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

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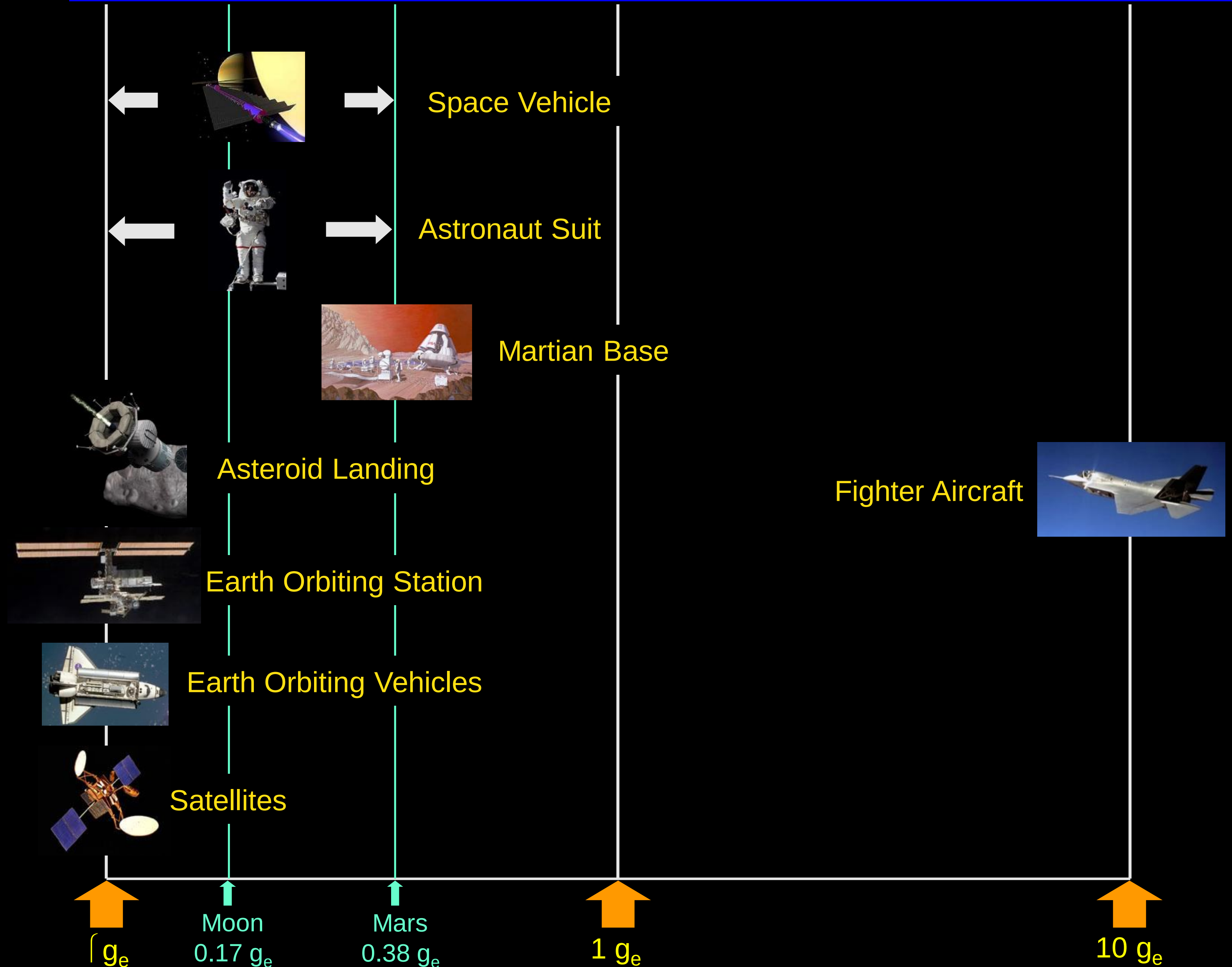
Examples of Systems Demanding Predictive Models of Effects of Gravity on Two-Phase Flow and Heat Transfer



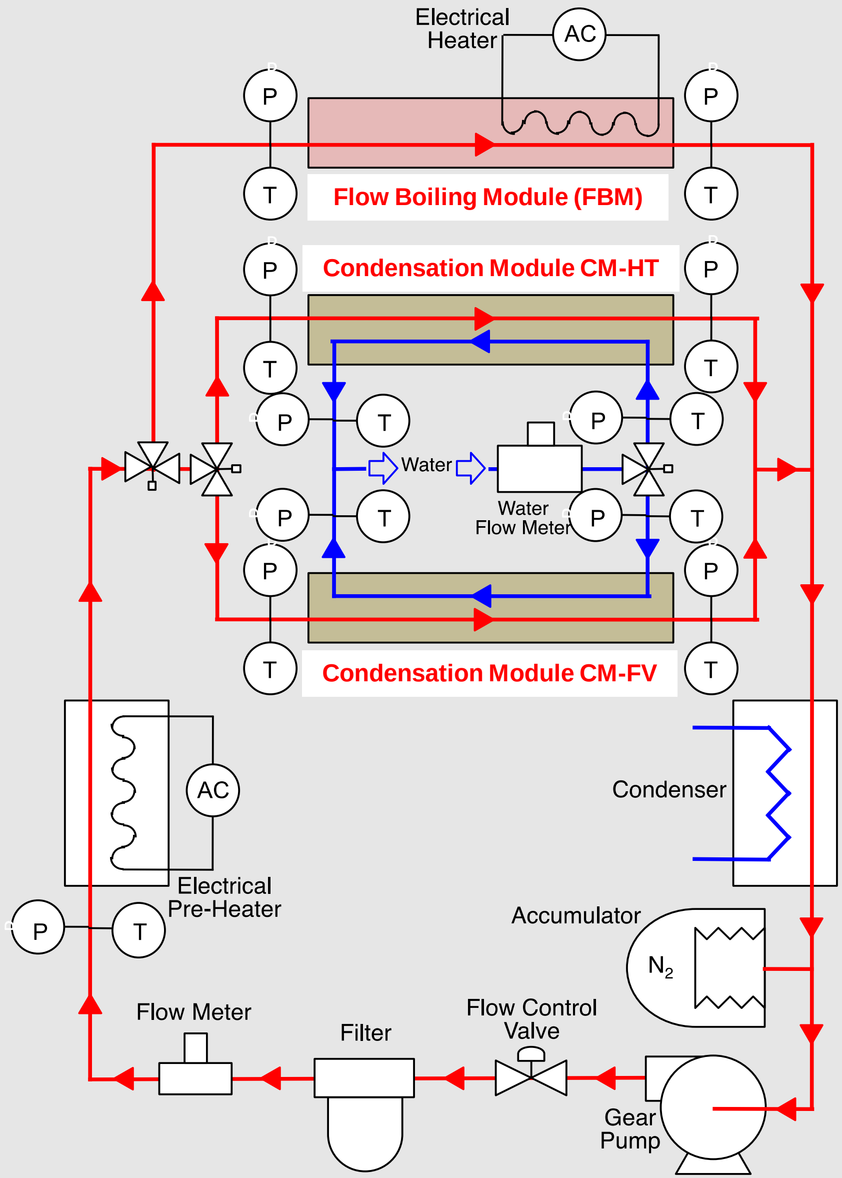
Overriding Objectives of FBCE

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:

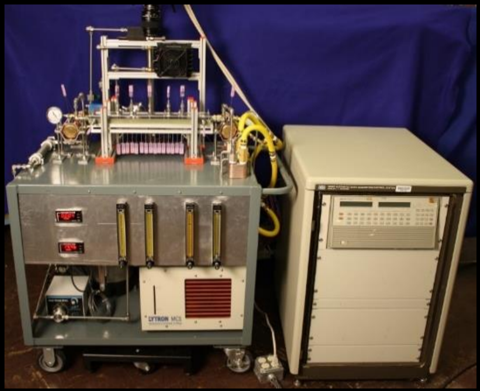
- Flow Boiling Module (FBM)
- Condensation Module for Heat Transfer Measurements (CM-HT)
- Condensation Module for Flow Visualization (CM-FV) ???

Aside from stated goals of FBCE:

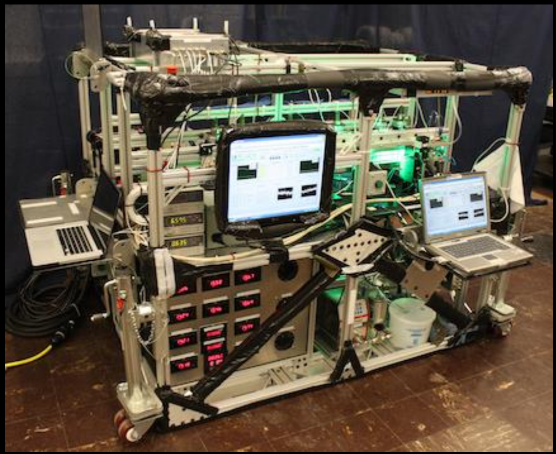
- Develop theoretical pressure drop models for adiabatic two-phase flow as well as boiling and condensing flows in reduced gravity
- Develop universal pressure drop correlations for adiabatic two-phase flow as well as boiling and condensing flows
- Develop universal heat transfer correlations for boiling and condensing flows
- Amass databases and video records for effects of flow orientation in one-G on boiling and condensing flows
- Initiate computational modeling of boiling and condensing flows
- Investigate transient behavior and instabilities in boiling and condensing flows
- Work closely with FBCE Engineering Team to expedite deployment on ISS
- Ensure readiness to utilizing future ISS databases and video records

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

High-Capacity Condensation Facility



Mini/micro-channel Condensation Facility



Parabolic Flight Condensation Facility

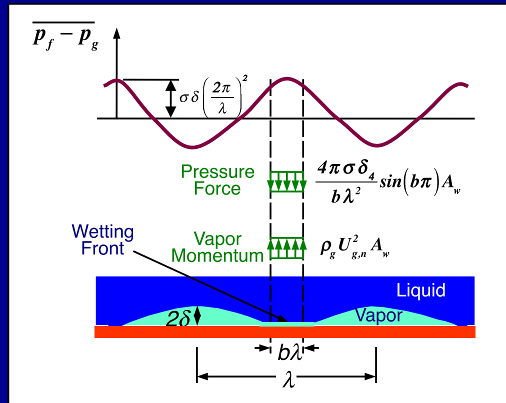
Falling-Film Heating/Evaporation Facility

One-G Flow Boiling Facility

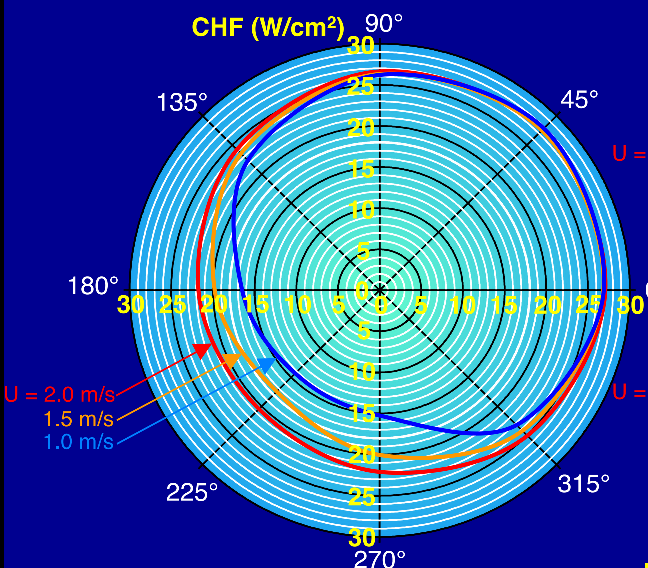
Parabolic Flight Flow Boiling Facility

Hybrid Thermal Control System (H-TCS)

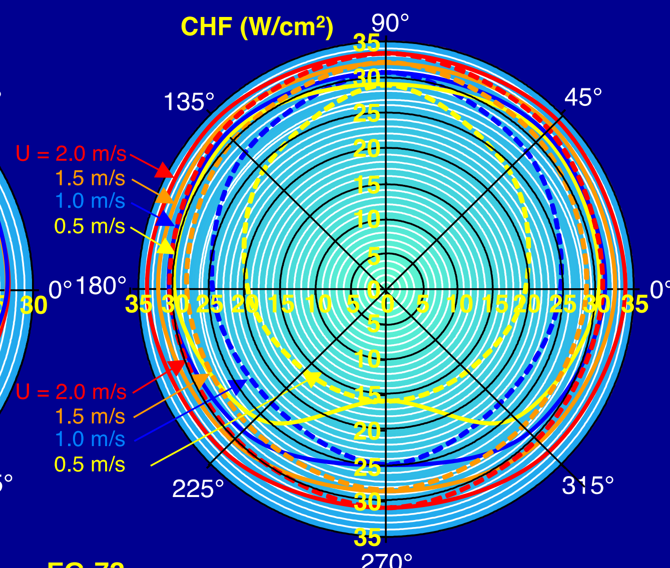
Flow Boiling CHF: Microgravity, One-G



Single-sided Heating



Double-sided Heating

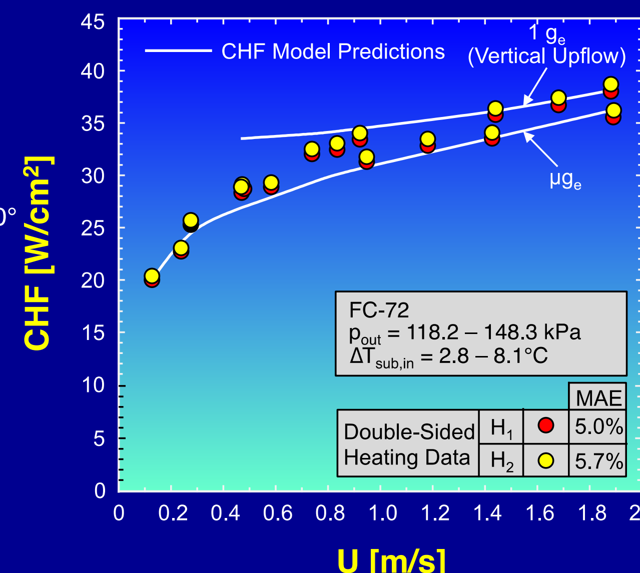


Heater H_a

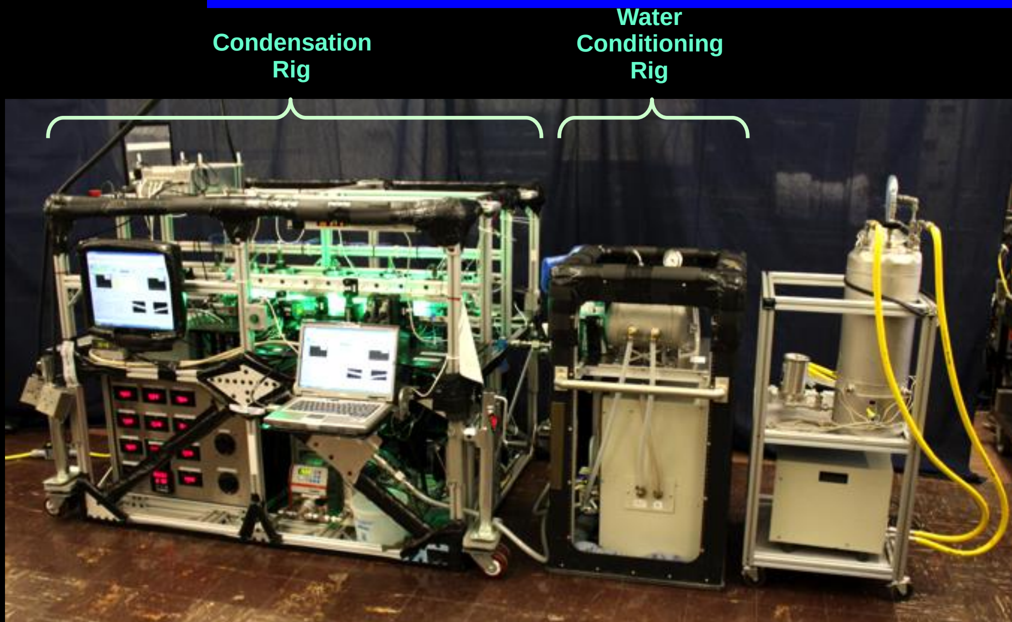
FC-72
p_{in} = 100 kPa
$\Delta T_{sub,in}$ = 3°C

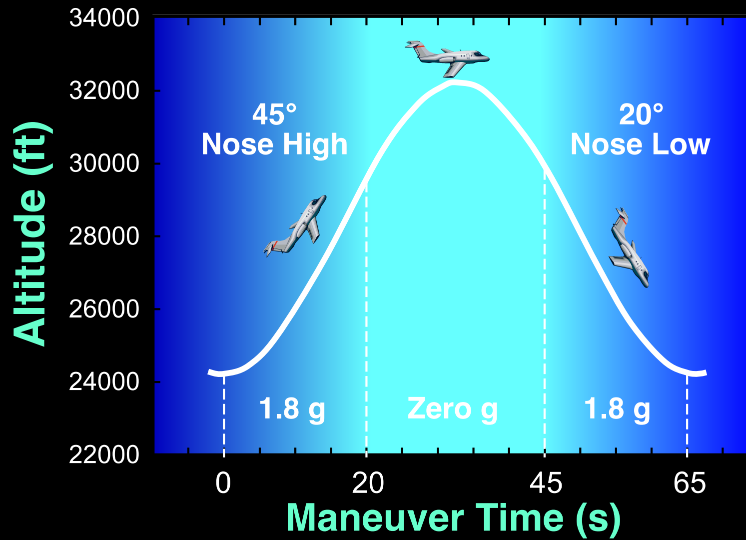
Upward-facing Heater
Downward-facing Heater

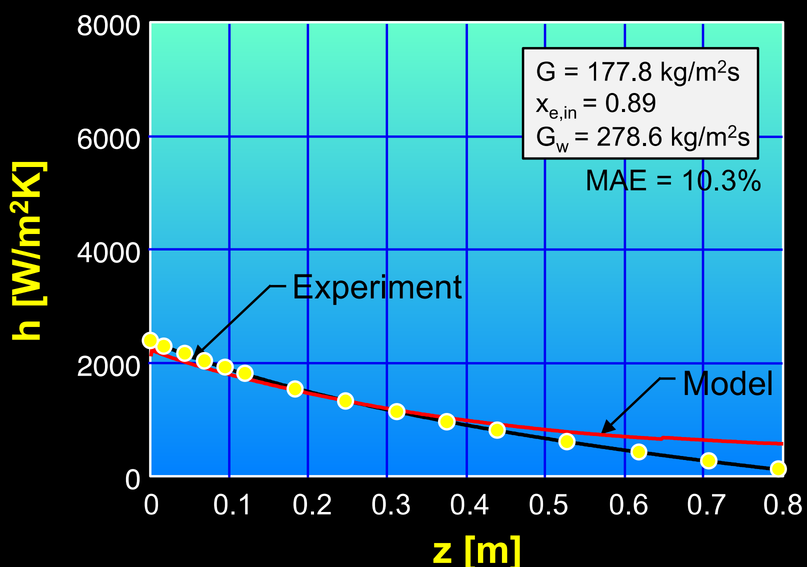
Microgravity & One g_e Vertical Upflow

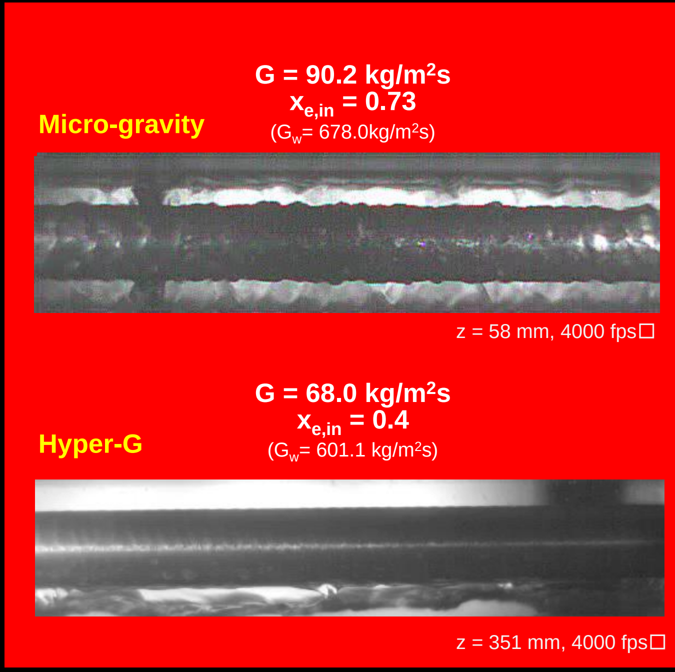


Heat Transfer in Annular Condensation in Microgravity



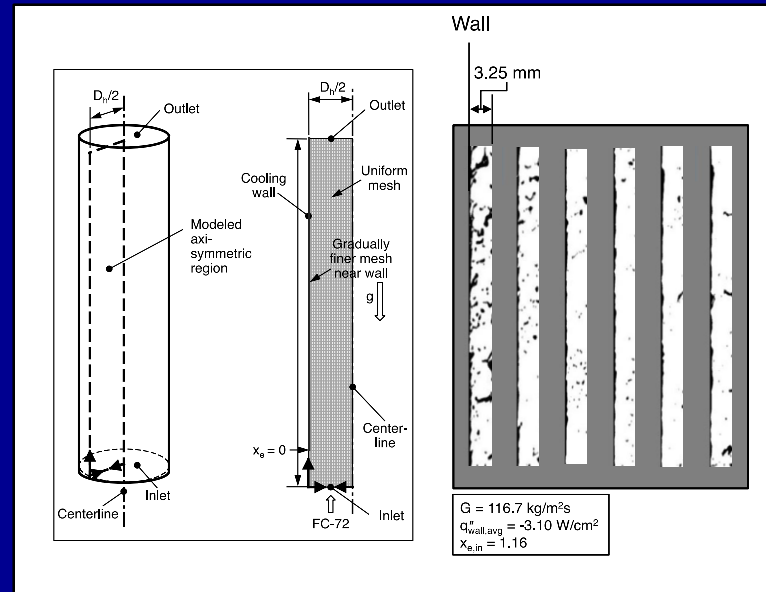


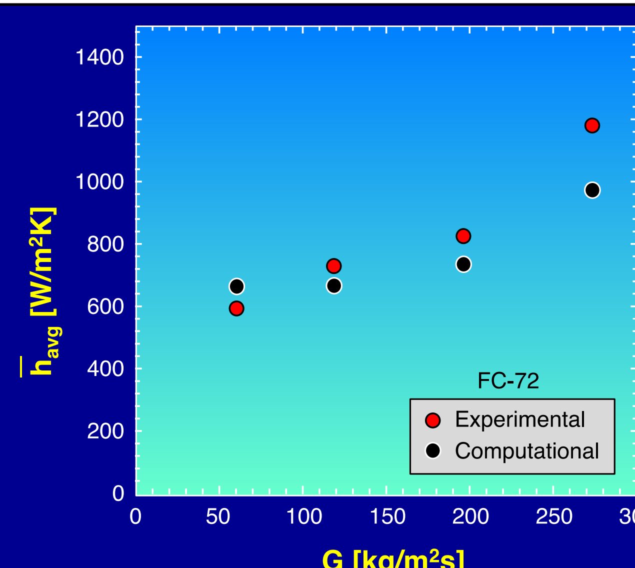




Heat Transfer in Annular Condensation at One-G

- Effects of flow orientation
- Control volume model
- Interfacial behavior
- Computational model





Universal Correlations for:

- **Two-Phase Frictional Pressure Drop for Adiabatic and Condensing Flows**
- **Heat Transfer Coefficient for Condensation**
- **Two-Phase Frictional Pressure Drop for Saturated Boiling**
- **Heat Transfer Coefficient for Saturated Flow Boiling**
- **Dryout Incipience Quality**

Universal Correlation for Heat Transfer Coefficient in Saturated Flow Boiling in Small Channels

Consolidated database:
10,805 saturated boiling heat transfer coefficient data points from 37 sources

- FC72, R11, R113, R123, R1234yf, R1234ze, R134a, R152a, R22, R236fa, R245fa, R32, R404A, R407C, R410A, R417A, CO_2, water
- $0.19 < D_h < 6.5$ mm
- $19 < G < 1608$ kg/m^{2}s
- $57 < Re_{fo} = GD_h/\mu_f < 49{,}820$
- $0 < x < 1$
- $0.005 <$ *Reduced pressure* < 0.69

$$Bo = \frac{q''_H}{G\,h_{fg}}$$

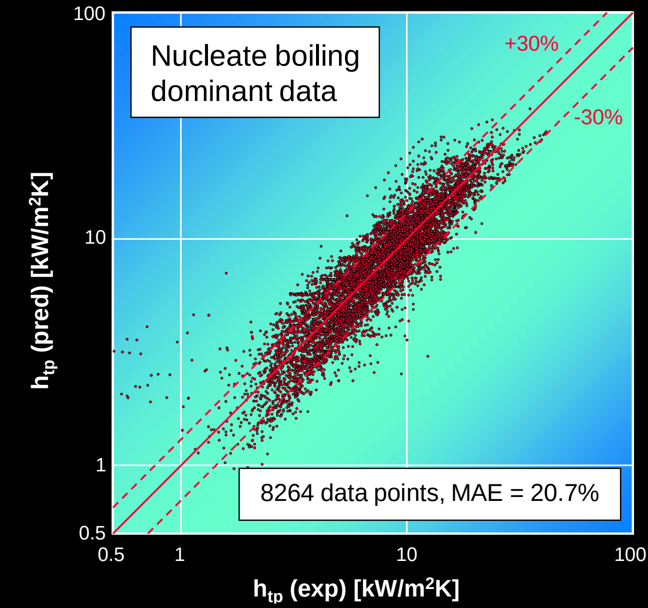
$$h_{tp} = \left(h_{nb}^2 + h_{cb}^2\right)^{0.5}$$

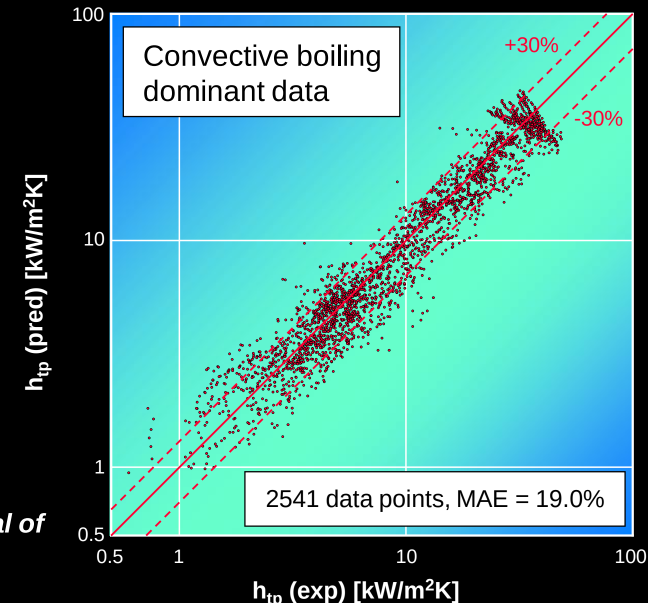
For nucleate boiling dominant regime :

$$h_{nb} = \left[2345\left(Bo\frac{P_H}{P_F}\right)^{0.70} P_R^{0.38}(1-x)^{-0.51}\right]\left(0.023\,Re_f^{0.8}\,Pr_f^{0.4}\frac{k_f}{D_h}\right)$$

For convective boiling dominant regime :

$$h_{cb} = \left[5.2\left(Bo\frac{P_H}{P_F}\right)^{0.08} We_{fo}^{-0.54} + 3.5\left(\frac{1}{X_{tt}}\right)^{0.94}\left(\frac{\rho_g}{\rho_f}\right)^{0.25}\right]\left(0.023\,Re_f^{0.8}\,Pr_f^{0.4}\frac{k_f}{D_h}\right)$$





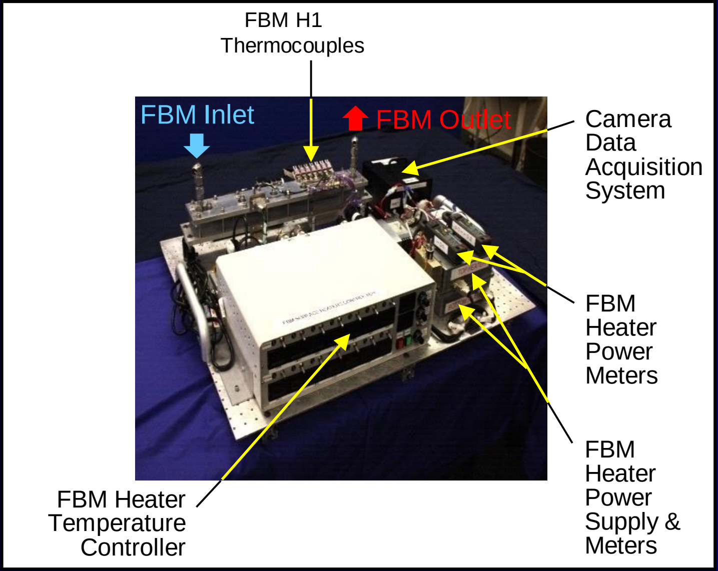
Kim, S.M. and Mudawar, I., 2013, "Universal Approach to Predicting Saturated Flow Boiling Heat Transfer in Mini/Micro-Channels Part II. Two-Phase Heat Transfer Coefficient," ***International Journal of Heat and Mass Transfer***, Vol. 64, pp. 1239-1256.

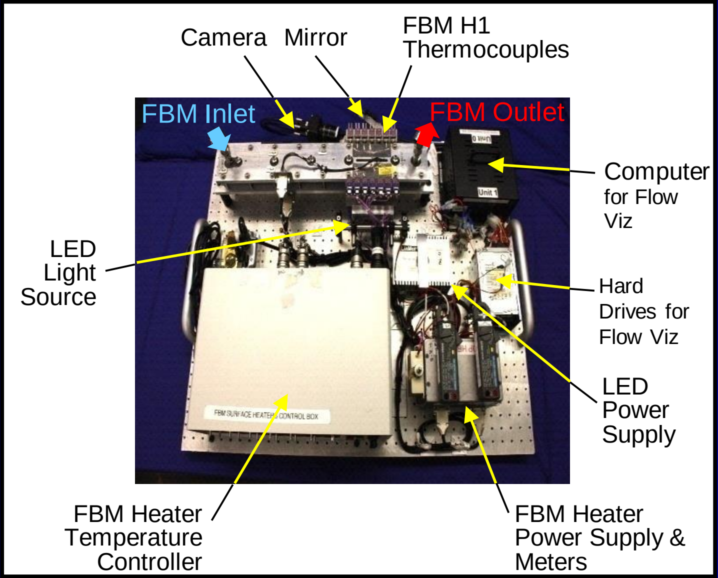
Metrics

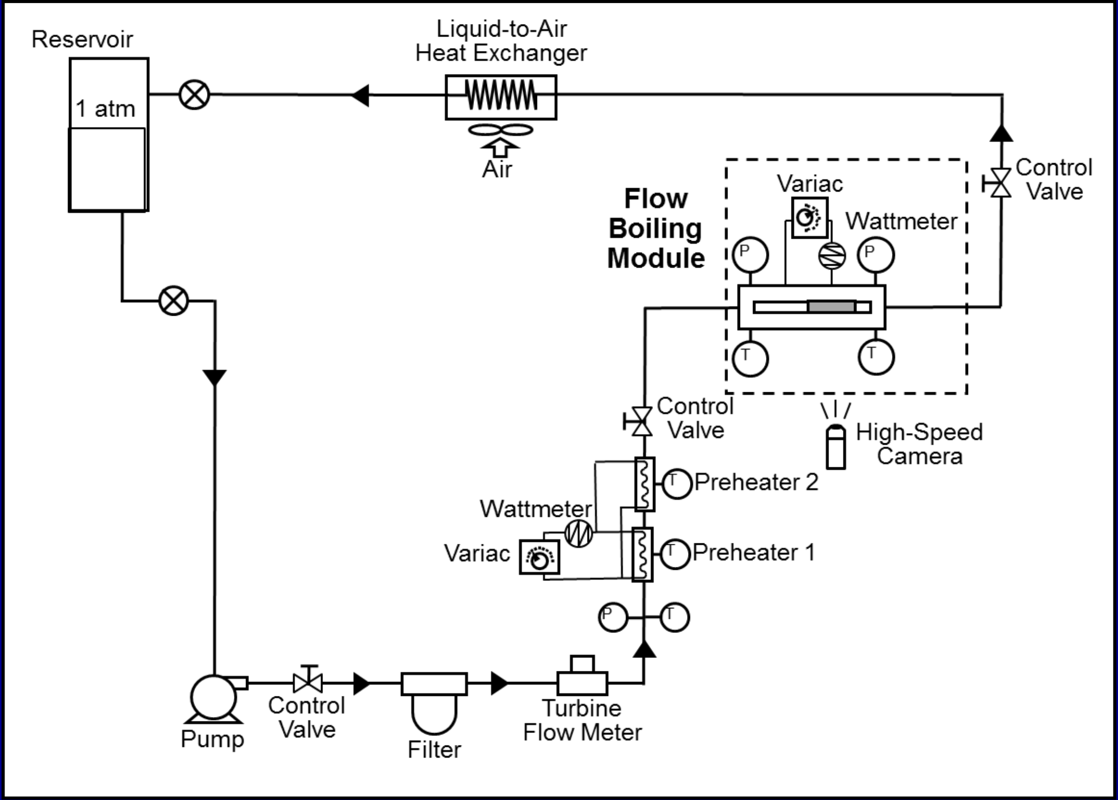
Since 2012:

- **6 Ph.D. and 2 M.S. degrees**
- **48 articles published in *International Journal of Heat and Mass Transfer***

Pressure Drop in Flow Boiling Systems

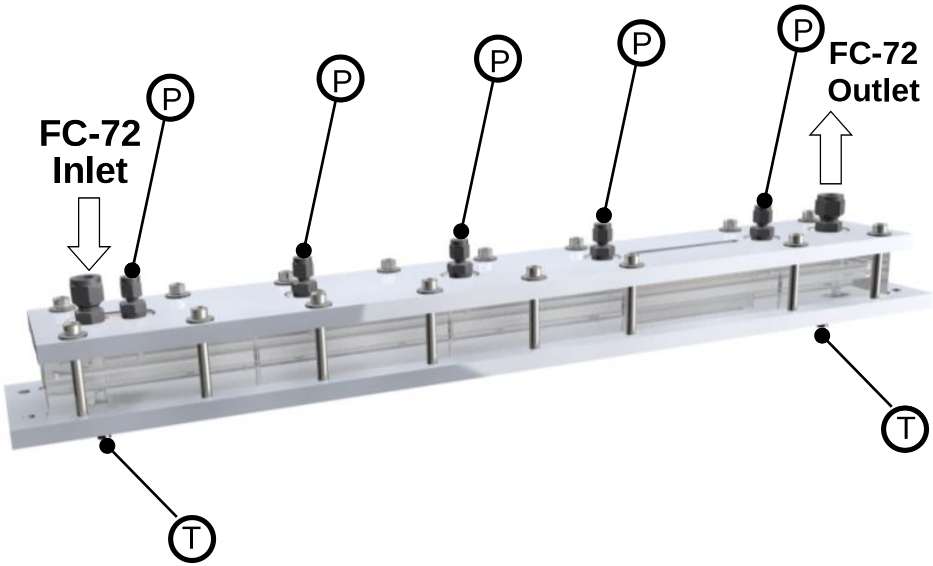


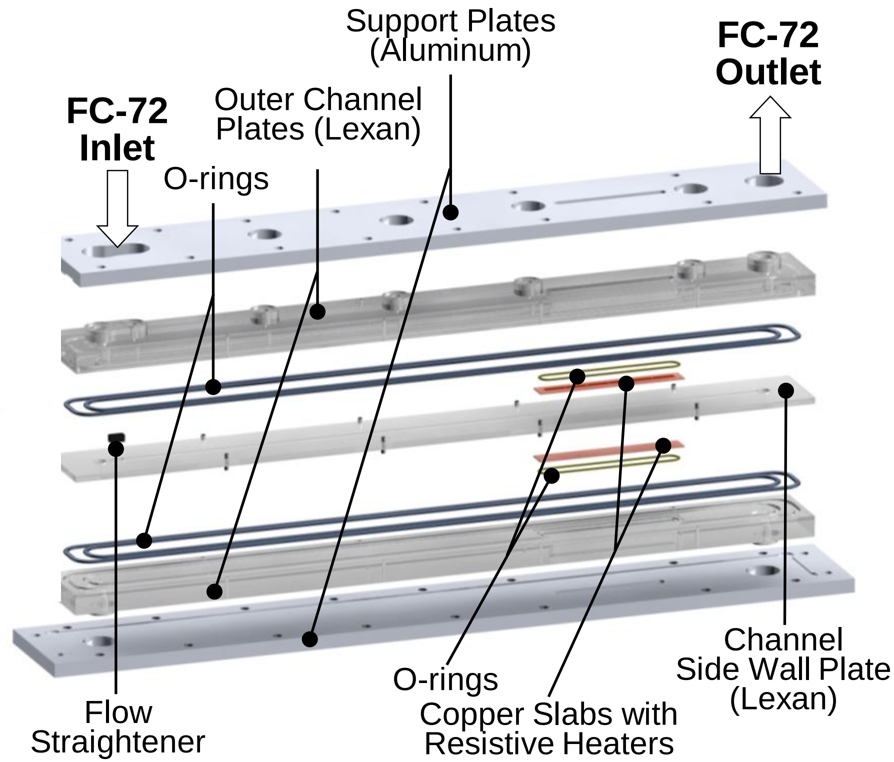


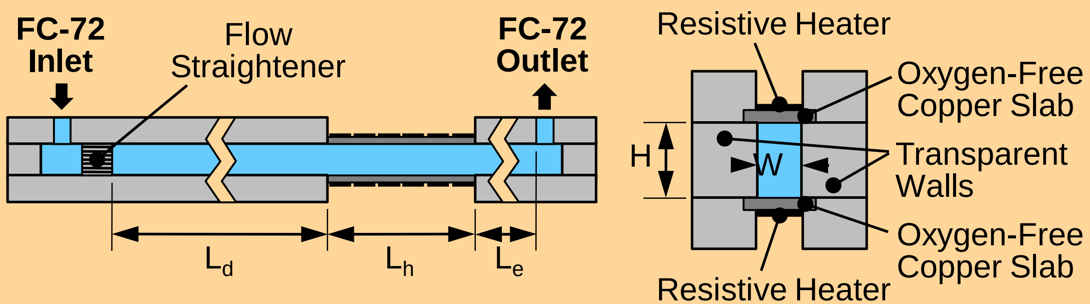


- **Pressure drop measurements provide insight into dominant fluid physics**
- **Experiments run in Vertical Upflow, Vertical Downflow, and Horizontal Flow**
- **Total of 829 ΔP data points**

Flow Boiling Module

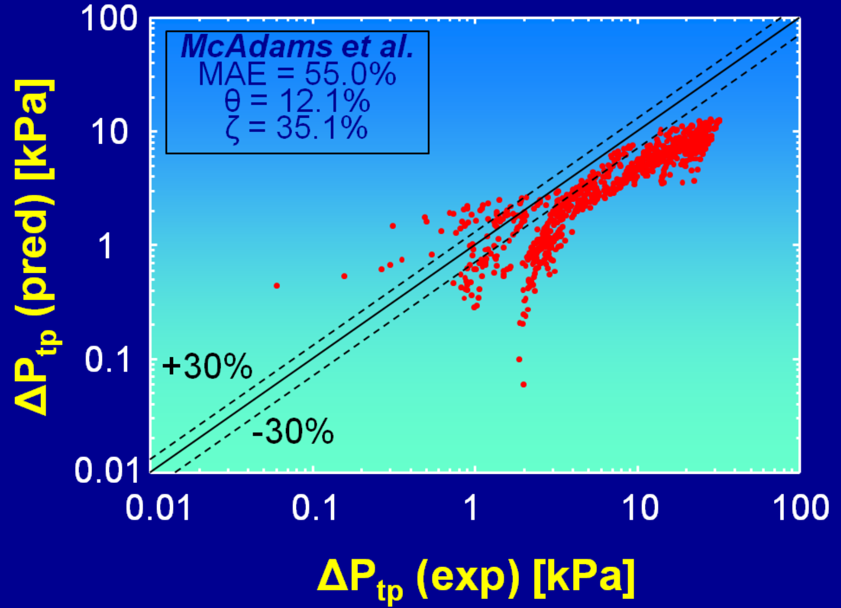


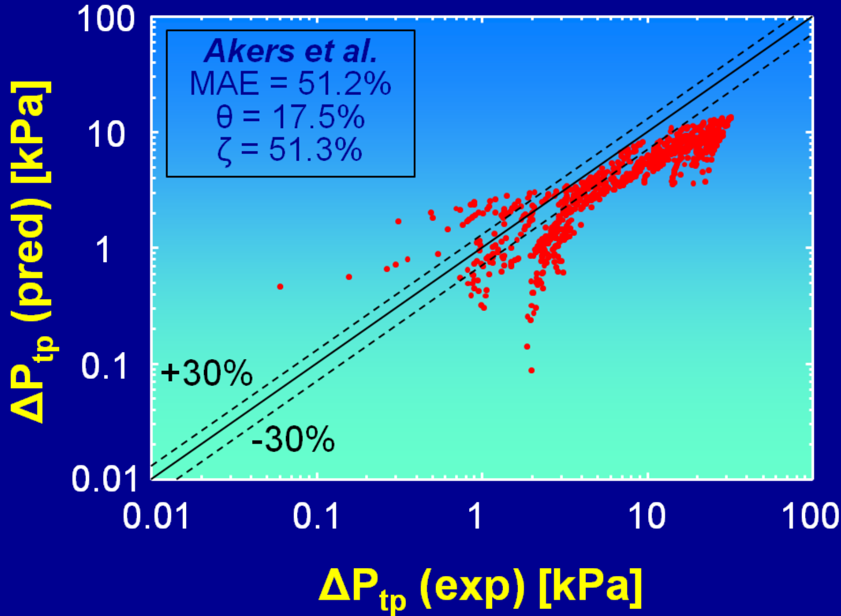




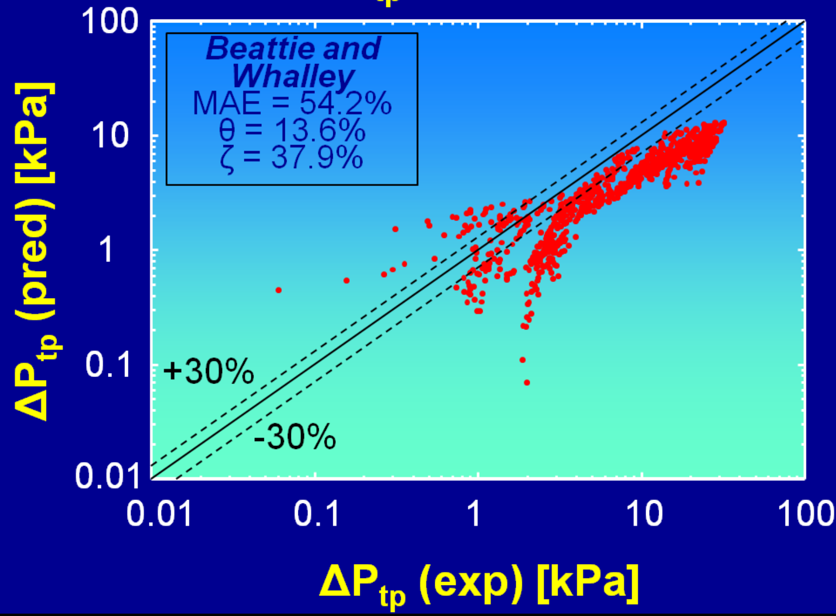
Development Length: L_d = 327.9 mm
Heated Length: L_h = 114.6 mm
Exit Length: L_e = 60.9 mm

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

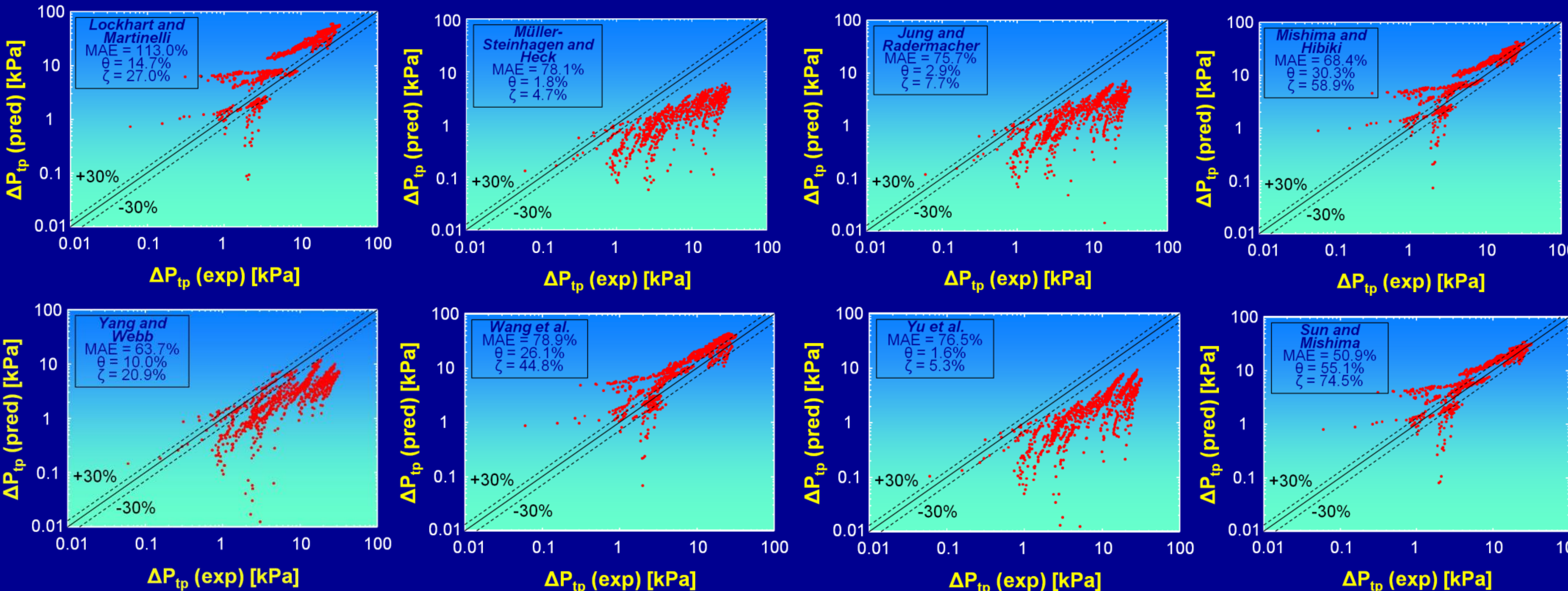




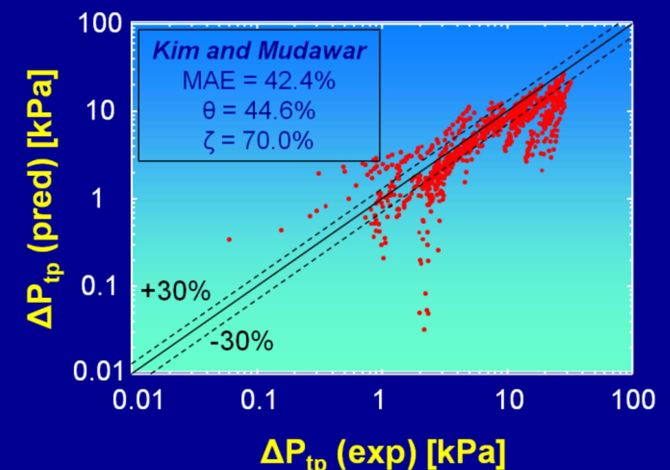
- **Correlations based on Homogeneous Equilibrium Model (HEM) perform fairly well overall**
- **At low mass velocities, "fish-tail effect" compromises overall accuracy (due to over-prediction of horizontal flow, under-prediction of vertical downflow)**



Pressure Drop in Flow Boiling Systems – Evaluation of Predictive Tools

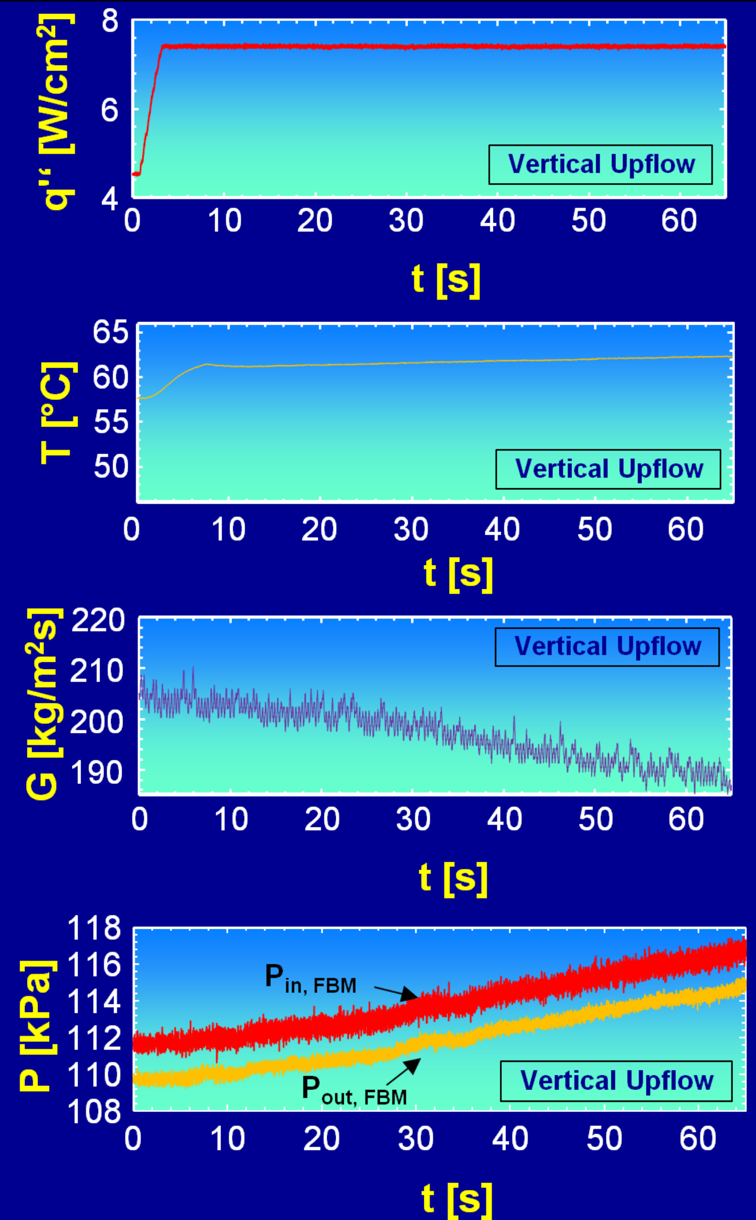


- **Large differences in predictive accuracy for correlations based on Separated Flow Model (SFM)**
- **Highest accuracy achieved with Kim & Mudawar (2012) universal correlation**



Flow Boiling System Dynamic Behavior

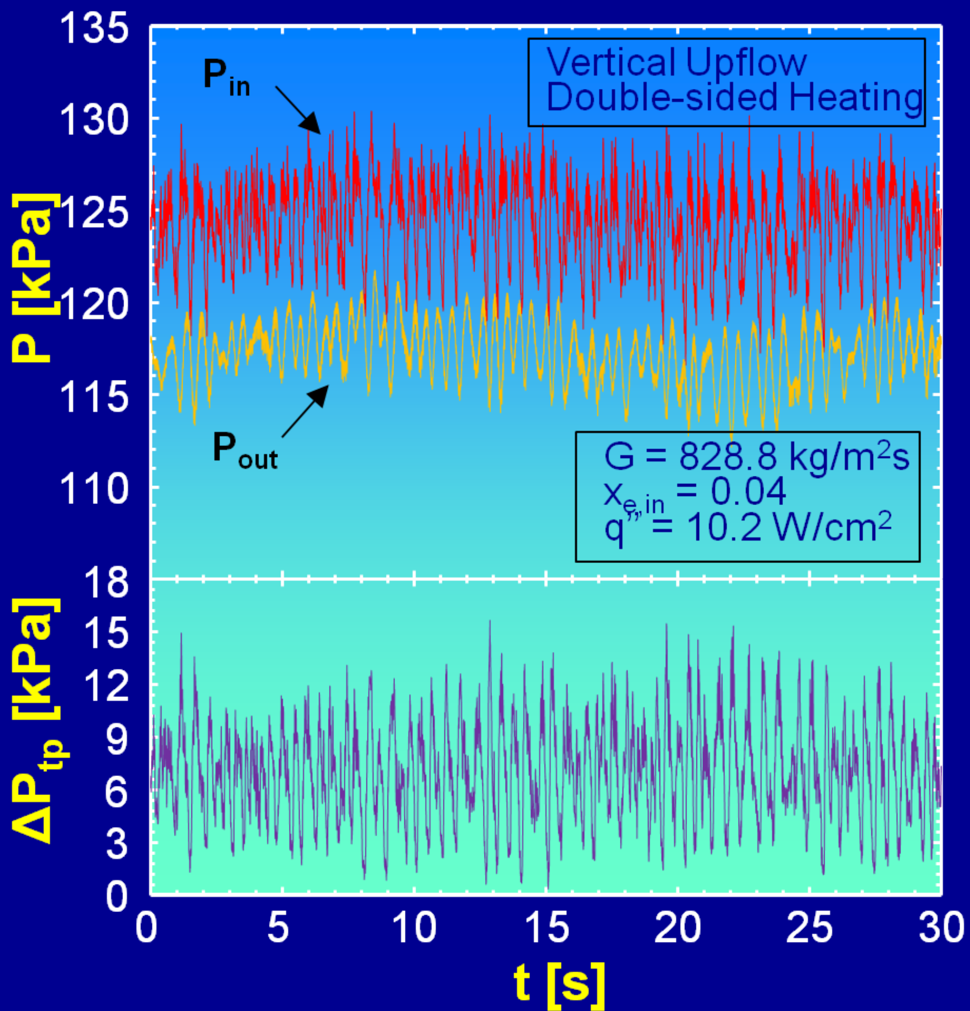
- **Study of two-phase flow heat transfer primarily deals with key time-averaged design parameters**
  - **Heat transfer coefficient, pressure drop, critical heat flux (CHF)**
- **Oscillations, instabilities, and other dynamic events can significantly impact system performance when:**
  - **Concerned with precise system control**
  - **Operating near a critical point (e.g., CHF, choking)**
  - **Undergoing continuous changes to operating environment**
- **Changing gravitational environment of space missions heightens importance of transient phenomenon**

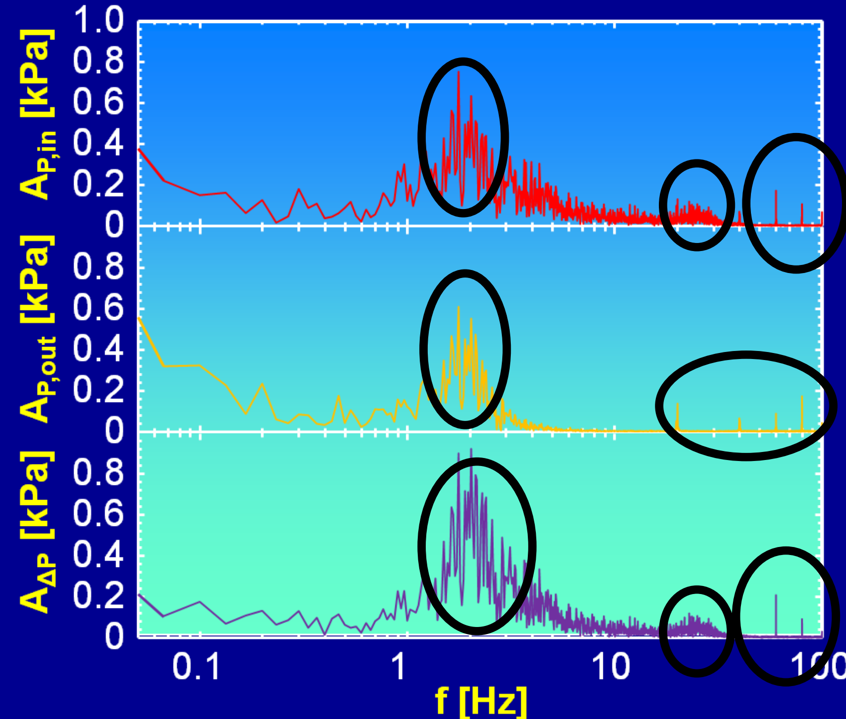


Flow Boiling System Dynamic Behavior - Background

- Investigation of two-phase flow instabilities originates with Ledinegg (Ledinegg Instability)
- Broadly classifiable as:
  - Dynamic Instabilities (Pressure Drop Oscillation, Density Wave Oscillation, Parallel Channel Instability, etc)
  - Static Instabilities (Ledinegg Instability, Flow Pattern Transition)
- Significant analytic and numeric work focused on characterization of system transient behavior
  - Stability maps & transition correlations, 1-D and lumped parameter models, 2D/3D dynamic flow models
- However, there is insufficient overlap with experimental work in many cases

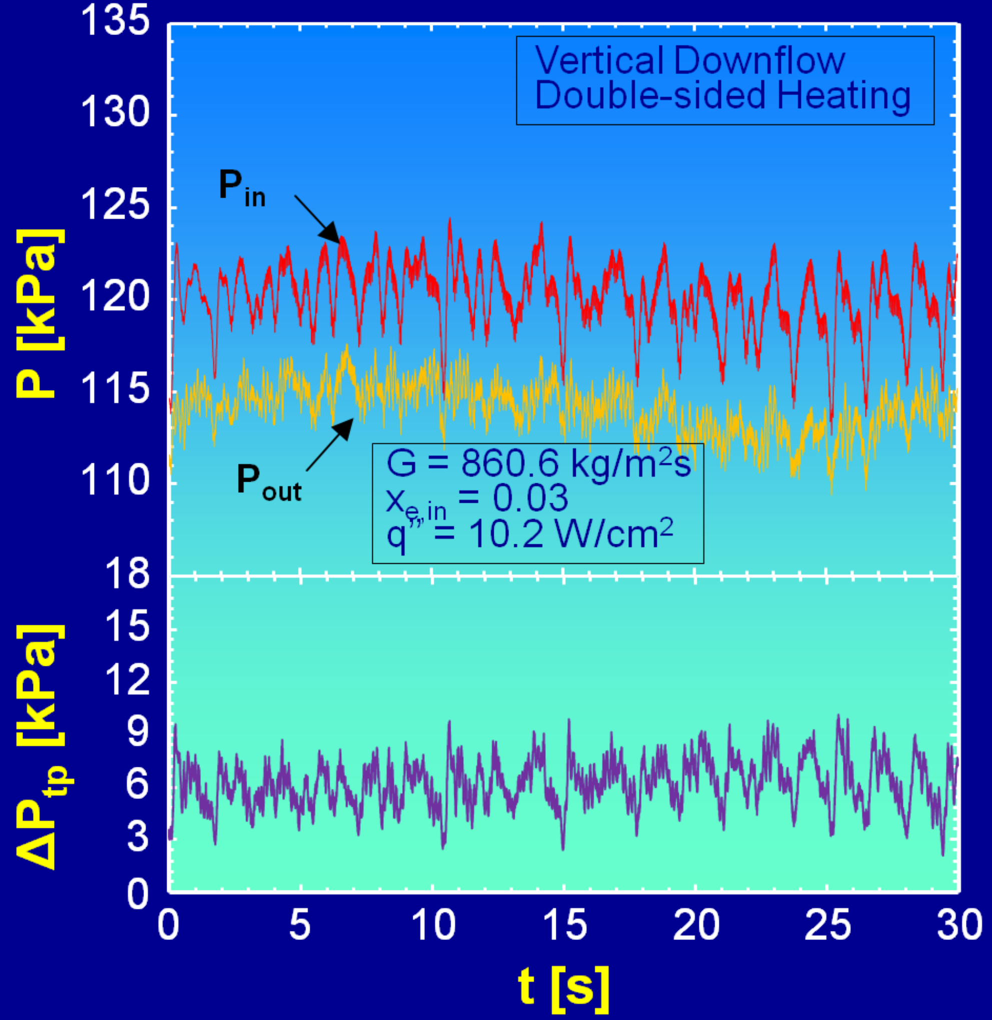
Vertical Upflow

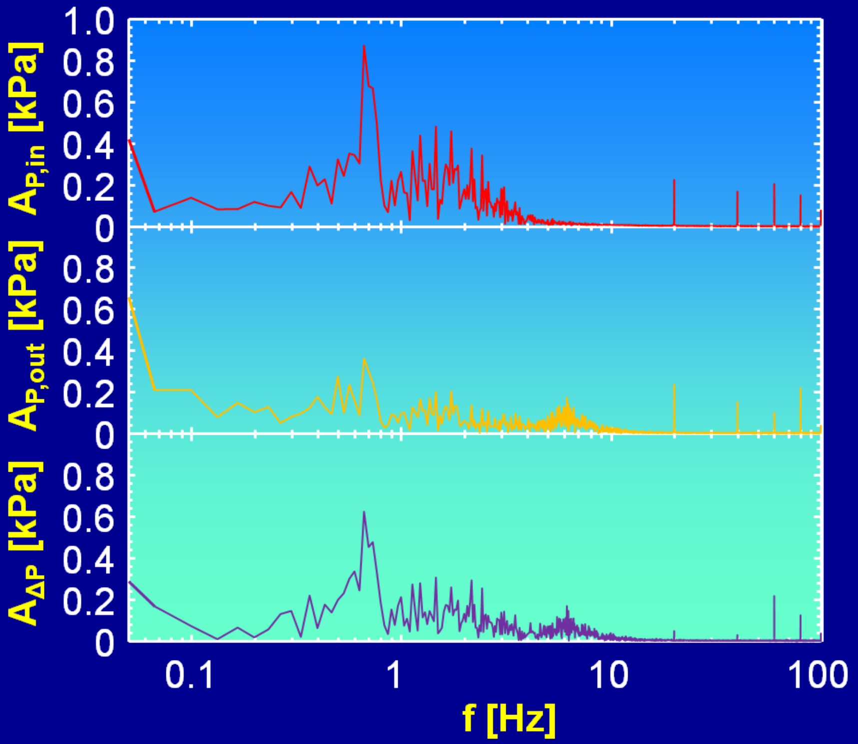




- Dominant frequency at ~2 Hz
- Secondary peak in 20-30 Hz range
- Sharp peaks in at 20, 40, 60, 80 Hz

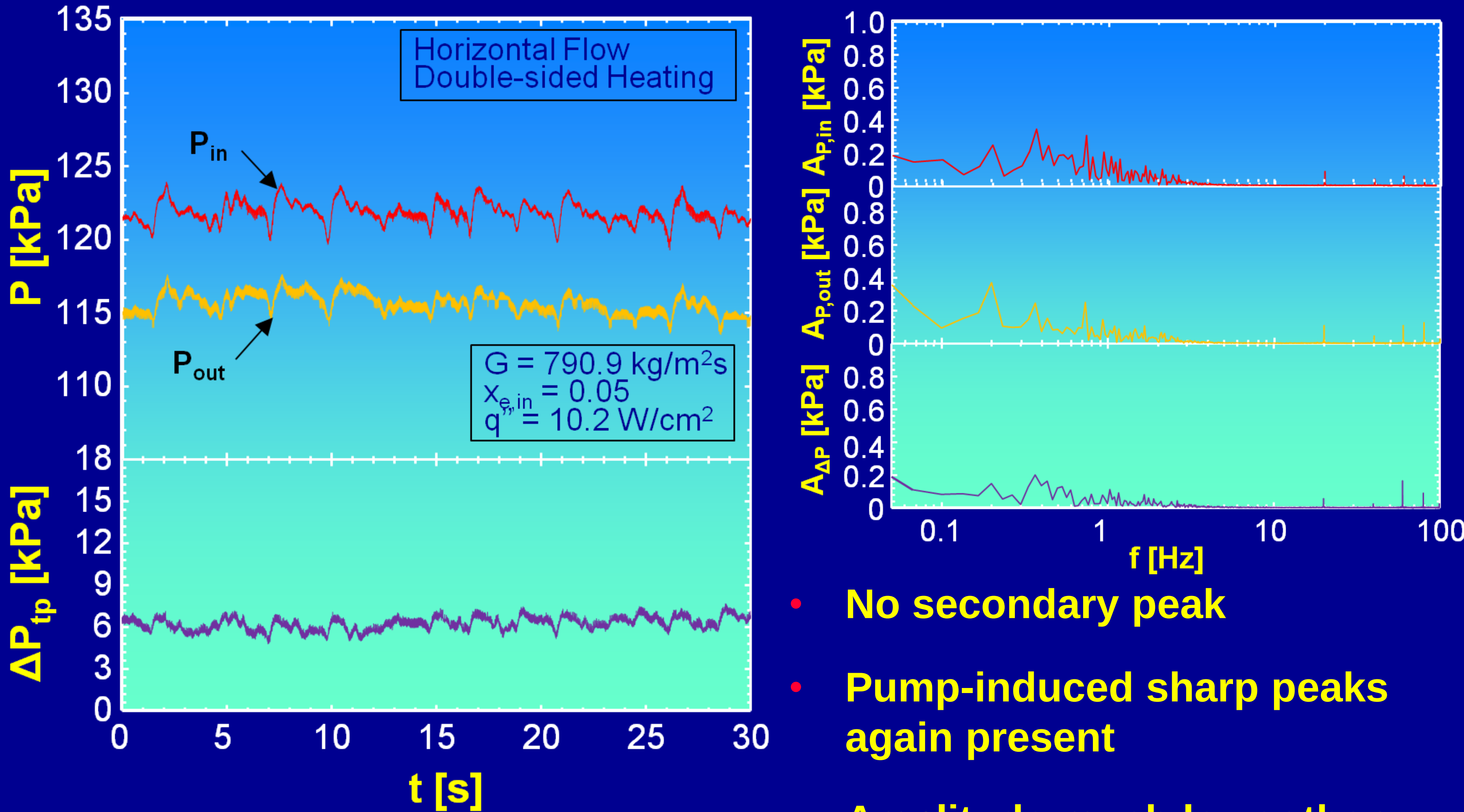
Vertical Downflow





- **Similar primary and secondary peaks as vertical upflow, although with frequency shift**
- **Pump-induced sharp peaks again present**

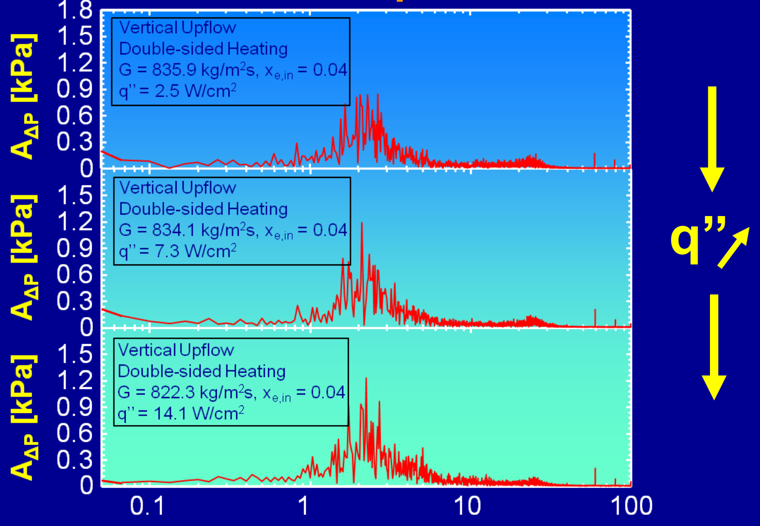
Horizontal Flow



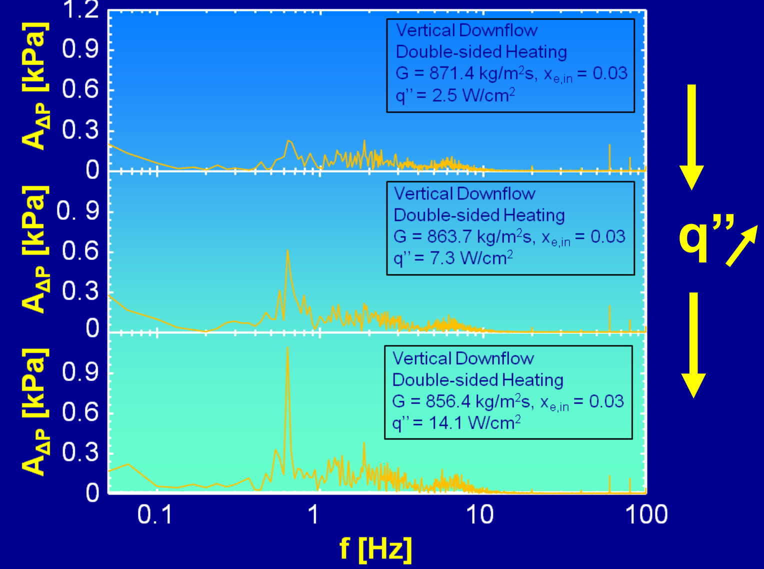
- **No secondary peak**
- **Pump-induced sharp peaks again present**
- **Amplitude much lower than vertical upflow and downflow**

Flow Boiling System Dynamic Behavior – Effect of Heat Flux

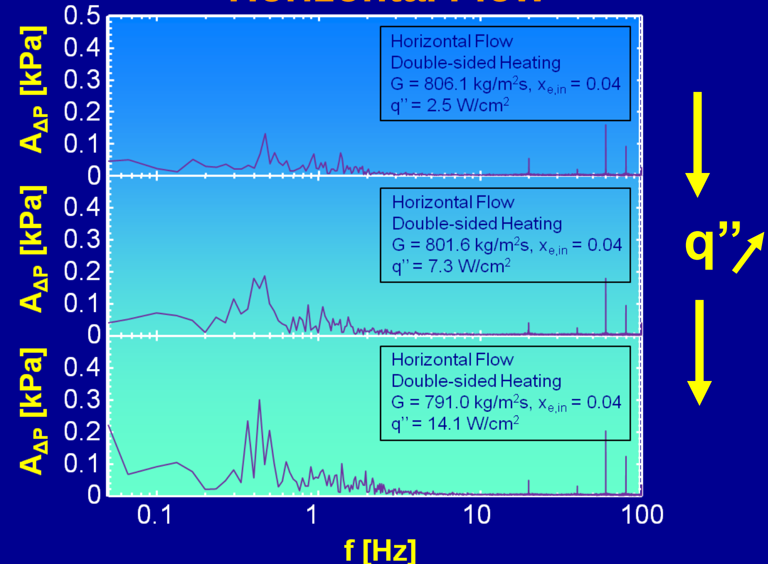
Vertical Upflow



Vertical Downflow

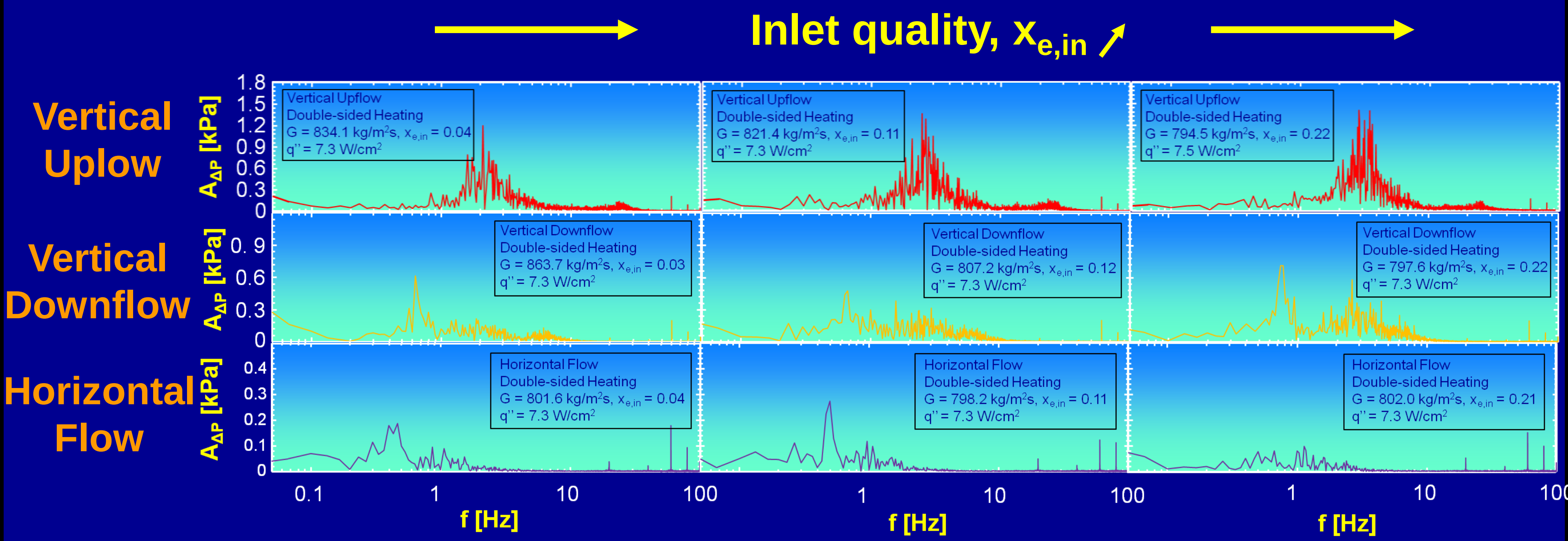


Horizontal Flow



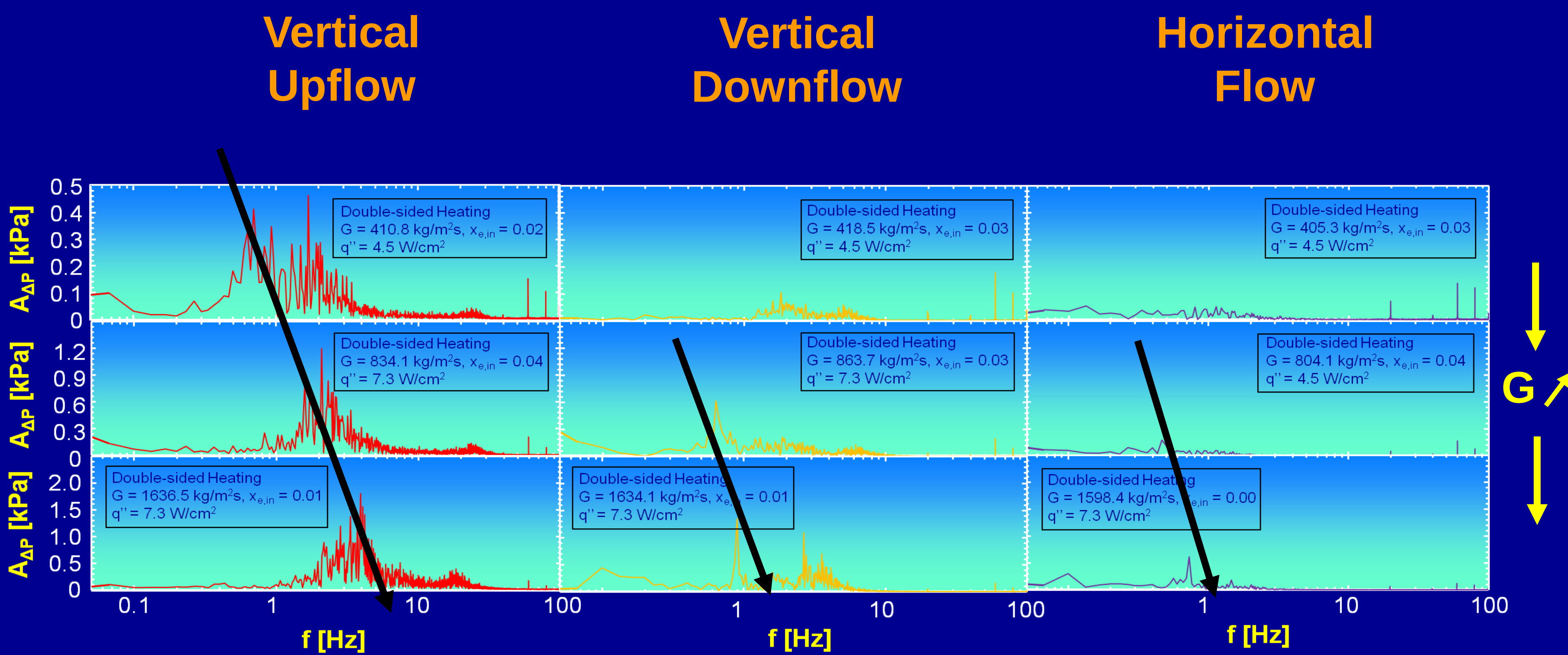
- **Amplitude of primary oscillations increases with increasing heat flux**
- **Frequency of primary oscillation remains constant**

Flow Boiling System Dynamic Behavior – Effect of Inlet Quality



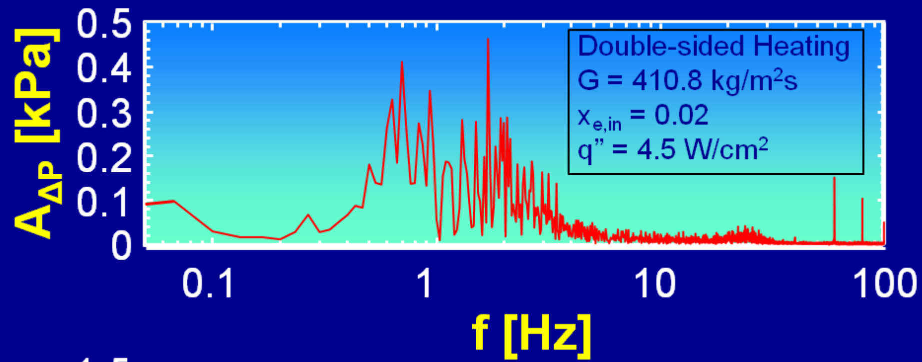
- **Amplitude increases for Vertical Upflow**
- **Amplitude remains ~ constant for vertical downflow**
- **Amplitude decreases for horizontal flow**

Flow Boiling System Dynamic Behavior – Effect of Mass Velocity

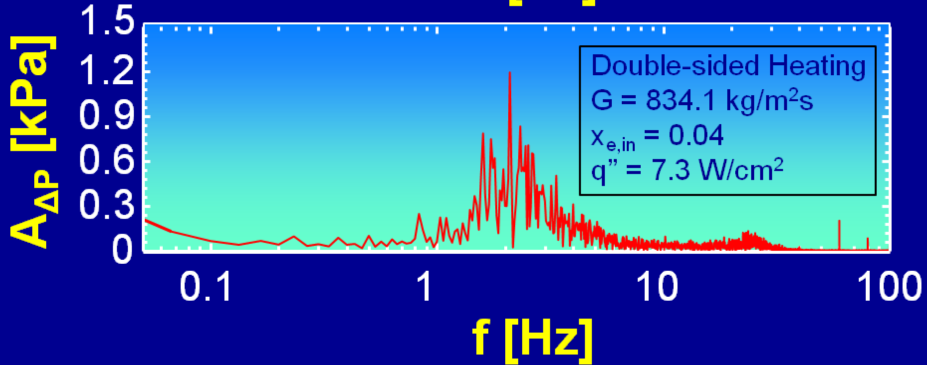


- **Amplitude of oscillations increase with increasing mass velocity**
- **Frequency of primary oscillation also increases with increasing mass velocity**

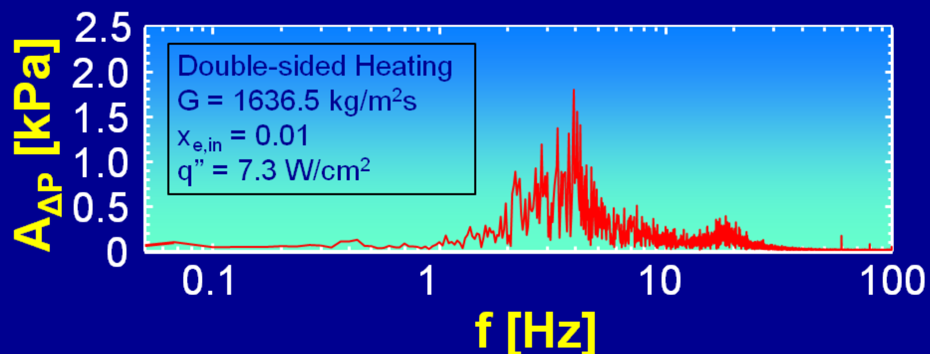
Vertical Upflow



G = 410.8 kg/m²s



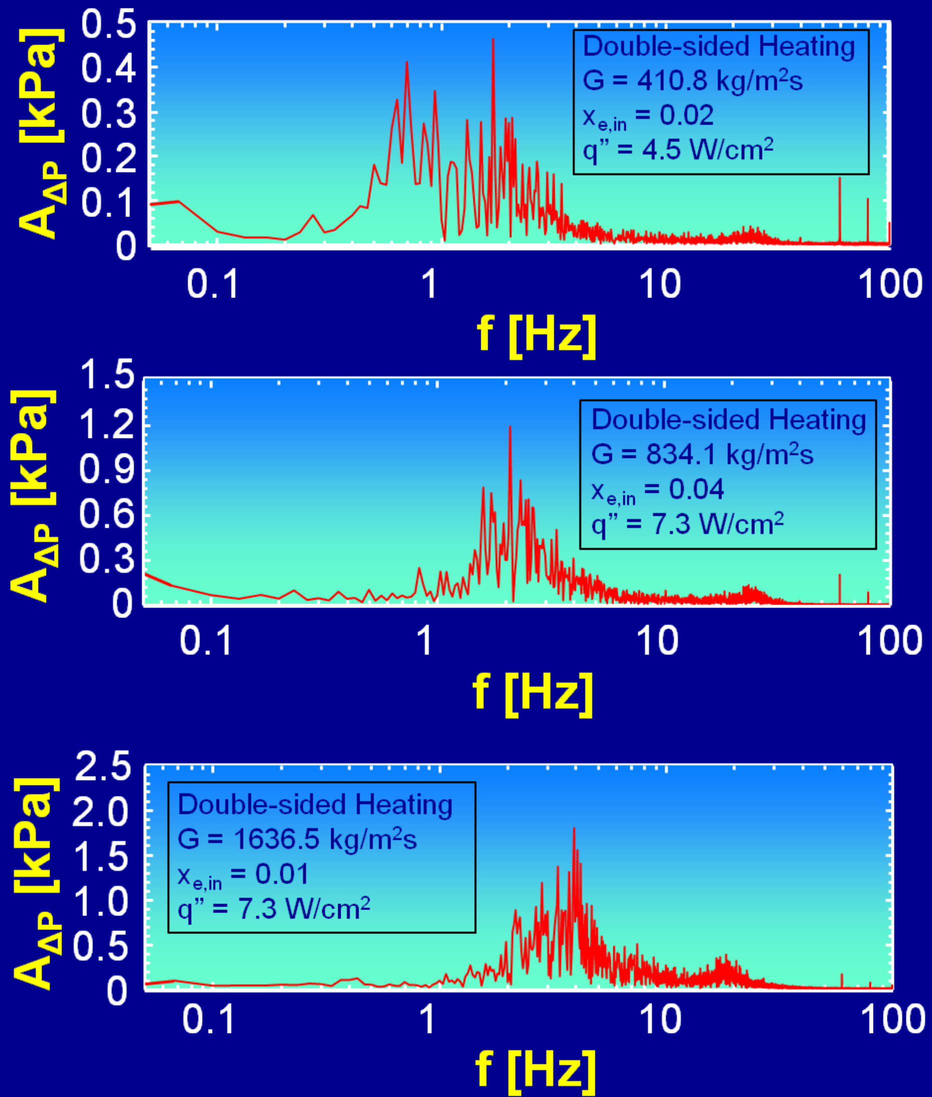
G = 834.1 kg/m²s



G = 1636.5 kg/m²s

Flow Boiling System Dynamic Behavior – Effect of Mass Velocity

Vertical Upflow



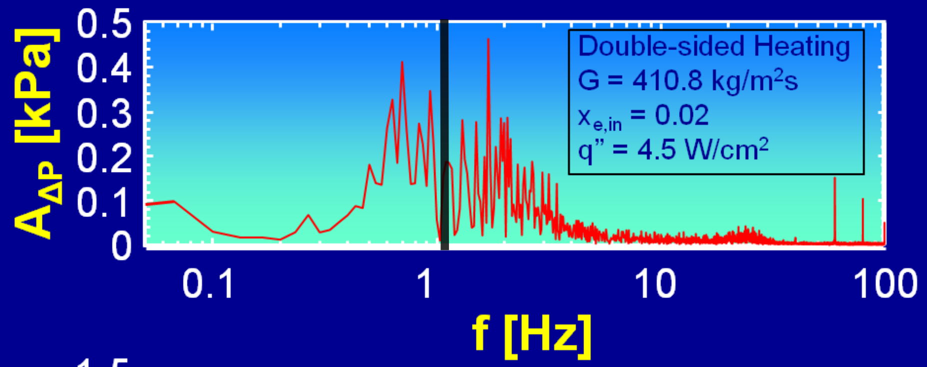
Density Wave Oscillations

Lahey & Podowski (1989):

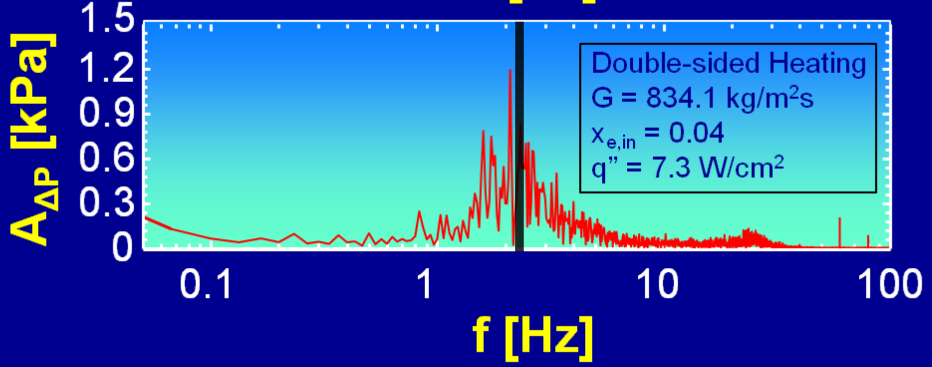
$$\tau_{DWO} \sim 2\frac{L_{ts}}{U_{FC}}$$

$$f_{DWO} = \frac{1}{\tau_{DWO}} \sim \frac{U_{FC}}{2L_{ts}}$$

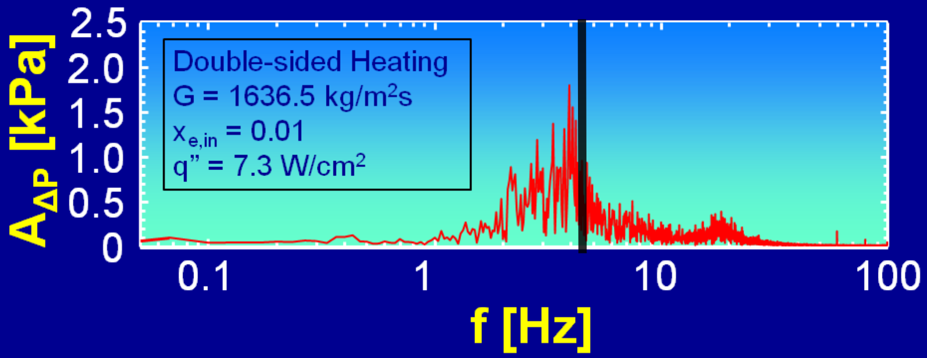
Vertical Upflow



f_{DWO} ~ 1.09 Hz

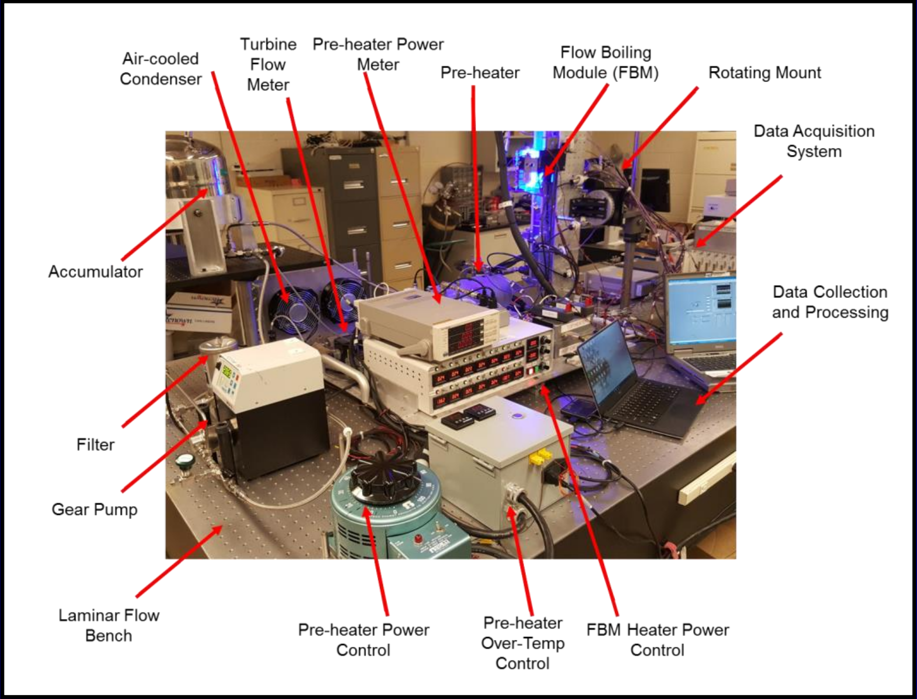


f_{DWO} ~ 2.27 Hz

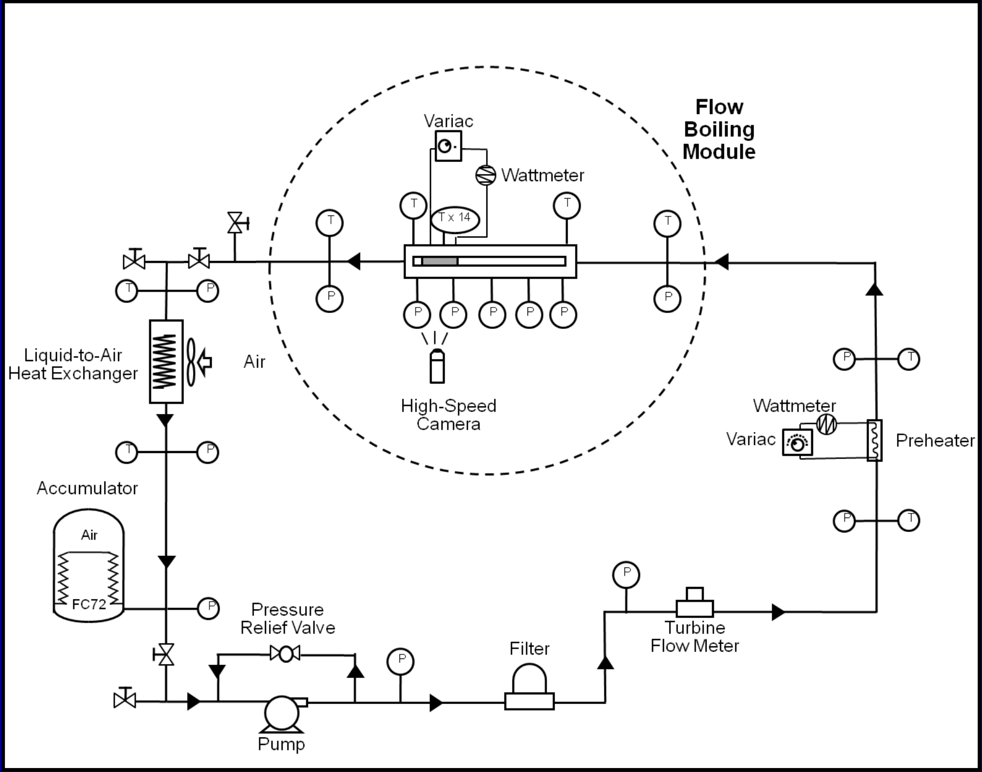


f_{DWO} ~ 4.49 Hz

Flow Boiling System Dynamic Behavior – New Experimental Approach



- **Perform pressure measurement at more locations throughout the flow loop**



- **Use information to isolate effect of upstream and downstream components**
- **Include accumulator for more representative system dynamics**

1. Fast Fourier transform of transient ΔP results reveals three key dynamic phenomenon:
   - Low frequency (1-10 Hz), high amplitude oscillation with characteristics of Density Wave Oscillations
   - Moderate frequency (5-30 Hz), low amplitude oscillation for vertical upflow and downflow
   - High frequency (20-100 Hz), sharp peaks attributable to pump behavior
2. Clear impact of changes to flow rate, heat flux, and orientation on flow oscillatory behavior
   - Effects of flow quality unclear
3. Identification of dominant oscillatory frequency possible for vertical upflow using simple, classic approach
4. Insufficient information on upstream and downstream dynamic behavior limits modelling

Acknowledgements

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The system dynamic behavior work was supported by NASA Space Technology Research Fellowship NNX15AP29H.

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