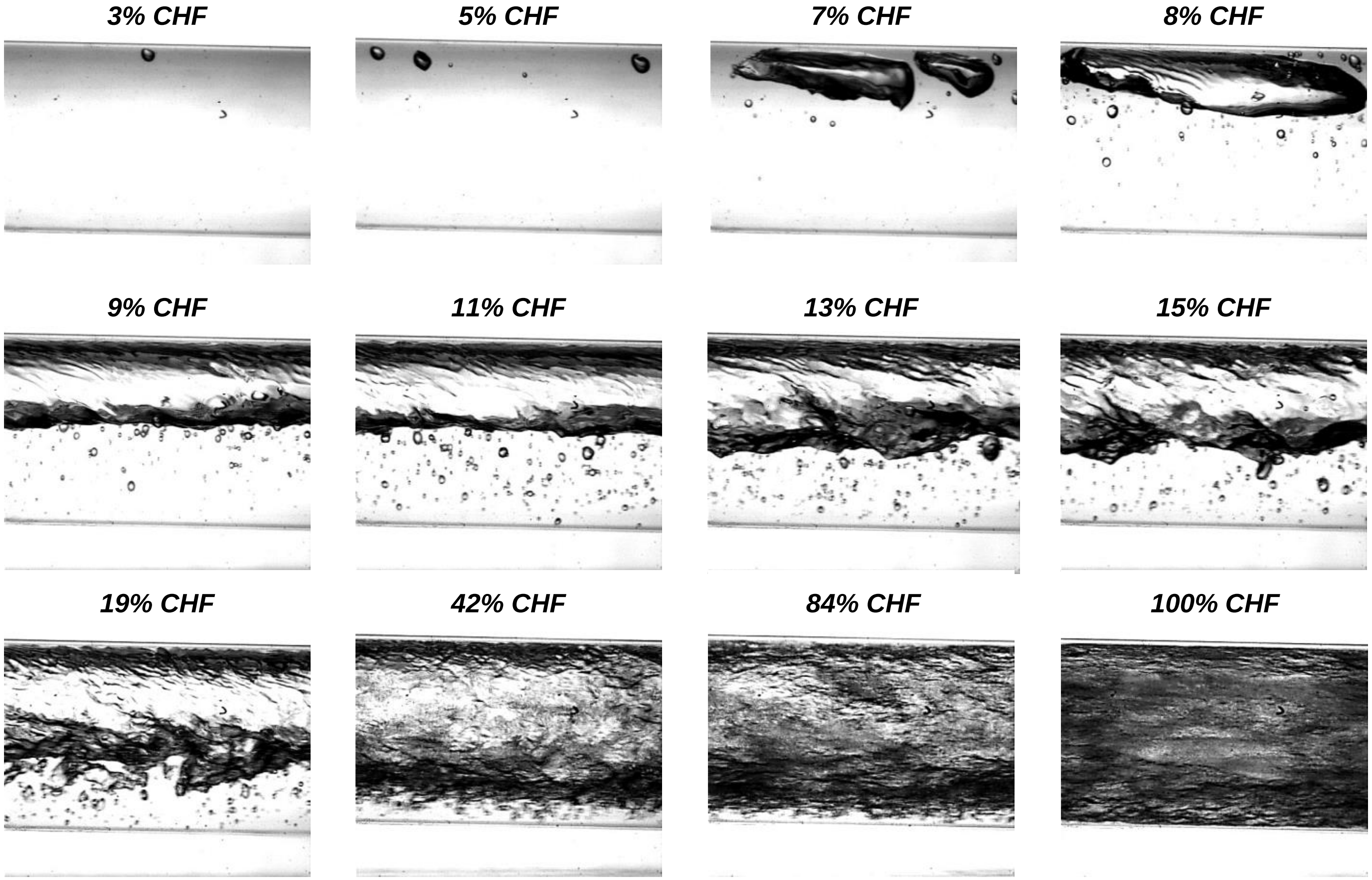
Flow Visualization Results : 1-g_e Vertical Downflow



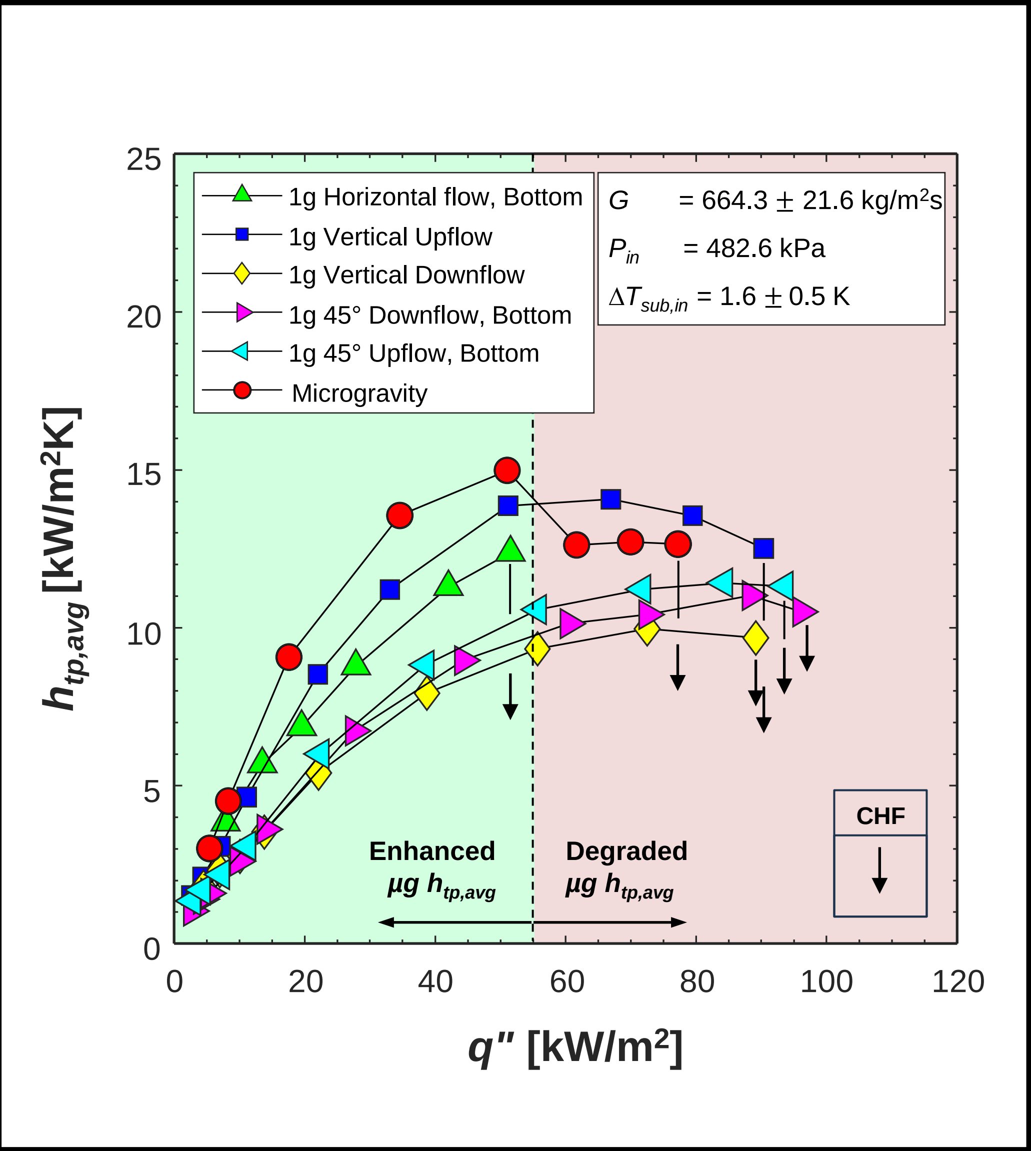
Flow Visualization Results : 1-g_e Horizontal Flow



G = 544.9 kg/m²s, P_{in} = 356.6 kPa, $\Delta T_{sub,in}$ = 1.89 K, CHF = 91.67 kW/m²



Heat transfer coefficient, h_{tp}



$$h_{nb} = hpb * S$$

$h_{pb} = f(q'')$: As q'' ↑ h_{pb} ↑

$S = f(G, xe)$: As q'' ↑ x_e ↑ S ↑

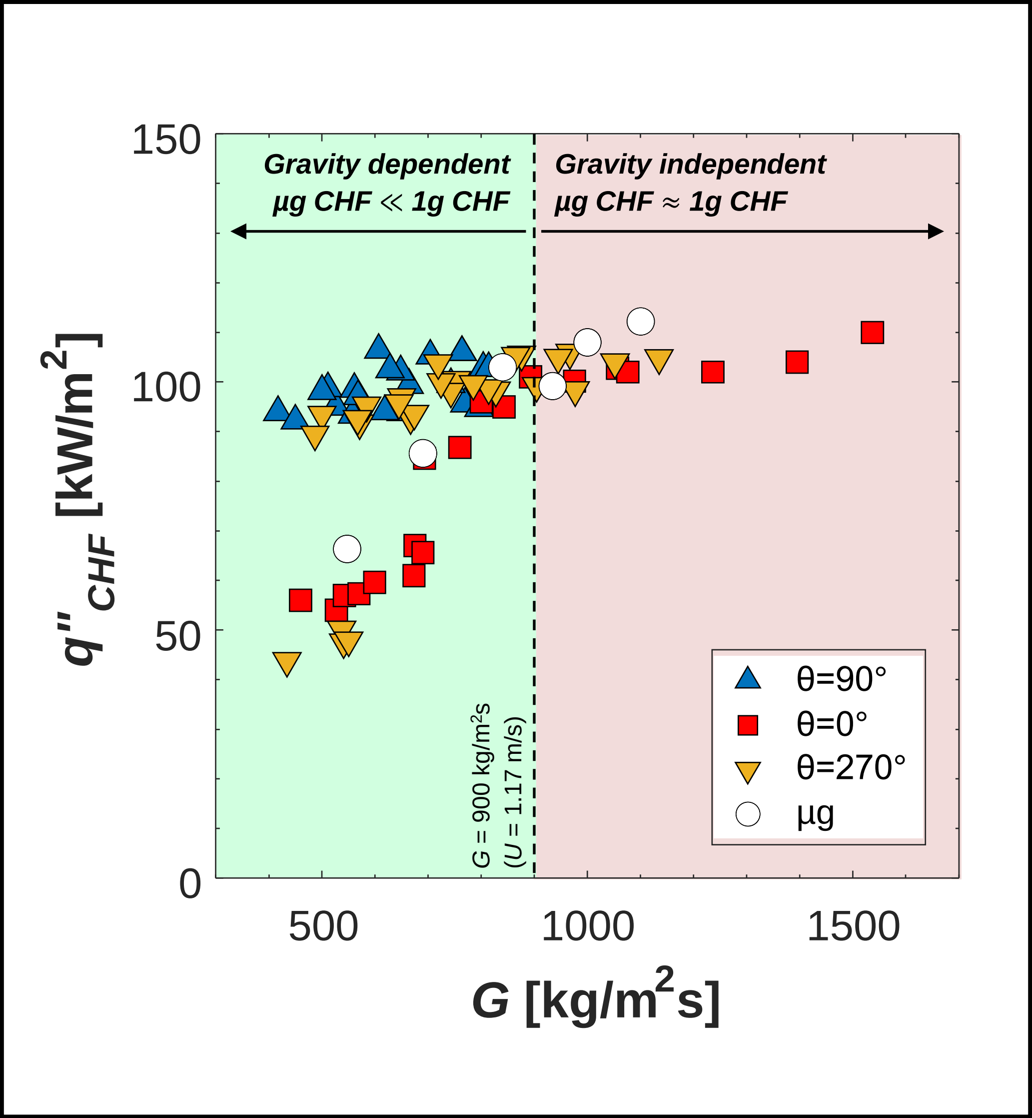
HTC trend by flow orientation

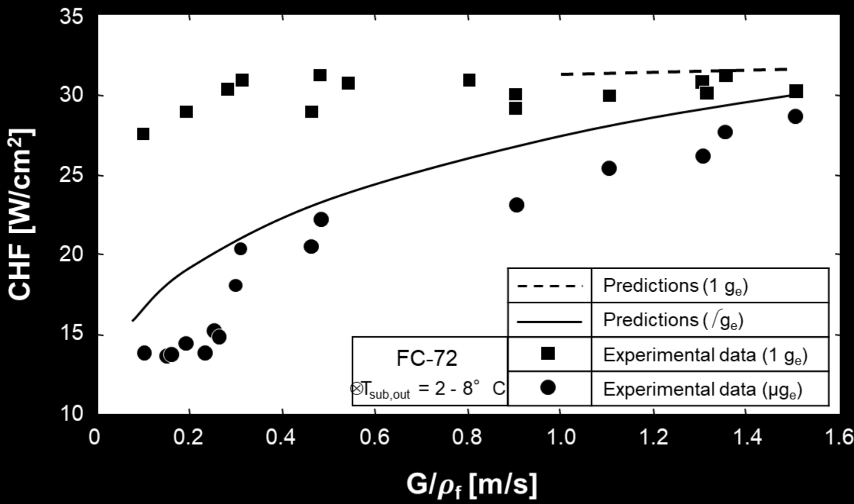
- μg > vertical up > horizontal > vertical down
- 45 inclined orientations very similar to each other

HTC trend by q''

- Steep increase of HTC from low *q''* to medium *q''*
  - → *Nucleate Boiling Dominant*
  - → *PDB to FDB to Saturated Boiling*
- Sustaining HTC over high q'' range
  - → *Suppression of N.B.*
  - → *Aggressive bubble departure leading to increased mixing and turbulence effect causing decreased wall superheat*

Gravity effect on CHF



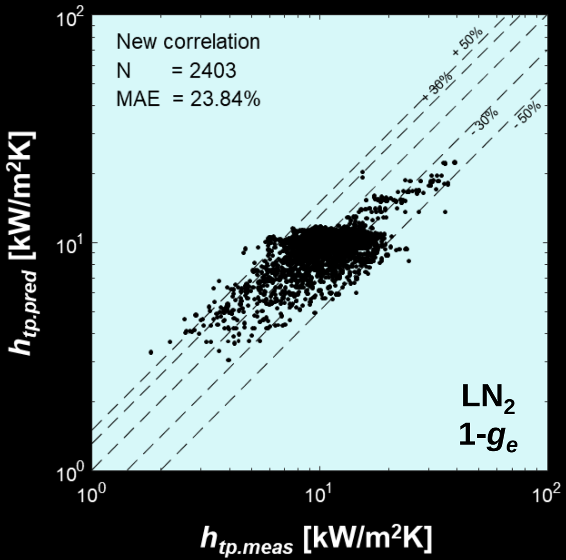


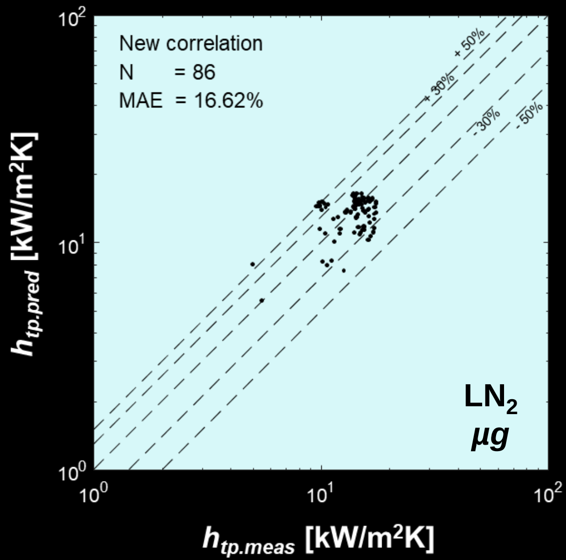
CHF trend

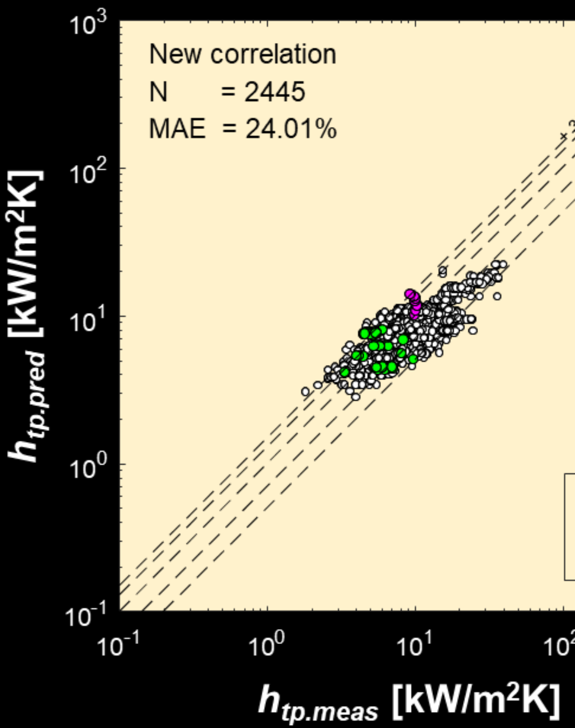
- Increasing CHF with increasing *G*
  - → *Effect of flow inertia*
  - → *Stagnation at high G*
- Body force effect on CHF
  - → *Microgravity CHF << 1g vertical upflow CHF*
  - → *Microgravity CHF ≈ 1g horizontal CHF*
  - → *Stronger gravity influence at low G*
  - → *Gravity independent at G higher than 900 kg/m²s*

Universal Correlations

Newly developed Saturated HTC correlation







$IF\ PR < 0.41$

$$h_{NB} = h_{PB} \cdot \left[1.36 \cdot tanh\left(\frac{g_e}{g}\right)\right] \cdot \left[\frac{1}{1 + 10^3 \cdot \exp(Bo^2 We)}\right]^{0.475}$$

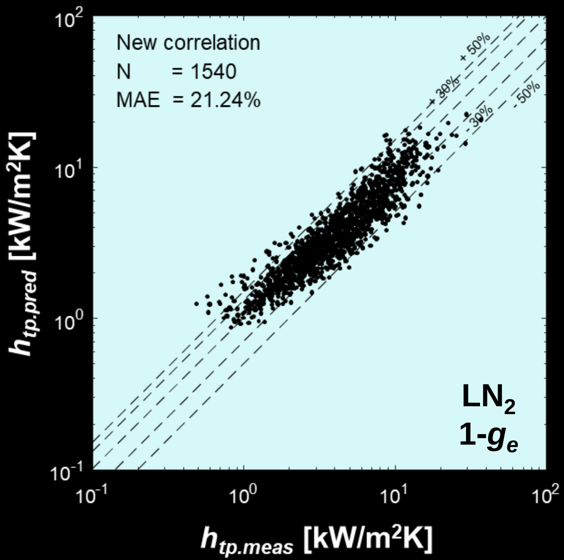
$IF\ PR \geq 0.41$

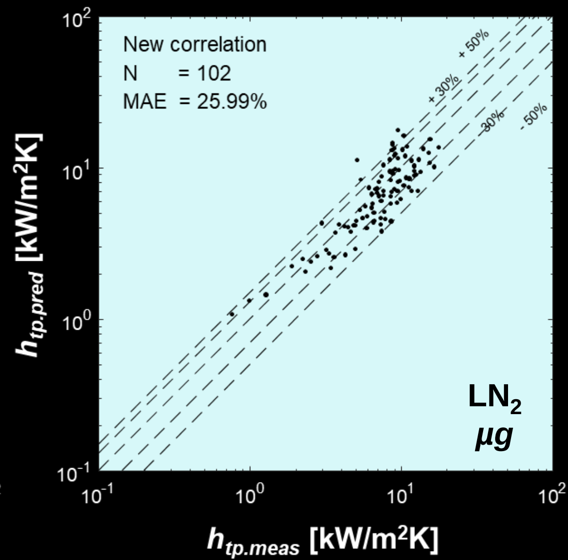
$$h_{NB} = h_{PB} \cdot \left[1.2 \cdot tanh\left(\frac{g_e}{g}\right)\right]$$

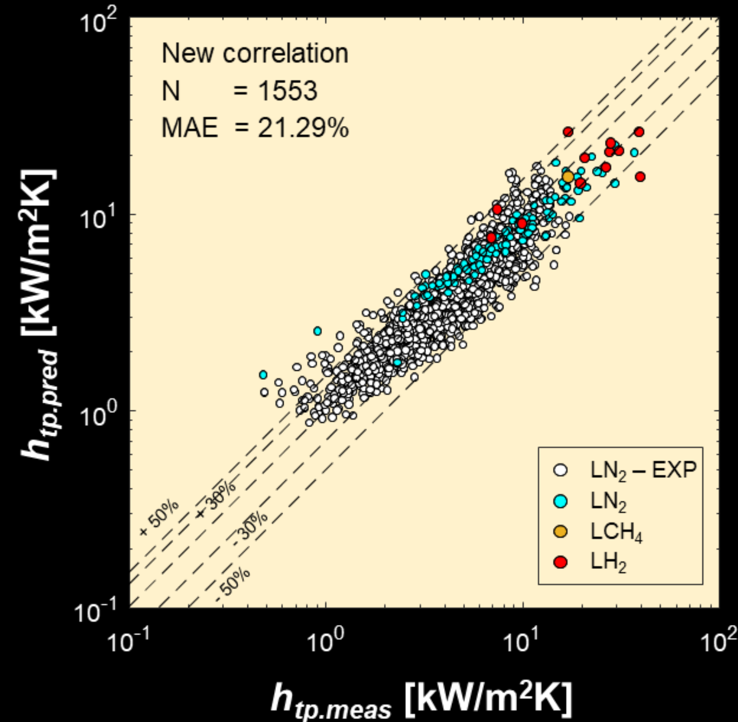
$$h_{CB} = h_{sp} \cdot 7 \cdot \left(\frac{1}{X_{tt}}\right)^{0.39} \cdot \left(\frac{\rho_f}{\rho_g}\right)^{-0.34}$$

$$h_{tp} = \left[{h_{NB}}^2 + {h_{CB}}^2\right]^{1/2}$$

Newly developed Subcooled HTC correlation







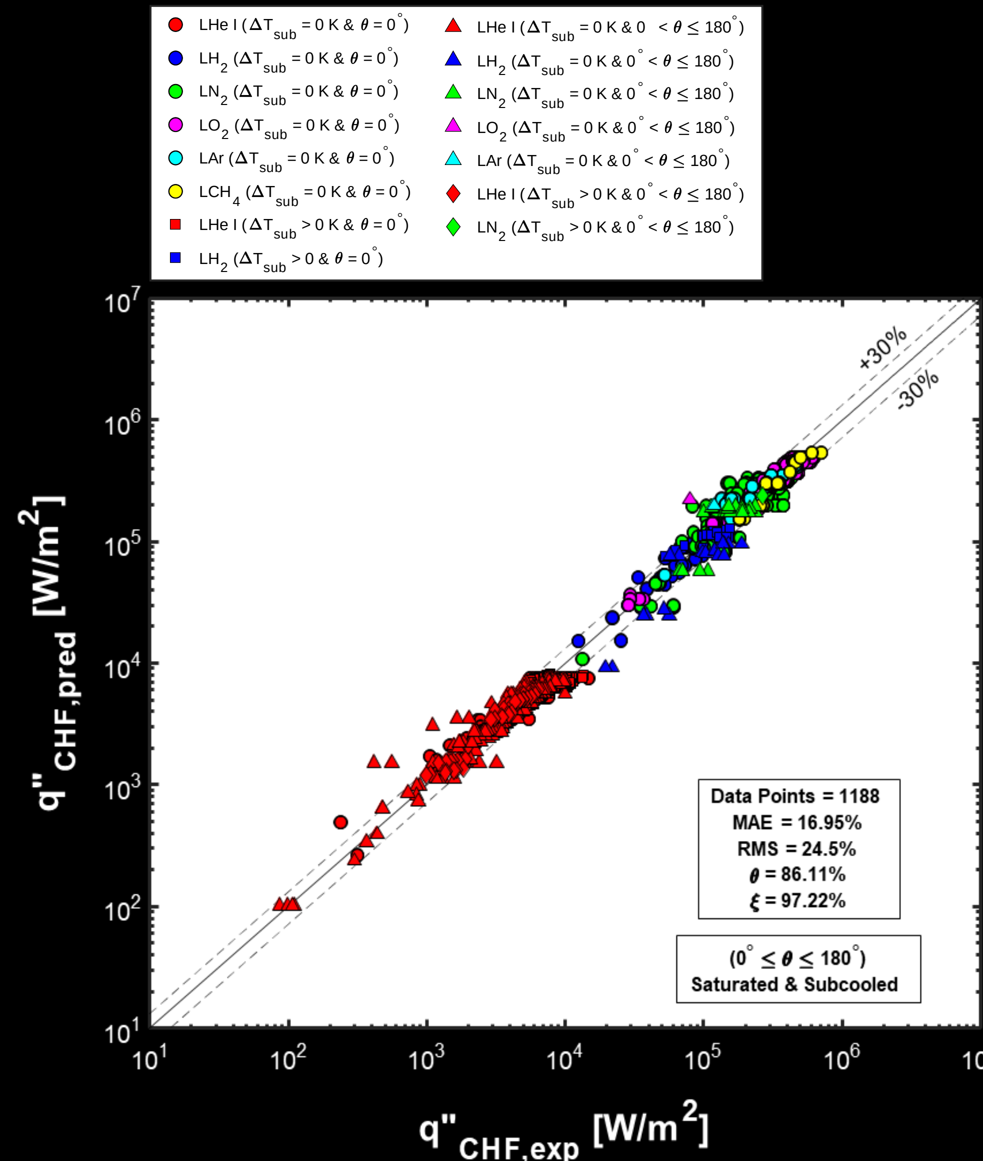
$$\frac{h_{tp}}{h_{sp}} = 6.58Bo^{0.68}(0.1 + Ja^{**})^{-1.3}\left(\frac{\rho_g}{\rho_f}\right)^{-0.4} Pr_f^{0.46}\left(\frac{\bar{M}_{LN_2}}{\bar{M}}\right)^{0.42}$$

$$h_{sp} = \frac{(4f_{sp}/8)(Re_{fo,D} - 1000)Pr_f}{1 + 12.7(4f_{sp}/8)^{0.5}(Pr_f^{2/3} - 1)} \cdot \left(\frac{k_f}{D}\right)$$

↑ *Gnielinski correlation*

Newly developed Pool boiling CHF correlation

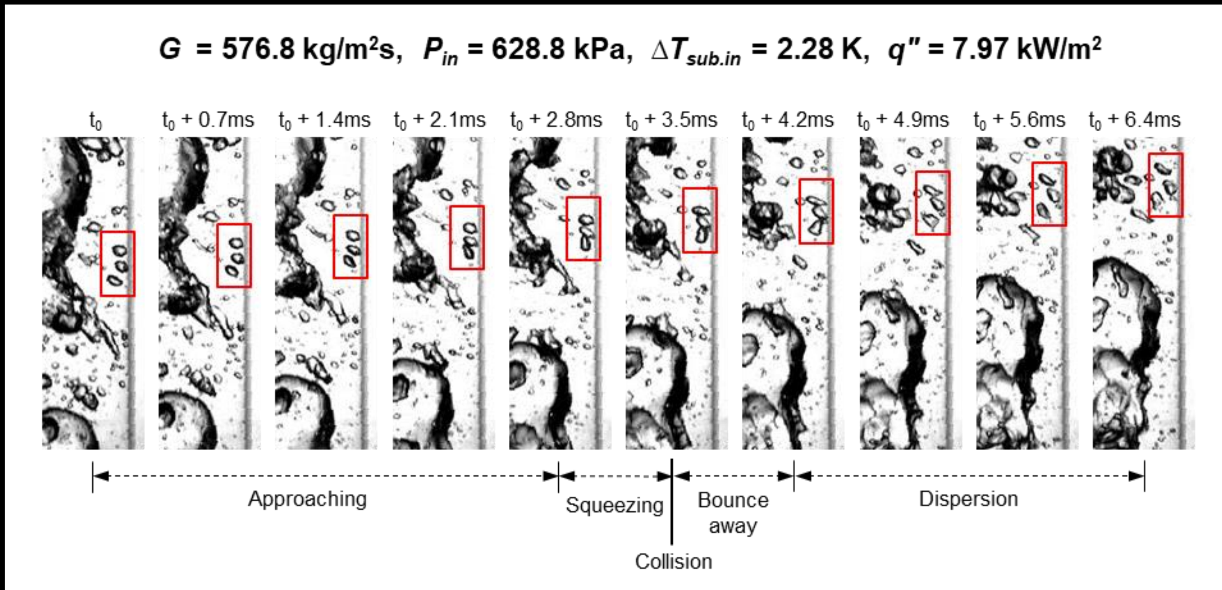
$$q''_{CHF} = \left[0.16 - 0.104\left(\frac{P}{P_c}\right)^{10}\right]$$
$$\times\left[1 - 0.004\left(\frac{P}{P_c}\right)\theta\right]\left|cos\left(\left(\frac{88}{180}\theta\right)\right)\right|^{0.364}$$
$$\times\left[1 + 0.16\left(\frac{c_{p,f}\Delta T_{sub}}{h_{fg}}\right)\right]$$
$$\times\left[\rho_g h_{fg}\left(\frac{\sigma(\rho_f-\rho_g)}{\rho_g{}^2}\right)^{0.25}\right]$$



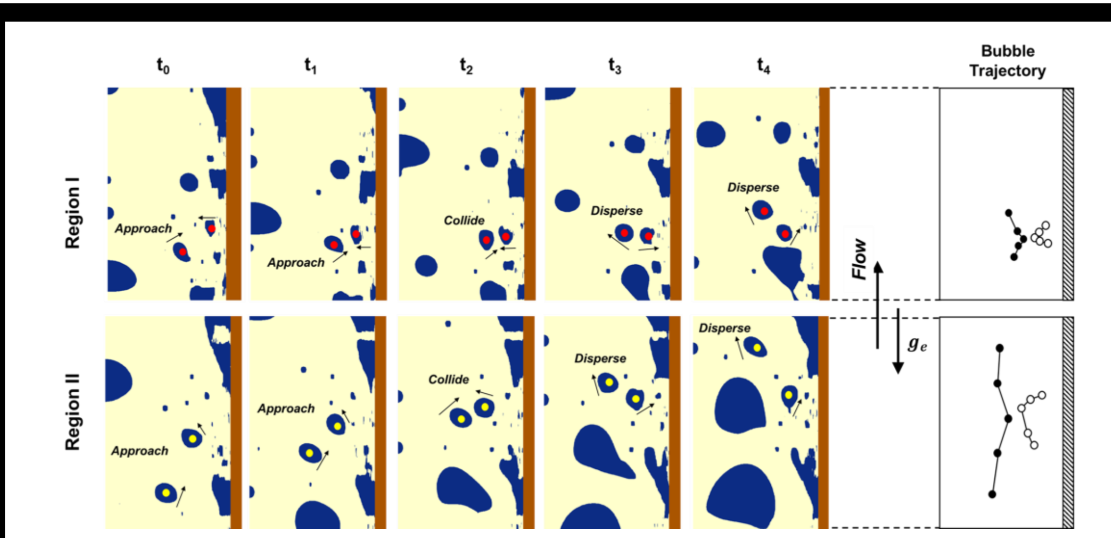
CFD Predictions

Bubble Collision Dispersion UDF

Bubble Collision Dispersion (EXP)



CFD predictions



$$F^{BCD} = -\left(K\frac{\rho_f u_t^2}{2\alpha_{max}^{2/3}}\right) f(\alpha)\nabla\alpha$$

$$f(\alpha) = \alpha_g^{2/3}\left[1 - \left(\frac{\alpha_g}{\alpha_{max}}\right)\right]$$

Bubble collision dispersion

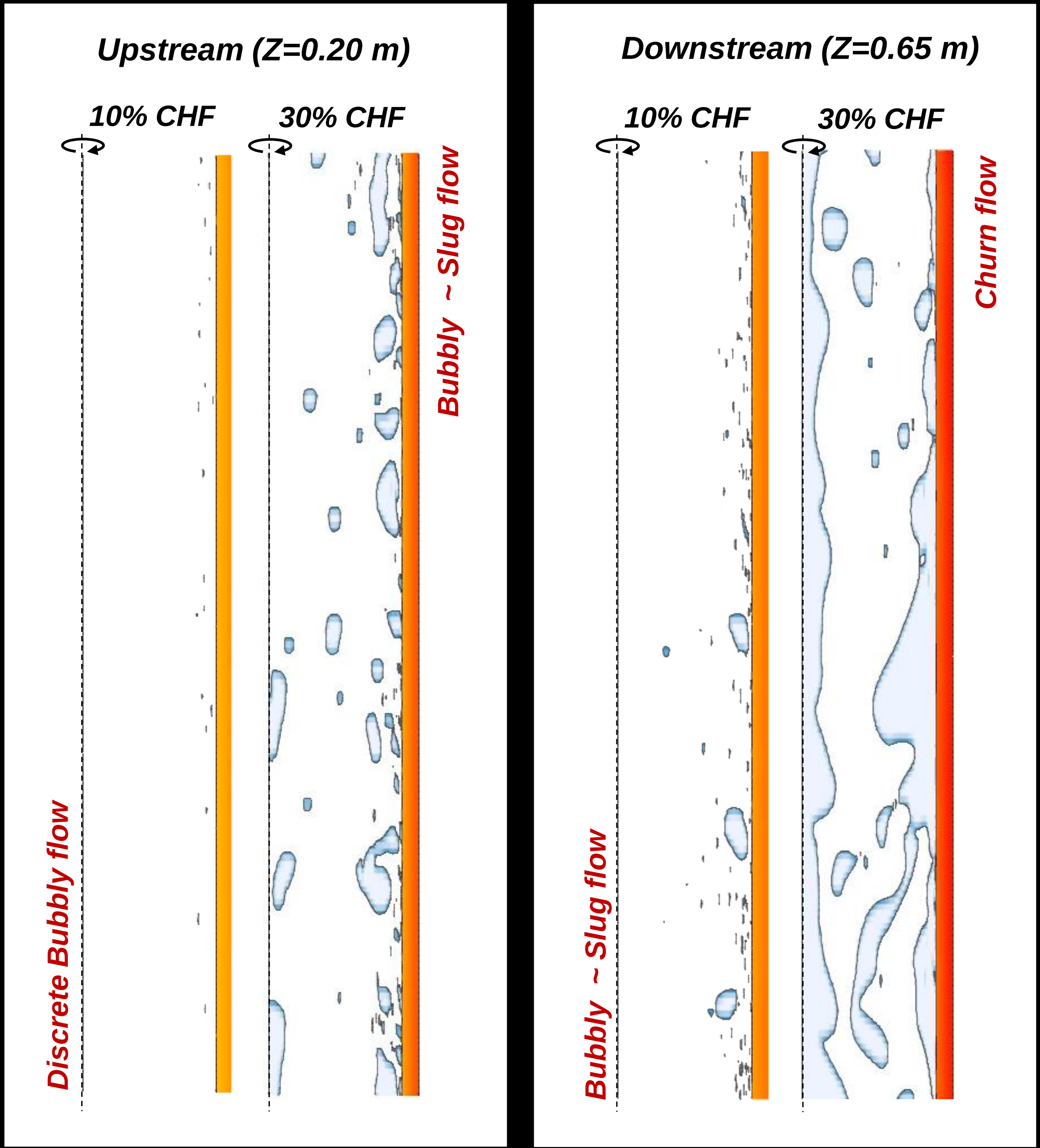
- *Reported by Sharma et al. (2017)*
- *Repelling force btw small bubbles*
- *Approach – Squeeze – Collision – Dispersion*

User defined function (UDF)

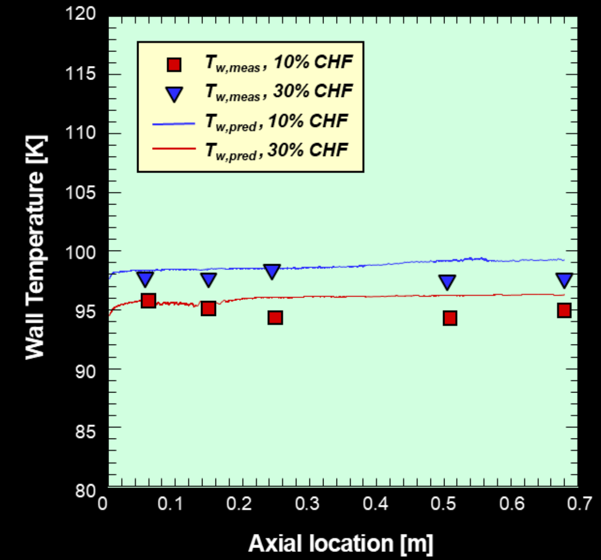
- Numerically formulated BCD function
- Coupling UDF with ANSYS Fluent
- Supplementing under-represented relative motion btw phases

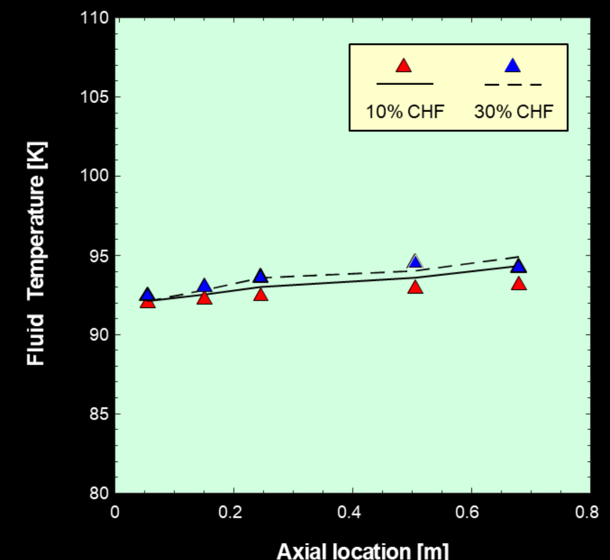
Flow Contours & Temperature predictions

Predicted flow patterns



G = 804 kg/m^{2}s, P_{in} = 551.6 kPa, $\Delta T_{sub,in}$ = 3.24 K

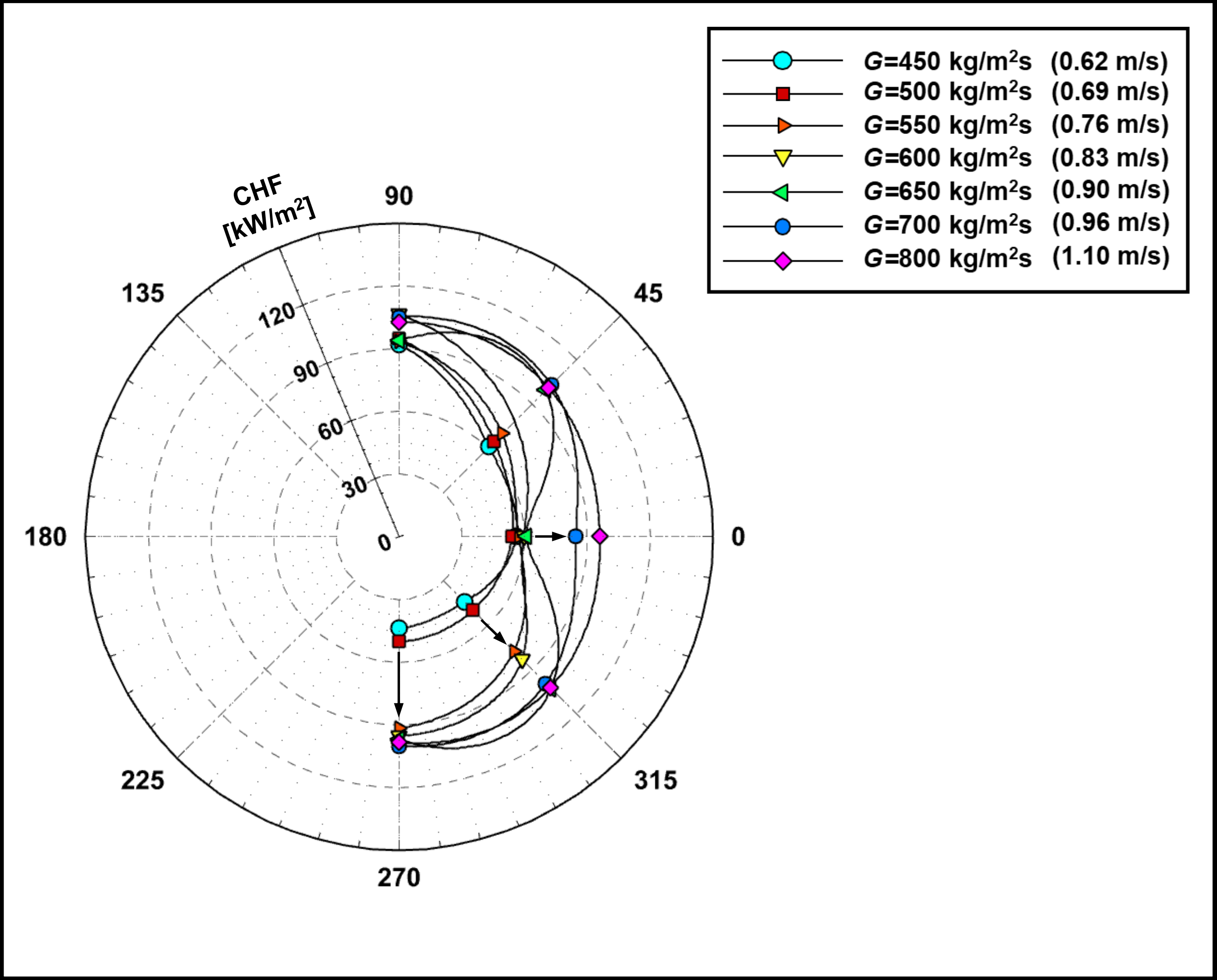




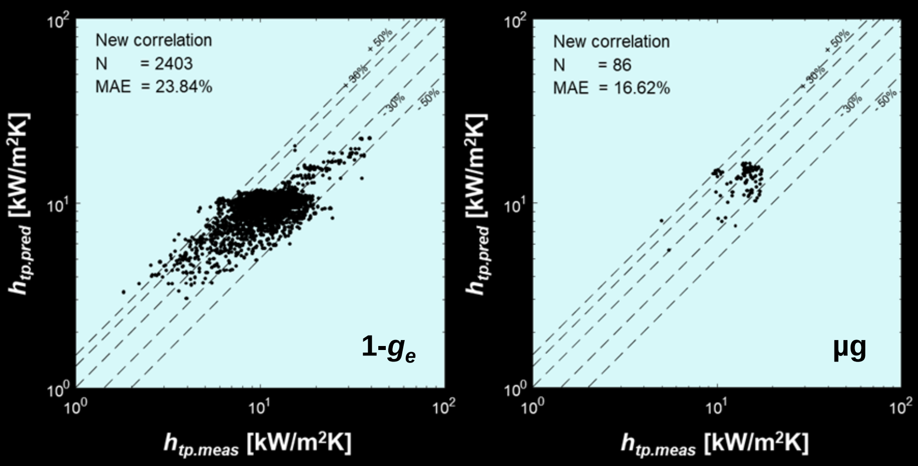
Thank you!

Supplement materials

$1\text{-}g_e$ CHF for all orientation



Suppression factor, S



IF $PR < 0.41$

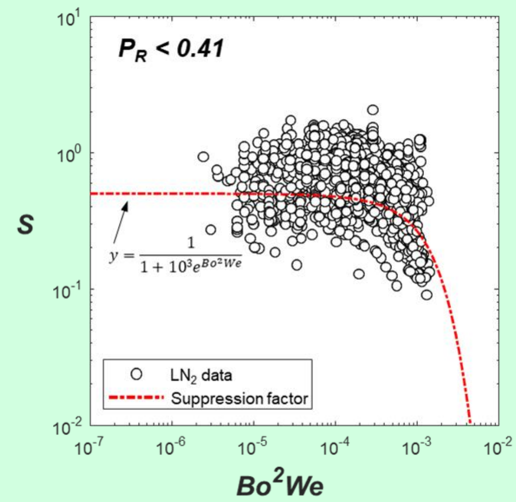
$$h_{NB} = h_{PB} \cdot \left[1.36 \cdot tanh\left(\frac{g_e}{g}\right)\right] \cdot \left[\frac{1}{1 + 10^3 \cdot \exp(Bo^2 We)}\right]^{0.475}$$

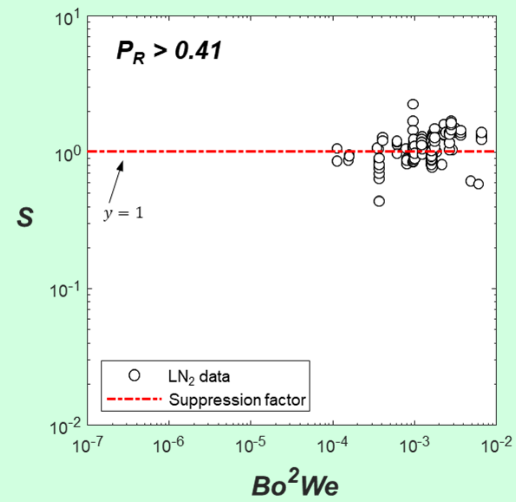
IF $PR \geq 0.41$

$$h_{NB} = h_{PB} \cdot \left[1.2 \cdot tanh\left(\frac{g_e}{g}\right)\right]$$

$$h_{CB} = h_{sp} \cdot 7 \cdot \left(\frac{1}{X_{tt}}\right)^{0.39} \cdot \left(\frac{\rho_f}{\rho_g}\right)^{-0.34}$$

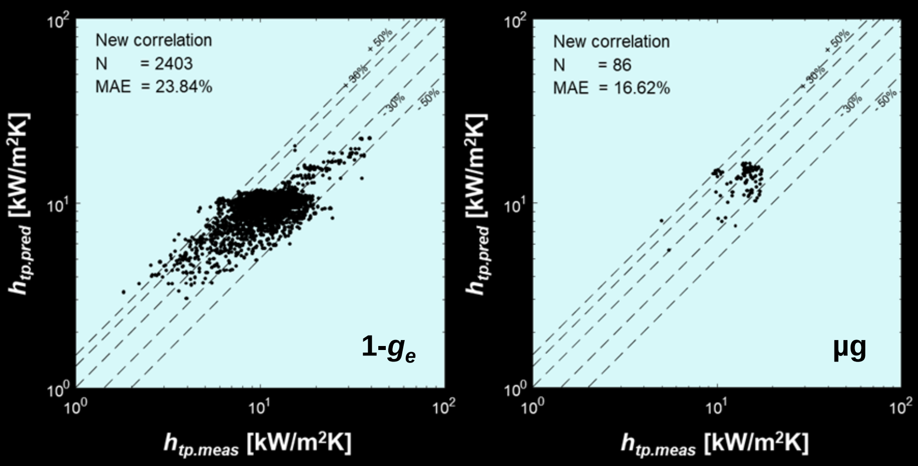
$$h_{tp} = \left[h_{NB}^{\ 2} + h_{CB}^{\ 2}\right]^{1/2}$$





Behavior of
Suppression factor

Gravity effect



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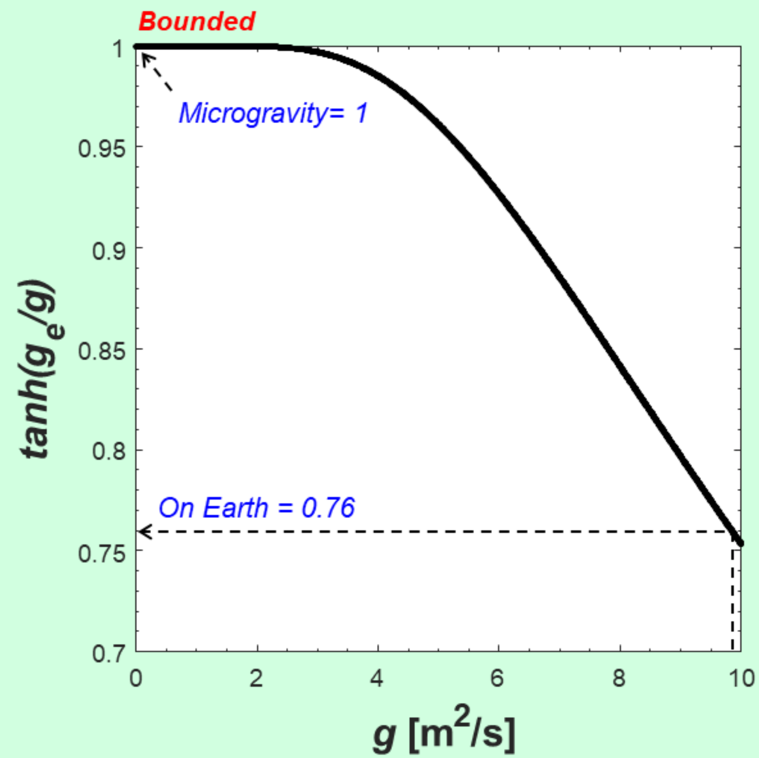
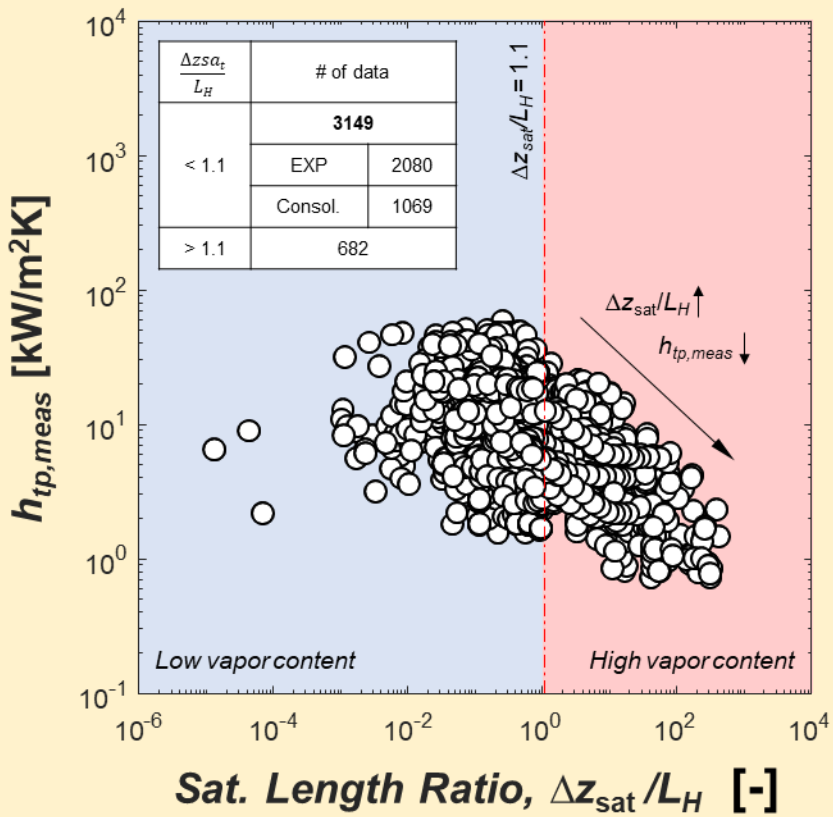
$$h_{tp} = \left[h_{NB}{}^2 + h_{CB}{}^2\right]^{1/2}$$

Behavior of
Gravity parameter, $tanh(g_e/g)$

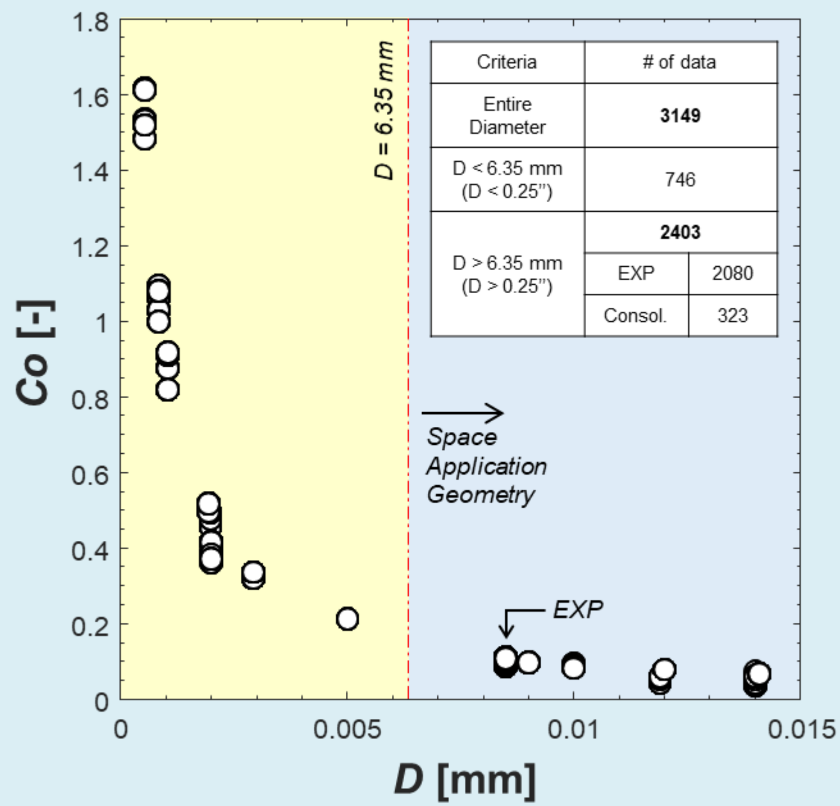


Segregation parameters

Saturation Length Ratio, $\Delta Zsat/L_H$



Tube Diameter, D



Relation between Molecular weight and HTC

Bubble Dynamics

$$J = 1.44(1040) \cdot \left[\frac{{\rho_f}^2 \sigma}{\bar{M}^3}\right]^{1/2} \cdot exp\left[\frac{-1.213(1024)\sigma^3}{T\left[\eta P_{sat} - P_f\right]^2}\right]$$

Rate of bubble formation is inversely proportional to molecular weight !!

Kinetic theory of gases

$$j_n = \left(\frac{1}{4}\right)\left(\frac{n}{V}\right)\left(\frac{8K_BT}{m\pi}\right)^{1/2}$$

Total rate of molecules passing through a plane surface per unit area, j_n, is inversely proportional to molecular weight !!

Heat transfer coefficient

$$q_i'' \approx (\bar{M})^{\frac{1}{2}} \cdot exp\left(\frac{1.3}{\overline{M^{0.5}}}\right) \cdot (\bar{M})^{-1}$$

Heat transfer rate, q_i, inversely proportional to molecular weight !!

Target Question

What is the relation between h and M_w?

Answer

Heat transfer coefficient, $\left(h_i = \frac{q_i}{\Delta Ti}\right)$, is inversely proportional to molecular weight !!