CFD Modeling of Cryogenic Chill-down through a Complex Channel

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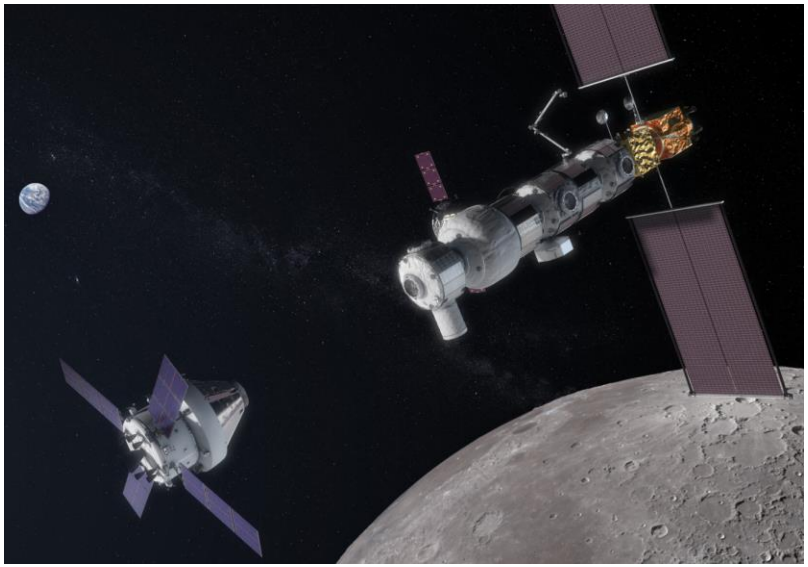
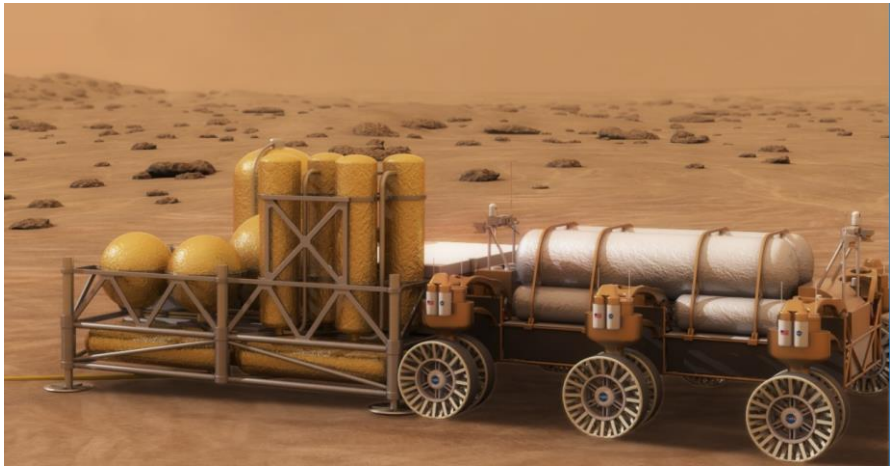
Motivation

- 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.



Lunar Gateway with Orion Approaching (source: NASA)

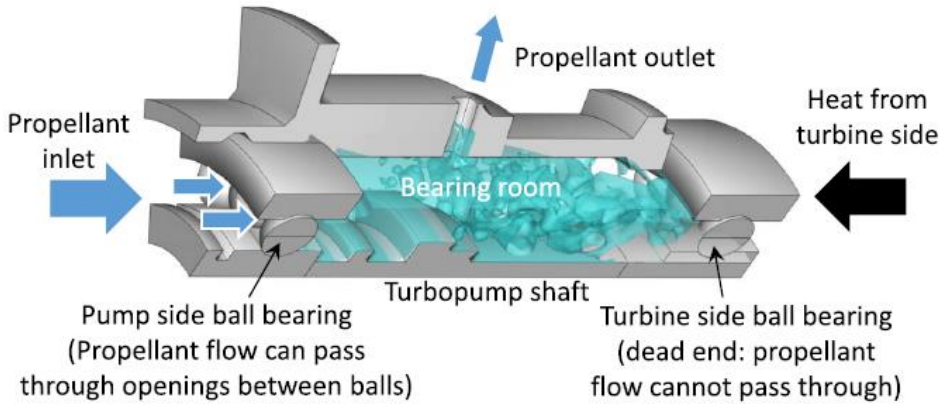


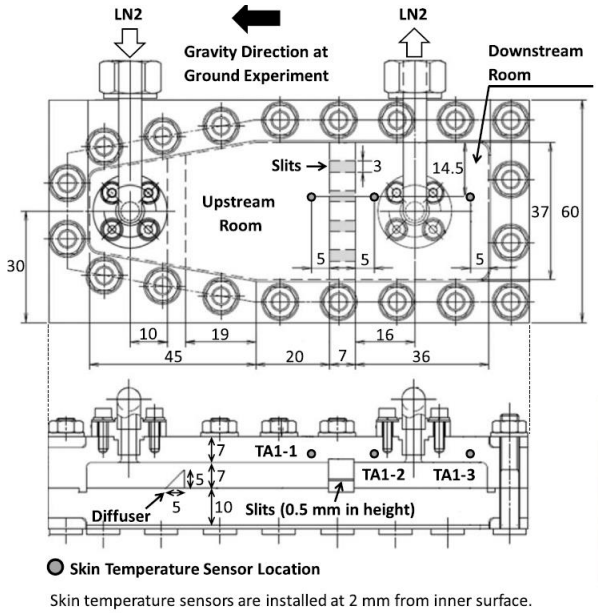
In-Situ Resource Utilization Concept on Mars (source: NASA)

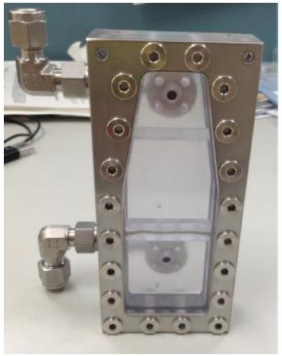
Work funded by Development & Validation of Analysis Tools under the eCryo project as part of the Space Technology Mission Directorate

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+.

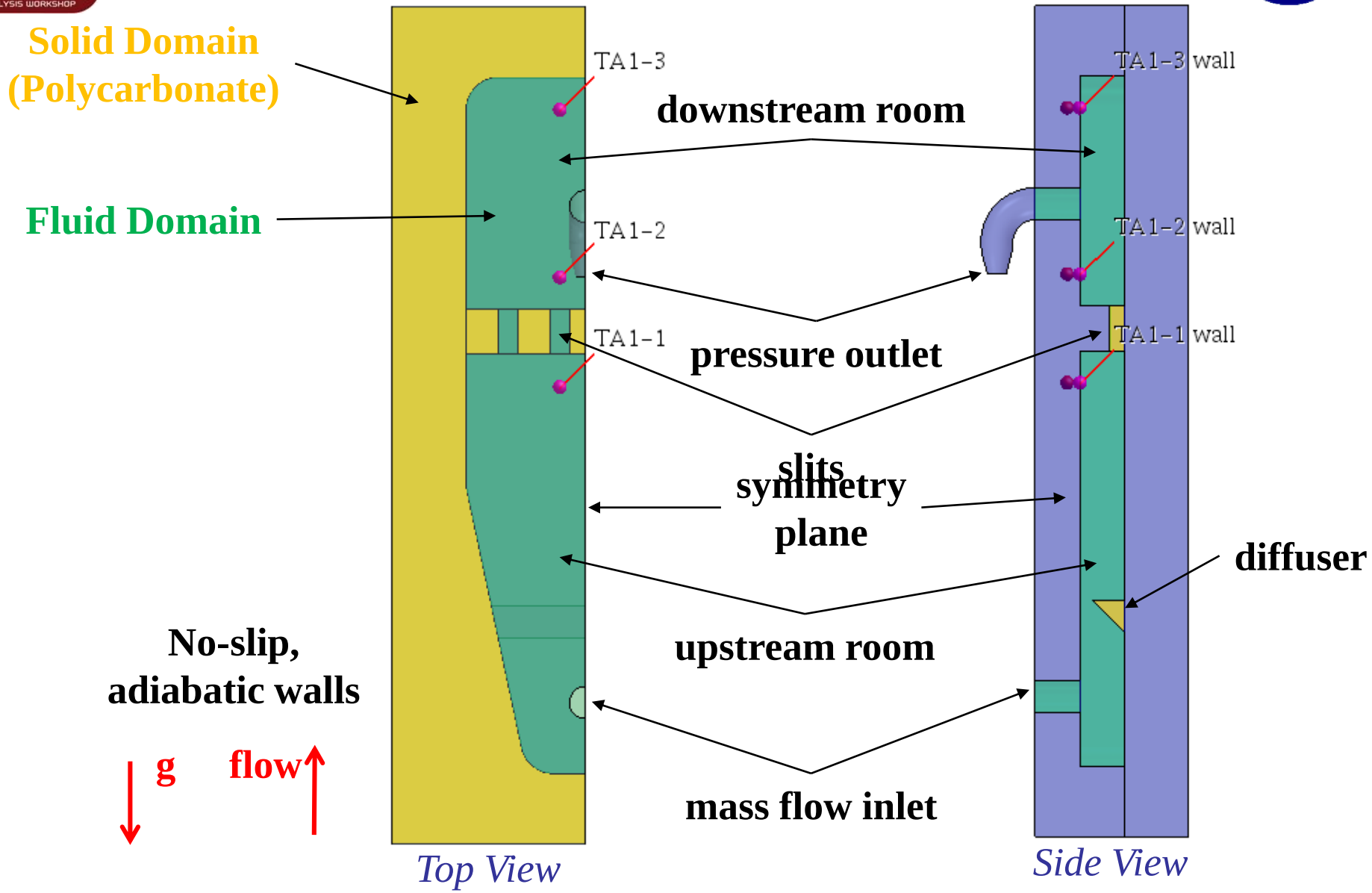






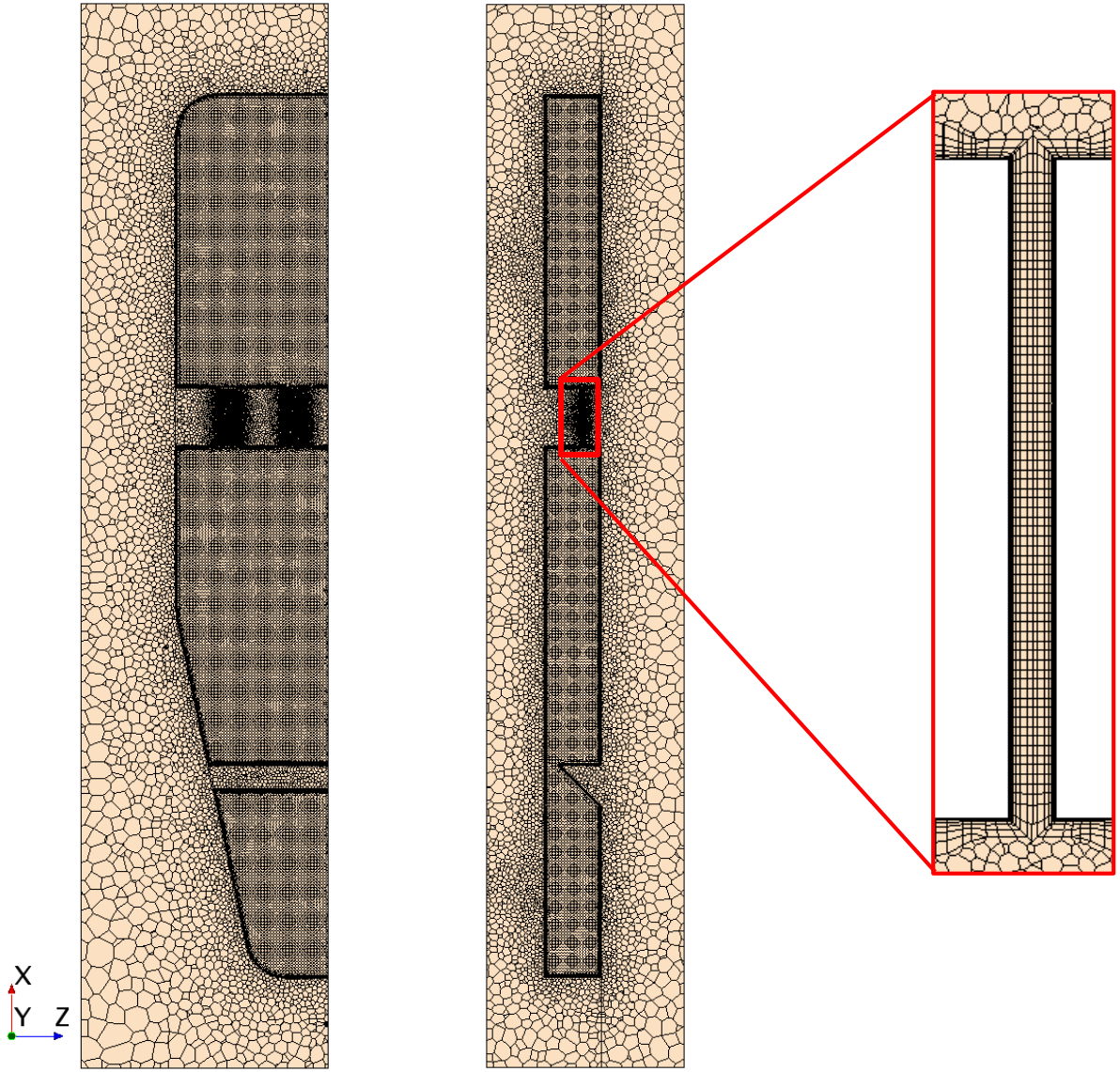
source: Japan Aerospace Exploration Agency (JAXA)

Computational Domain



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)

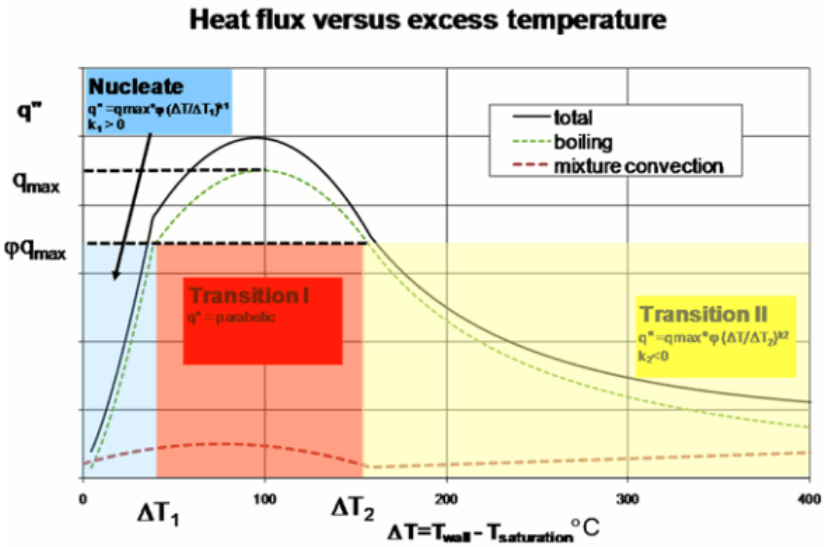
- Solves one set of conservation equations for both phases
- Assumes immiscible fluids*
- Phase interactions can be implemented but are not necessary
- Stable and fast

***unless domain is resolved to DNS scales**

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

VOF Transition Boiling Model



$$q_{boiling}(\Delta T) = q_{max} S \phi \left(\frac{\Delta T}{\Delta T_1}\right)^{K_1} \qquad 0 \le \Delta T \le \Delta T_1$$

$$q_{boiling}(\Delta T) = q_{max} S \left[1 - 4(1-\phi)\left(\frac{\Delta T - \Delta T_{max}}{\Delta T_2 - \Delta T_1}\right)^2\right] \qquad \Delta T_1 \le \Delta T \le \Delta T_2$$

$$q_{boiling}(\Delta T) = q_{max} S \phi \left(\frac{\Delta T}{\Delta T_2}\right)^{-K_2} \qquad \Delta T_2 \le \Delta T$$

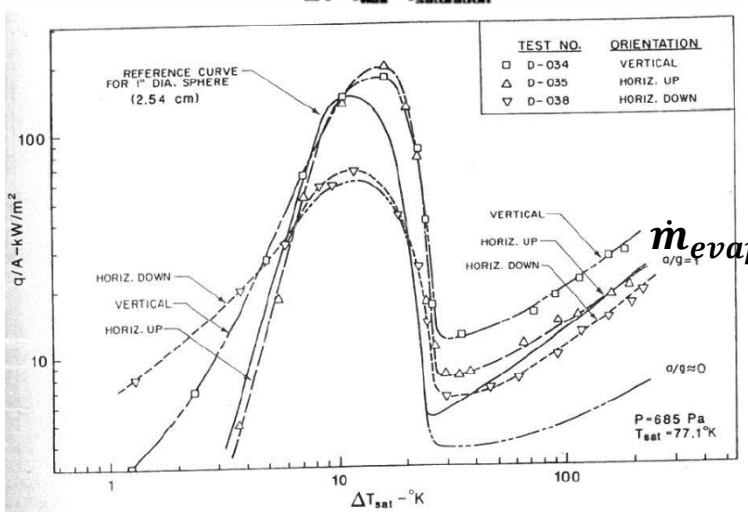


Fig. 26 Disk in saturated LN_2. All orientations at $a/g = 1$. All boiling regimes.

source: Low-Gravity Fluid Dynamics and Transport Phenomena
Koster and Sani

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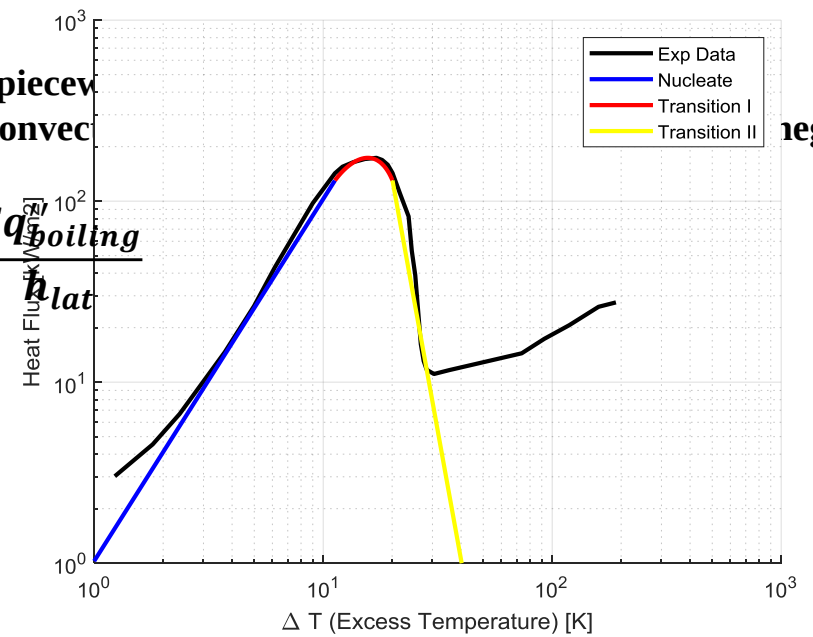
neglected)

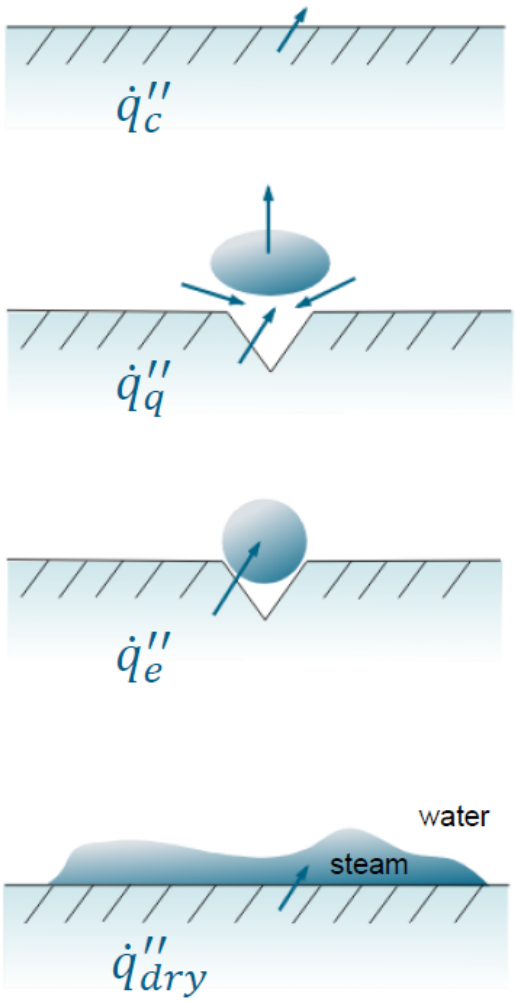
$$\dot{m}_{evap} = \frac{C q''_{boiling}}{h_{lat}}$$



EMP Boiling Model

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:

$$q''_w = q''_{conv} + \underbrace{q''_{evap} + q''_{quench}}$$

Equivalent to $q_{boiling}$ in VOF model

$$q''_{conv} = f\left(T_{wall} - T_{liq}, \textit{boundary layer flow properties}\right)$$

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

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

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

Cole model determined by photographic study of pool boiling

$$d_{departure} = f\left(\Delta T_{subcooling}\right) = f(T_{sat} - T_{liq})$$

$$n'' = f\left(\Delta T_{superheat}\right) = f(T_{wall} - T_{sat})$$

Determined experimentally by Bartolomei and Chanturiya for forced convection, subcooled boiling of water in a vertical pipe at 45 bar, 0.57 MW/m^2 in 1G.

Flow Schematic and Instrumentation

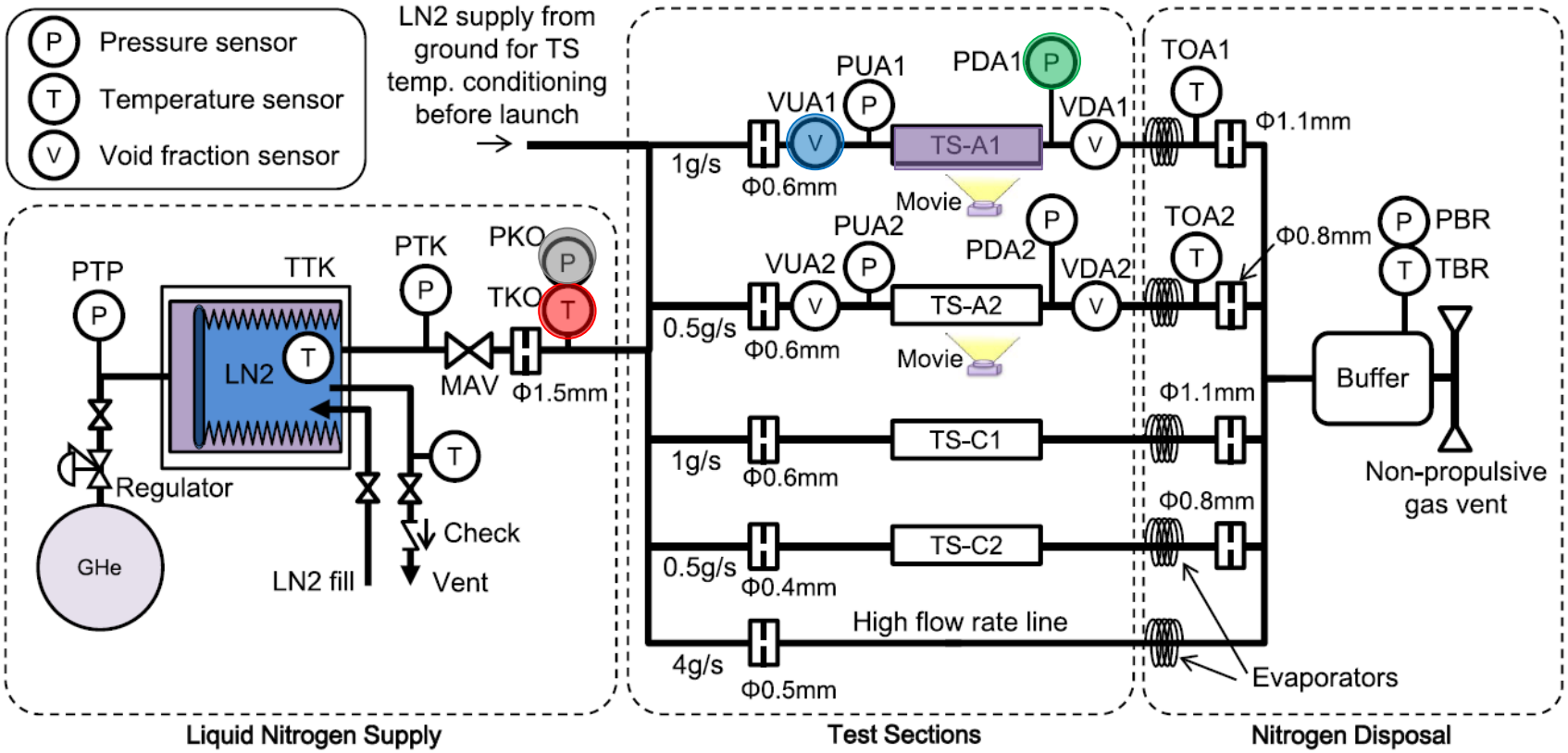


Fig. 4 Liquid and gas flow schematic (TS-C1 and TS-C2 are not discussed in this paper).

Modeling TS-A1 test section

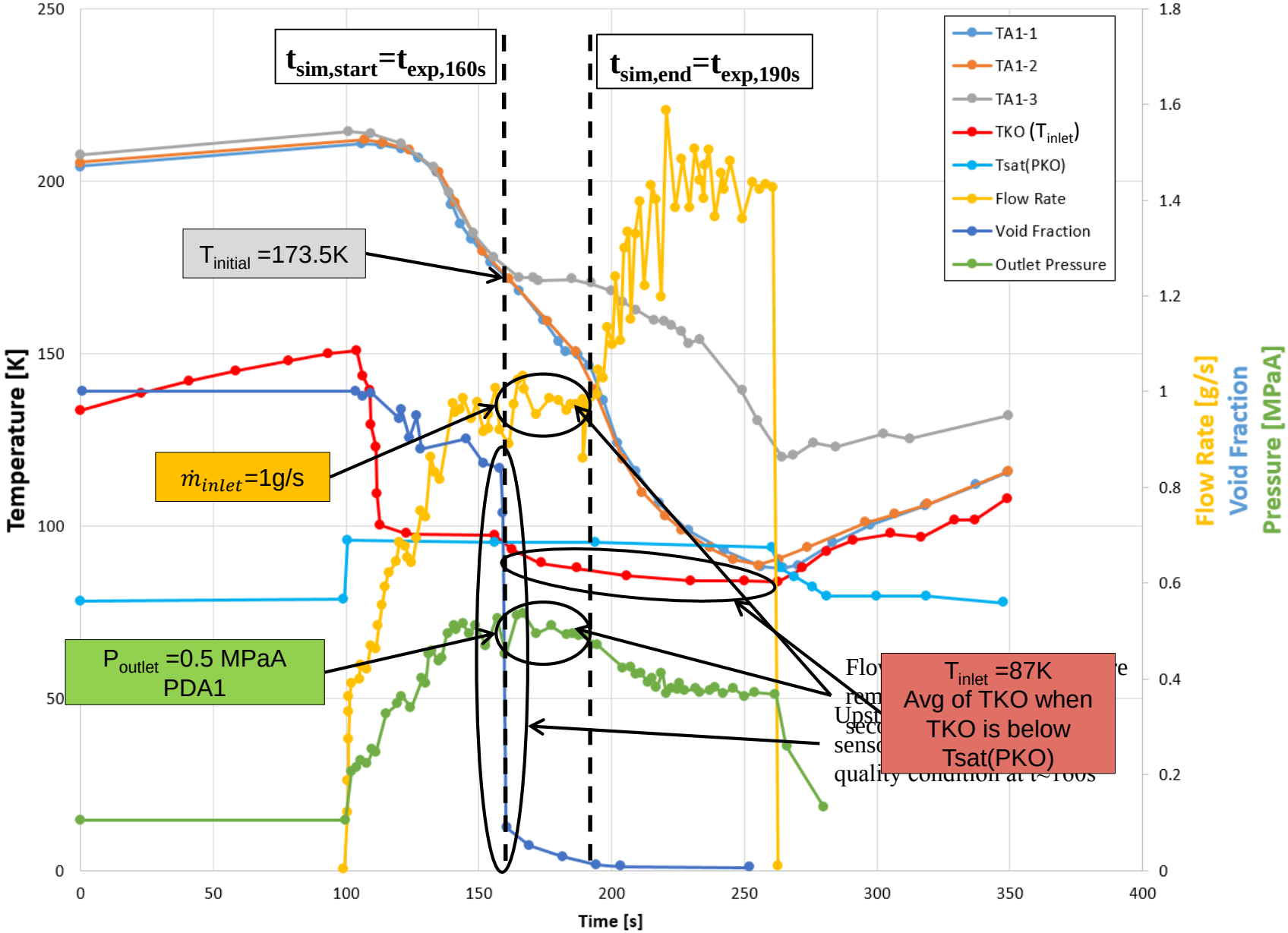
VUA1 indicates void fraction at inlet

PDA1 = P_{outlet}

TKO = T_{inlet}

PKO gives saturation temperature at inlet

ICs and BCs: Chill-down 1G



Initial and Boundary Conditions Summary

Variable	Chill-down 1G
g [m/s^2]	9.81
$\dot{m}_{inlet}$ [gram/s]	1.0
T_{inlet} [K]	87
$T_{initial}$ [K]	173.5
$T_{saturation}$ [K]	93.987
P_{outlet} [MPaA]	0.5
$P_{initial}$ [MPaA]	0.5
VF_{inlet} (liq, vapor)	(1,0)
$VF_{initial}$ (liq, vapor)	(0,1)
$V_{initial}$ <i,j,k> [m/s]	<0,0,0>
$t_{sim,start}$ [s]	160
$t_{sim,end}$ [s]	190

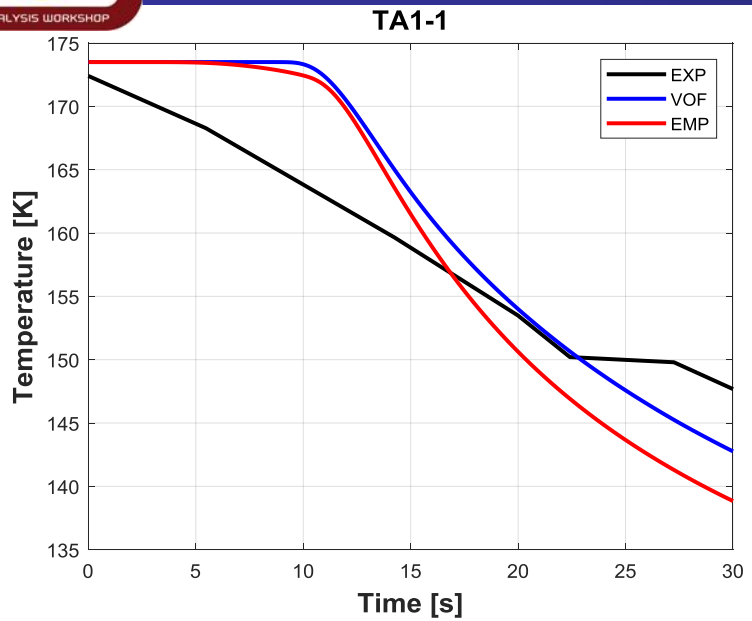
Modeling Description

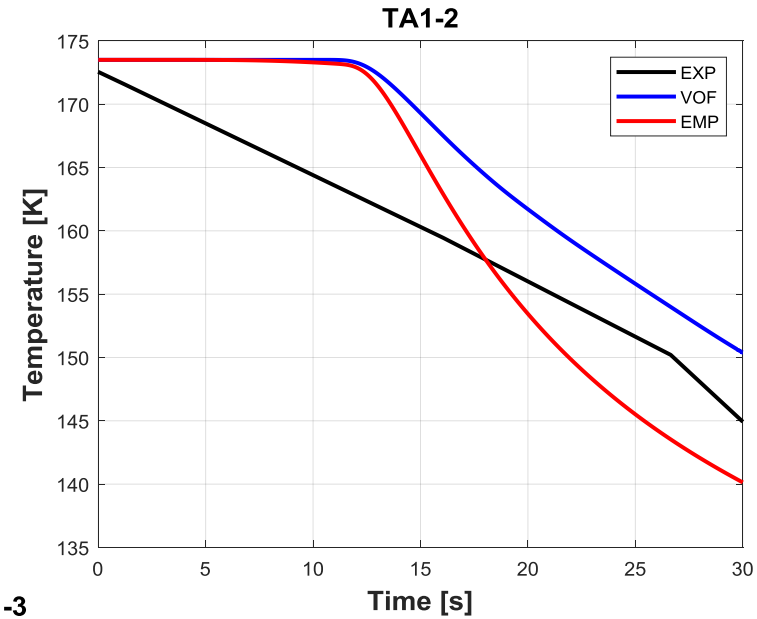
- Modeling Notes:
  - Laminar flow
  - Ideal gas for vapor phase
  - Temperature dependent material properties
  - Surface Tension Force modeled for only VOF cases (stability issues with EMP)
  - Wall boiling only (no bulk boiling / no mass transfer at interface)

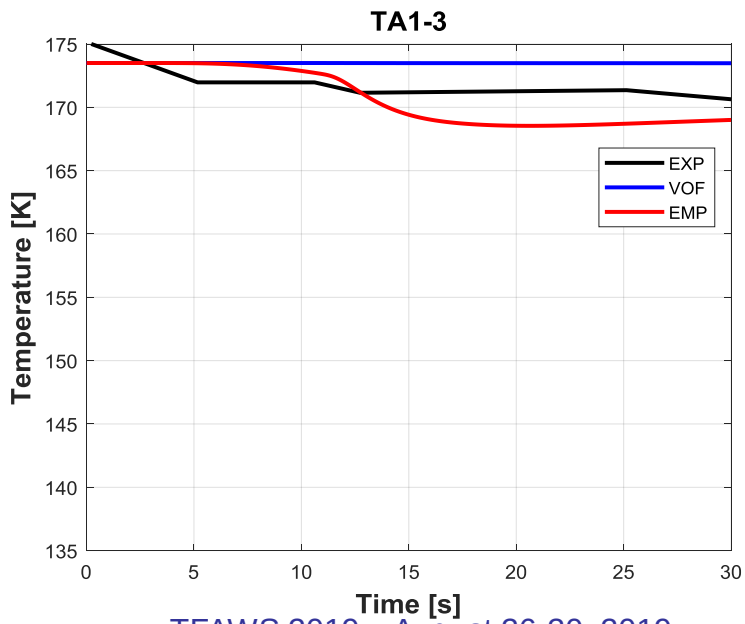
- Challenges/Assumptions
  - EMP boiling parameters based on flow boiling experiment using water at 45 bar, 0.57 MW/m^2 (future work may include LN2 specific boiling parameters)
  - Boundary conditions based on averaged experimental data quantities (inlet mass flow, outlet pressure, inlet volume fraction)
  - Surface Tension creates extremely unstable solution using EMP ruling out microG simulations

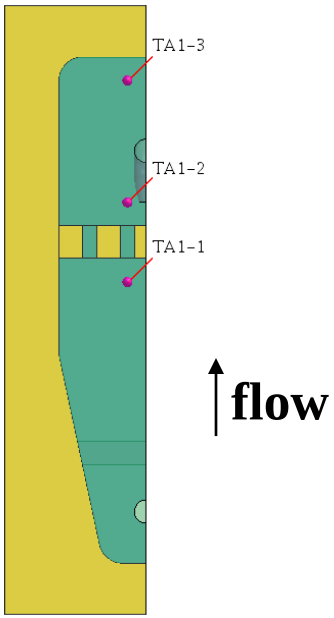
Chill-down, 1G, 1.0g/s
Results

Temperature Data

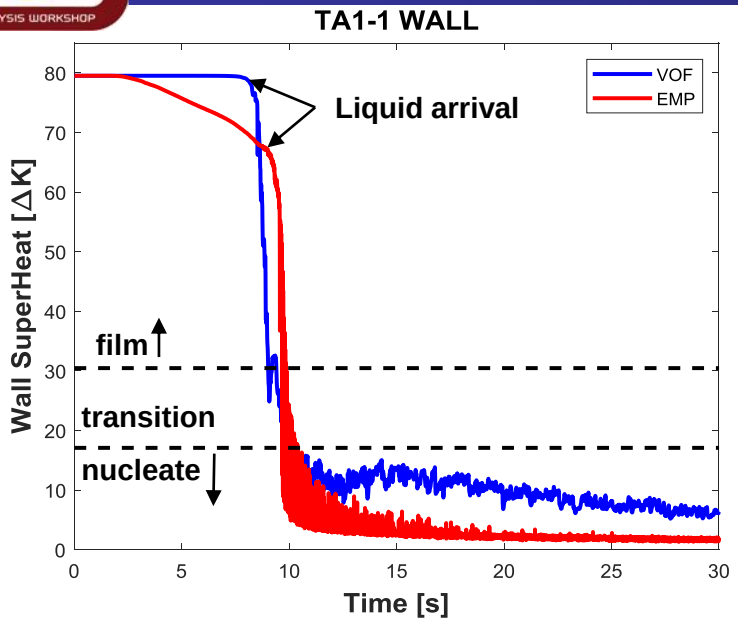


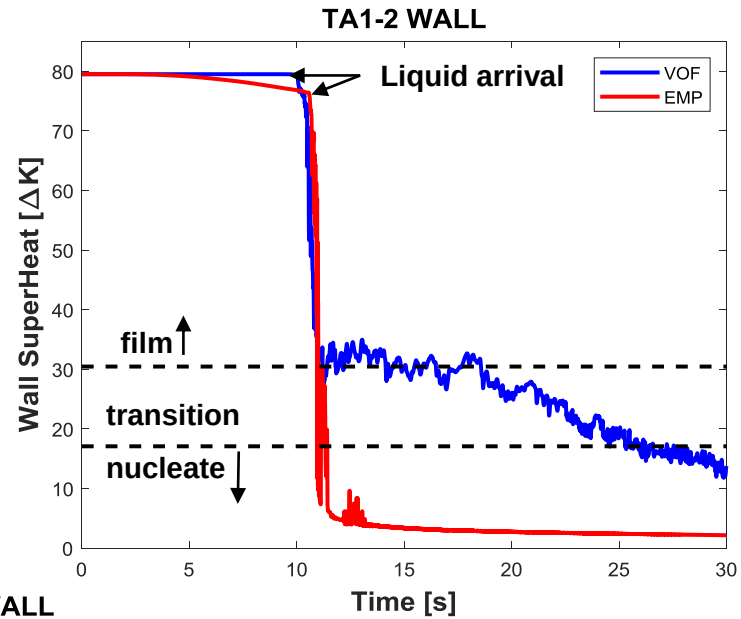




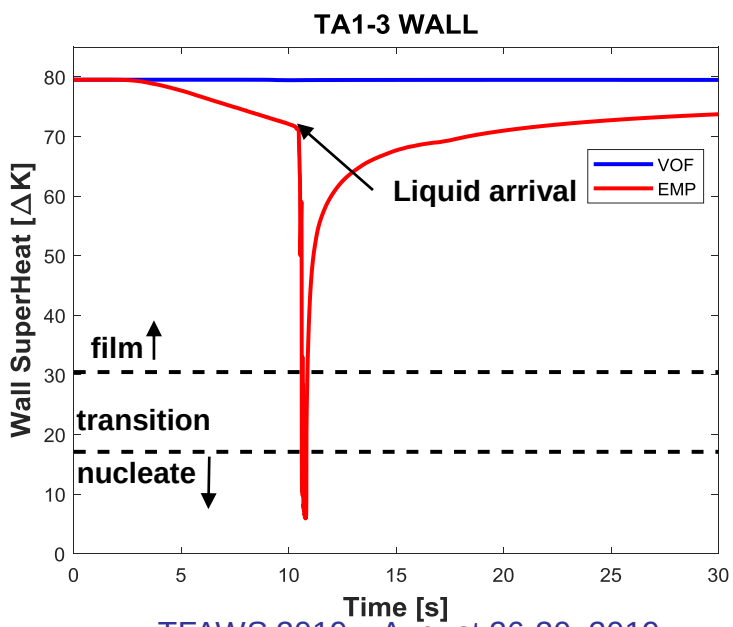


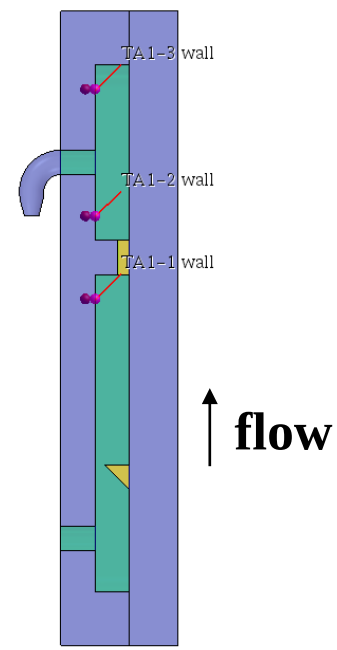
Wall Superheat and Boiling Regime



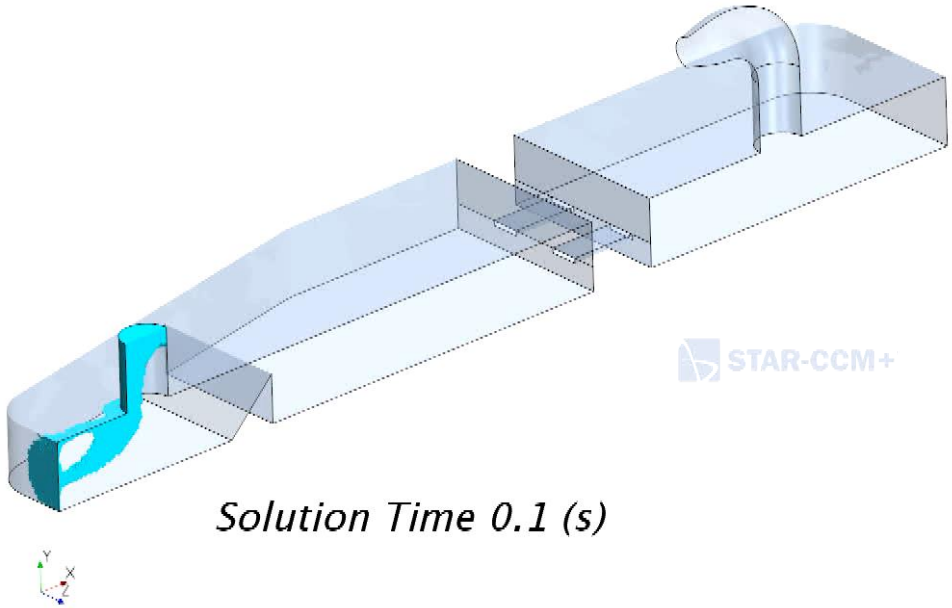


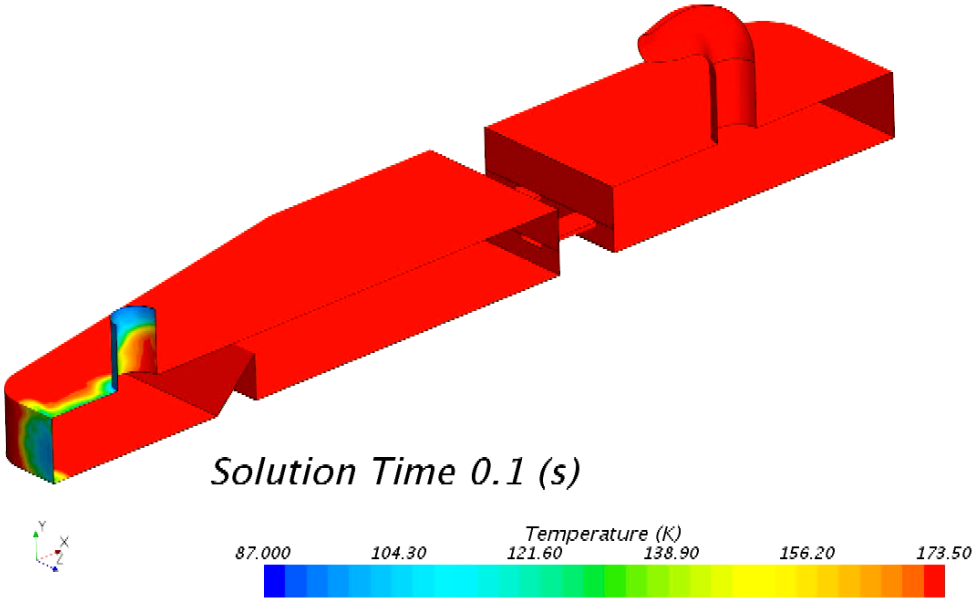
$$\Delta T_{superheat} = T_{wall} - T_{sat}$$



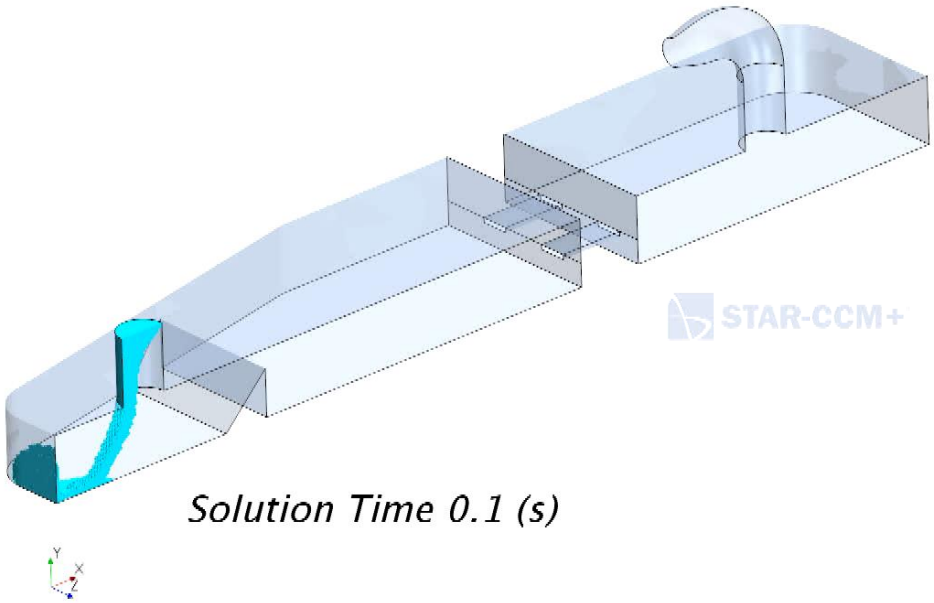


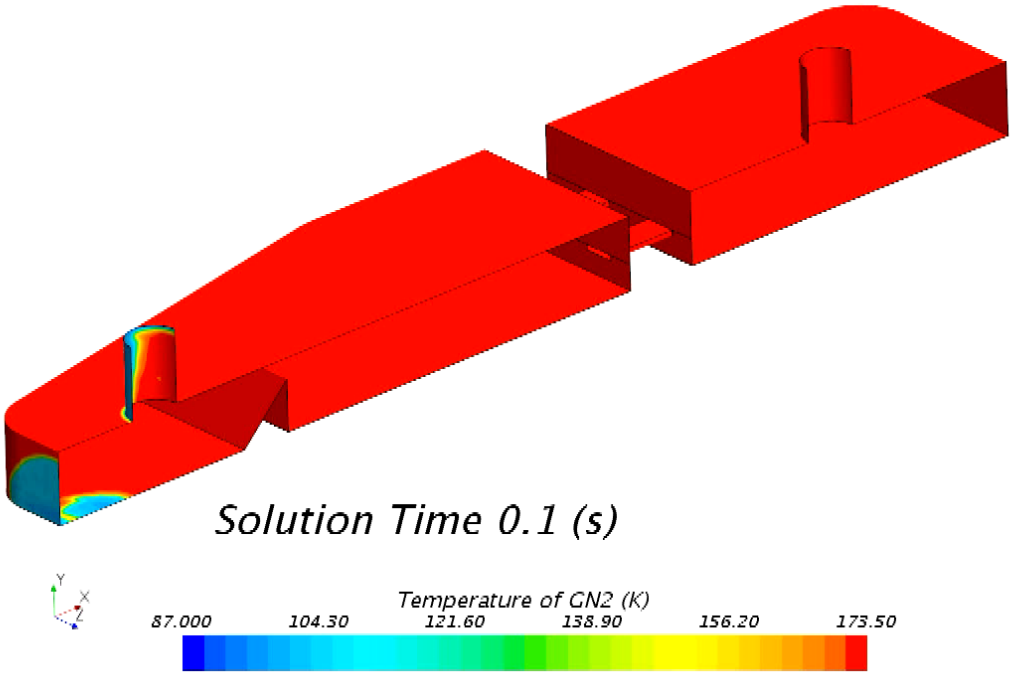
VOF Flow and Wall Temperature



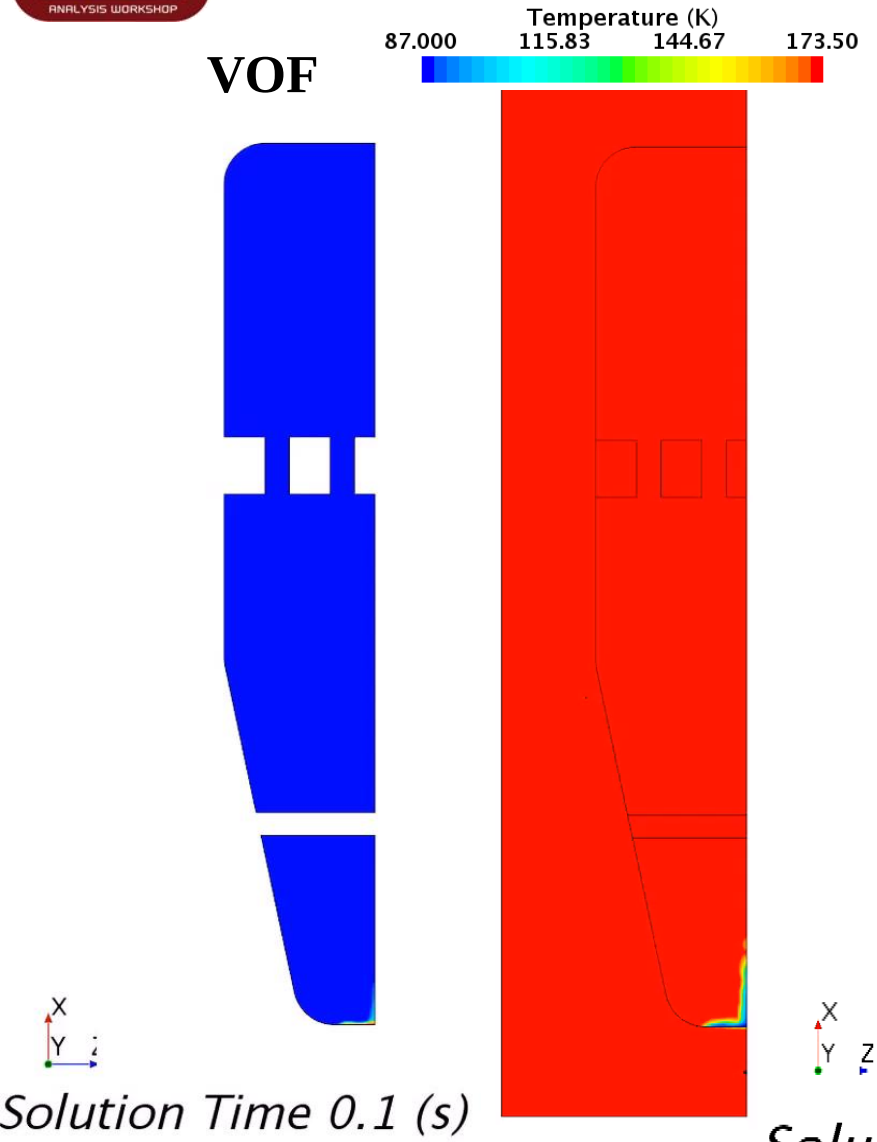


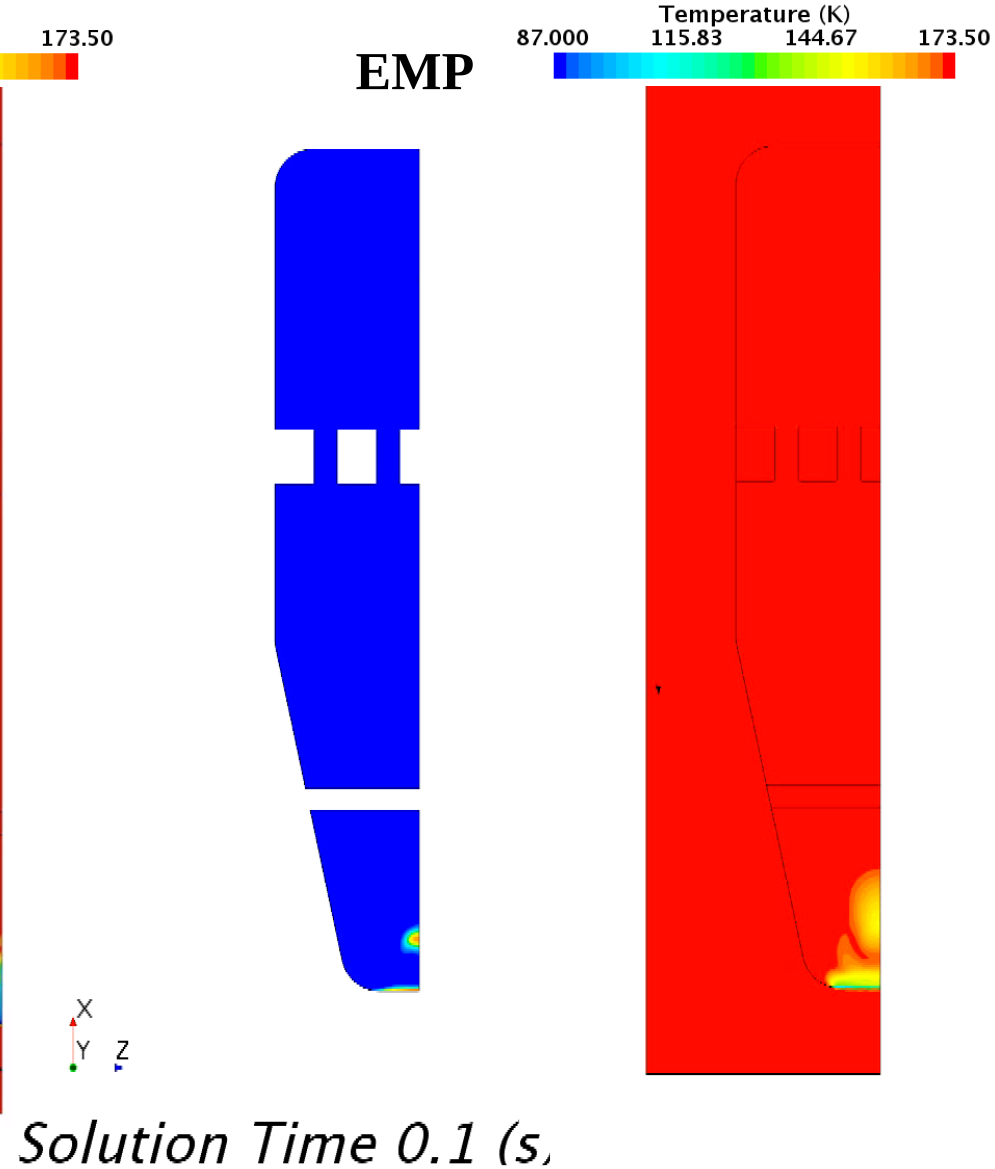
EMP Flow and Wall Temperature



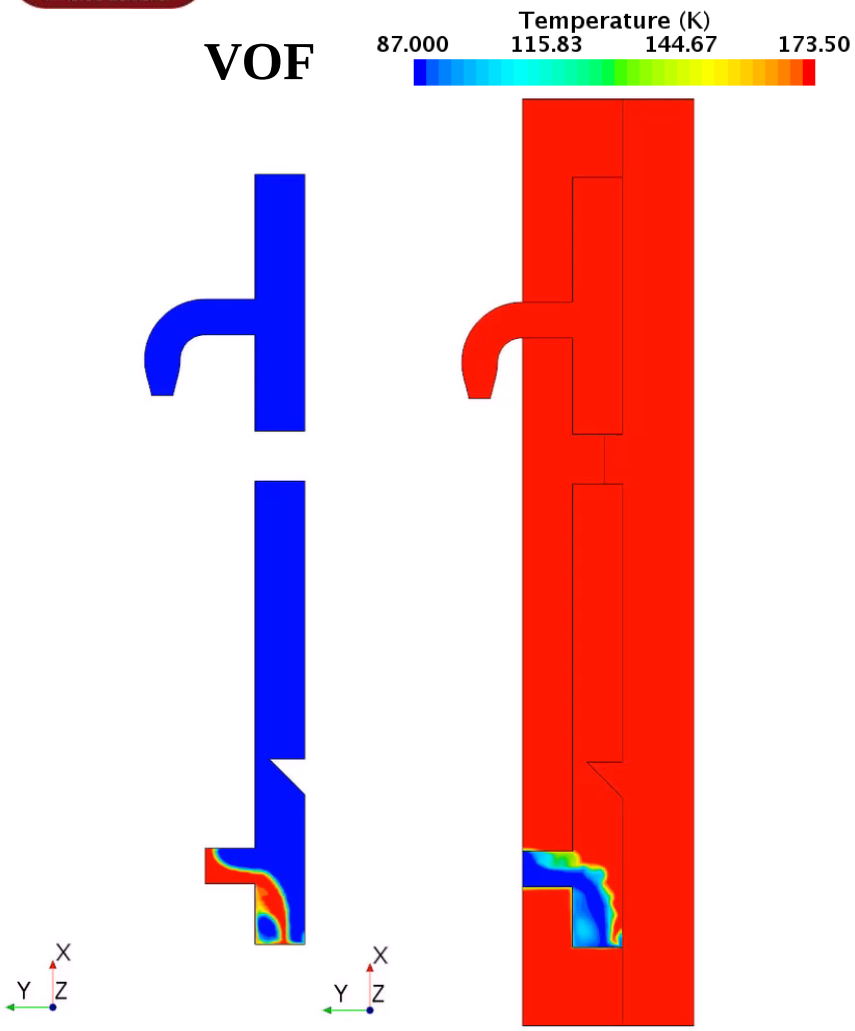


Flow & Temp Evolution on XZ Plane

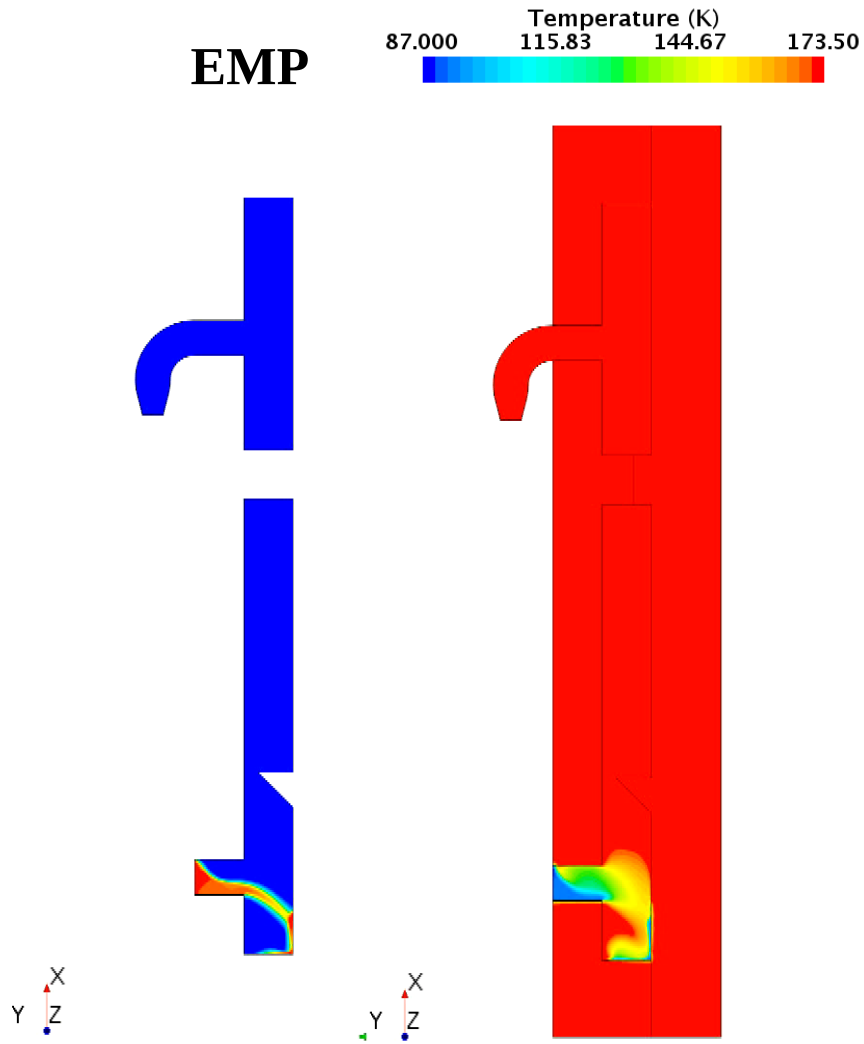




Flow & Temp Evolution on Symmetry Plane

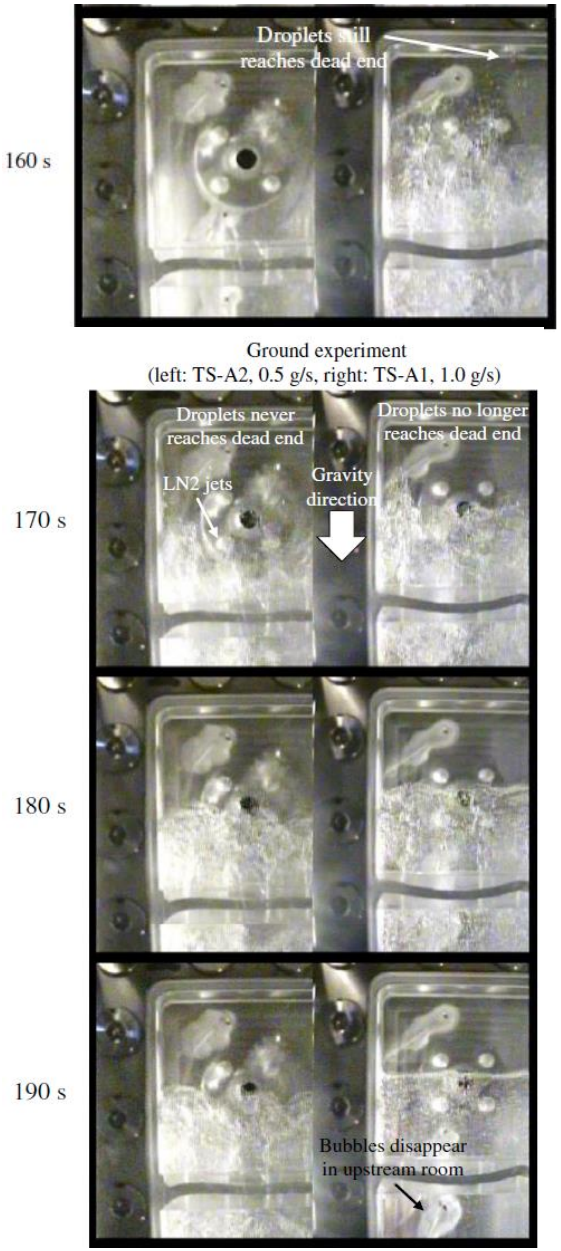


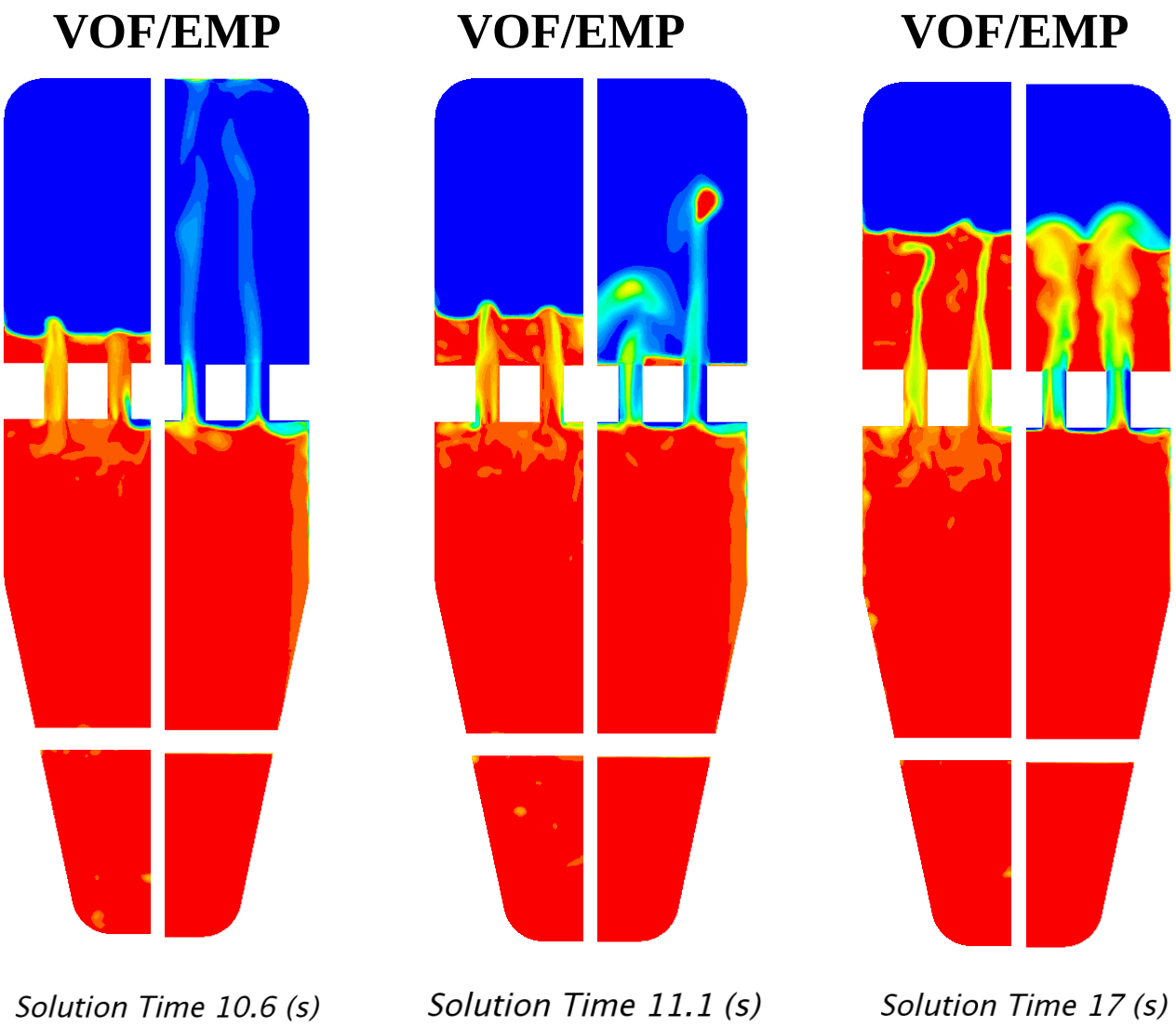
Solution Time 0.1 (s)



Solution Time 0.1 (s)

Comparison to Experimental Still Frames

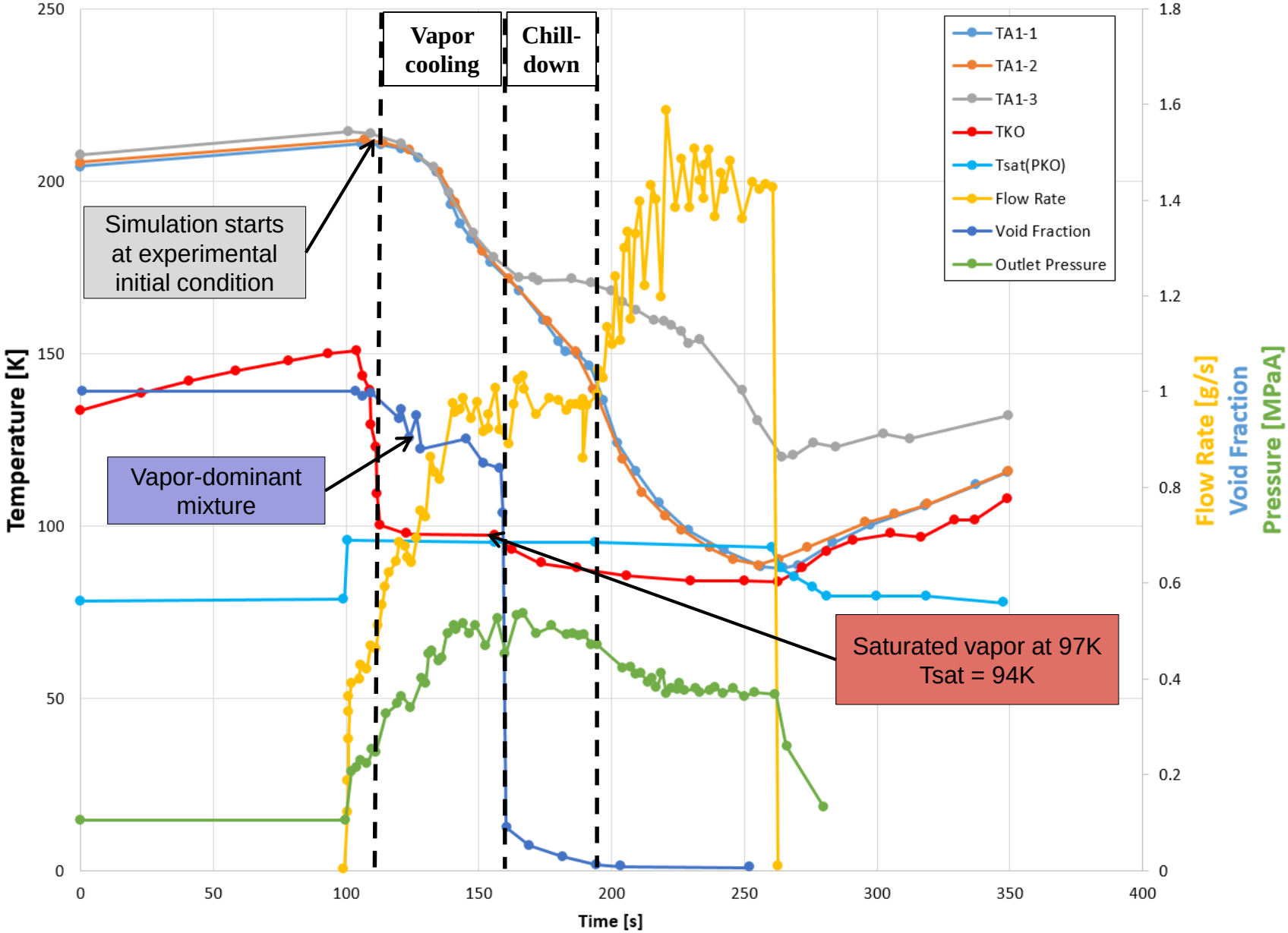




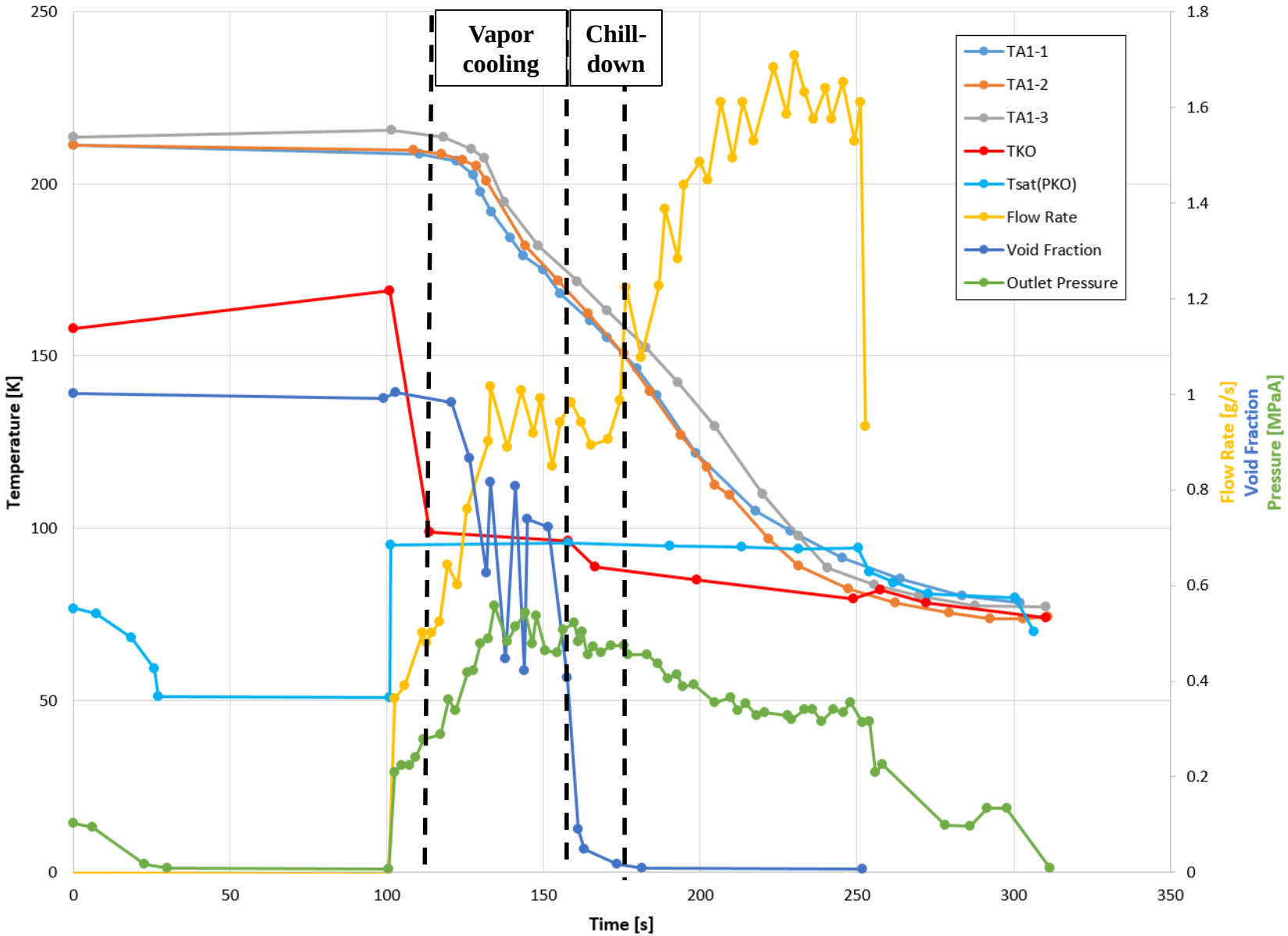
Chill-down 1G Conclusions

- 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



ICs and BCs: Vapor Cooling + Chill-down microG

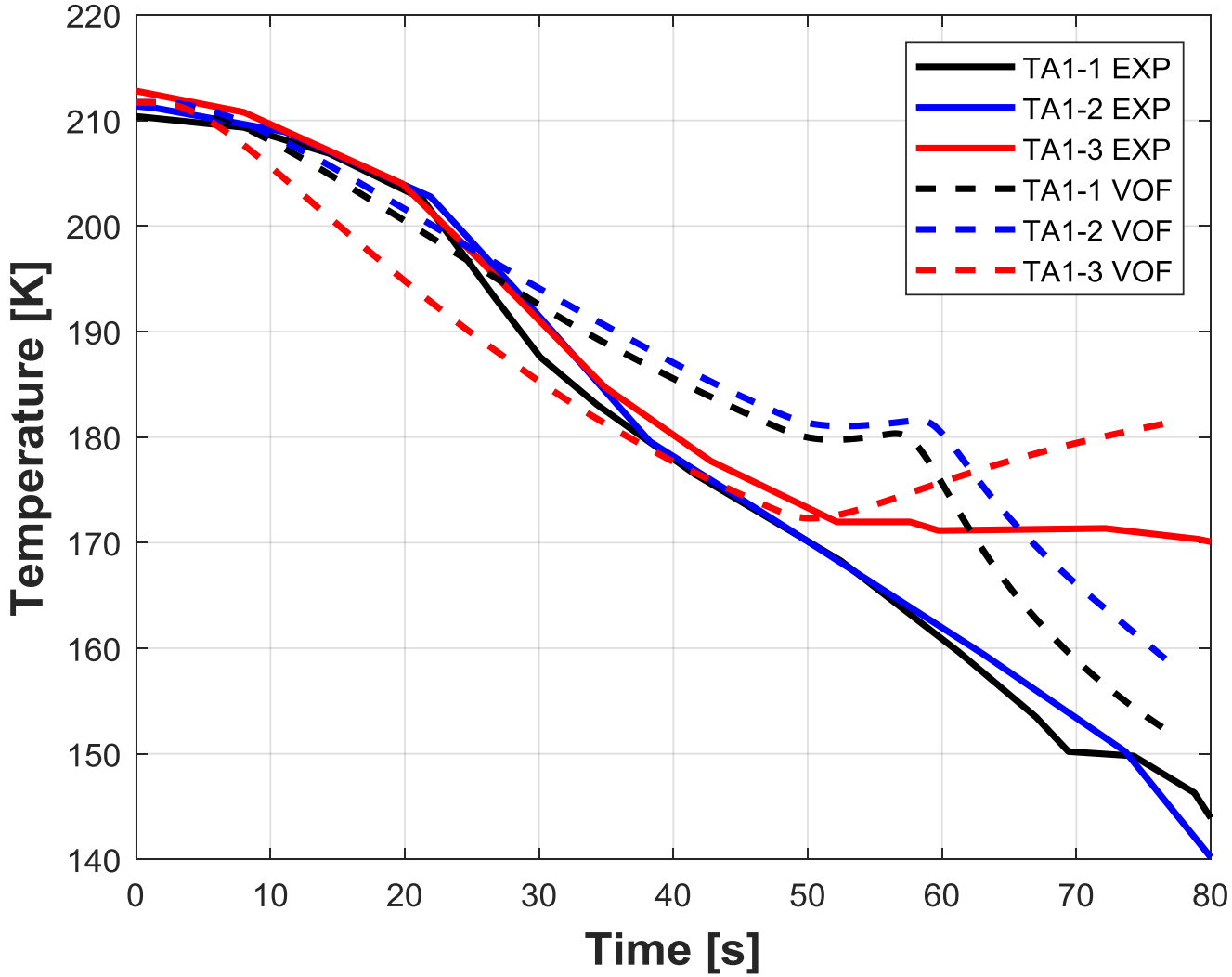


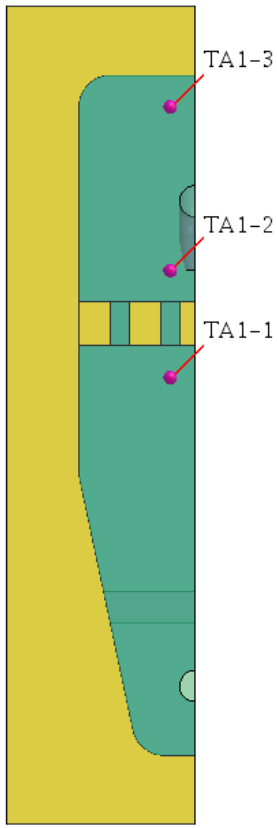
Initial and Boundary Conditions Summary

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

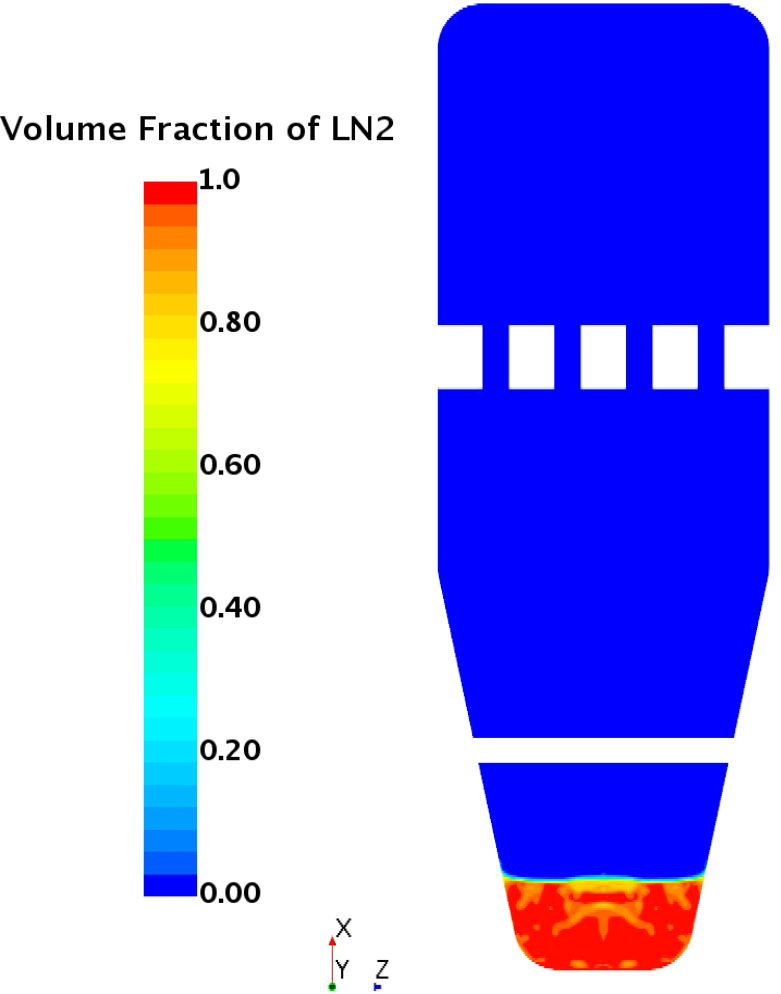
Vapor Cooling + Chill-down 1G and microG, 1.0g/s Results

Temperature Data 1G

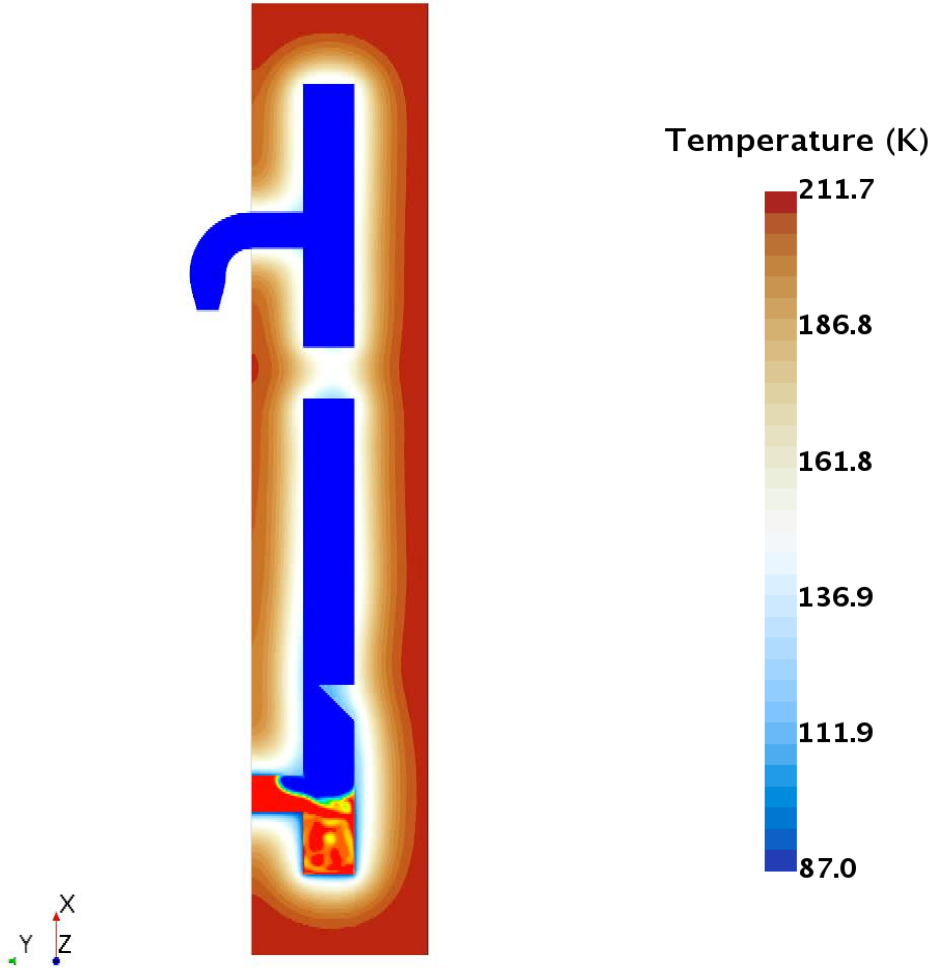




Flow Evolution 1G

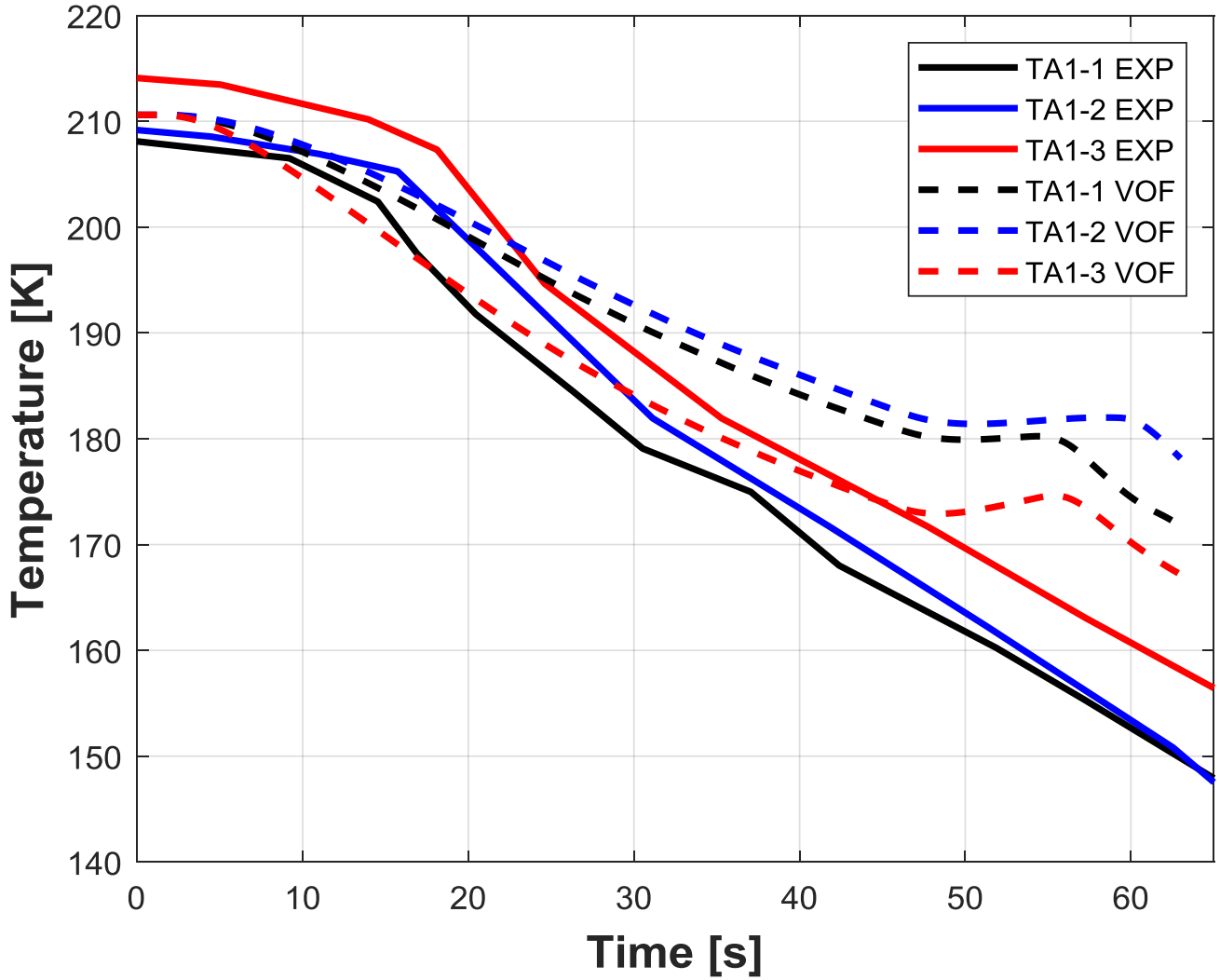


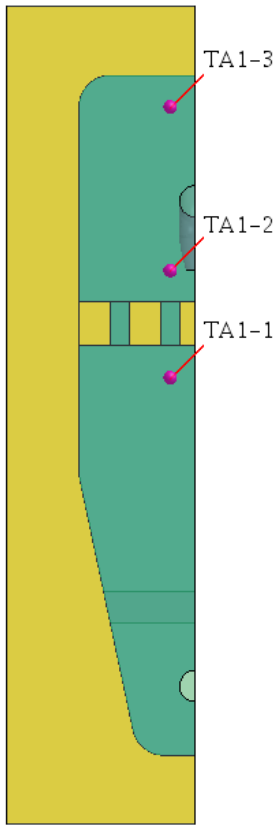
Solution Time 48.1 (s)



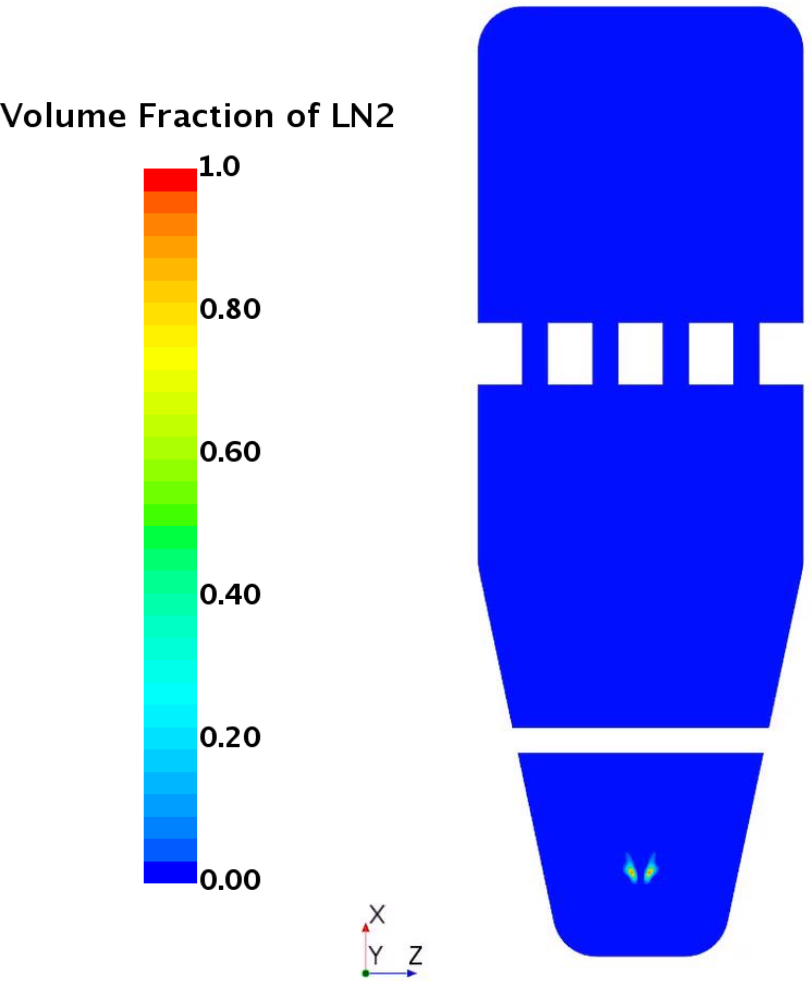
Solution Time 48.1 (s)

Temperature Data microG

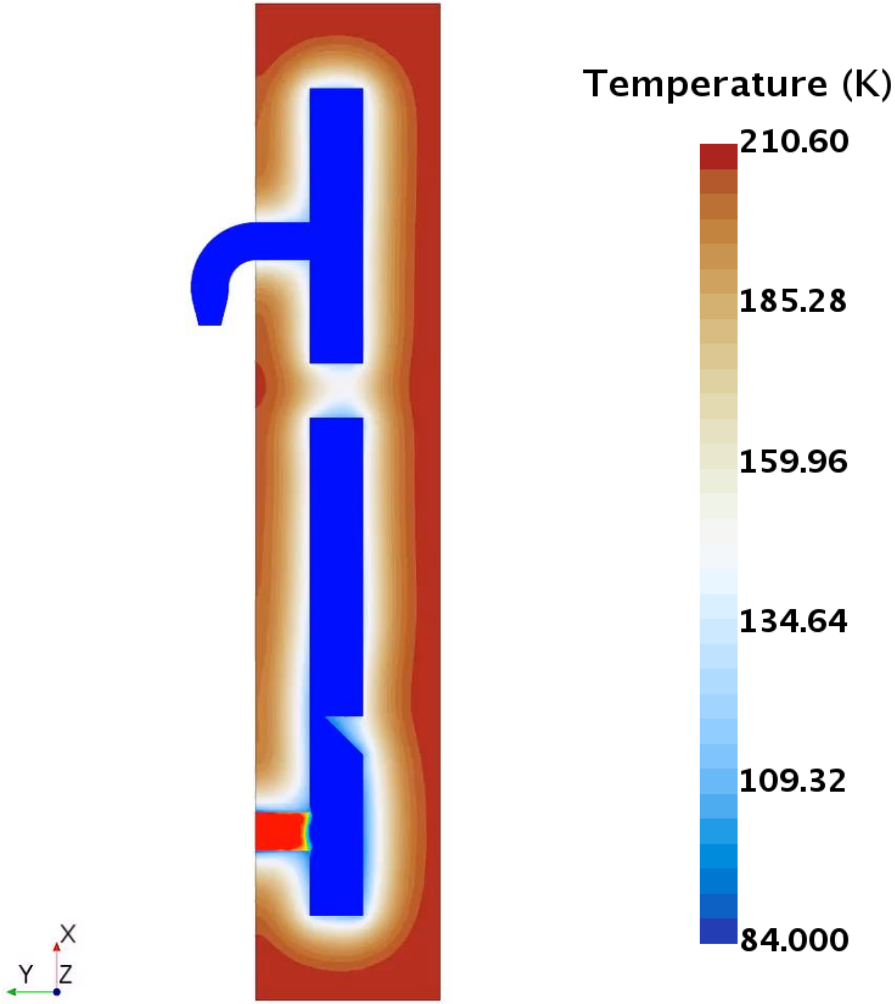




Flow Evolution microG



Solution Time 45.1 (s)



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!