Prediction of Cryogenic Propellant Tank Active Pressure Control by Jet Induced Mixing

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Contents

Background

- Refueling in LEO for deep space missions have several challenges
- Cryogenic propellant storage tank
  - Liquid hydrogen (LH2) and liquid oxygen (LOX)
- Cryogenic fluid management technologies
  - Mixing destratification
  - Filling and venting
  - Refrigeration
  - Pressurization
  - Liquid acquisition device (LAD)

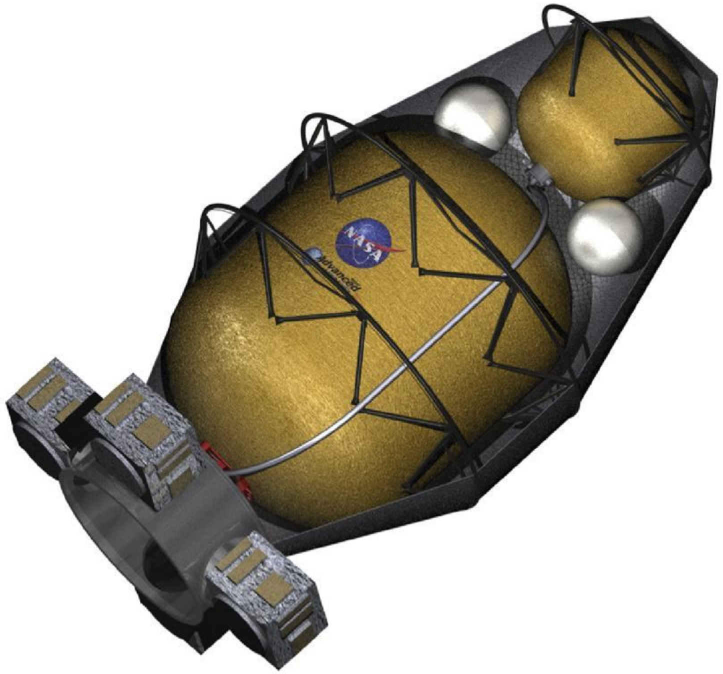
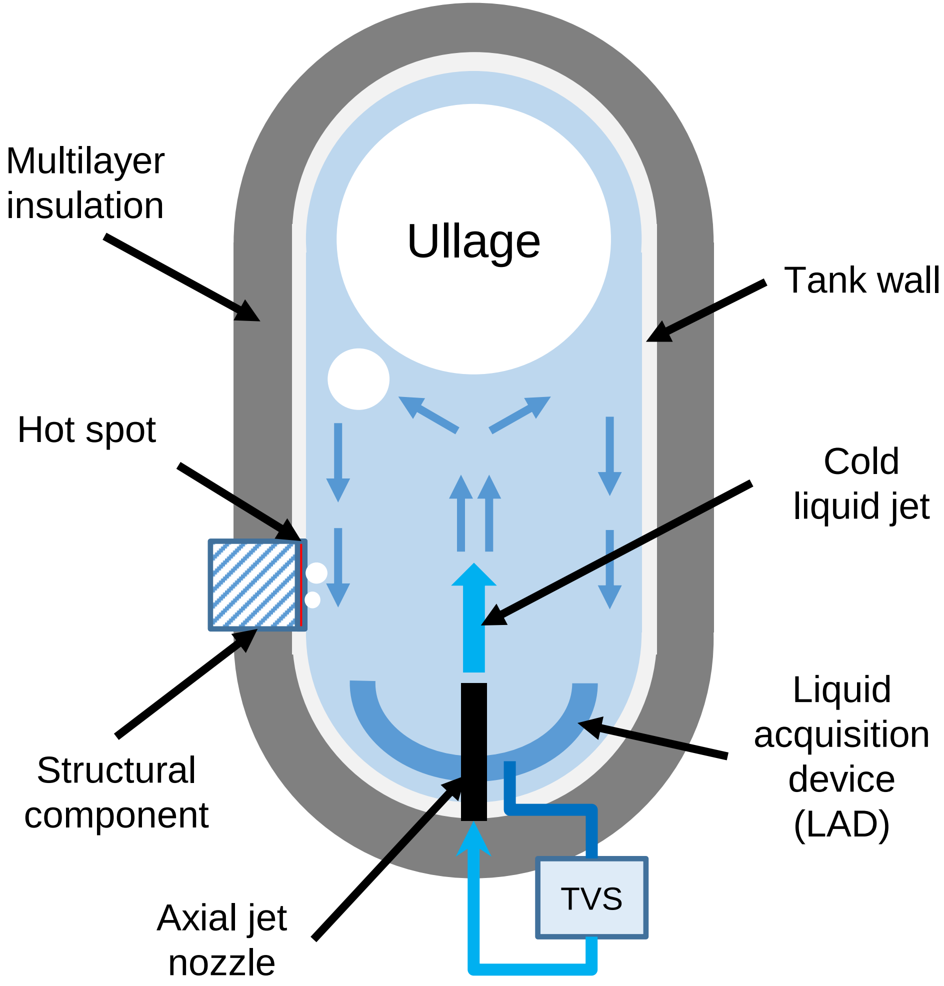


Image: NASA

Background (Cont’d)

- “Heat is the enemy”
  - Radiation heat penetrates through insulation layers
  - Heat leaks through conduction from structural components such as struts (localized heating)
  - Causes thermal stratification in microgravity
- Thermodynamic vent system (TVS) operates with jet mixing technology
  - Reduces thermal gradients within the fluid
  - Promotes condensation at the interface to reduce tank pressure



Research Objective

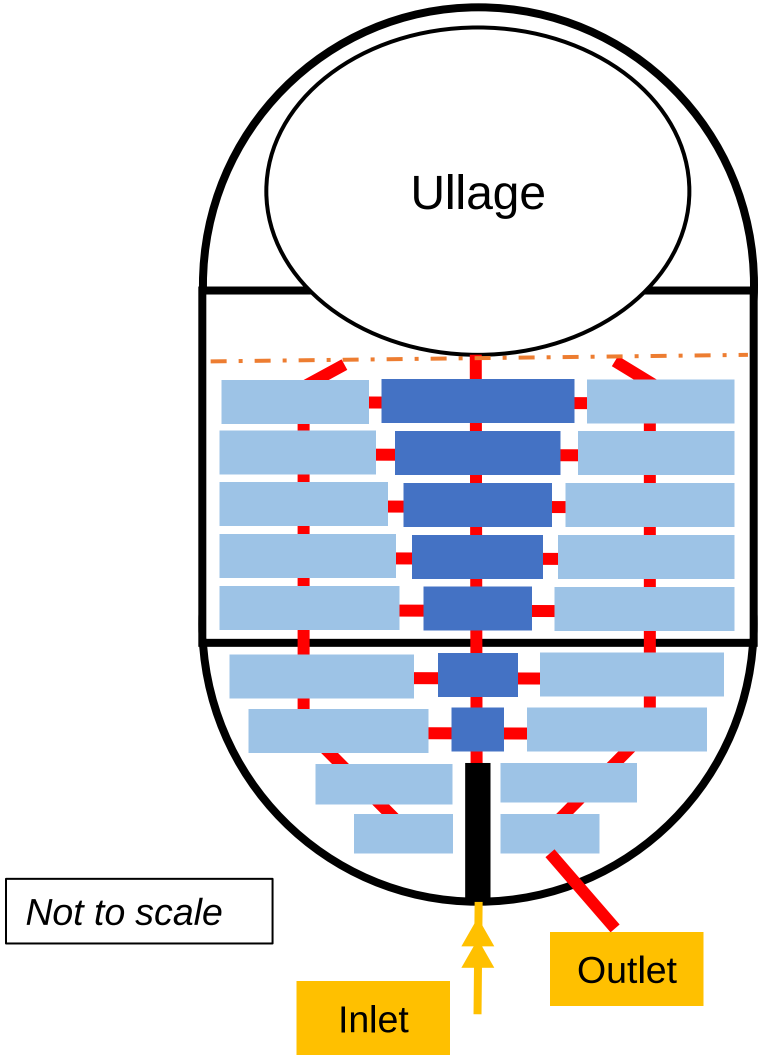
- Develop a comprehensive nodal model to predict active pressure control of cryogenic propellant tanks
- Simulate jet induced mixing and interfacial heat and mass transfer
  - Need accurate closure relations using system level analysis code
  - Jet is not self-similar near the nozzle ($L/D < 25$)
  - Confined flow due to both wall and bubble interface
- Demonstrate the capabilities of SINDA/FLUINT for fast simulation of jet induced mixing inside a cryogenic propellant tank

Technical Approach

- Primarily leverage a nodal code, namely SINDA/FLUINT, to reduce computational cost
- Construct a nodal model representing ullage, jet flow, and bulk liquid regions in a cryogenic propellant tank
- Use CFD code simulations to obtain closures for internal flow parameters such as jet velocity, volumetric flow rate, and radius
- Implement various closures into the nodal model accounting for jet mixing and vapor condensation
- Validate predicted pressure evolution against Tank Pressure Control Experiment (TPCE) experimental results

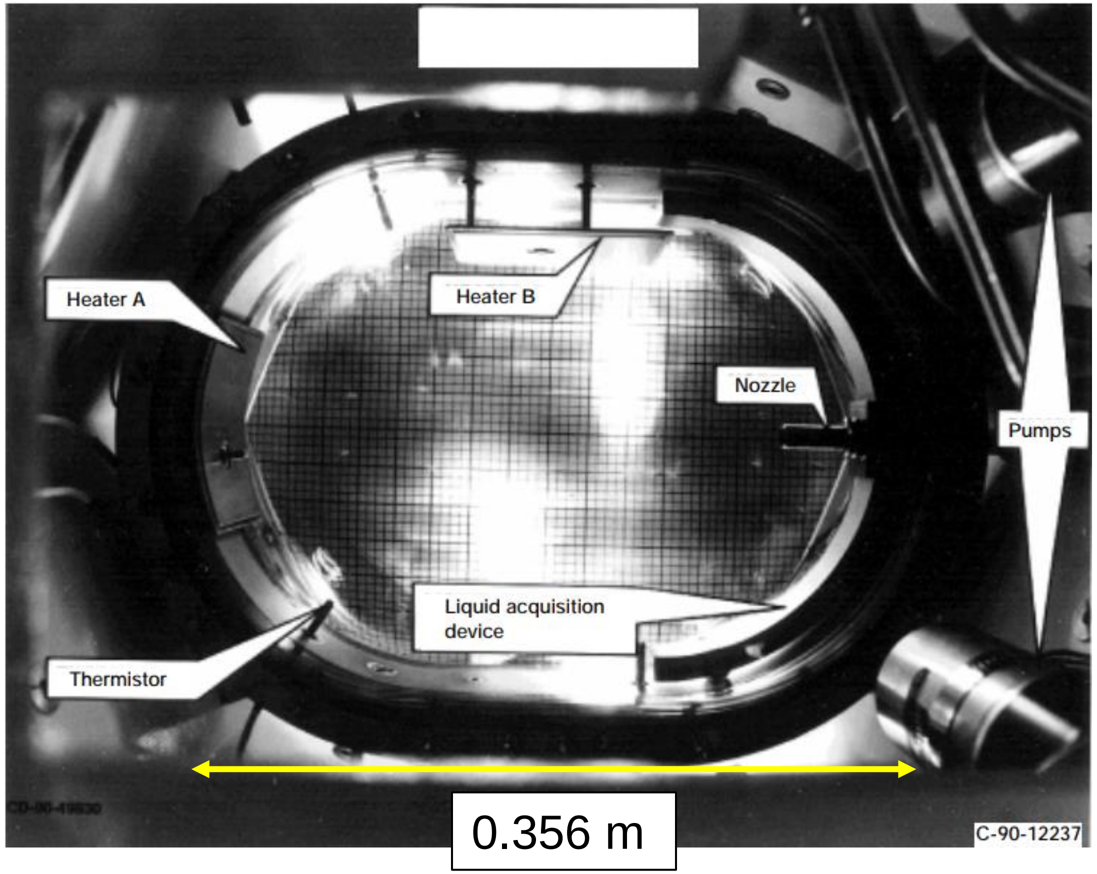
Nodal Modeling Framework

- Jet induced mixing nodal model
  - Strategically discretized fluid domains
    - Ullage region
    - Jet region
    - Bulk liquid region
  - Requires correlations to resolve the internal flow
    - Volumetric flow rate of the jet flow
    - Radius of the jet flow
  - Requires correlation for mass and heat transfer at the interface
  - Liquid entrainment indirectly modeled
    - Mass flow rate increases downstream of jet due to entrainment
    - Satisfy conservation of mass within lumped nodes



Tank Pressure Control Experiment

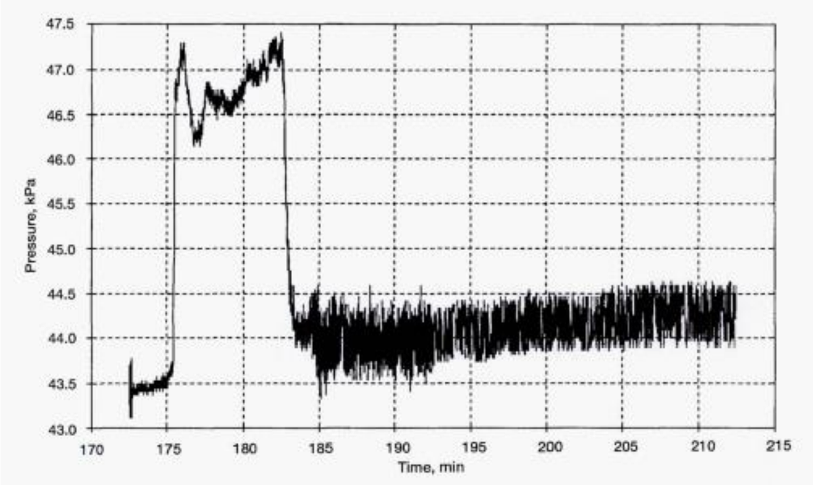
- Test conditions
  - Working fluid: Freon 113
  - Acceleration: 1e-6g
  - System pressure ≈ 41 kPa
  - Temperature ≈ 296K (near saturation temperature)
  - Jet flow rate: 0.38 to 3.36 liters/min
  - Bond number : 0.034
  - Jet Reynolds number: 1,800 to 16,100
  - Jet Weber number: 0.29 to 22.29
  - Heaters A & B (0.05 to 0.12 W/cm^2)

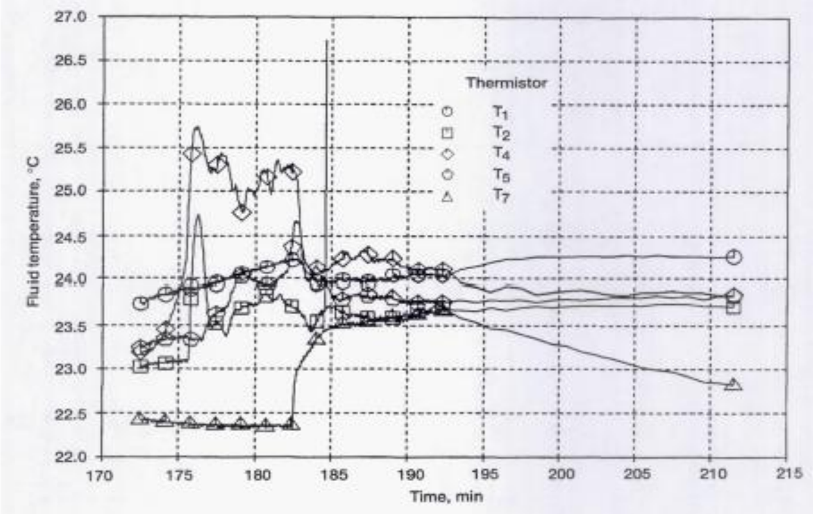


M.D. Bentz, J. Meserole, and R. Knoll, Jet Mixing in Low Gravity - Results of the Tank Pressure Control Experiment, AIAA, Proc. of 28th Joint Propulsion Conference and Exhibit, Nashville, TN, USA, July 06-08, (1992).

Tank Pressure Control Experiment (Cont’d)

- Experimental jet mixing case Run #6





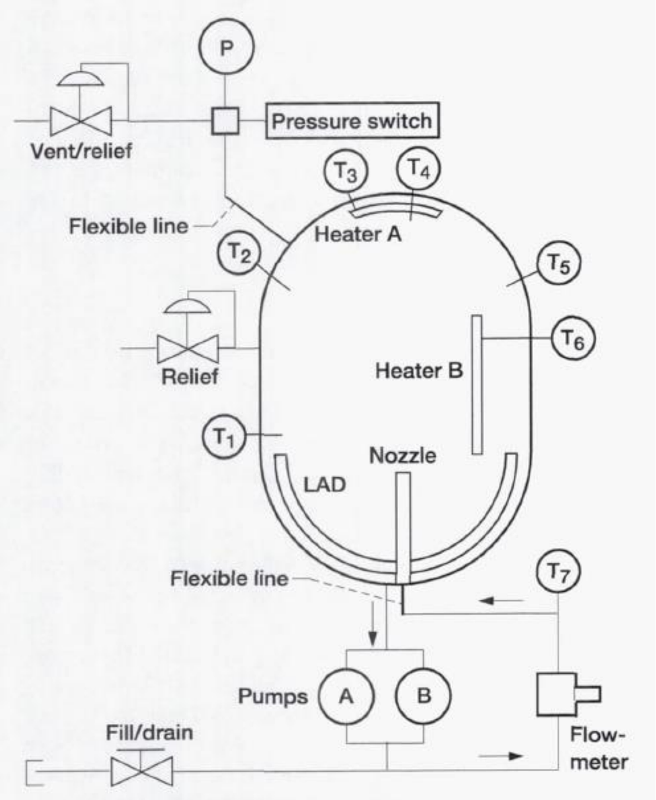


Figure 2.—Schematic of experimental system.

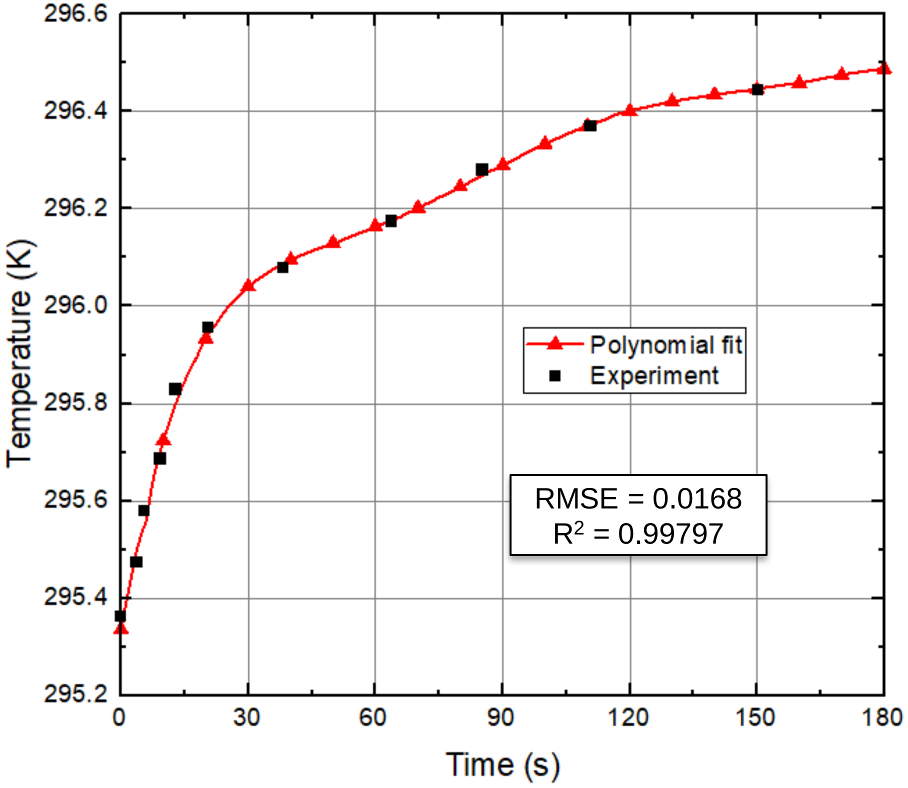
M.M. Hasan, C.S. Lin, R.H. Knoll, and M.D. Bentz, “Tank Pressure Control Experiment: Thermal Phenomena in Microgravity,” NASA Technical Paper 3564, National Aeronautics and Space Administration (1996).

Case Setup (Nodal)

- Case description: Tank depressurization due to jet induced mixing
  - Simulation time: 3 minutes (180 seconds)
  - Working fluid: Freon 113
  - Acceleration: 1e-6g
  - Fill level: 84%
  - Re = 2,217 (u_j = 0.0933 m/s)
- Initial conditions:
  - Tank pressure = 47.15 kPa
  - T_{liq} = 296.7K
- Boundary conditions
  - Inlet: mass flow rate
  - Outlet: pressure outlet

Case Setup (Nodal)

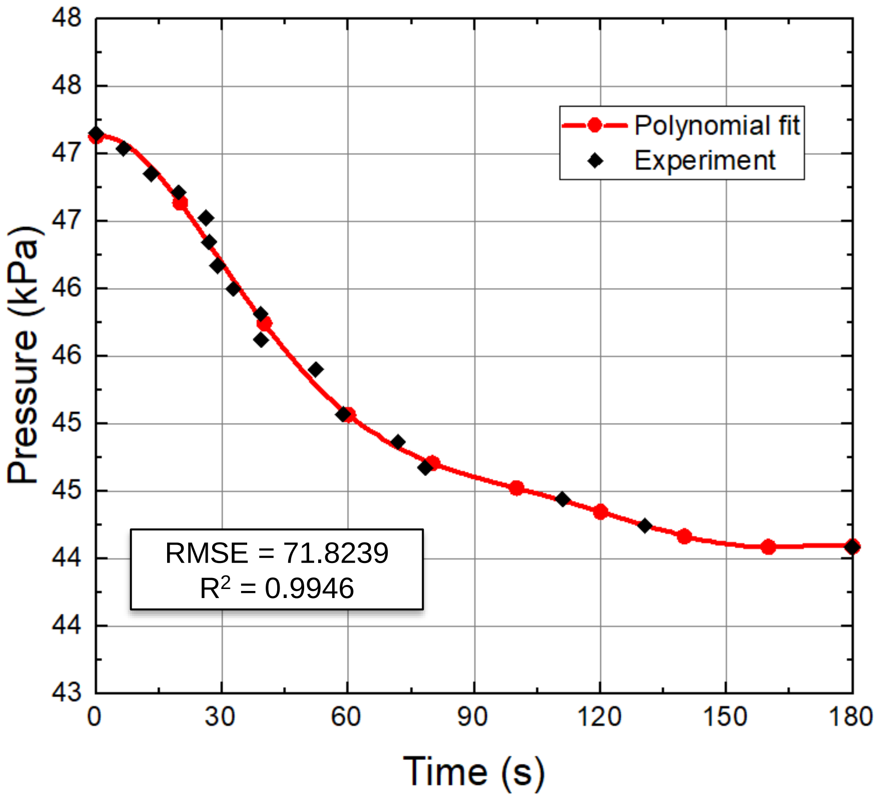
- Inlet temperature



Polynomial coefficients:
a = -9.1208e-13
b = 6.148e-10
c = -1.6252e-07
d = 2.1249e-05
e = -0.001437
f = 0.0513650
g = 295.337

$$T(t) = at^6 + bt^5 + ct^4 + dt^3 + et^2 + ft + g$$

- Pressure outlet



Polynomial coefficients:
a = -1.2934e-11
b = 5.3478e-9
c = -2.3603e-7
d = -1.8669e-4
e = 0.0343
f = -2.0247
g = 3.5741
h = 47130

$$p(t) = at^7 + bt^6 + ct^5 + dt^4 + et^3 + ft^2 + gt + h$$

Required Closures for Nodal Code

- Interfacial mass transfer

$$\dot{m}_v = -\left(\frac{q_{il} + q_{iv}}{h_{fg}}\right) = -\left[\frac{U_l A\left(T_{sat} - T_l\right) + U_v A\left(T_{sat} - T_v\right)}{h_{fg}}\right]$$

- Liquid to interface heat transfer

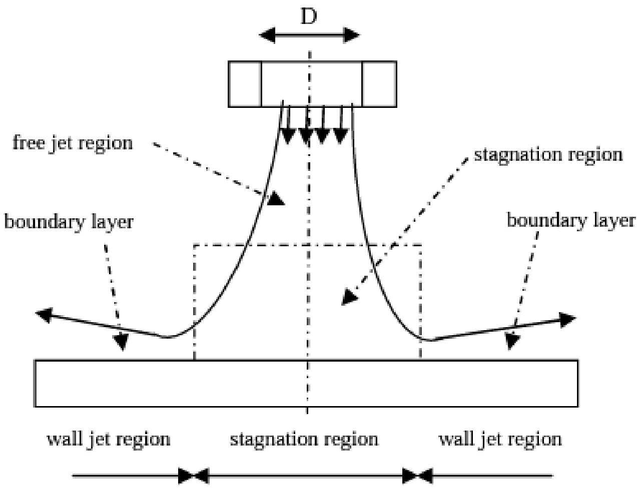
$$\overline{\mathrm{Nu}_c} = C\,\mathrm{Pr}^m\,\mathrm{Re}^n_{j,r}$$

$$\mathrm{Re}_{j,r} = \frac{\rho v r}{\mu}$$

$$0.88 < C < 1.09$$

$$m = 1/3, \quad n = 1/2$$

J.N.B. Livingood and P. Hrycak, "Impingement Heat Transfer From Turbulent Air Jets to Flat Plates – A Literature Survey," NASA TM X-2778, (1973).

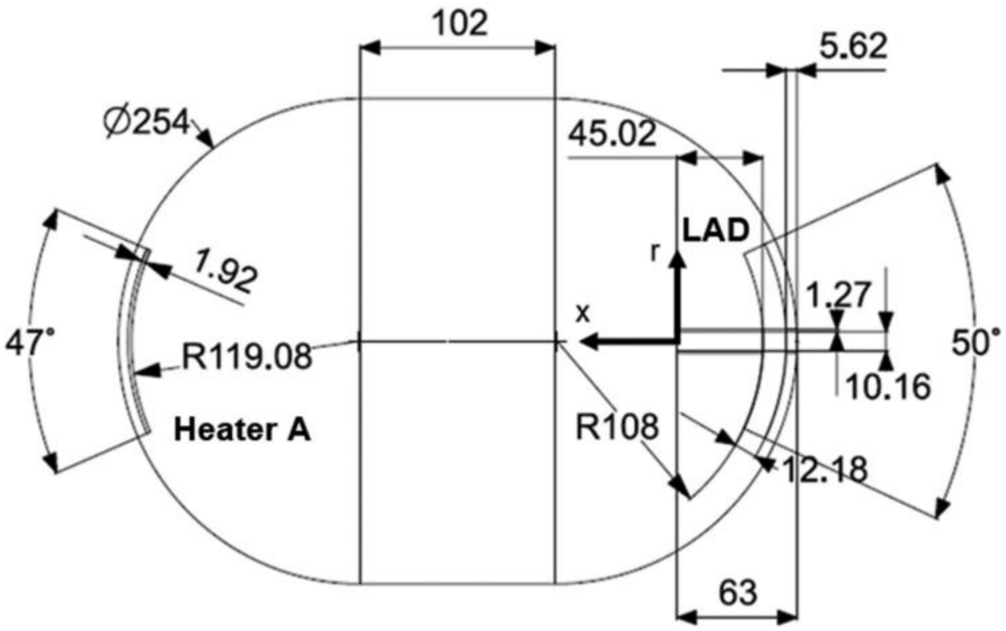


K. Marzec and A. Kucaba-Pietal, "Heat Transfer Characteristics of an Impingement Cooling System with Different Nozzle Geometry," J. Physics.: Conf. Ser. 530, 012038, (2014).

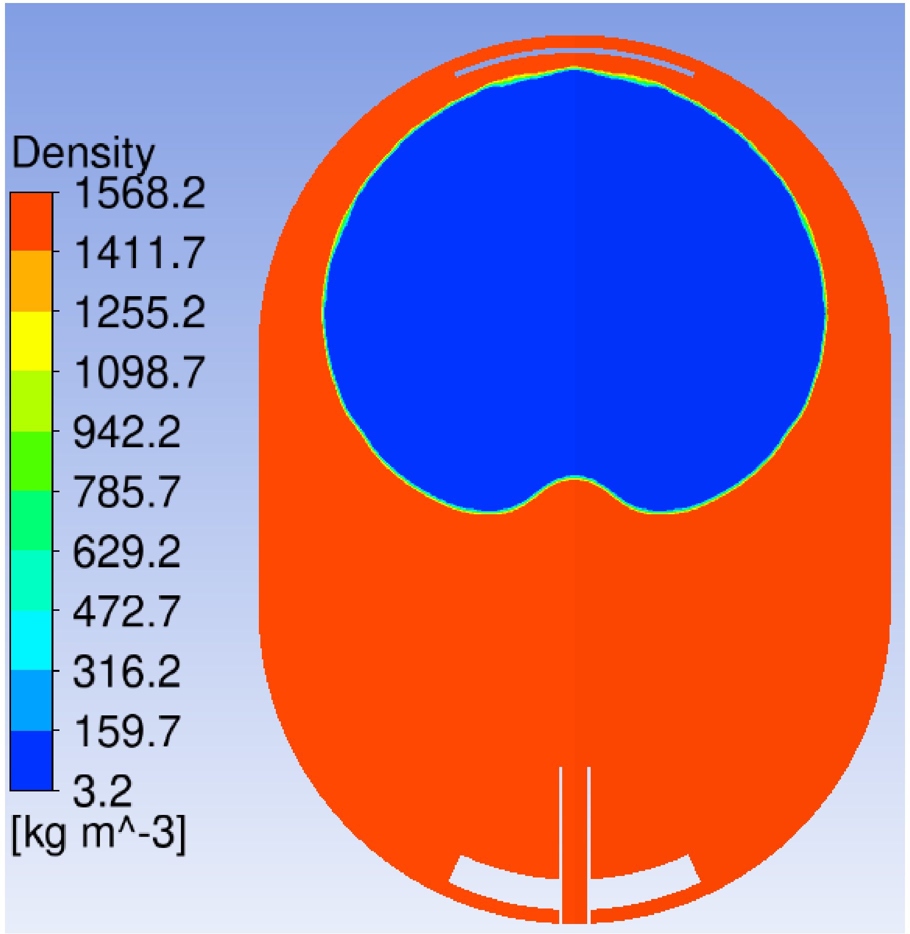
- Vapor to interface heat transfer
  - Assumes solid conduction (Nusselt number roughly equals to 1)

Required Closures for Nodal Code (Cont'd)

- Momentum closures for internal flow obtained through CFD model
  - 2D volume of fluid (VOF) model
  - Circular turbulent jet

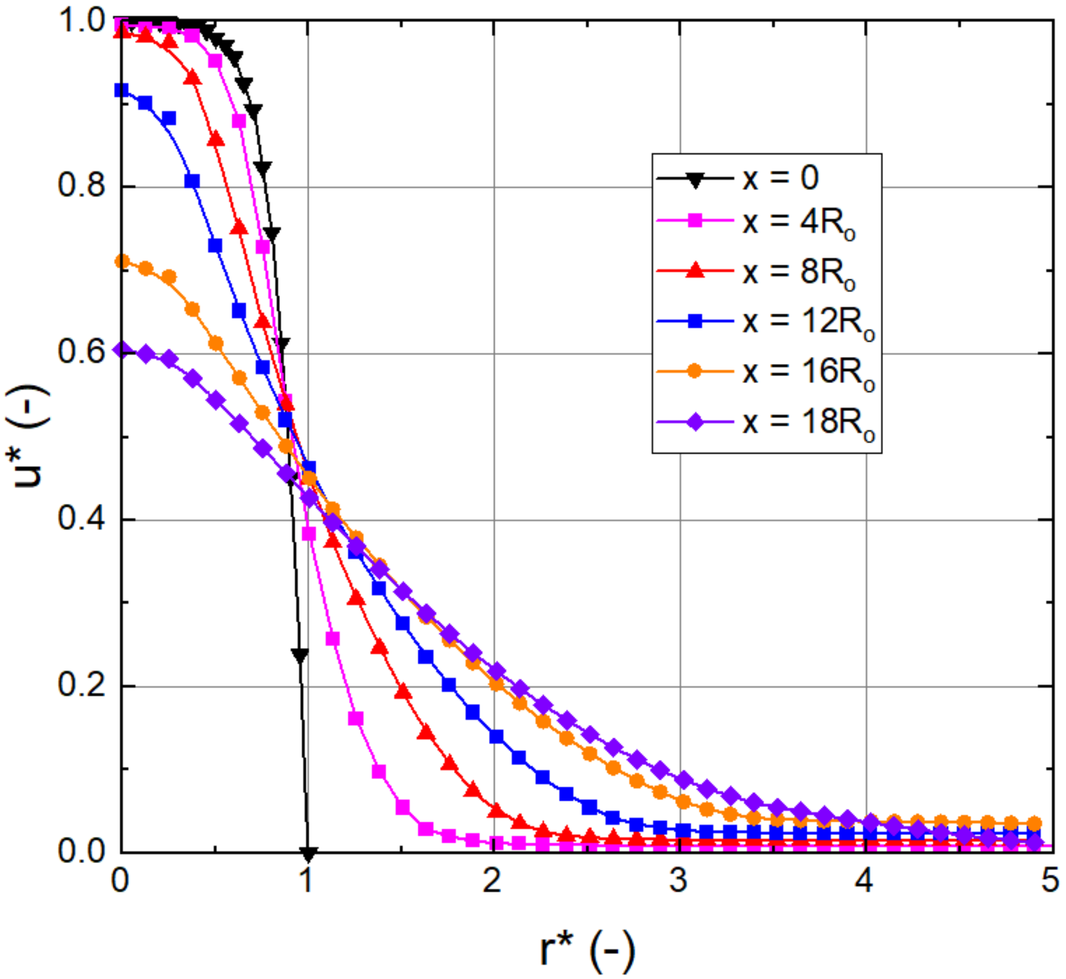


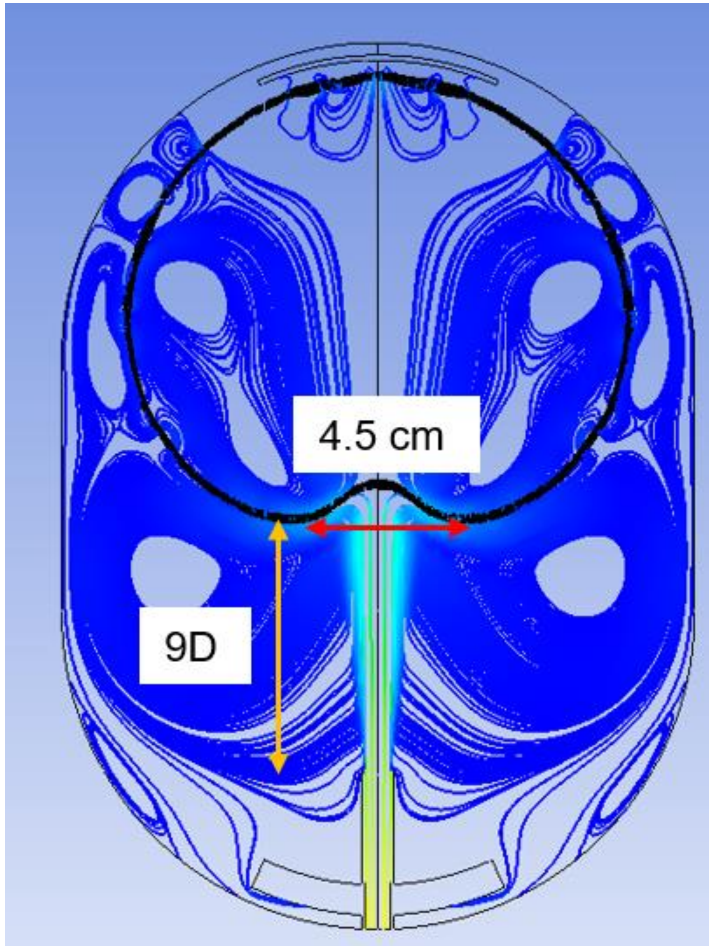
E. Lan and S. Shi, "RANS-Based CFD Simulation of Jet-Induced Mixing and Jet Impingement on Large Bubble in Microgravity, Nuclear Technology, (2023).



Required Closures for Nodal Code (Cont’d)

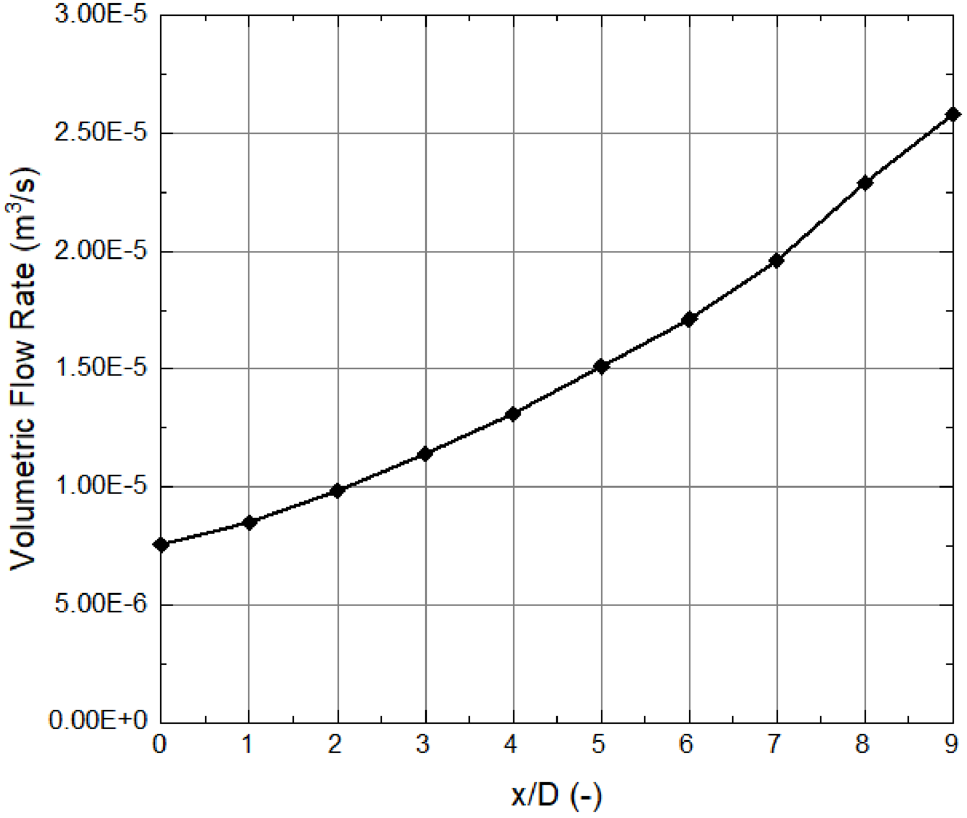
- Nondimensionalized jet velocity

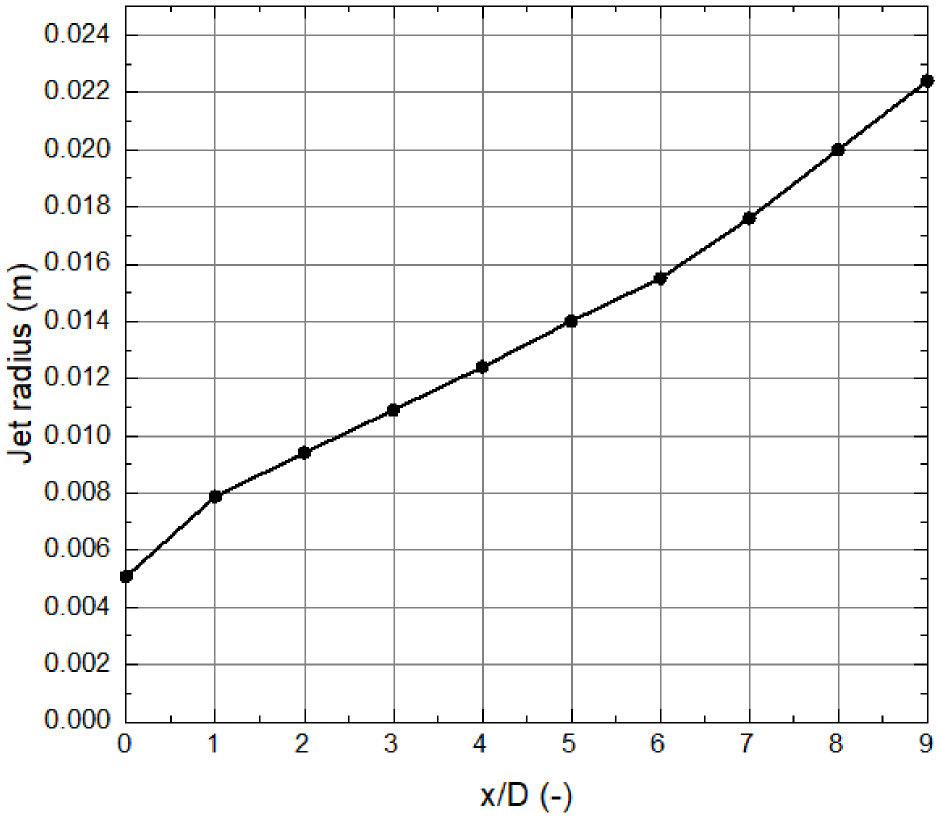




Required Closures for Nodal Code (Cont'd)

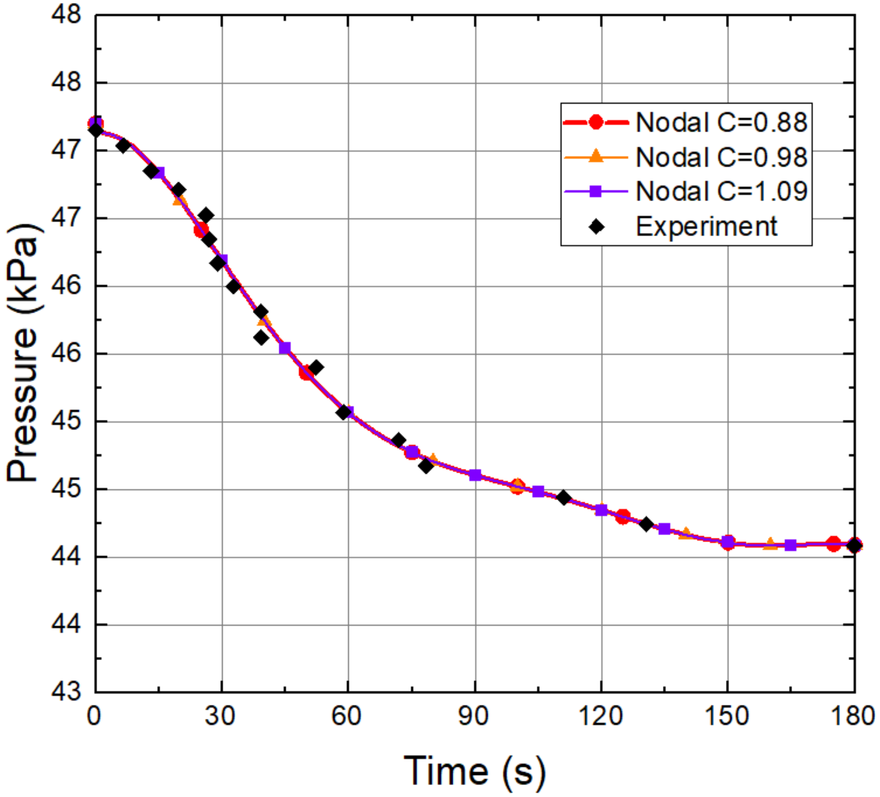
- Jet radius and volumetric flow rate from CFD simulation
- Volumetric flow rate obtained numerically by integrating the velocity profile up to jet radius

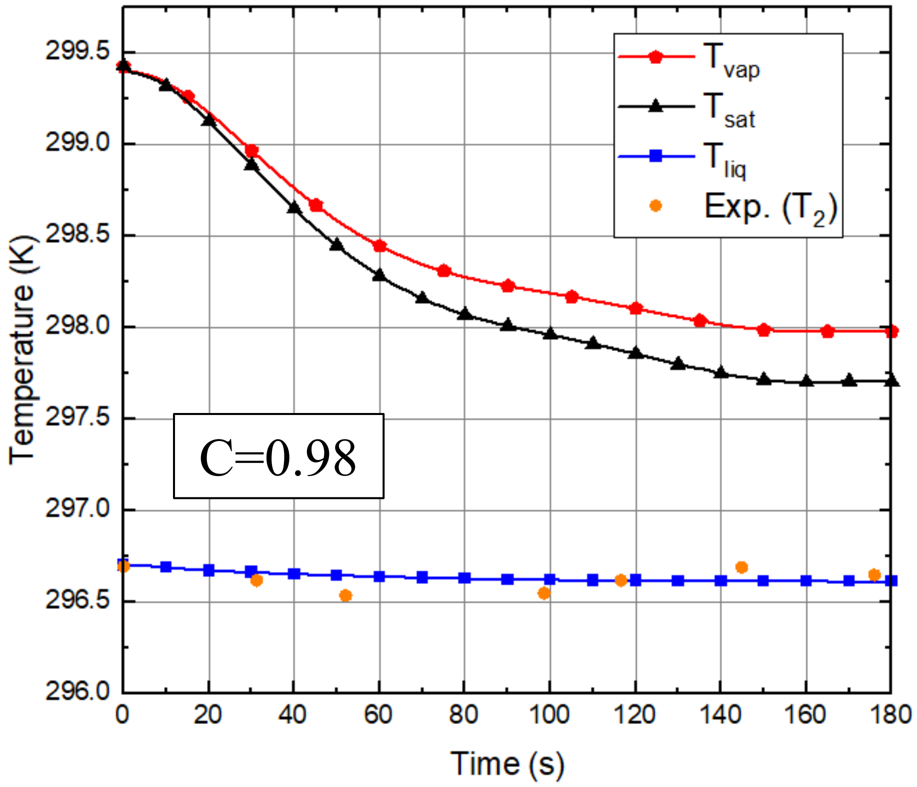




Results

- Tank pressure and temperature





$$\overline{\mathrm{Nu}}_c = C\,\mathrm{Pr}^m\,\mathrm{Re}_j^n$$

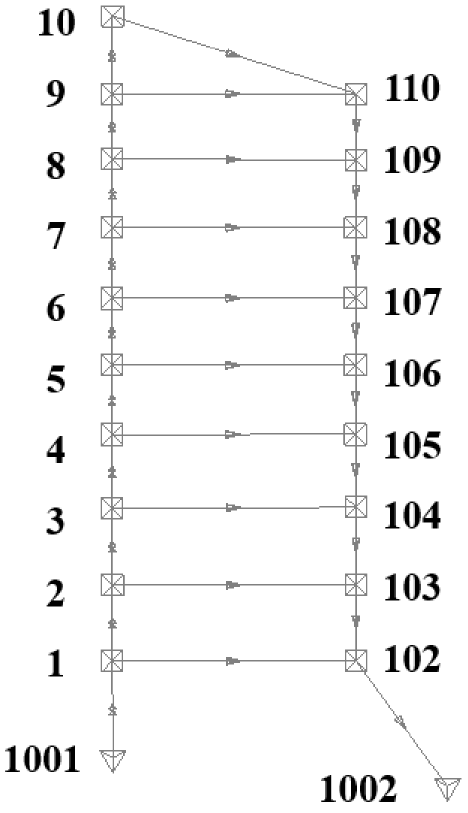
$$0.88 < C < 1.09$$

$$m = 1/3$$

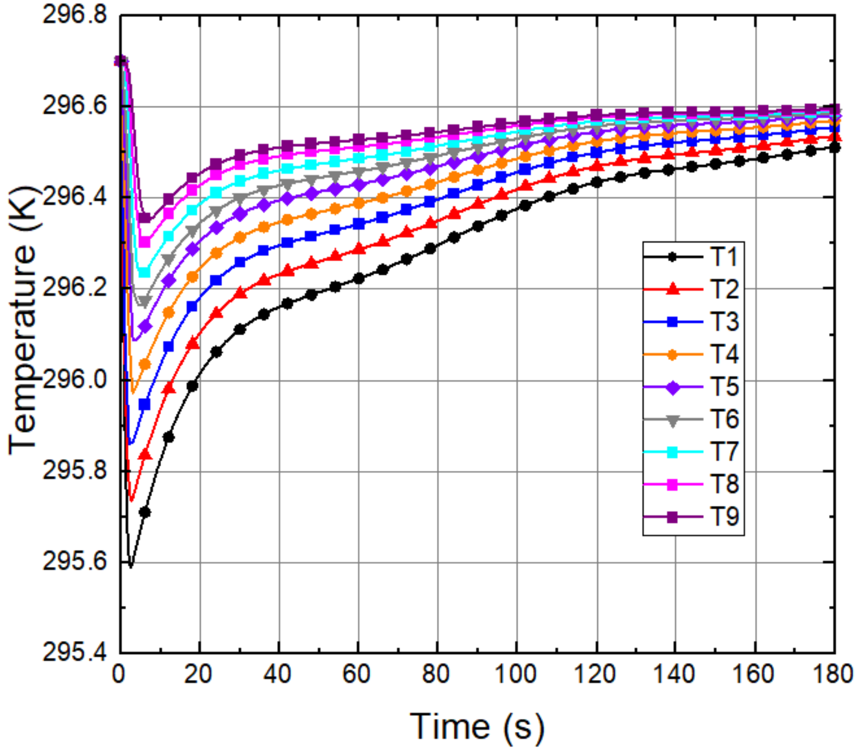
$$n = 1/2$$

Results (Cont’d)

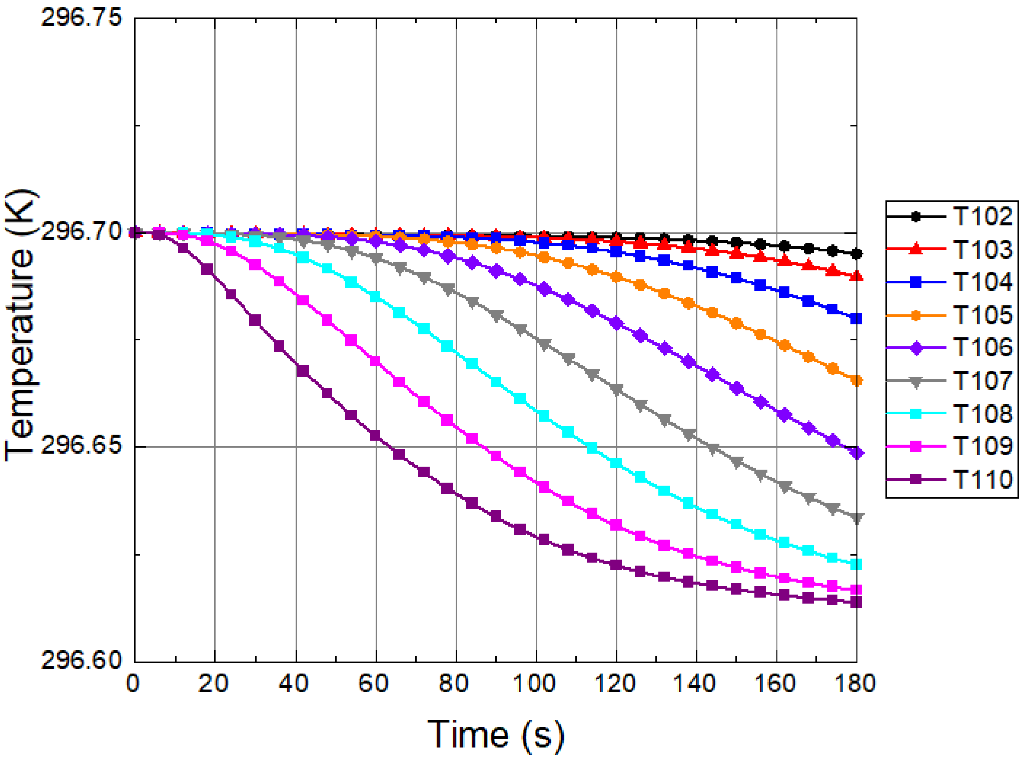
- Nodal code takes approximately 5 seconds to run a 3 minutes jet mixing case
- CFD code takes approximately 2 days



Jet region



Bulk region



Conclusions

- A nodal framework was developed based on SINDA/FLUINT to simulate jet induced mixing and interface heat and mass transfer
- Jet closure models were obtained through CFD simulations
- A transient jet induced mixing case was simulated referencing TPCE jet mixing case Run #6
  - Pressure profile agrees well with experimental data
  - Liquid temperature agrees reasonably well
- Demonstrated capabilities of SINDA/FLUINT for fast simulation of jet induced mixing inside a cryogenic propellant tank

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Thank You
and
Questions?