CFD Modeling of Cryogenic Chill-down through a Complex Channel
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Presented By
Justin Pesich
Motivation

- Future NASA architectures plan to use cryogenic propulsion systems and cryogenic fluid management to support lunar and Mars missions.
- In lieu of expensive tests conducted on-orbit, accurate predictive computational models of these chill-down processes can be used to reduce system and propellant mass as well as mission risk.
- Computational models must be validated to experimental data in relevant environments.

Work funded by Development & Validation of Analysis Tools under the eCryo project as part of the Space Technology Mission Directorate.
Problem Overview

- JAXA conducted ground and suborbital flight experiments to investigate chill-down of a test article representative of a cryogenic fluid turbopump bearing cavity in 1G and microG environments.

- LN2 injected at relatively low flow rates (0.5 & 1.0 g/s).

- **Objective:** model 1G and microG flow experiments to predict temperature drop and flow structures/surface wetting using commercial CFD code STAR-CCM+.

source: Japan Aerospace Exploration Agency (JAXA)
Computational Domain

Solid Domain (Polycarbonate)

Fluid Domain

No-slip, adiabatic walls

Top View

g flow

mass flow inlet

TA1-1

TA1-2

TA1-3

downstream room

pressure outlet

slits symmetry plane

upstream room

TA1-1 wall

TA1-2 wall

TA1-3 wall

diffuser

Side View

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Computational Mesh

- Fluid Domain 0.375mm
- Slits 0.1mm
- Conformal mesh at fluid-solid interfaces
- Max cell size 4.0mm
Multiphase Flow Solvers

Volume of Fluid (VOF)
- Solves one set of conservation equations for both phases
- Assumes immiscible fluids*
- Phase interactions can be implemented but are not necessary
- Stable and fast

Eulerian Multiphase (EMP)
- Solves a set of conservation equations for each phase
- Assumes continuous-dispersed or separated phase distribution
- Requires closure relations to define interaction between phases at an interface
- Powerful flow solver, however easily becomes unstable, slow

*unless domain is resolved to DNS scales
Boiling heat flux determined by user-defined piecewise curve.

Total wall heat flux is the sum of the boiling heat flux and convection of the liquid-vapor mixture (radiation neglected).

\[
q_{\text{boiling}}(\Delta T) = q_{\text{max}} S \phi \left( \frac{\Delta T}{\Delta T_i} \right)^{K_1} \quad 0 \leq \Delta T \leq \Delta T_i
\]

\[
q_{\text{boiling}}(\Delta T) = q_{\text{max}} S \left[ 1 - 4 \left( 1 - \phi \right) \left( \frac{\Delta T - \Delta T_{\text{max}}}{\Delta T_2 - \Delta T_i} \right)^2 \right] \quad \Delta T_1 \leq \Delta T \leq \Delta T_2
\]

\[
q_{\text{boiling}}(\Delta T) = q_{\text{max}} S \phi \left( \frac{\Delta T}{\Delta T_2} \right)^{-K_2} \quad \Delta T_2 \leq \Delta T
\]

\[
\dot{m}_{\text{evap}} = \frac{C q_{\text{boiling}}}{\dot{h}_{\text{lat}}}
\]

Source: Low-Gravity Fluid Dynamics and Transport Phenomena
Koster and Sani
Four components of the heat flux from the wall.

- **Single-phase liquid** convection – Removal of heat on parts not affected by boiling.
- **Quenching** – Replacement of departing bubble by influx of cooler liquid.
- **Evaporation** – Power used to produce bubble from nucleation to departure.
- **Dryout** heat transfer – Removal of heat on parts covered by steam.

*source: Siemens 2018 Eulerian Multiphase*
EMP Boiling Model

EMP uses a partitioned wall heat flux approach:

\[ q''_w = q''_{conv} + q''_{evap} + q''_{quench} \]

Equivalent to \( q_{boiling} \) in VOF model

\[ q''_{conv} = f(T_{wall} - T_{liq}, \text{boundary layer flow properties}) \]

\[ q''_{quench} = f(T_{wall} - T_{liq}, f_{departure}, d_{departure}, \text{local flow properties}) \]

\[ q''_{evap} = f(f_{departure}, d_w, n'', h_{lat}) \rightarrow \dot{m}_{evap} = \frac{q''_{evap}}{h_{lat}} \]

\[ f_{departure} = \sqrt{\frac{4 g (\rho_l - \rho_g)}{3 d_w \rho_l}} \]

Cole model determined by photographic study of pool boiling

\[ d_{departure} = f(\Delta T_{subcooling}) = f(T_{sat} - T_{liq}) \]

\[ n'' = f(\Delta T_{superheat}) = f(T_{wall} - T_{sat}) \]

Determined experimentally by Bartolomei and Chanturiya for forced convection, subcooled boiling of water in a vertical pipe at 45 bar, 0.57 MW/m² in 1G.
Modeling TS-A1 test section

VUA1 indicates void fraction at inlet

PDA1 = P_{outlet}

TKO = T_{inlet}

PKO gives saturation temperature at inlet
ICs and BCs: Chill-down 1G

- Upstream void fraction sensor indicates near 100% quality condition at $t \approx 160s$
- $t_{\text{sim, start}} = t_{\text{exp, 160s}}$
- $t_{\text{sim, end}} = t_{\text{exp, 190s}}$
- $m_{\text{inlet}} = 1 \text{g/s}$
- $P_{\text{outlet}} = 0.5 \text{ MPaA}$
- $T_{\text{inlet}} = 87K$
- Avg of TKO when TKO is below $T_{\text{sat(PKO)}}$
- $T_{\text{initial}} = 173.5K$
<table>
<thead>
<tr>
<th>Variable</th>
<th>Chill-down 1G</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g$ [$m/s^2$]</td>
<td>9.81</td>
</tr>
<tr>
<td>$\dot{m}_{inlet}$ [gram/s]</td>
<td>1.0</td>
</tr>
<tr>
<td>$T_{inlet}$ [$K$]</td>
<td>87</td>
</tr>
<tr>
<td>$T_{initial}$ [$K$]</td>
<td>173.5</td>
</tr>
<tr>
<td>$T_{saturation}$ [$K$]</td>
<td>93.987</td>
</tr>
<tr>
<td>$P_{outlet}$ [MPaA]</td>
<td>0.5</td>
</tr>
<tr>
<td>$P_{initial}$ [MPaA]</td>
<td>0.5</td>
</tr>
<tr>
<td>$VF_{inlet}$ (liq, vapor)</td>
<td>(1,0)</td>
</tr>
<tr>
<td>$VF_{initial}$ (liq, vapor)</td>
<td>(0,1)</td>
</tr>
<tr>
<td>$V_{initial}$ $\langle i,j,k \rangle$ [m/s]</td>
<td>$&lt;0,0,0&gt;$</td>
</tr>
<tr>
<td>$t_{sim,start}$ [s]</td>
<td>160</td>
</tr>
<tr>
<td>$t_{sim,end}$ [s]</td>
<td>190</td>
</tr>
</tbody>
</table>
Modeling Description

• Modeling Notes:
  – Laminar flow
  – Ideal gas for vapor phase
  – Temperature dependent material properties
  – Surface Tension Force modeled for only VOF cases (stability issues with EMP)
  – Wall boiling only (no bulk boiling / no mass transfer at interface)

• Challenges/Assumptions
  – EMP boiling parameters based on flow boiling experiment using water at 45 bar, 0.57 MW/m² (future work may include LN2 specific boiling parameters)
  – Boundary conditions based on averaged experimental data quantities (inlet mass flow, outlet pressure, inlet volume fraction)
  – Surface Tension creates extremely unstable solution using EMP ruling out microG simulations
Chill-down, 1G, 1.0g/s
Results
Temperature Data

TA1-1

TA1-2

TA1-3

flow

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\[ \Delta T_{\text{superheat}} = T_{\text{wall}} - T_{\text{sat}} \]
VOF Flow and Wall Temperature

Solution Time 0.1 (s)
Solution Time 0.1 (s)
Flow & Temp Evolution on XZ Plane

Solution Time 0.1 (s)
Comparison to Experimental Still Frames

**VOF/EMP**

160 s

Ground experiment
(left: TS-A2, 0.5 g/s, right: TS-A1, 1.0 g/s)

Droplets still reach dead end

170 s

Gravity direction

LN2 jets

180 s

Droplets no longer reach dead end

190 s

Bubbles disappear in upstream room

**Solution Time 10.6 (s)**

**Solution Time 11.1 (s)**

**Solution Time 17 (s)**
Chill-down 1G Conclusions

• Both EMP and VOF predict thermal response reasonably well where EMP predicts faster cooling rate.
• Both EMP and VOF lag experiment since simulation window was chosen in middle of experiment. Liquid must propagate through chamber before cooling occurs.
• EMP predicts convective cooling before liquid arrival while VOF does not.
• After liquid arrival, wall quickly moves to transition and nucleate boiling regimes.
• EMP predicts phase distribution/flow structures accurately while VOF fails to predict liquid dispersed in vapor.
ICs and BCs: Vapor Cooling + Chill-down 1G

Simulation starts at experimental initial condition

Vapor-dominant mixture

Saturated vapor at 97K
Tsat = 94K
ICs and BCs: Vapor Cooling + Chill-down microG
## Initial and Boundary Conditions Summary

<table>
<thead>
<tr>
<th>Variable</th>
<th>Vapor Cooling + Chill-down 1G</th>
<th>Vapor Cooling + Chill-down microG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g \ [m/s^2]$</td>
<td>9.81</td>
<td>0.001</td>
</tr>
<tr>
<td>$m_{inlet} \ [\text{gram/s}]$</td>
<td>0.53 [0-27s linear ramp], 1.0 [27-77s]</td>
<td>0.49 [0-20s linear ramp], 1.0 [20-63]</td>
</tr>
<tr>
<td>$T_{inlet} \ [K]$</td>
<td>97 (vapor), 87 (liquid)</td>
<td>99 (vapor), 84 (liquid)</td>
</tr>
<tr>
<td>$T_{initial} \ [K]$</td>
<td>211.7</td>
<td>210.6</td>
</tr>
<tr>
<td>$T_{saturation} \ [K]$</td>
<td>93.987</td>
<td>93.987</td>
</tr>
<tr>
<td>$P_{outlet} \ [\text{MPaA}]$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$P_{initial} \ [\text{MPaA}]$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$VF_{inlet} \ (\text{liq, vapor})$</td>
<td>(0,1) [0-47s] : (1,0) [47-77s]</td>
<td>(0,1) [0-45s] : (1,0) [45-63s]</td>
</tr>
<tr>
<td>$VF_{initial} \ (\text{liq, vapor})$</td>
<td>(0,1)</td>
<td>(0,1)</td>
</tr>
<tr>
<td>$V_{initial} \ &lt;i,j,k&gt; \ [m/s]$</td>
<td>$&lt;0,0,0&gt;$</td>
<td>$&lt;0,0,0&gt;$</td>
</tr>
<tr>
<td>$t_{sim,start} \ [s]$</td>
<td>113</td>
<td>113</td>
</tr>
<tr>
<td>$t_{sim,end} \ [s]$</td>
<td>190</td>
<td>176</td>
</tr>
</tbody>
</table>
Vapor Cooling + Chill-down 1G and microG, 1.0g/s
Results
Temperature Data 1G

Temperature [K]

Time [s]

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Flow Evolution microG

Volume Fraction of LN2

Solution Time 45.1 (s)

Temperature (K)

Solution Time 45.1 (s)
Vapor Cooling + Chill-down Conclusions

- Adding the vapor cooling segment captured the initial chill-down reasonably well, however once liquid was introduced, CFD still lagged the experiment.
- Therefore, there must be some amount of liquid filling the chamber once the valve is opened.

Future Work:

- Explore various volume fraction inlet conditions
- Implement LN2 boiling properties such as departure diameter, departure frequency, and nucleation site density
- Investigate challenges associated with surface tension and EMP model
Please Ask Questions!

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