Universal Two-Phase Convection Heat Transfer Correlations for Cryogenic Pipe Chilldown

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INTRODUCTION

The transfer of cryogenic propellant through a pipe initially at room temperature results in flow boiling conjugate heat transfer that proceeds until the pipe is cooled to the liquid temperature. The heat transfer regimes during chilldown are divided as follows:

Single-phase vapor convection: Far downstream of the quench front where only cold vapor flow remains

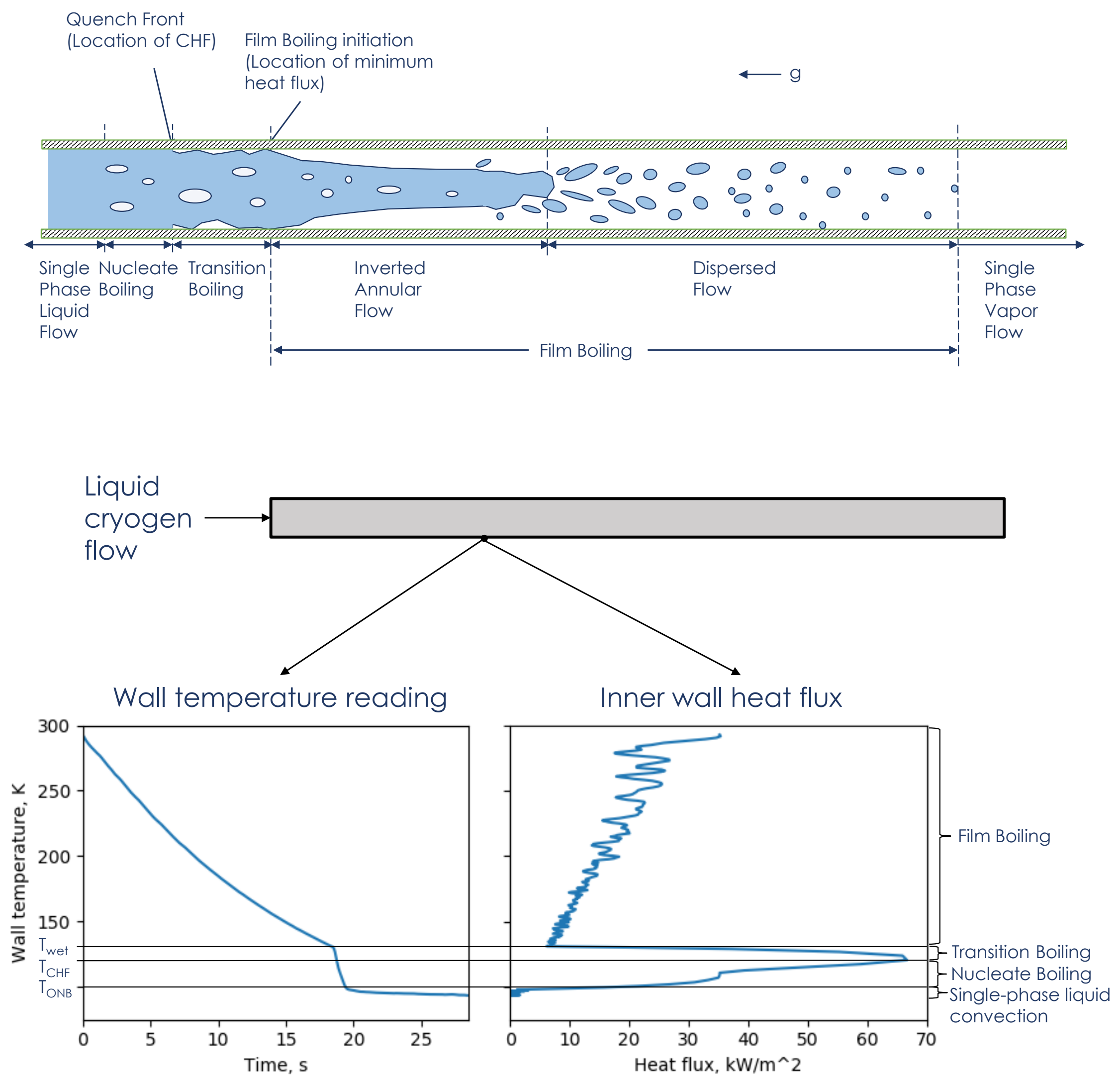
Film boiling: the wall temperature is above the *rewetting temperature* (T_{wet}), liquid approaching the wall evaporates entirely or is pushed away by the propulsive force of near-wall evaporation. Includes both Inverted Annular Flow and Dispersed Flow.

Transition boiling: the liquid sporadically touches the wall, producing a mixture of film and nucleate boiling

Nucleate boiling: after the *critical heat flux (CHF)* the liquid makes full contact with the wall, and boiling heat transfer generated from surface nucleation sites dominates

Single-phase liquid convection: boiling ceases below the onset of *nucleate boiling (ONB)*, and the temperature difference between the liquid and the wall drives heat transfer

Heat Transfer Regimes in Line Chilldown



OBJECTIVES

This goal of this project is to develop a set of universal heat transfer correlations for flow boiling heat transfer during cryogenic pipe chilldown applicable over a wide range of cryogenic fluids and thermodynamic conditions. The correlations improve upon prior correlations that were developed separately for liquid nitrogen and liquid hydrogen pipe quenching datasets. The new correlations include equations to calculate:

- The wall-to-fluid heat transfer in the 5 regimes shown above
- The bulk vapor temperature during high quality film boiling
- The wall temperature at the rewetting point or minimum film boiling heat flux
- The CHF and the wall temperature at CHF
- The wall temperature at ONB

METHODS

Datasets: To validate the correlations, eight cryogenic pipe chilldown datasets were gathered that cover the following parameter ranges:

Fluid: H_2, N_2, CH_4, O_2, and Ar
Pipe length: of 0.1 to 6.5m
Outer pipe diameter: 12.7 to 25.4 mm
Pipe wall thickness: 0.51 to 1.64 mm
Flow direction: upward, downward, and horizontal
Gravity level: 1g and 0g±0.01g.

Pipe Chilldown Model:

Wall Conservation of Energy

$$\rho_w c_w \frac{\partial T_w}{\partial t}\delta V_w = \dot{q}_{in} - \dot{q}_{out} - \dot{q}_{wf} - \dot{q}_{par} \qquad \text{Eq. 1}$$

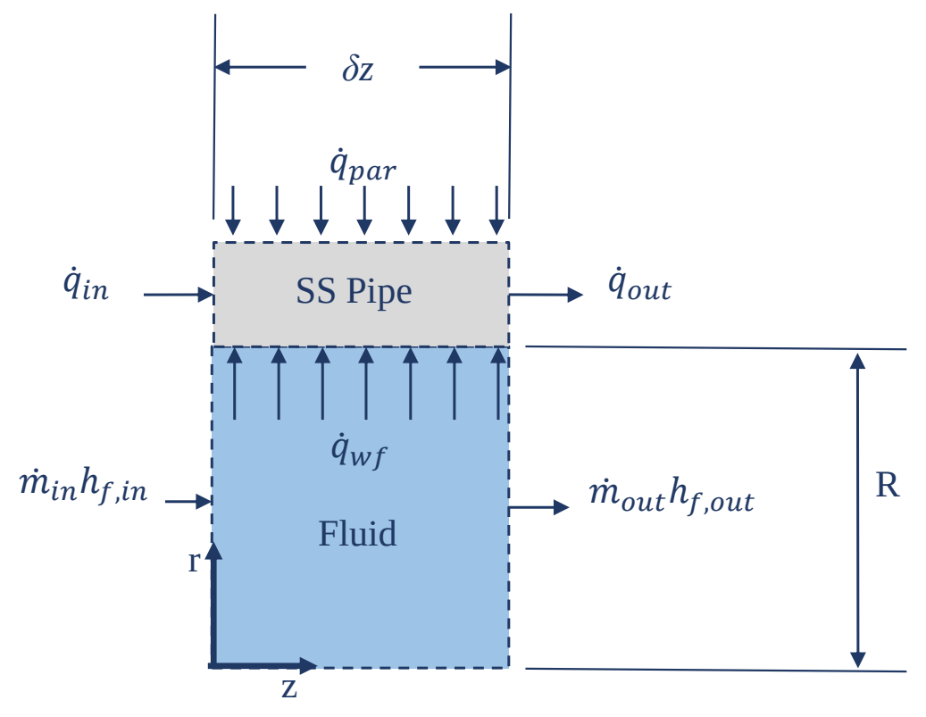
Fluid Conservation of Energy

$$m_f \frac{\partial h_f}{\partial t} = \dot{m}_{in}\left(h_{f,in} - h_f\right) - \dot{m}_{out}\left(h_{f,out} - h_f\right) + h_{wf}\left(T_{w,i} - T_{f,i}\right)\delta A_{wf} + \frac{\partial}{\partial t}\left(m_f \frac{P_f}{\rho_f}\right) \qquad \text{Eq. 2}$$

Conservation of Mass

$$\delta V_f \frac{\partial \rho_f}{\partial t} = \dot{m}_{in} - \dot{m}_{out} \qquad \text{Eq. 3}$$

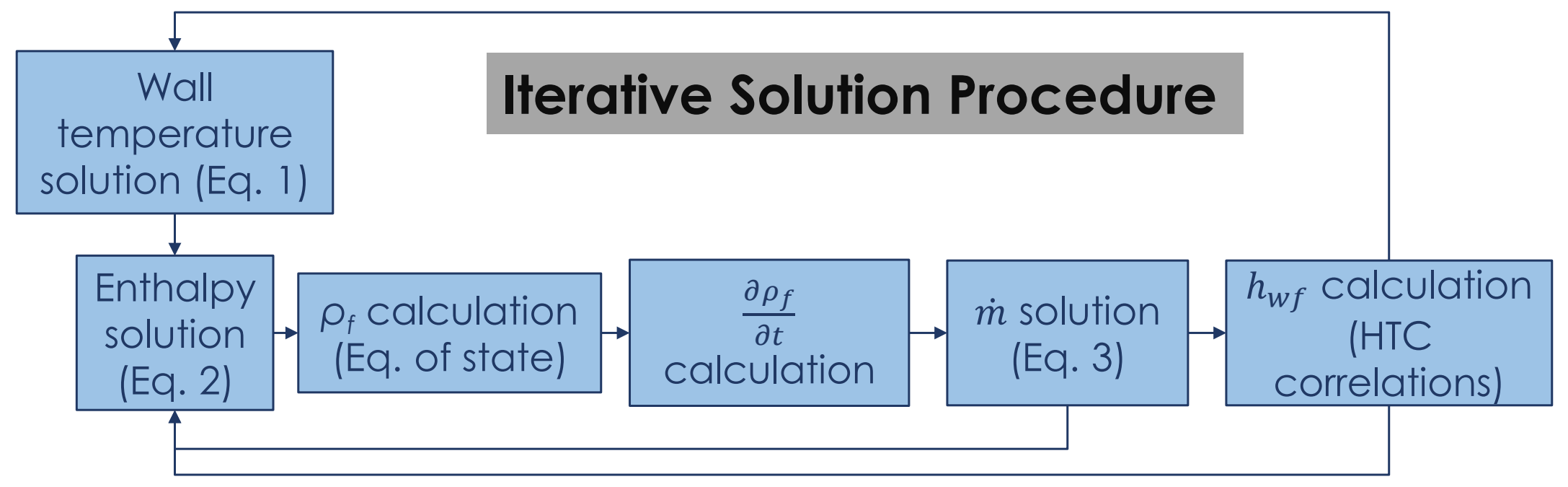
Pipe Cross-section



Solution

Each equation is solved numerically over axially-discretized wall and fluid control volumes.

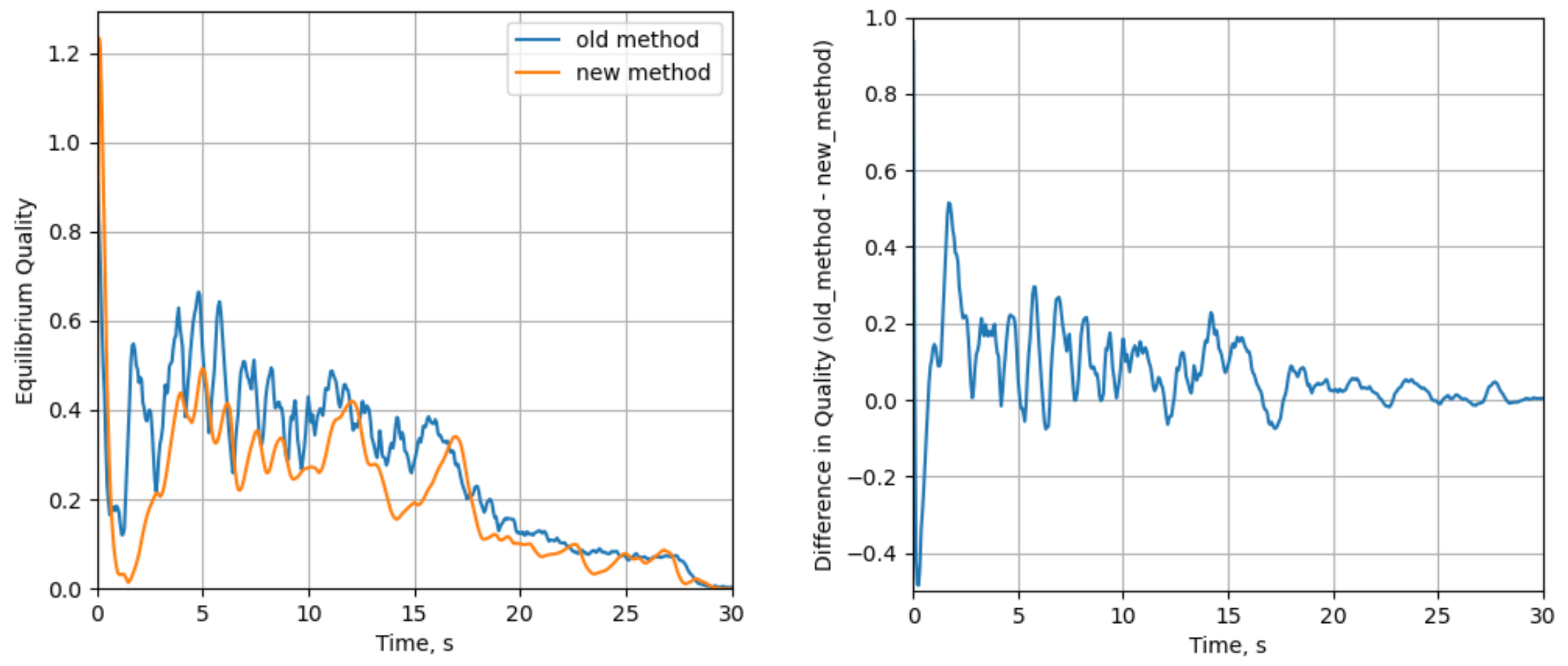
Iterative Solution Procedure



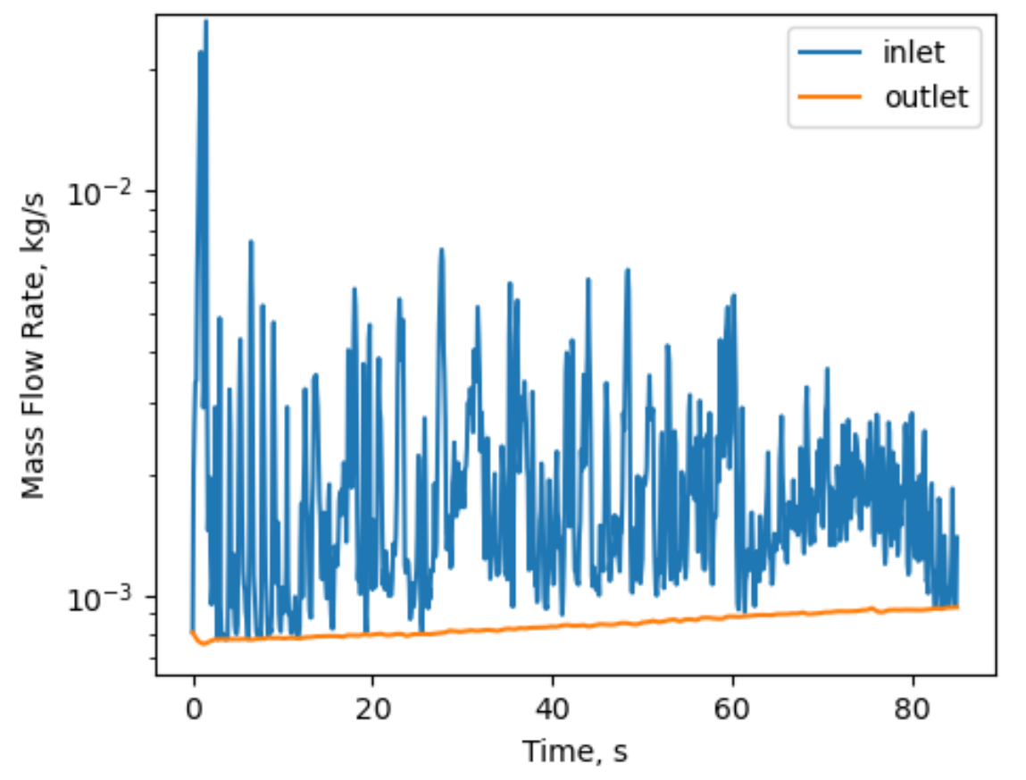
Equilibrium Quality: The equilibrium quality, x_e, is determined by an energy balance of the flow as though the phases were maintained at the saturation temperature, even though in an actual two-phase mixture the vapor could be superheated and/or the liquid could be subcooled. By this definition,

$$x_e = \frac{h - h_{l,sat}}{h_{fg}} \qquad \text{Eq. 4}$$

The pipe chilldown model is used to estimate the equilibrium quality along the test section. This new method is more accurate than prior methods by accounting for the spatial variation in mass flow rate along the pipe, rather than assuming a uniform mass flow rate at each timestep.

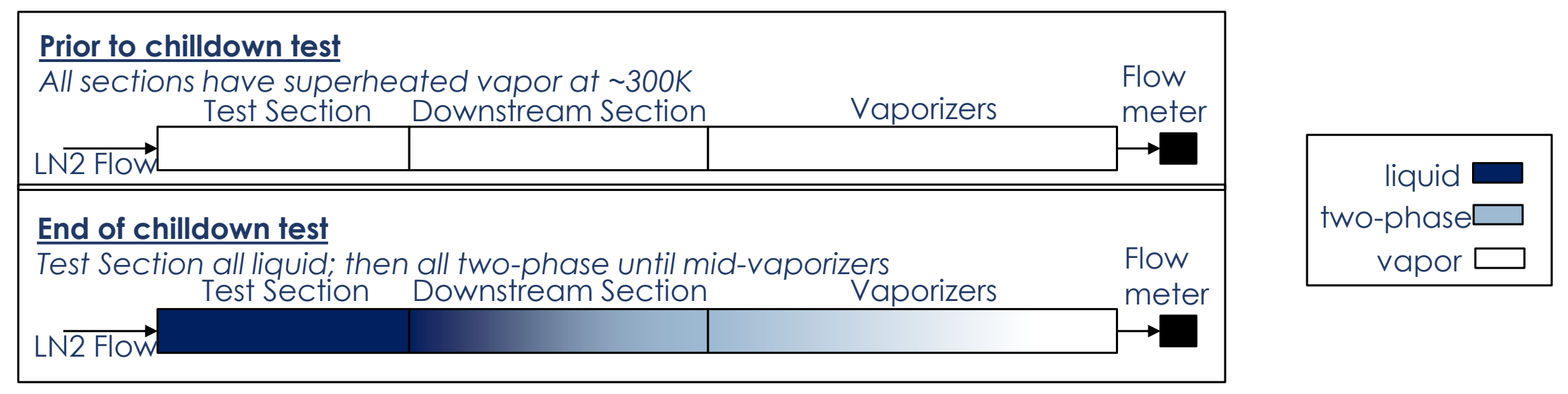


Inlet Mass Flow Rate: For tests that measured flow rate downstream of the test section, the pipe chilldown model was used to back-calculate the test section inlet mass flow rate. Without this data reduction step, the mass flow rate used for correlation development would be significantly underestimated.



METHODS Cont.

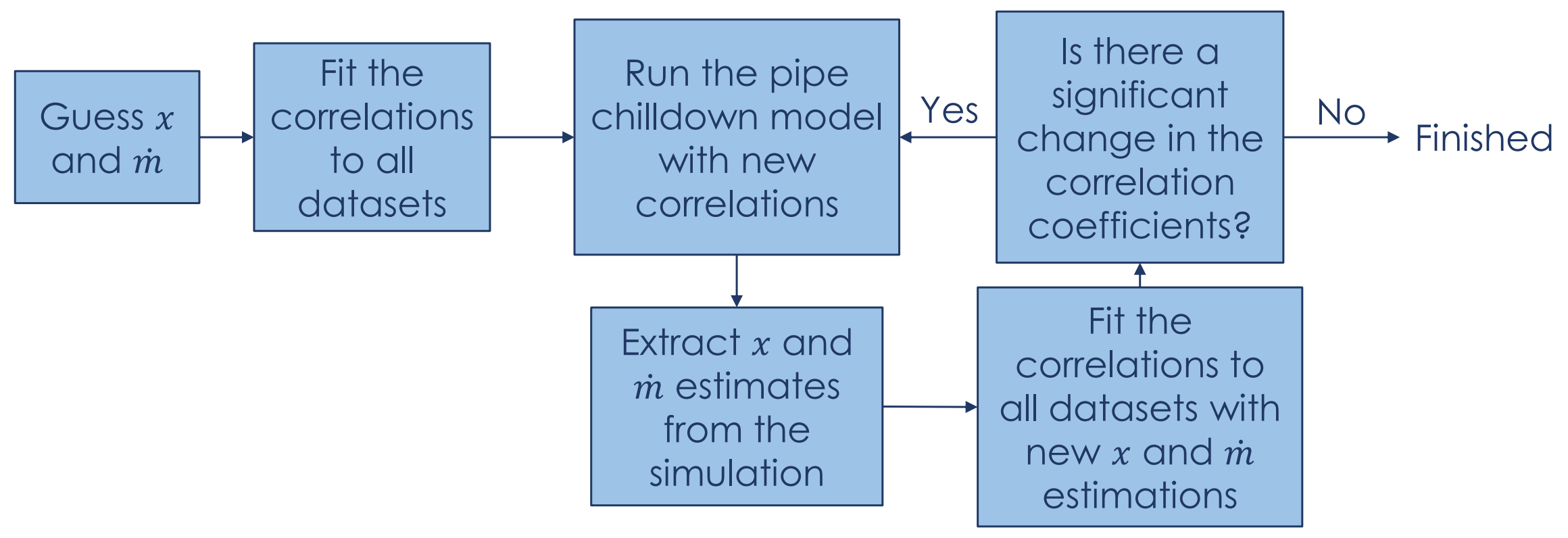
Fluid Mass Accumulation During Chilldown



Correlation Fitting Methodology:

The candidate correlation forms were created by combining correlations from prior work by our group. Terms within a correlation that do not improve the accuracy of the correlations will be eliminated.

Previous work has always considered the mass flux to be constant along the test section, leading to inaccuracies in correlations and the equilibrium quality estimation. Our method uses the iterative procedure below to calculate the mass flux, calculate the equilibrium quality, and fit the correlations.



RESULTS

Film Boiling Correlation:

The film boiling correlation improves upon others in the literature by smoothly transitioning between the different flow pattern regimes of dispersed flow and inverted annular flow. The correlation is a combination of four different heat transfer mechanisms.

Dispersed Flow	$Nu_{DF} = c_1 Re_{tp}^{c_2} Pr_{v,film}^{c_3}$	Eq. 5
Buoyancy-driven inverted annular flow	$Nu_{BIAF} = c_4 \frac{D}{k_{v,sat}}\left[\frac{\rho_{v,sat}(\rho_{l,sat}-\rho_{v,sat})g h_{fg} k_{v,sat}^3}{L\mu_v(T_w - T_{sat})}\right]^{1/4}$	Eq. 6
Flow-driven inverted annular flow	$Nu_{FIAF} = c_5\left[1 + \left(\frac{1}{\frac{L}{D}+c_6}\right)^{c_7}\right]\mathrm{erf}\left[\frac{x_a+1}{\log_{c_8}(Re_{v,sat})}\right]^{c_9}(1 - x_a)^{c_{10}} Re_{v,sat}^{c_{11}} Pr_{v,sat}^{c_{12}}\left(\frac{\mu_{v,sat}}{\mu_{vw}}\right)^{c_{13}}$	Eq. 7
Droplet-impact heat transfer	$Nu_{DI} = c_{14}\left(\frac{k_l}{k_{v,sat}}\right)e^{-\left(\frac{L}{D}\right)^{c_{15}}} We_l^{c_{16}} Ja_l^{c_{17}} Ja_v^{c_{18}}$	Eq. 8
Total film boiling heat transfer	$Nu_{FB} = \left(Nu_{DF}^p + Nu_{BIAF}^p + Nu_{FIAF}^p + +Nu_{DI}^p\right)^{1/p}$	Eq. 9
Actual quality	$x_a = \left(\frac{1}{x_e^K} + 1\right)^{-1/K}$	Eq. 10
Actual quality factor	$K = c_{19} Re_l + c_{20}$	Eq. 11

Rewetting Temperature Correlation:

The rewetting temperature correlation is derived from superheat limit theory (Spiegler et al., 1963), and accounts for effects of surface material (Baumeister et al., 1972) and flow rate.

$$T_{wet} = \left(\frac{\frac{27}{32}T_{cr} - T_{sat}}{B} + T_{sat}\right)\left(1 + \alpha_1 We_D^{\alpha_2} Re_L^{\alpha_3} Ja^{\alpha_4}\right) \qquad \text{Eq. 12}$$

$$B = \exp(3.06 \times 10^6 \beta_w)\,\mathrm{erfc}\left(1751.5\sqrt{\beta_w}\right) \qquad \text{Eq. 13}$$

$$\beta_w = \frac{1}{k_w \rho_w c_{pw}} \qquad \text{Eq. 14}$$

RESULTS Cont.

Nucleate Boiling Correlation:

An enhanced single-phase vapor correlation is used, where Nu_{sp} is the single-phase liquid convection heat transfer correlation and the remaining terms are nondimensional numbers that capture the heat transfer augmentation from surface boiling.

$$Nu_{NB} = c_1(1 - x_e)^{c_2}\, Re_l^{c_3} We_l^{c_4} Ja_l^{c_5} Ar^{c_6} Pr_l^{c_7} Nu_{sp} \qquad \text{Eq. 15}$$

Transition Boiling Correlation:

This is a novel approach to transition boiling where the heat flux smoothly transitions from the rewetting point to the CHF.

$$q''_{TB} = q''_{CHF}\theta^{c_1} + q''_{FB}\left(1 - \theta^{c_1}\right) \qquad \text{Eq. 16}$$

$$\theta = \frac{T_w - T_{wet}}{T_{CHF} - T_{wet}} \qquad \text{Eq. 17}$$

CONCLUSIONS

This work provided a new data reduction methodology to accurately determine equilibrium quality and local mass flow rate. The improvement in accuracy of these quantities will enable more accurate line chilldown predictions.

The forms of the correlations were determined by compiling equations from prior chilldown development efforts that were fit to smaller datasets. An iterative approach to fitting the correlations, using a numerical pipe chilldown model, was formulated for handling datasets where the equilibrium quality estimation is challenging. Future work will involve fitting these new correlations to the large cryogenic chilldown dataset and presenting the final correlations and coefficients.

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