Numerical Simulation of the Liquid Nitrogen Chilldown of a Vertical Tube

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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).
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.

$$h = \frac{q''}{T_w - T_f} = f(\dot{m}, x, P, \text{fluid properties, etc.})$$
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.
3 different boiling regimes during chilldown

2. **Transition Boiling**: $T_w$ drops below the *rewetting temperature*, $T_{wet}$. Liquid is able to intermittently touch the wall.
3 different boiling regimes during chilldown

3. **Nucleate Boiling**: $T_w$ 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 $T_{\text{wet}}$, CHF, and $T_{\text{ONB}}$. These help determine the current boiling regime in a childdown simulation.

• Develop a 1-D numerical simulation of the childdown of a pipe which uses these correlations to predict the wall heat flux and compare to the results to recent LN$_2$ childdown experiments
• 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$^2$s
• P = 174 to 817 kPa
• Subcooled inlet temp from 0 to 14 K
Dark blue lines: liquid nitrogen precool lines
Red lines: nitrogen gas lines
Green: mixed venting gas lines
Blue lines: liquid nitrogen transport lines
Black lines: air lines
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

\[ Nu_{fb} = h_{fb} D / k_v = \left( 7.55 \times 10^{-4} - 7.43 \times 10^{-6} \frac{z}{D} \right) Re_v^{0.941} \left( 1 - x_e \right)^{-5.23} Pr_v^{0.4} + 0.0568 \left( k_l / k_v \right) We \theta_{fb}^3 \]

- \( Re_v = GD/\mu_v \) accounts for the single-phase vapor convection along the wall.
- \( (7.55 \times 10^{-4} - 7.43 \times 10^{-6} \frac{z}{D}) \) 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.
- \( (k_l / k_v) We \theta_{fb}^3 \), where \( We = G^2 z / (\rho \sigma) \) 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%
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

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

Heat transfer from nucleate boiling

$$h_b = 0.00122 \kappa_i^{0.79} \sigma_i^{0.29} \nu_i^{-0.24} \rho_i^{0.49} \left[ \frac{T_w - T_{sat}(P)}{T_{sat}(w)} - P \right]^{0.24} S$$

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

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

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

$$S = \frac{1}{1 + 2.53 \times 10^{-6} Re_t^{-1.17} F^{1.4625}}$$

Martinelli parameter

$$X_n = \left[ \frac{(1 - x_e)}{x_e} \right]^{0.9} \left( \frac{\rho_v}{\rho_i} \frac{\rho_l}{\rho_v} \right)^{0.5} \left( \frac{\mu_l}{\mu_v} \right)^{0.1}$$

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.
- \(q''_{\text{Nuc}} \gg q''_{\text{Film}}\), so a fit was applied to the data with the Chen correlation HTC and the nondimensional temperature \(\theta_{tb} = (T_{\text{wet}} - T_w)/(T_{\text{wet}} - T_{\text{sat}})\):

\[
h_{tb} = 0.523\theta_{tb}^{0.390} h_{nb}
\]
Rewetting Temperature Correlation

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

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

$$d = \exp \left[ 3.06 \times 10^6 / \left( k \rho C_p \right)_w \right] \text{erfc} \left[ 1751.5 \left( k \rho C_p \right)_w^{0.5} \right]$$

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

- MAE = 5.08%

Critical Heat Flux (CHF) Correlation

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

\[ q''_{CHF} = 0.0527Gh_{lv}We_{z}^{-0.2894} \]

\[ We_{z} = \frac{G^{2}z}{\rho\sigma} \]

- MAE = 12.6%

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

- Only models the energy equation of the pipe material.

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

- 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 \( q''_{\text{parasitic}} \)

- Time integration: 1\textsuperscript{st} order fully implicit

- Spatial discretization: 2\textsuperscript{nd} order central difference

- \( L = 22.5'' \), \( N = 40 \), so \( dz=L/N=0.5625'' \)
At each time step the enthalpy of a fluid node, $h_i$, was calculated by

$$h_i = h_{i-1} + q_{\text{conv},i-1} \left[ \frac{4}{\pi D^2 G} \right]$$
Convergence Study

- $\Delta t = 0.04$ s, $0.02$ s, $0.01$ s, and $0.005$ s were used to simulate the fastest chilldown run.
- $\Delta t = 0.01$ s gave acceptable level of convergence
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 $T_{\text{wet}}$
- the time from start to $T_{\text{ONB}}$

<table>
<thead>
<tr>
<th>Time Metric</th>
<th>MAE, s</th>
<th>MAPE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{wet}}$</td>
<td>4.83</td>
<td>24</td>
</tr>
<tr>
<td>$t_{\text{ONB}}$</td>
<td>5.15</td>
<td>25</td>
</tr>
</tbody>
</table>
Simulation vs Data

\( G = 126 \text{ kg/m}^2\text{s}, \quad Re_l = 11,046, \quad P_{inlet} = 176 \text{ kPa}. \)
Simulation vs Data

\[ G = 220 \text{ kg/m}^2\text{s}, \quad Re_{\text{l}} = 21,695, \quad P_{\text{inlet}} = 252 \text{ kPa}. \]
Simulation vs Data

\[ G = 342 \text{ kg/m}^2\text{s}, \quad Re = 37,810, \quad P_{\text{inlet}} = 420 \text{ kPa}. \]
Simulation vs Data

\[ G = 627 \text{ kg/m}^2\text{s}, \quad Re_l = 65,575, \quad P_{\text{inlet}} = 561 \text{ kPa} \]
Simulation vs Data

- $G = 888\ \text{kg/m}^2\text{s},\ \text{Re}_l = 91,433,\ P_{inlet} = 690\ \text{kPa}$. 

![Graph showing temperature vs time for TC1 and TC2 data compared to TC1 and TC2 models.](chart.png)
Simulation vs Data

\[ G = 1179 \text{ kg/m}^2\text{s}, \quad Re_l = 113,762, \quad P_{\text{inlet}} = 723 \text{ kPa} \]
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