Numerical Simulation of the Liquid Nitrogen Chilldown of a Vertical Tube

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Funding Source

- This work was funded by the NASA MSFC Space Launch System Advanced Development Project under Grant NNM13AA08G with Melinda Nettles as the Program Director

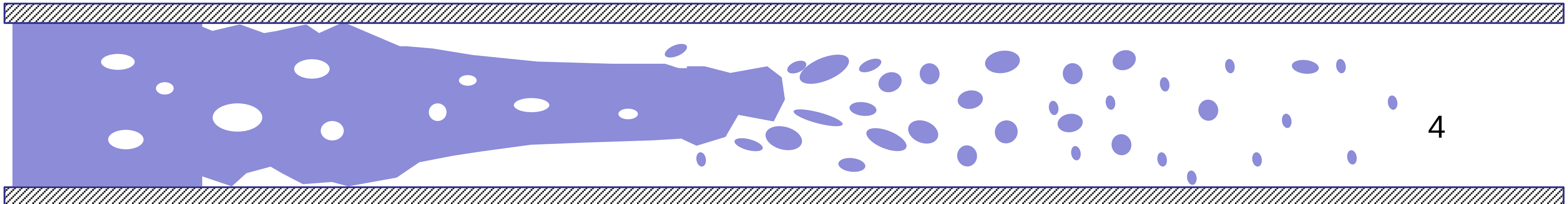
- The purpose of this project is to develop new and improved two-phase flow boiling heat transfer correlations for the Generalized Fluid System Simulation Program (GFSSP)

Background

- In many cases, cryogenic systems require single-phase liquid transfer to a destination.
- For the cryogen to remain a liquid, the hardware must be chilled down to cryogenic temperatures.
- The amount of hardware to chill down can be quite large, such as a feed line to a propellant storage tank.

Background

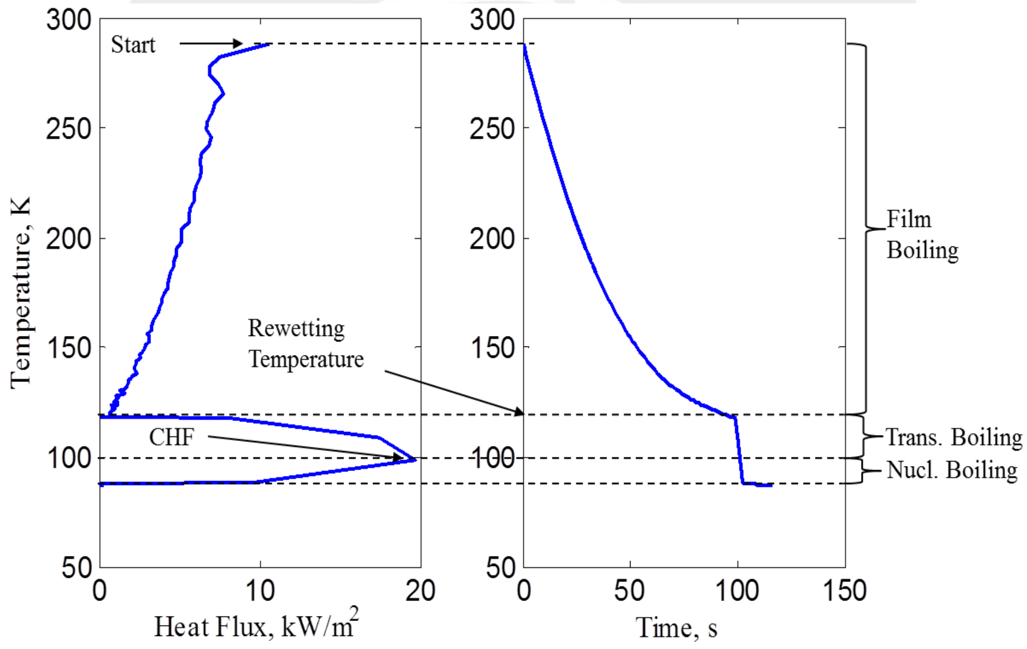
- Cryogen is fed through the hardware to chill it down. An initial portion of cryogen absorbs the heat from the pipe and boils off into vapor.
- This quantity of cryogen is sacrificed to allow single-phase liquid transfer.
- System design requires accurate knowledge of the necessary amount of sacrificed cryogen. Minimization of the sacrificed cryogen is desirable.
- The amount depends on the q" from pipe to fluid and the FR of the fluid.
- The robust, accurate prediction of the two-phase flow boiling heat flux continues to be a challenge
- $h = \frac{q"}{T_w - T_f} = f(\dot{m}, x, P, fluid\ properties, etc.)$



Boiling Regimes

3 different boiling regimes during chilldown

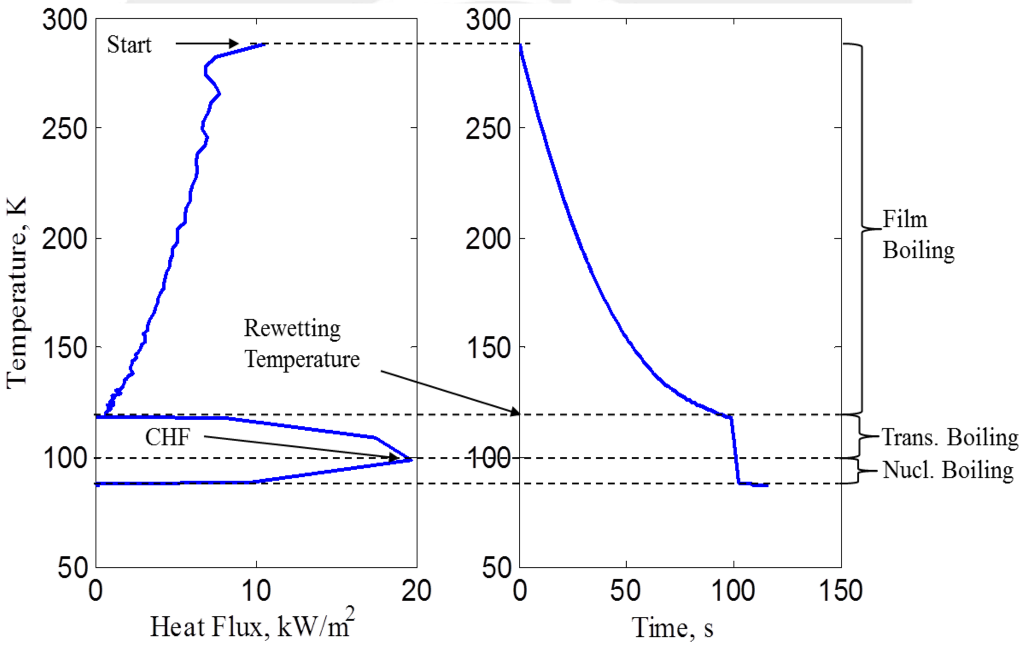
1. Film boiling: In this regime $T_w >> T_{sat}$. Any liquid approaching the wall is vaporized before touching the wall.



Boiling Regimes

3 different boiling regimes during chilldown

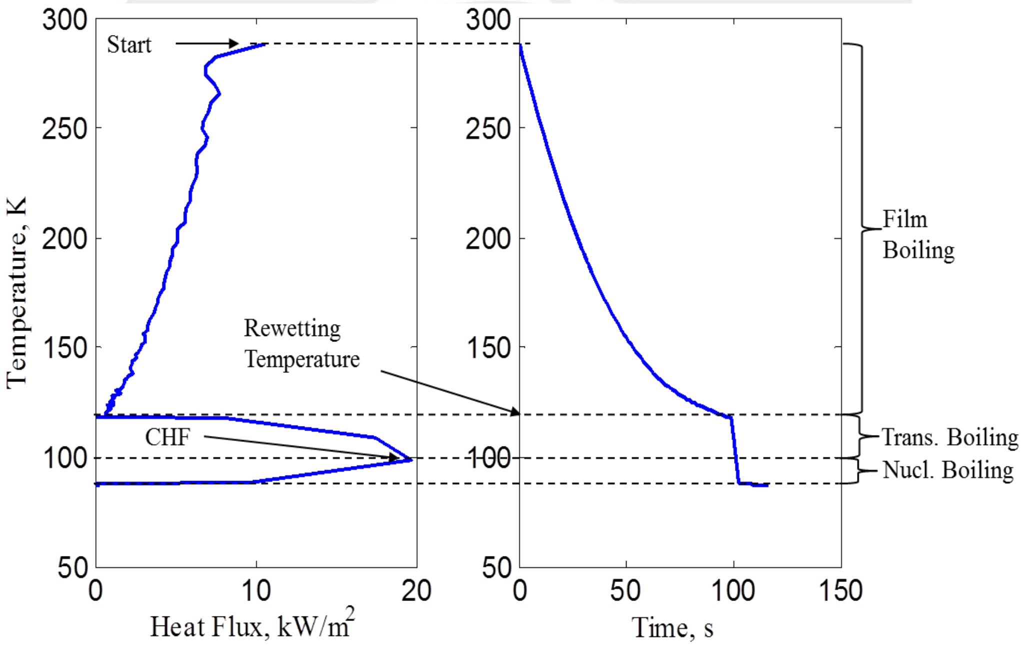
2. <u>Transition Boiling</u>: T_w drops below the *rewetting temperature*, T_{wet}. Liquid is able to intermittently touch the wall.



Boiling Regimes

3 different boiling regimes during chilldown

3. <u>Nucleate Boiling</u>: T_w drops below the temperature corresponding to the critical heat flux (CHF). This marks the start of full nucleate boiling. Liquid remains in contact with the wall. Heat is transferred by vapor bubbles generated in surface cavities and swept away from the surface.



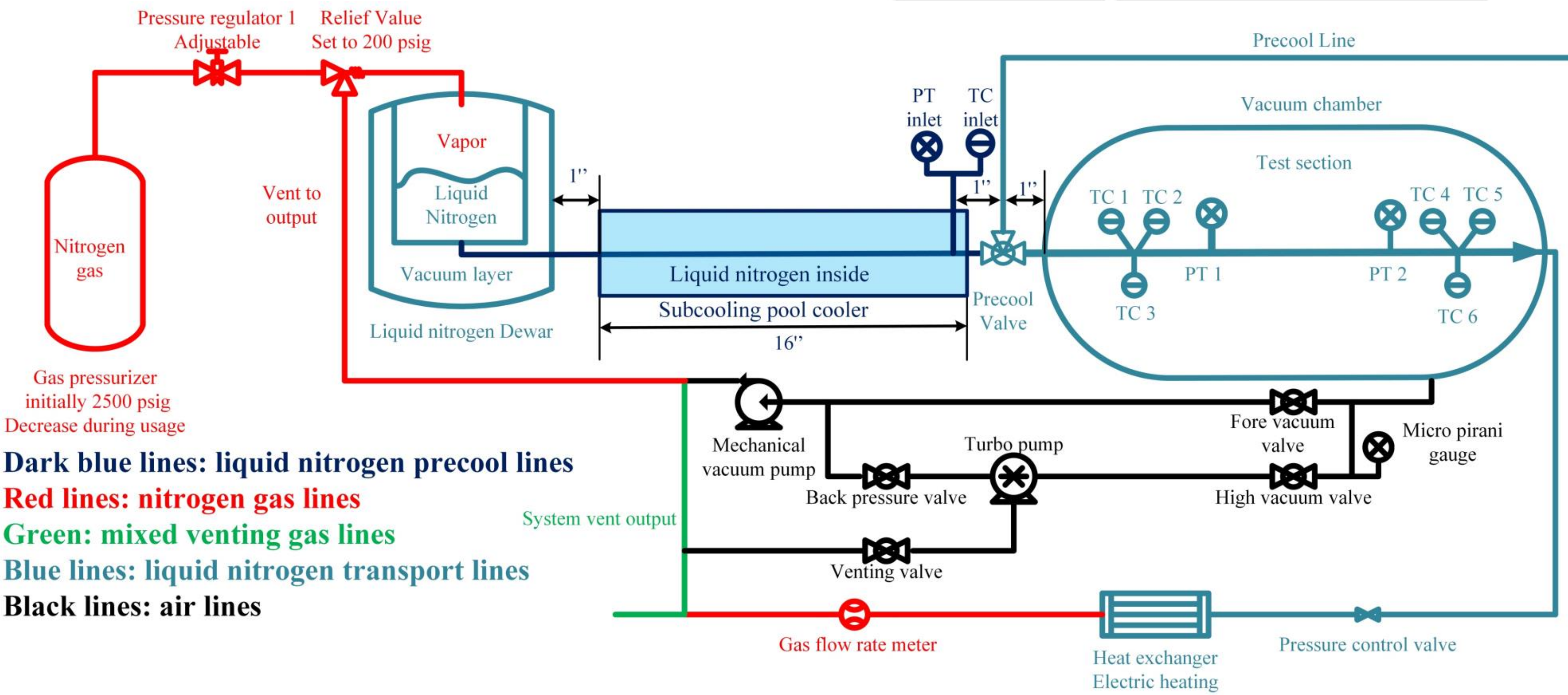
Goals of this work

- Determine accurate correlations for the film, transition, and nucleate boiling heat transfer coefficients
- Determine accurate correlations for T_{wet}, CHF, and T_{ONB}. These help determine the current boiling regime in a chilldown simulation.
- Develop a 1-D numerical simulation of the chilldown of a pipe which uses these correlations to predict the wall heat flux and compare to the results to recent LN_2 chilldown experiments

Experiment

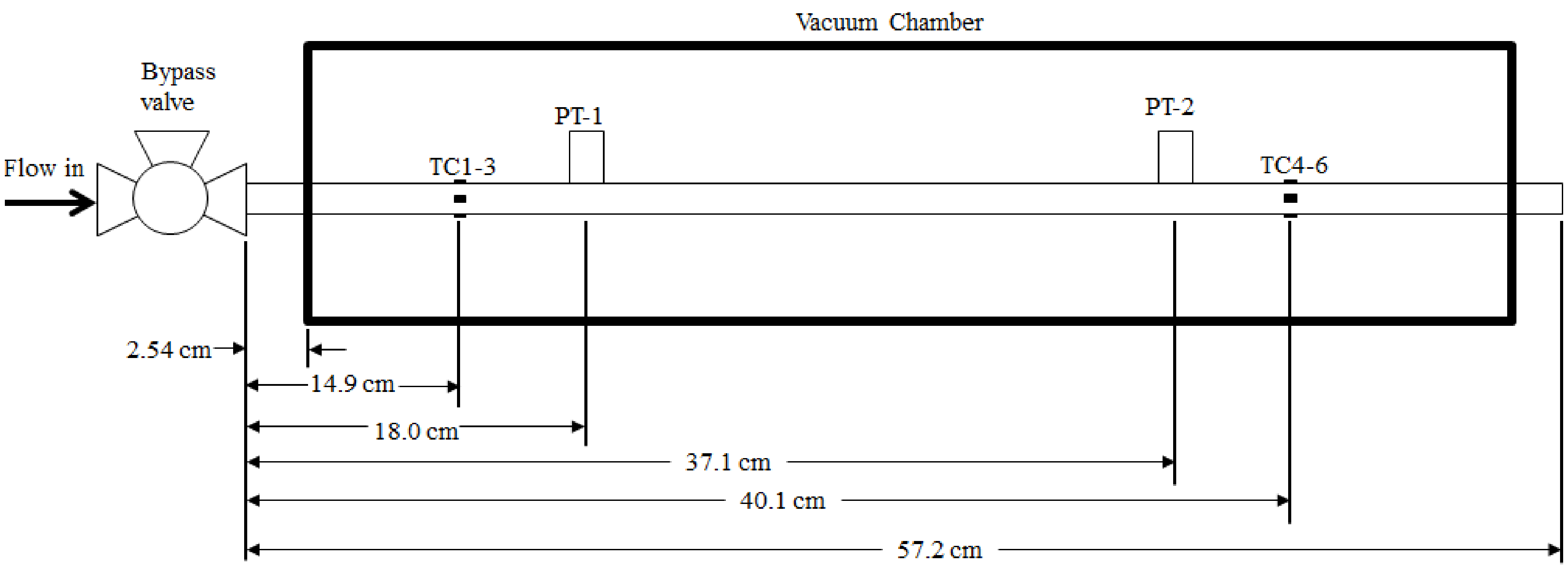
- Wall temperature and wall heat flux measurements were obtained from experiments in which a thin, vertically-aligned tube was chilled down with the downward flow of LN_2.
- 54 tests were completed.
- $G = 61.2$ to $1150\ kg/m^2s$
- $P = 174$ to 817 kPa
- Subcooled inlet temp from 0 to 14 K

Experiment Schematic



Test Section

- 2 stations, 1 PT and 3 TC's placed at each station
- At each station a TC is placed on the top, the side, and the bottom of the tube



PT = pressure transducer

TC = thermocouple

Film Boiling Correlation

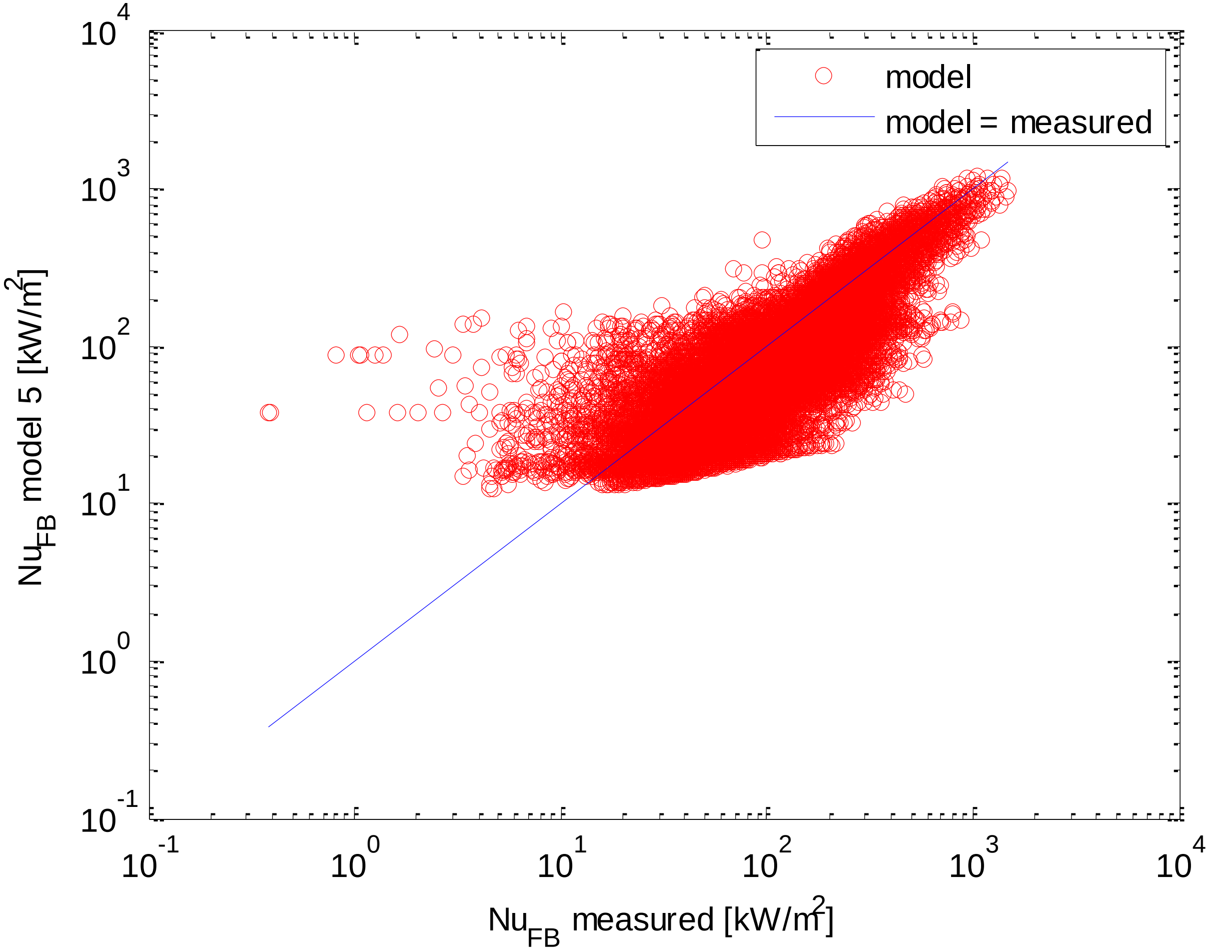
$$Nu_{fb} = h_{fb}D/k_v = \left(7.55\times10^{-4} - 7.43\times10^{-6} z/D\right) Re_v^{0.941}\left(1-x_e\right)^{-5.23} Pr_v^{0.4} + 0.0568\left(k_l/k_v\right)We_z\theta_{fb}^3$$

- $Re_v = GD/\mu_v$ accounts for the single-phase vapor convection along the wall
- $(7.55 \times 10^{-4} – 7.43 \times 10^{-6}\, z/D)$ accounts for the axial dependence of the convection as a cause of developing flow near the inlet
- $(1-x_e)$ accounts for the size of the vapor layer and thus the actual speed of the vapor layer.
- $Pr_v=(C_p\mu/k)_v$ accounts for the differences between fluids.
- $(k_l/k_v)We_z\theta_{fb}^3$, where $We = G^2z/(\rho_l\sigma)$ and $\theta_{fb} = (300 – T_w)/(300 – T_{wet})$ accounts for the heat flux enhancement due to liquid droplet impingement

Film Boiling Correlation

- Model compared with 21,907 data points of vertical downflow data

- MAE = 47%



Nucleate Boiling Correlation

The Chen* Correlation is based on the physics of the heat transfer process and thus doesn't involve an empirical correlation in terms of the Boiling number Bo = q"/(Gh$_{fg}$)

HTC is the summation of forced liquid convection heat transfer and nucleate boiling heat transfer

$$h_{nb} = h_{fc} + h_b$$

Forced convection with the liquid

$$h_{fc} = 0.023\left[Re_l\left(1-x_e\right)\right]^{0.8} Pr_l^{0.4}\frac{k_l}{D}F$$

Heat transfer from nucleate boiling

$$h_b = 0.00122\frac{k_l^{0.79}C_{p,l}^{0.45}\rho_l^{0.49}}{\sigma_l^{0.5}\mu_l^{0.29}\gamma_{lv}^{0.24}\rho_v^{0.24}}\left[T_w - T_{sat}\left(P\right)\right]^{0.24}\left[P_{sat}\left(T_w\right)-P\right]^{0.75}S$$

Accounts for the flow structure effect on convection – function of quality and ratio of vapor/liquid properties

$$F = \left(\frac{1}{X_{tt}}+0.213\right)^{0.736}$$

Accounts for the change in the vapor bubble temperature due to the thermal boundary layer

$$S = \frac{1}{1+2.53\times10^{-6}Re_l^{1.17}F^{1.4625}}$$

Martinelli parameter

$$X_{tt} = \left[\left(1-x_e\right)/x_e\right]^{0.9}\left(\rho_v/\rho_l\right)^{0.5}\left(\mu_l/\mu_v\right)^{0.1}$$

*Chen, J. C., "Correlation for Boiling Heat Transfer to Saturated Fluids in Flow," *Industrial and Engineering Chemistry Process Design and Development*, Vol. 5, No. 3, 1966, pp. 322-329

Nucleate Boiling Correlation

- When fitting against the data it was found that the Chen model drastically overestimated the heat flux.
- This had negligible affect on the results because only a small fraction of time was spent in the nucleate boiling regime
- For larger tube thicknesses the error in chilldown time would be more noticeable
- Future work will include developing a more accurate nucleate boiling correlation

Transition Boiling Correlation

- Transition boiling = film boiling + nucleate boiling
- The TB correlation could use either or both of these correlations with an additional empirical constant.
- $q''_{Nuc} >> q''_{Film}$, so a fit was applied to the data with the Chen correlation HTC and the nondimensional temperature $\theta_{tb} = (T_{wet} - T_w)/(T_{wet} - T_{sat})$:

$$h_{tb} = 0.523\theta_{tb}^{0.390} h_{nb}$$

Rewetting Temperature Correlation

- The De Salve and Panella* correlation was used to calculate T_{wet}

$$T_{wet} = T_{sat}(P) + 0.29d^{-1}\left[T_{MS} - T_{sat}(P)\right]\left(1 + 0.279G^{0.49}\right)$$

$$d = \exp\left[3.06\times10^{6} / \left(k\rho C_p\right)_w\right]\mathrm{erfc}\left[1751.5\left(k\rho C_p\right)_w^{0.5}\right]$$

$$T_{MS} = 0.844T_{cr}$$

- MAE = 5.08%

*De Salve, M. and Panella B., "Analytical Model for Bottom Reflooding Thermal-Hydraulics in Circular Ducts and Comparison with Experimental Results," *International Centre for Heat and Mass Transfer Seminar on Nuclear Reactor Safety Heat Transfer*, Hemisphere Publishing Corporation, Managua, Nicaragua, CA, edited by S. G. Bankoff and N. H. Afgan, 1982, pp. 742-762.

Critical Heat Flux (CHF) Correlation

- A similar form to the Katto* correlation was used to calculate CHF

$$q''_{CHF} = 0.0527 G h_{lv} We_z^{-0.2894}$$

$$We_z = \frac{G^2 z}{\rho \sigma}$$

- MAE = 12.6%

*Katto, Y. and Kurata, C., "Critical Heat Flux of Saturated Convective Boiling on Uniformly Heated Plates in a Parallel Flow," *International Journal of Multiphase Flow*, Vol. 6, 1980, pp. 575-582

Temperature at Onset of Nucleate Boiling (T_{ONB})

- There is a minimum superheat ($T_w - T_{sat}$) > 0 required to achieve fully-developed nucleate boiling
- If $T_w < T_{ONB}$ the heat flux is mostly from single-phase liquid convection with the w, even though $T_w > T_{sat}$.
- A simple empirical fit to the data was used to correlate the ONB temperature:

$$T_{ONB} = T_{sat}(P) + 0.0071P + 5$$

- Future work will include a more robust, non-dimensional correlation for T_{ONB}

Simulation Logic

For each solid node:

1. Calculate T_{wet} for the mass flow rate and pressure.
2. If $T_w > T_{wet}$ then use film boiling correlation
3. If $T_w < T_{wet}$, then:
    1. Calculate T_{ONB}
    2. If $T_w > T_{ONB}$, then:
        1. Calculate CHF
        2. Calculate q_{nb}" prediction from Chen correlation
        3. If $q_{nb}" > q_{CHF}"$ then use h_{tb} (transition boiling)
        4. If $q_{nb}" < q_{CHF}"$ then use h_{nb}
4. If $T_w < T_{ONB}$ then use then use single-phase liquid Dittus-Boelter heat flux

1D Simulation Description

- Only models the energy equation of the pipe material.

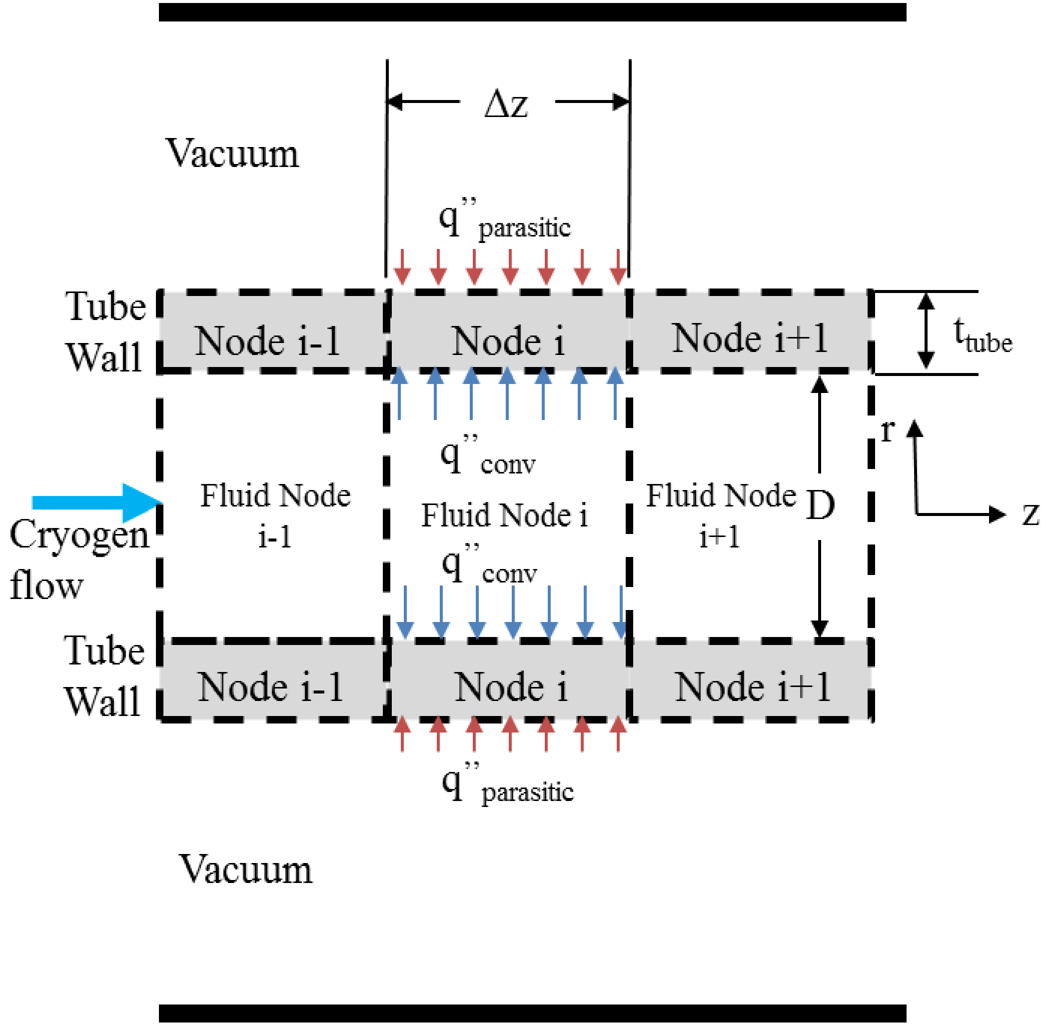
$$\rho_w C_{p,w} \frac{\partial T_w}{\partial t} = k_w \frac{\partial^2 T_w}{\partial z^2} + q''_{conv}(z) + q''_{parasitic}(z)$$

- Assume constant mass flow rate and time-independent pressure distribution of the fluid
  - therefore the momentum and continuity equations do not need to be solved.
- Radiation and gas conduction are included in the term $q''_{parasitic}$
- Time integration: 1st order fully implicit
- Spatial discretization: 2nd order central difference
- L = 22.5”, N = 40, so dz=L/N=0.5625”

1D Simulation Description

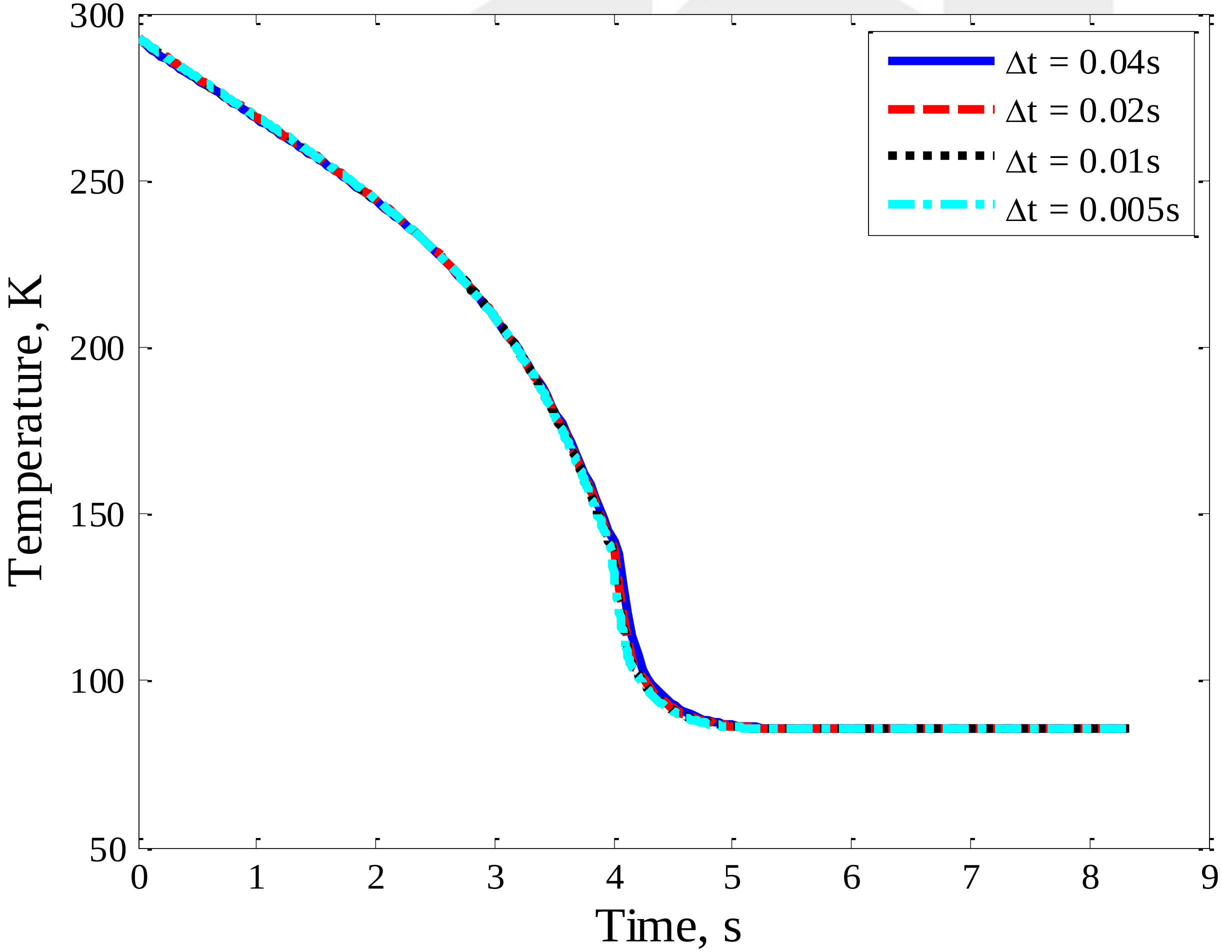
At each time step the enthalpy of a fluid node, h_i, was calculated by

$$h_i = h_{i-1} + q_{conv,i-1}\left[4/\left(\pi D^2 G\right)\right]$$



Convergence Study

- Δt = 0.04 s, 0.02 s, 0.01 s, and 0.005 s were used to simulate the fastest chilldown run.
- Δt = 0.01 s gave acceptable level of convergence



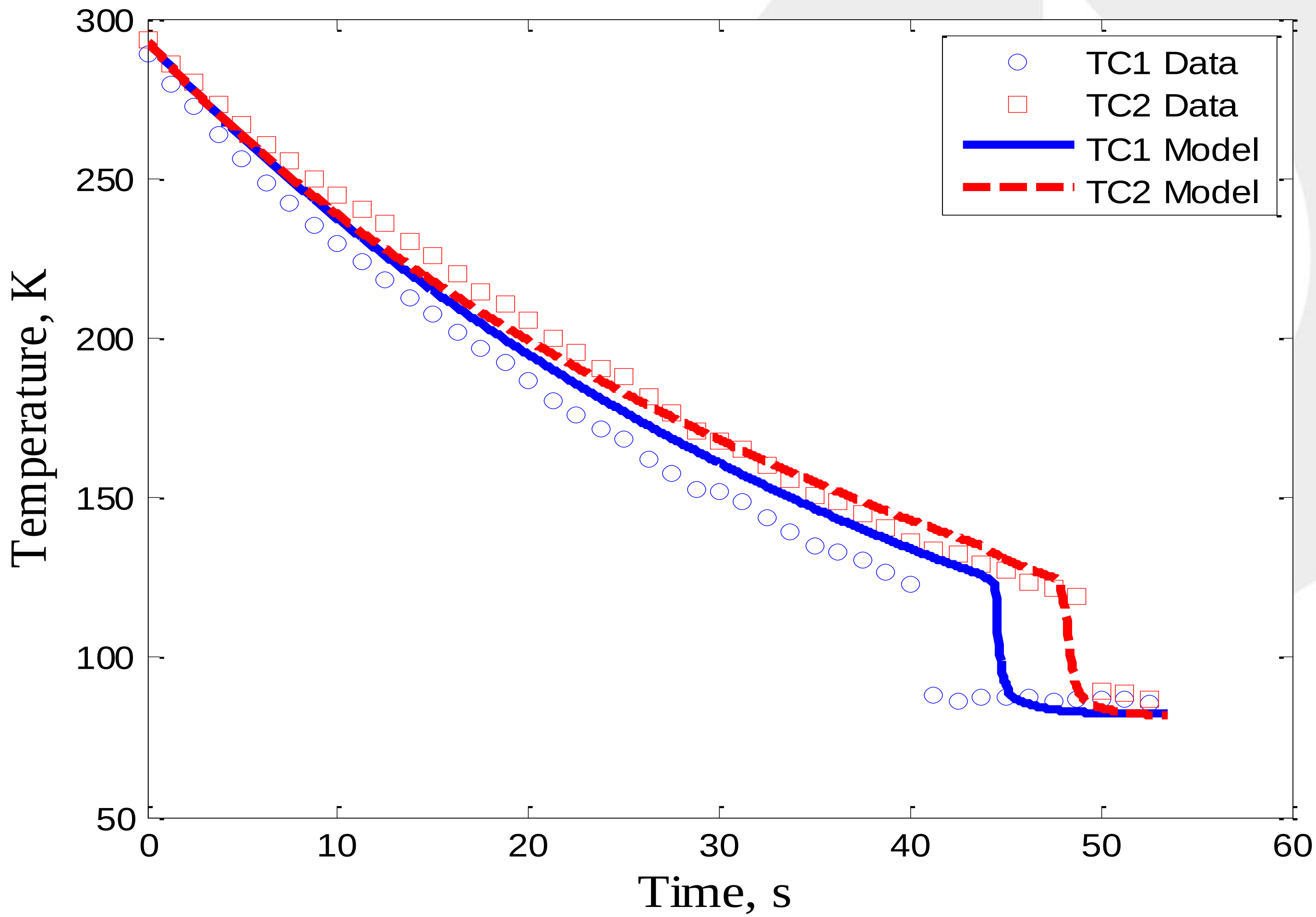
Simulation vs. Data

- The simulation was run for all 54 tests
- The usefulness of the correlations was determined by the accuracy of the chilldown time.
- Two different time errors were considered
  - the time from start to T_{wet}
  - the time from start to T_{ONB}

Time Metric	MAE, s	MAPE, %
t_{wet}	4.83	24
t_{ONB}	5.15	25

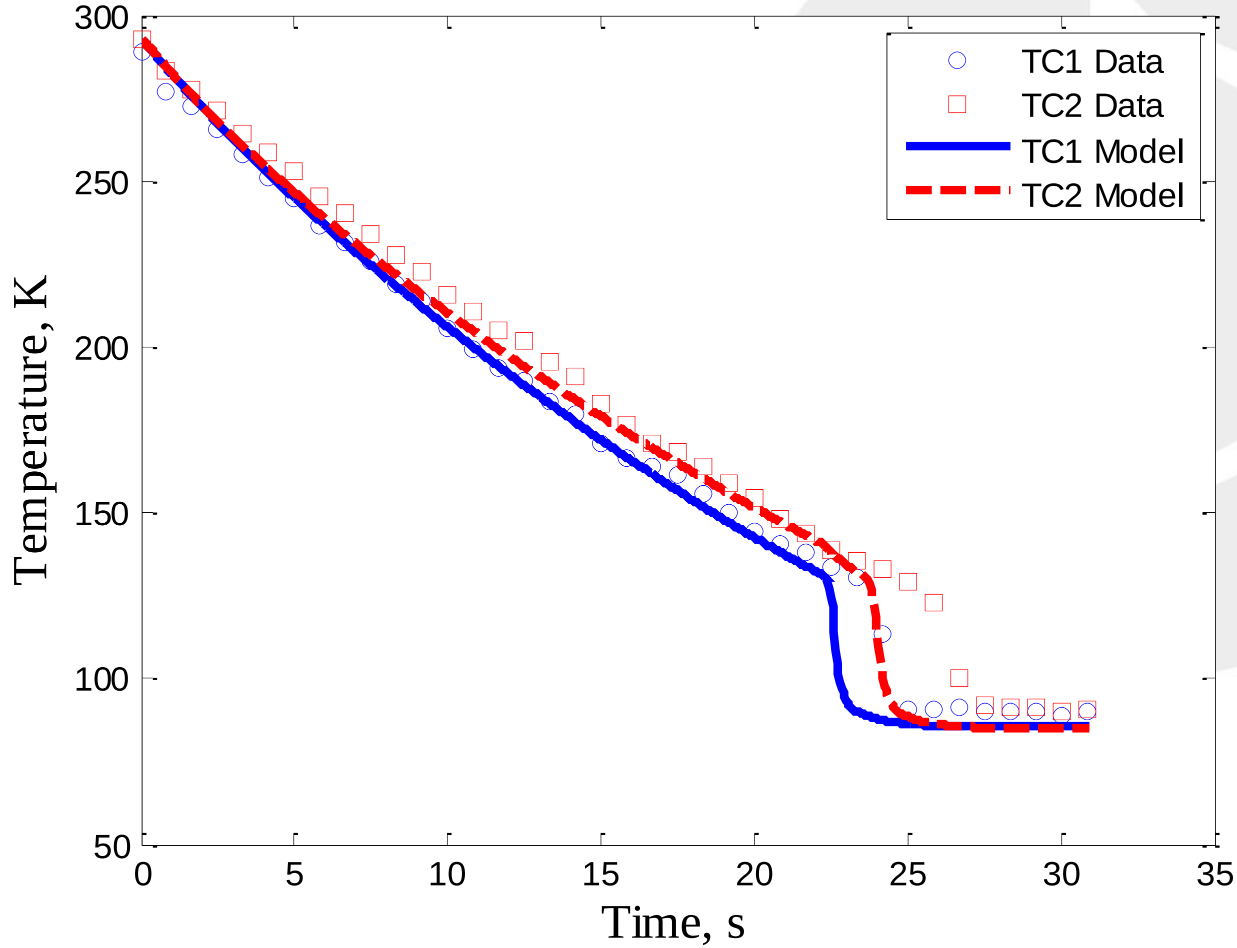
Simulation vs Data

G = 126 kg/m^{2}s, Re_l = 11,046, P_{inlet} = 176 kPa.



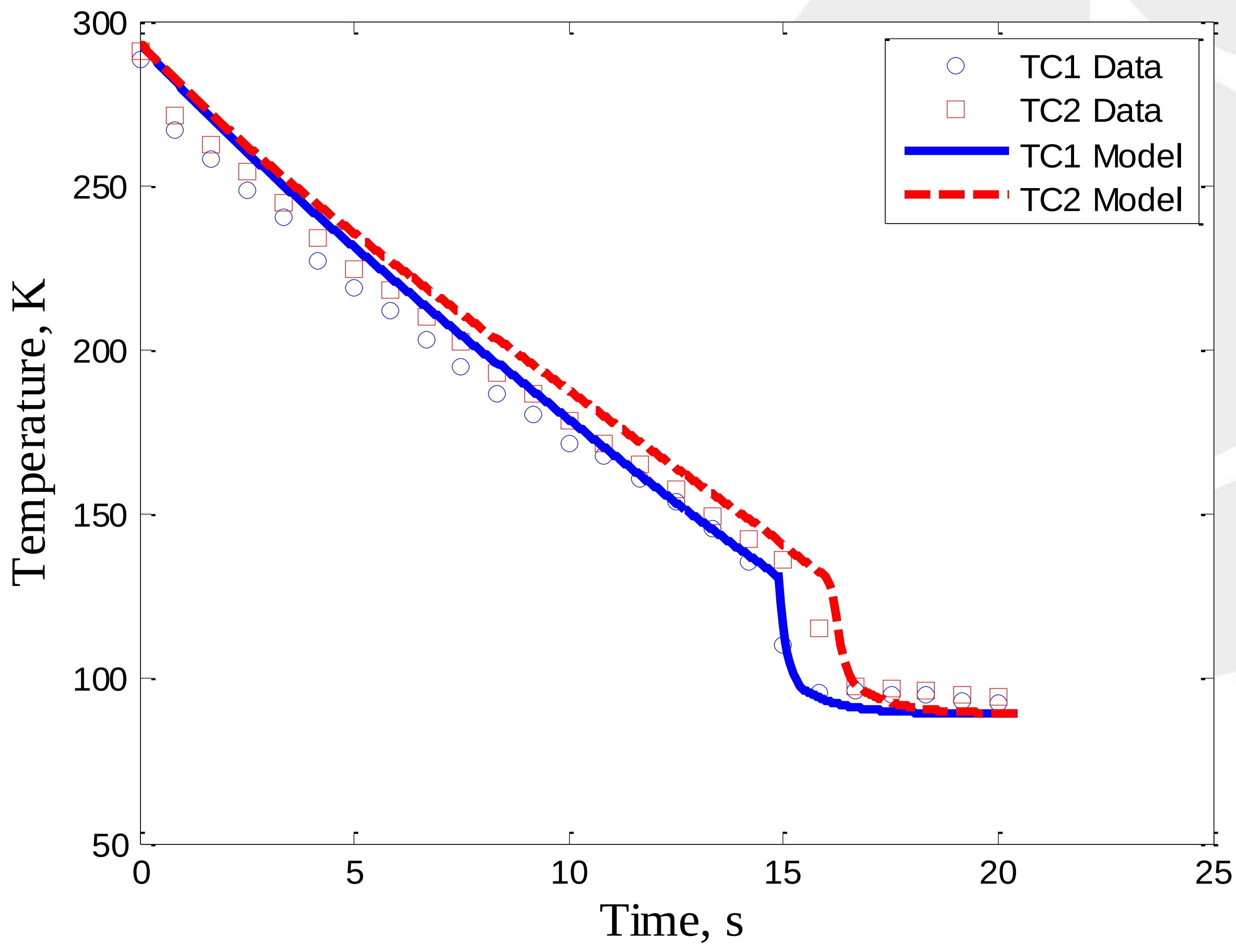
Simulation vs Data

G = 220 kg/m^{2}s, Re_l = 21,695, P_{inlet} = 252 kPa.



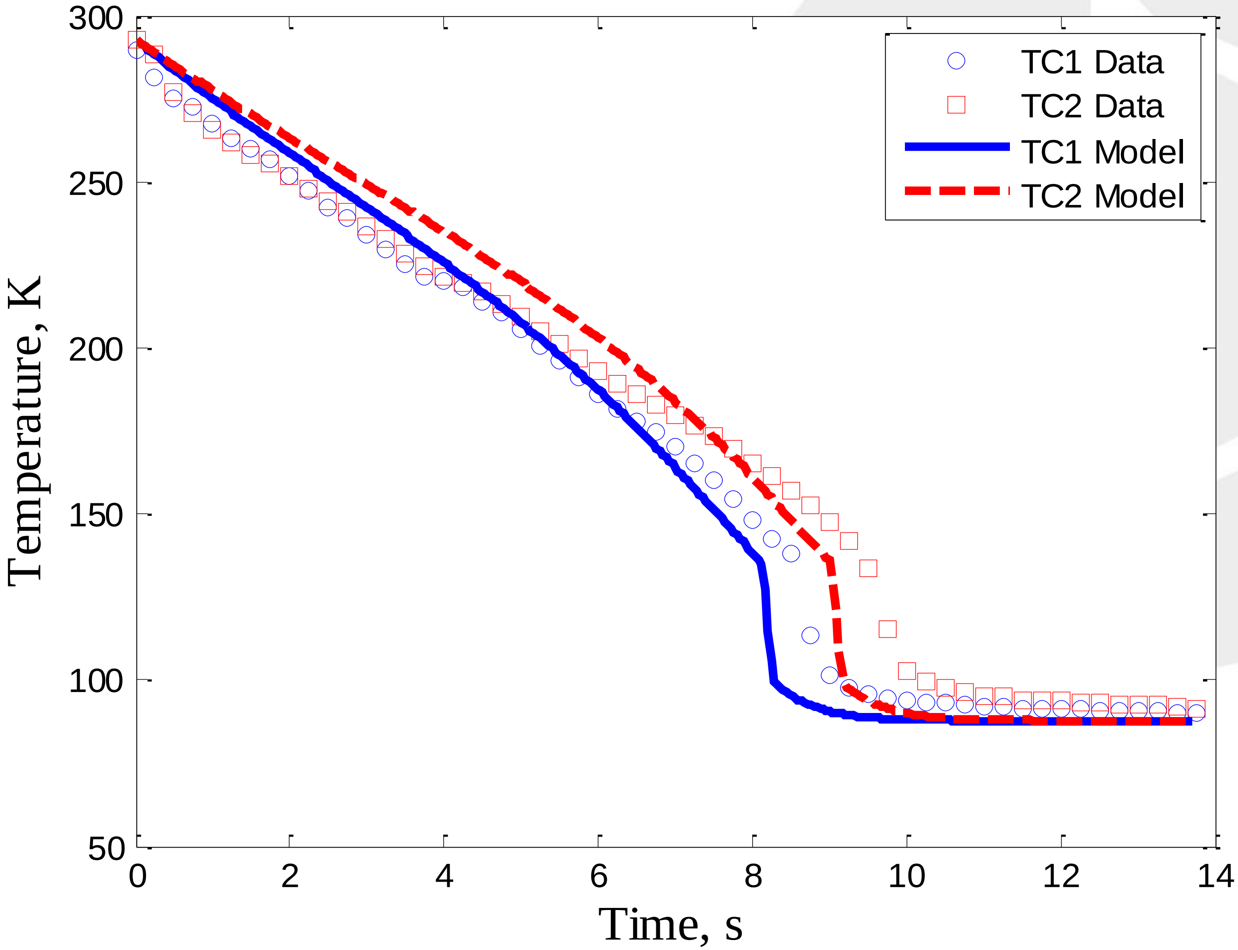
Simulation vs Data

G = 342 kg/m^{2}s, Re_l = 37,810, P_{inlet} = 420 kPa.



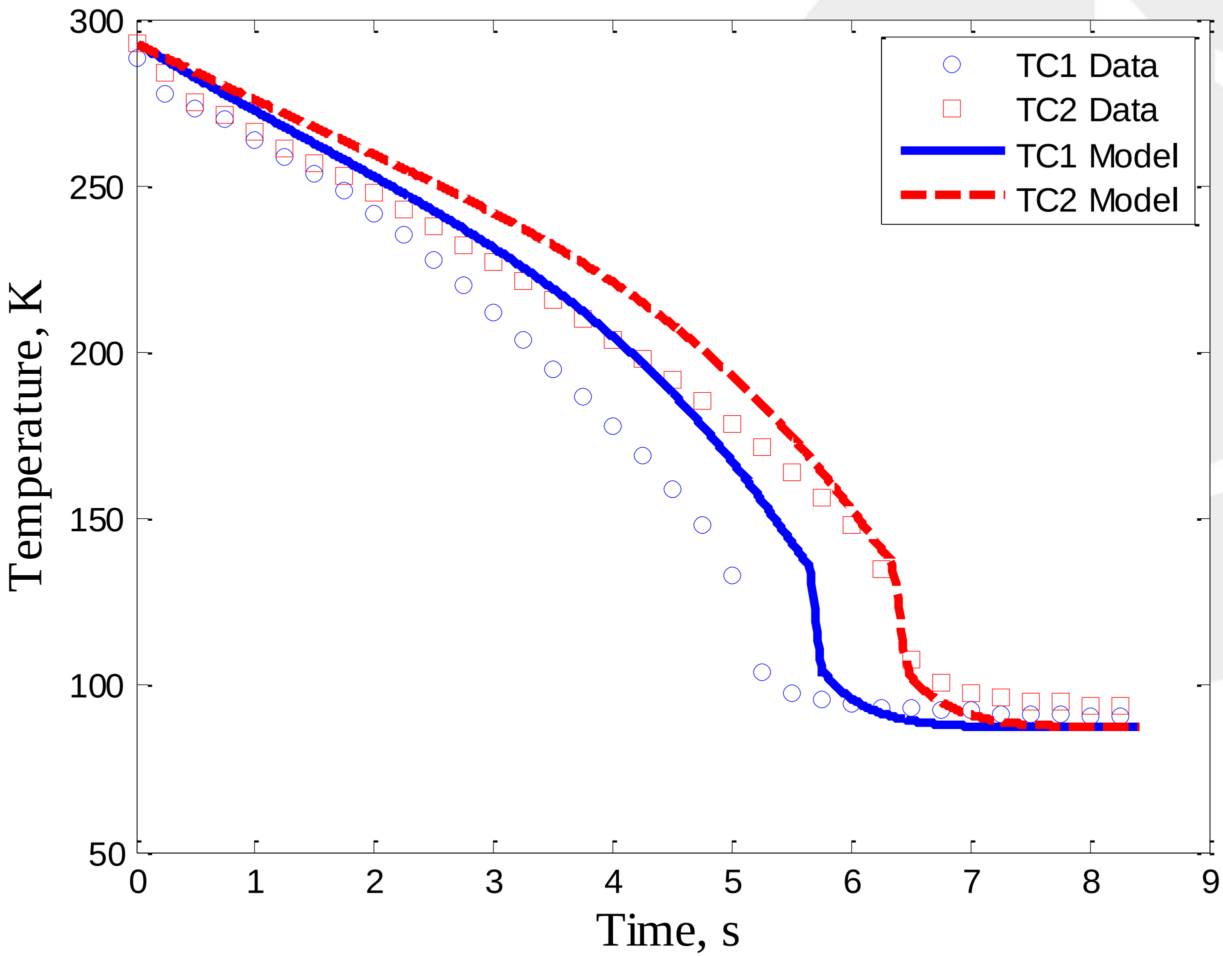
Simulation vs Data

G = 627 kg/m^{2}s, Re_l = 65,575, P_{inlet} = 561 kPa



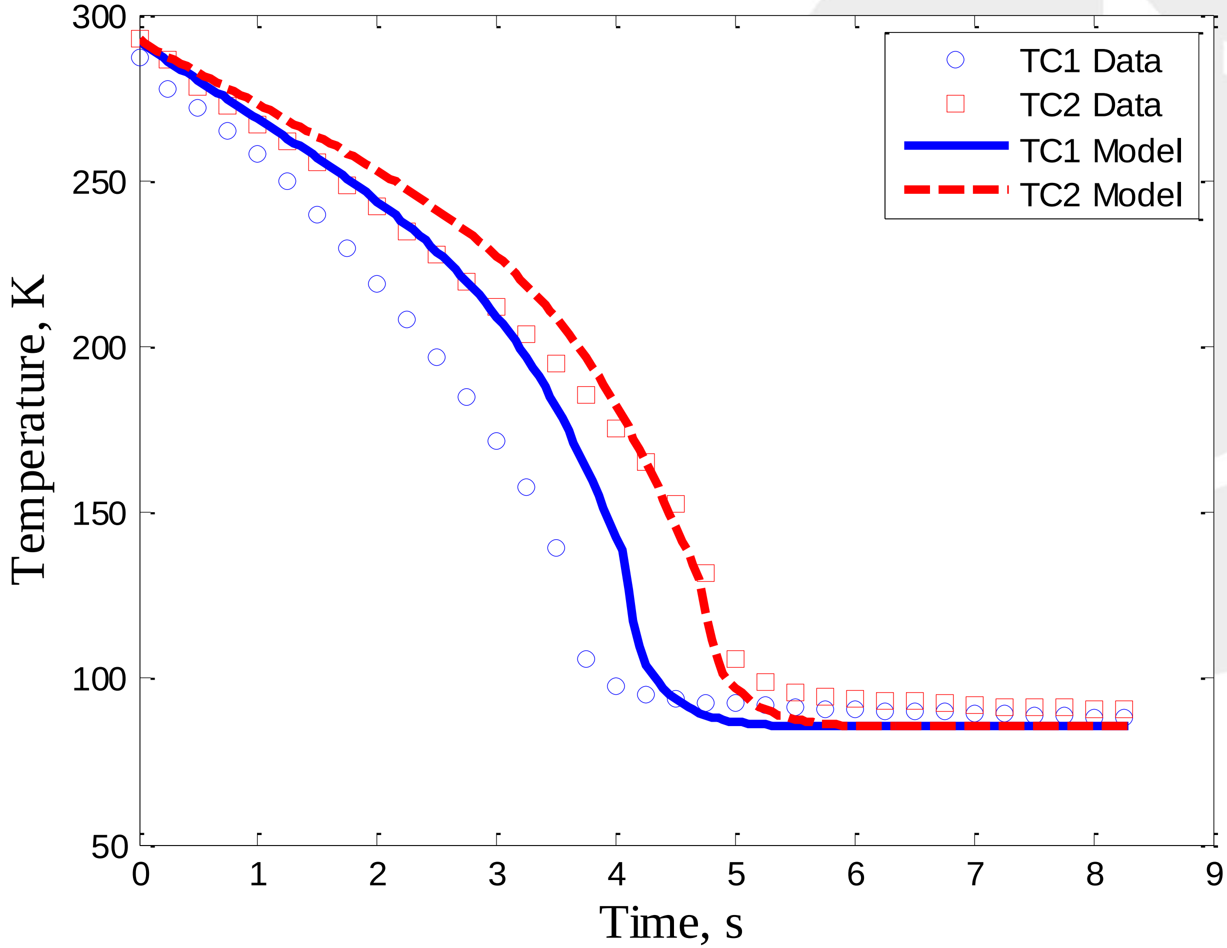
Simulation vs Data

- G = 888 kg/m^{2}s, Re_l = 91,433, P_{inlet} = 690 kPa.



Simulation vs Data

G = 1179 kg/m^{2}s, Re_l = 113,762, P_{inlet} = 723 kPa



Conclusion

- The 1D simulation was able to predict the transient temperature of the tube with good agreement with the data over a wide range of conditions.
- This supports the validity of:
  - Film Boiling HTC
  - Rewetting temperature
  - CHF
  - the logic to choose which correlation to use

Future Work

- Develop an accurate nucleate boiling correlation and corresponding transition boiling correlation
- Develop a robust T_{ONB} correlation
- Extend the correlations to different flow angles

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