



CFD Predictions of Boiling Regime Transitions during Line Childdown validated against a 1G LN2 Experiment

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Thursday, September 5, 2024

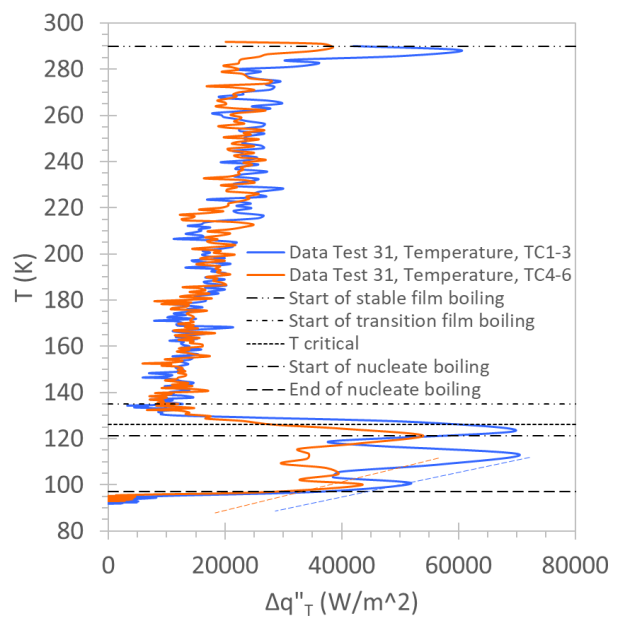
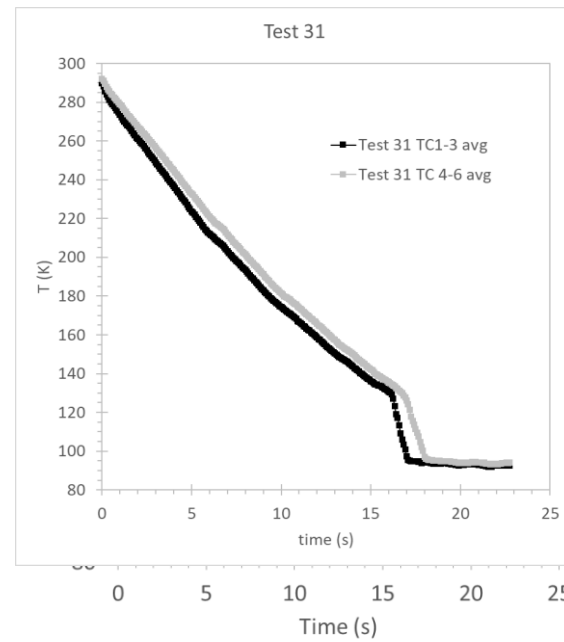
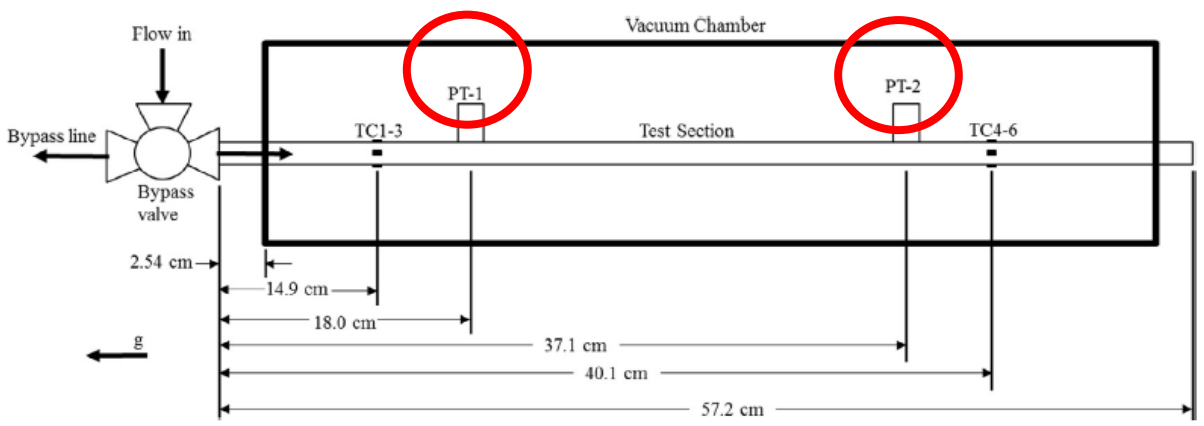
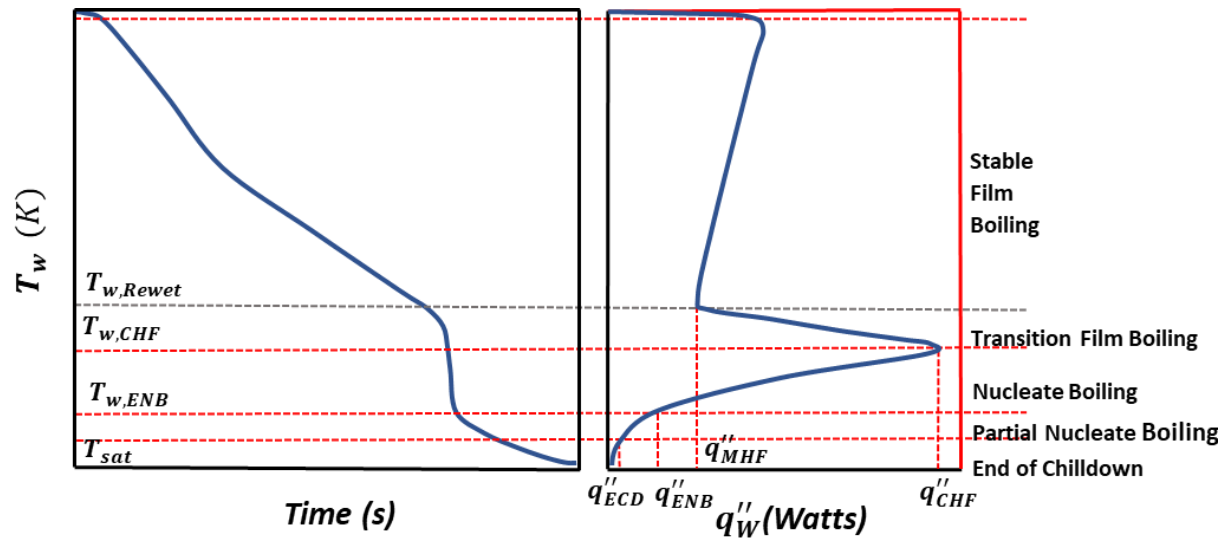


- ZBOT-FT (Filling and Transfer Experiment) was initiated as a collaboration between DLR, NASA, the University of Bremen, and Case Western Reserve University to study tank-to-tank transfer using a simulant fluid in microgravity. The experiment has three components:
 - Donor (supply) tank
 - Receiver tank
 - Transfer line that connects the two tanks
- Before the receiver tank can be filled, the transfer line needs to be chilled down
- In this work, we present a CFD model that we have developed for simulating the film, transitional, and nucleate boiling that occur in the tank during the chill-down process
- This model has been developed within the framework of the ANSYS Fluent code where the film boiling is captured by the Fluent Mixture model and the nucleate boiling has been incorporated into Fluent as an in-house developed sub-grid model
- As a preliminary effort to validate this model, numerical predictions have been compared to recent liquid nitrogen experiments performed at the University of Florida

University of Florida LN2 1G Line Chillover Experiment (Darr, et al, IJHMT 2016)



- University of Florida Experiment by Darr et. al. (2016)
- Thin-walled stainless steel tube at room temperature
 - Liquid nitrogen flows in
 - Film boiling is followed by nucleate boiling quenching
 - Film boiling is modeled via Fluent’s existing capabilities: Eulerian mixture model and Lee phase change model
 - Nucleate boiling is incorporated via an in-house developed subgrid model within a customized User Defined Function



“An experimental study on terrestrial cryogenic transfer line chillover I. Effect of mass flux, equilibrium quality, and inlet subcooling,” IJHMT, Darr et. al, 2016

Film Boiling Model

Film boiling

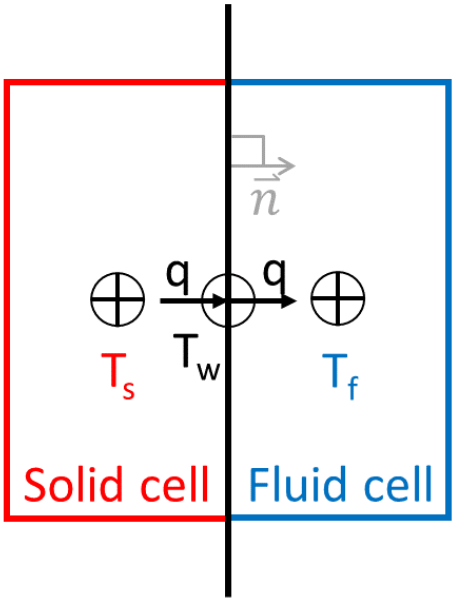
- Eulerian two-phase mixture model is used
 - Liquid and vapor are interpenetrating continua
 - Properties are determined from volume fraction of the phases
- Phase change is captured by the Lee model
 - Phase change mass transfer: $\frac{\partial}{\partial t} (\alpha_v \rho_v) + \nabla \cdot (\alpha_v \rho_v \vec{V}_v) = \dot{m}_{lv} - \dot{m}_{vl}$
 - Where evaporation = $\dot{m}_{lv} = coeff * \alpha_l \rho_l \frac{T_l - T_{sat}}{T_{sat}}$
 - And condensation = $\dot{m}_{vl} = coeff * \alpha_v \rho_v \frac{T_{sat} - T_v}{T_{sat}}$
 - Lee coefficient can be interpreted as a relaxation time that can be tuned as part of the simulation
- Wall temperatures are solved via a conjugated heat transfer model

Fluent Theory Guide, Release
2021 R2, ANSYS Inc., 2021





Nucleate Boiling Model: Implemented within the Conjugated Heat Transfer Approach



Wall Boundary

Energy balance at the wall:

$$-k_s \frac{\partial T}{\partial n} \Big|_{w,s} + \alpha \Delta q_{nb}(T_w) = -k_f \frac{\partial T}{\partial n} \Big|_{w,f}$$

$\alpha = \text{volume fraction of liquid}$

Rearranged and discretized:

$$k_f \frac{T_w - T_f}{\Delta n_f} + \alpha \Delta q_{nb}(T_w) = k_s \frac{T_s - T_w}{\Delta n_s}$$

Two possible methods for applying it in Fluent

Applied as Effective Conductivity

$$\alpha k_{l,eff}(T_w) \frac{T_w - T_f}{\Delta n_f} + (1 - \alpha) k_v \frac{T_w - T_f}{\Delta n_f} = k_s \frac{T_s - T_w}{\Delta n_s}$$

$$k_{l,eff}(T_w) = k_l + \frac{\Delta q_{nb}(T_w) * \Delta n_f}{T_w - T_f}$$

Applied as T_{wall}

$$T_w = \frac{\frac{k_s}{\Delta n_s} T_s + \left(\frac{\alpha k_l + (1 - \alpha) k_v}{\Delta n_f} \right) T_f - \alpha \Delta q_{nb}(T_w)}{\frac{\alpha k_l + (1 - \alpha) k_v}{\Delta n_f} + \frac{k_s}{\Delta n_s}}$$

$\Delta q_{nb}(T_w)$ is calculated by the subgrid model



Nucleate Boiling Model: Calculating Δq_{nb}

Sub-Grid Nucleate Boiling Model

Nucleation site density

- $N = (185 * |T_{wall} - T_{sat}|)^{1.805}$

Departure diameter

- $d_w = d1 * \theta_{contact} * \left(\frac{\sigma_{dw}}{g(\rho_{liquid} - \rho_{vapor})} \right)^{0.5} * \left(\frac{\rho_{liquid} - \rho_{vapor}}{\rho_{vapor}} \right)^{0.9}$

Departure frequency

- $f = \sqrt{\frac{4}{3} g \frac{\rho_{liquid} - \rho_{vapor}}{d_w \rho_{liquid}}}$
- $wait\ time = \frac{cwait_coeff}{f}$

Quench and evaporation coefficients

- $K_q = \frac{scale_coeff * \pi * d_w^2 * N}{4}$
- $quench\ coefficient = 2K_q * f * \sqrt{\frac{\rho_{liquid} \frac{dh_{liquid}}{dT} k_{liquid} * wait\ time}{\pi}}$
- $evaporation\ coefficient = \frac{N * f * \pi * d_w^3 * \rho_{vapor} * L}{6}$

Total boiling heat flux

- $\Delta q_{nb}(T_w) = evaporation\ coefficient + quench\ coefficient * |T_{wall} - T_{sat}|$

At Grid-Level film boiling / mixture flow

Fluid/Mixture wall interface energy balance

$$-k_s \frac{\partial T}{\partial n} \Big|_{w,s} + \alpha \Delta q_{nb}(T_w) = -k_{fm} \frac{\partial T}{\partial n} \Big|_{w,f}$$

Discretized wall interface energy balance

$$k_{fm} \frac{T_w - T_f}{\Delta n_f} + \alpha \Delta q_{nb}(T_w) = k_s \frac{T_s - T_w}{\Delta n_s}$$

Grid - Level Implementation

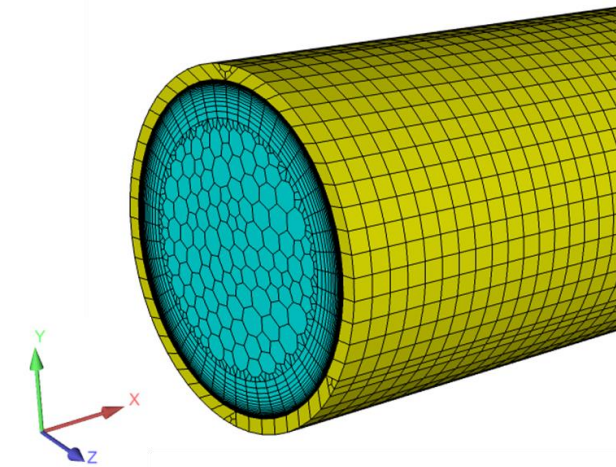
Applied as T_{wall}

$$T_w = \frac{\frac{k_s}{\Delta n_s} T_s + \left(\frac{\alpha k_l + (1 - \alpha) k_v}{\Delta n_f} \right) T_f - \alpha \Delta q_{nb}(T_w)}{\frac{\alpha k_l + (1 - \alpha) k_v}{\Delta n_f} + \frac{k_s}{\Delta n_s}}$$

Case Setup

T_{initial} (K)	288.54
\dot{m}_{inlet} , average (kg/s*m ²)	327.82
P_{outlet} (Pa)	325900
Inlet Re	35600
T_{inlet} (K)	86.61
$T_{\text{sat}}(P_{\text{outlet}})$ (K)	88.839

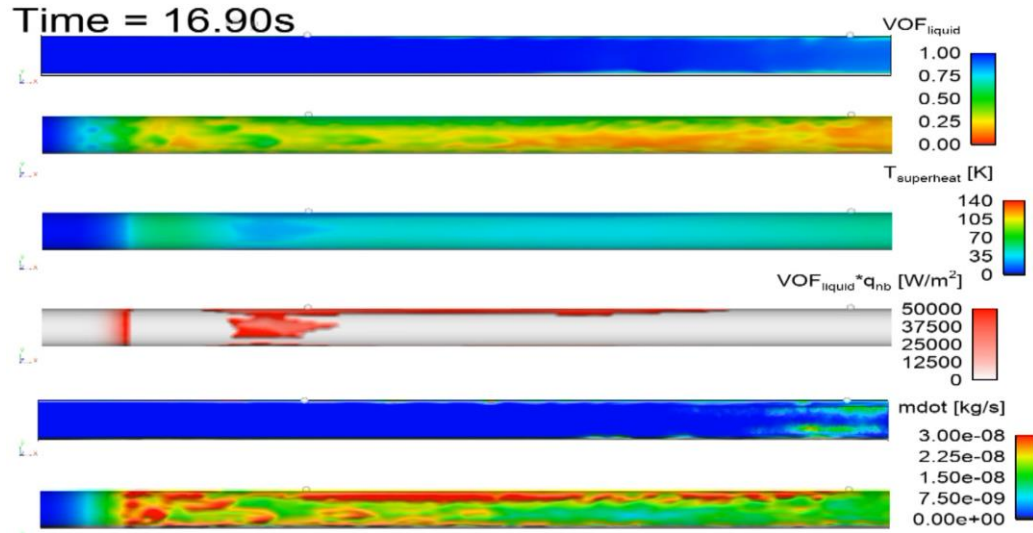
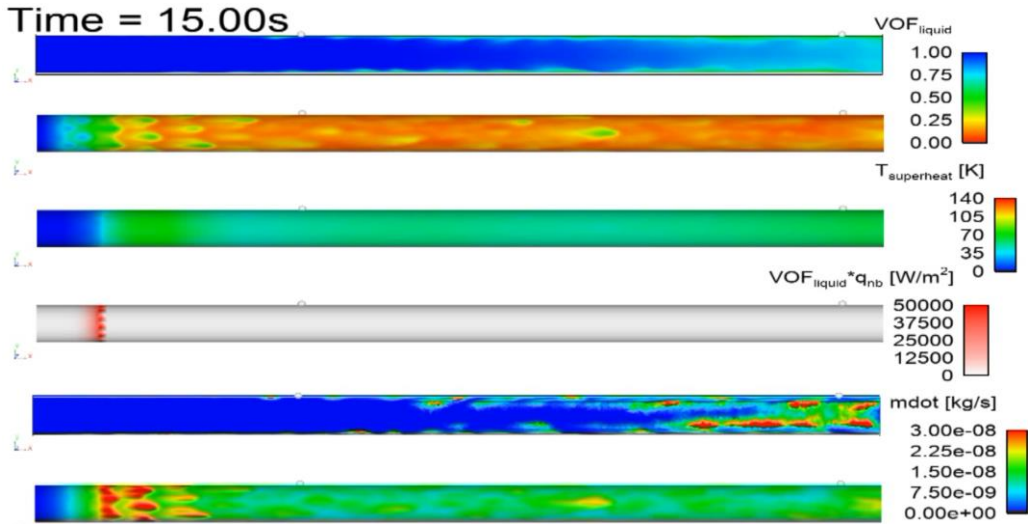
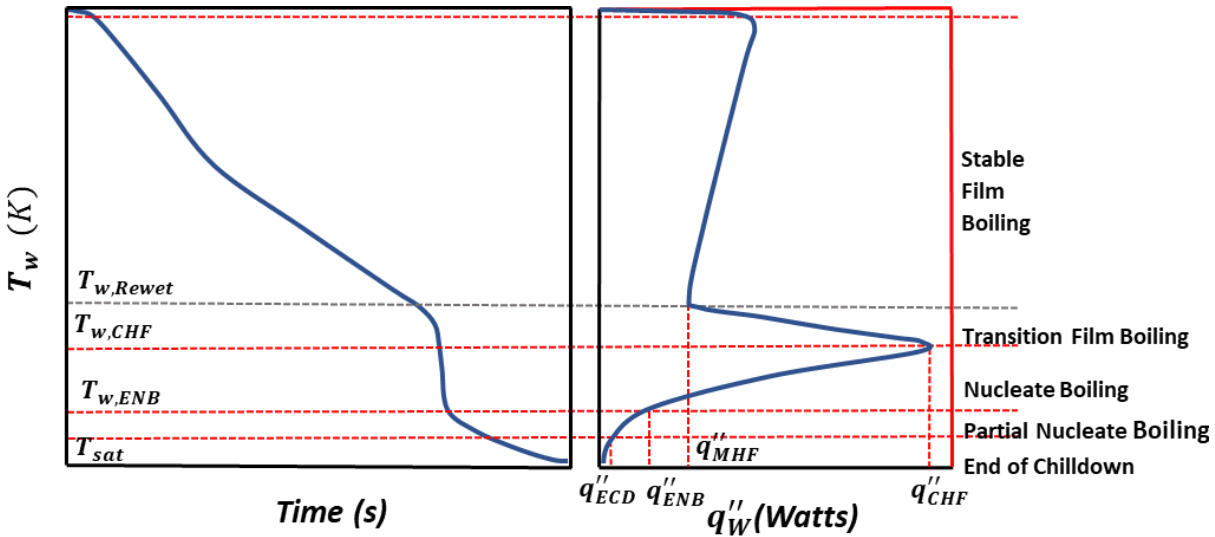
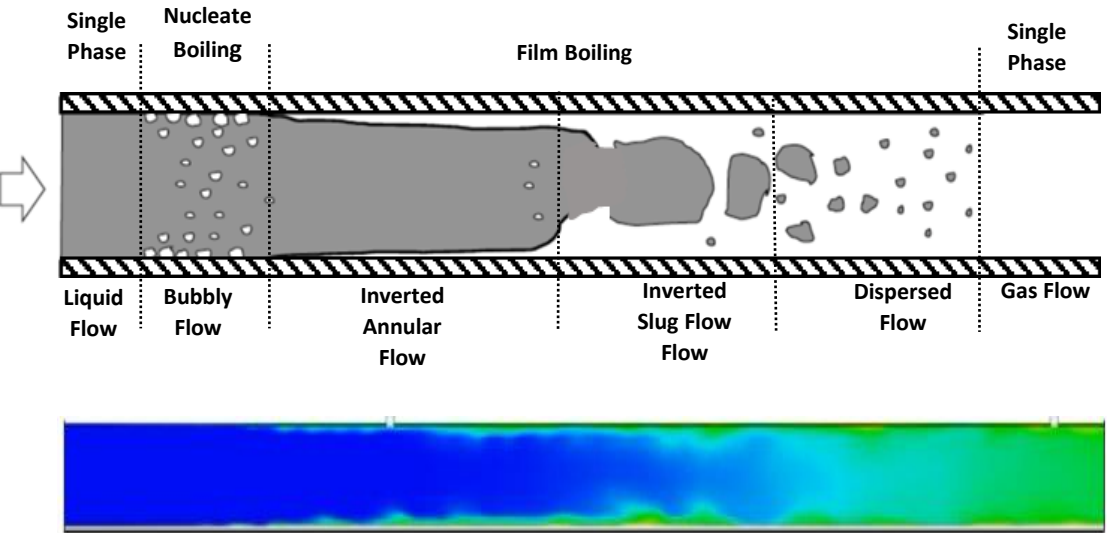
- Multiphase model
 - Mixture model
 - Wall interaction on (contact angle = 0°)
 - Surface tension is included
- Phase change during film boiling
 - Lee model
 - Evaporation coefficient = condensation coefficient = 5
- Nucleate boiling is handled by the subgrid model
- Fluid properties
 - Bulk properties are constant
 - Subgrid properties vary
 - Liquid is at saturation condition (properties at T_{fluid})
 - Vapor is at superheated condition (properties at T_{fluid} and P_{outlet})



3D:

- Mesh: 438000 cells
- Time step size
 - 1e-4s during film boiling
 - 2e-5s during quenching

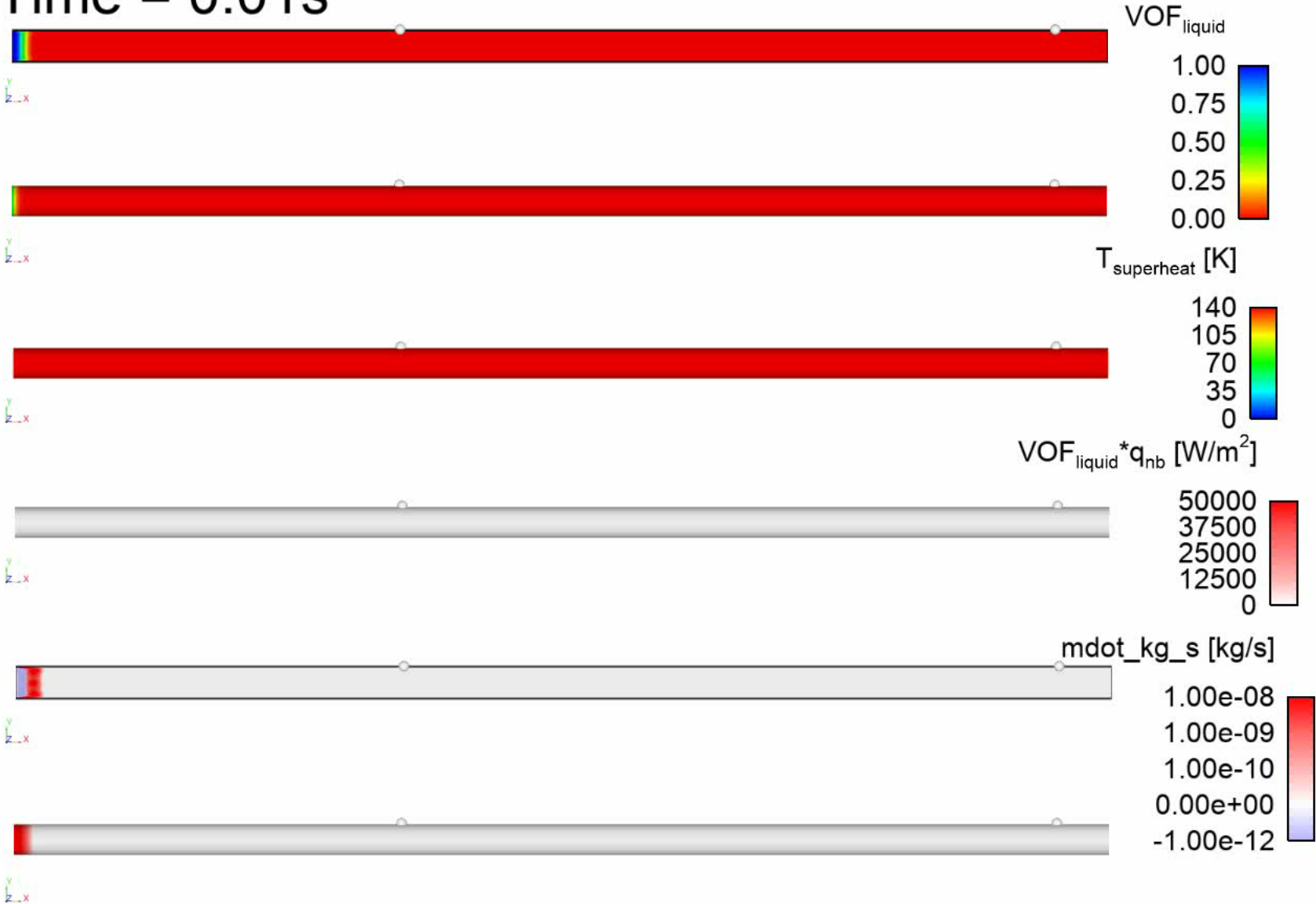
3D CFD-Coupled-Subgrid Model Simulations





3D CFD-Coupled-Subgrid Model Simulation Results: LN2 Test 31 (Darr 2016)

Time = 0.01s

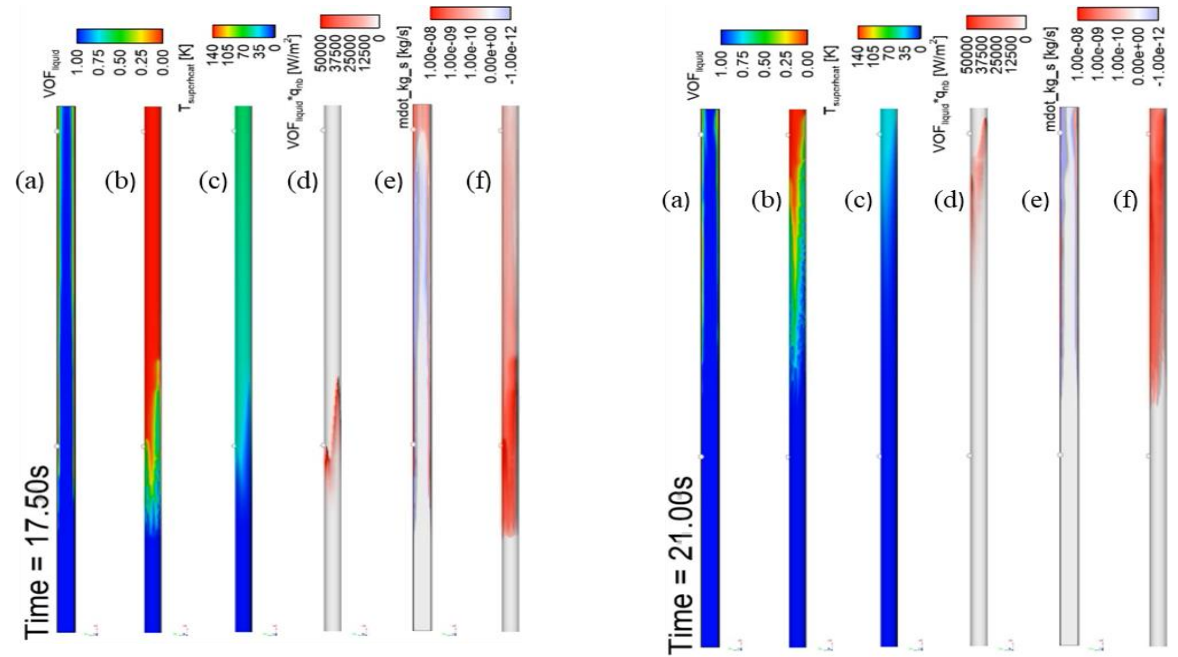
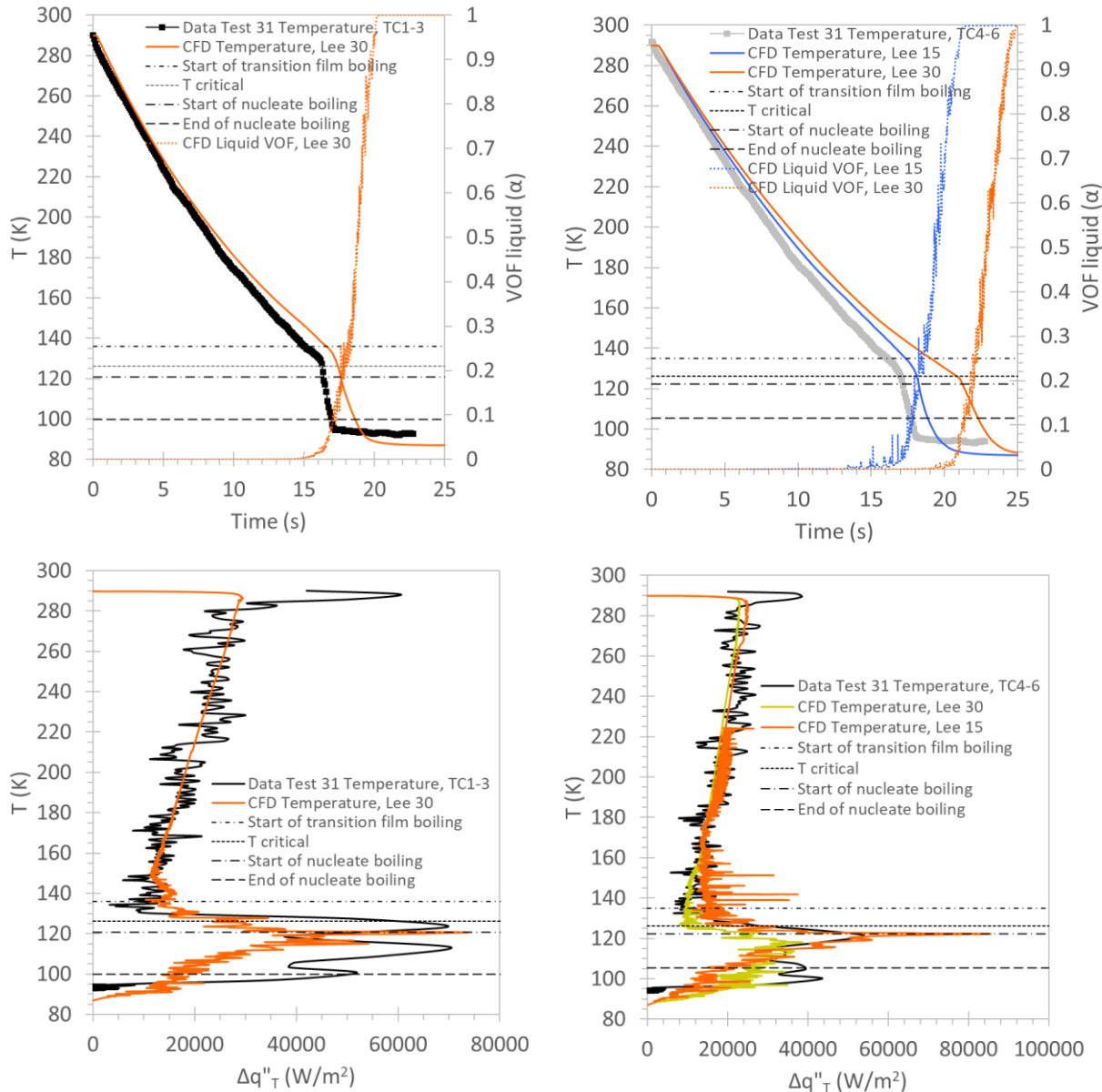


Contour Animations Central Axial Plane Cross-section View

- $T_o = 289.9$ K
- $T_i = 86.96$ K
- $P_{out} = 314.624$ kPa
- $T_{s_i} = T_s(P_i) = 88.44$ K
- $\dot{m}_i = 0.0334$ kg/s
- $\alpha_{l,i} = 1; Re_{in} = 33,940$.

$$C_{\tau, evap} = C_{\tau, cond} = 30 \text{ s}^{-1}$$

3D CFD-Coupled-Subgrid Model Simulation Results: LN2 Test 31 (Darr 2016)



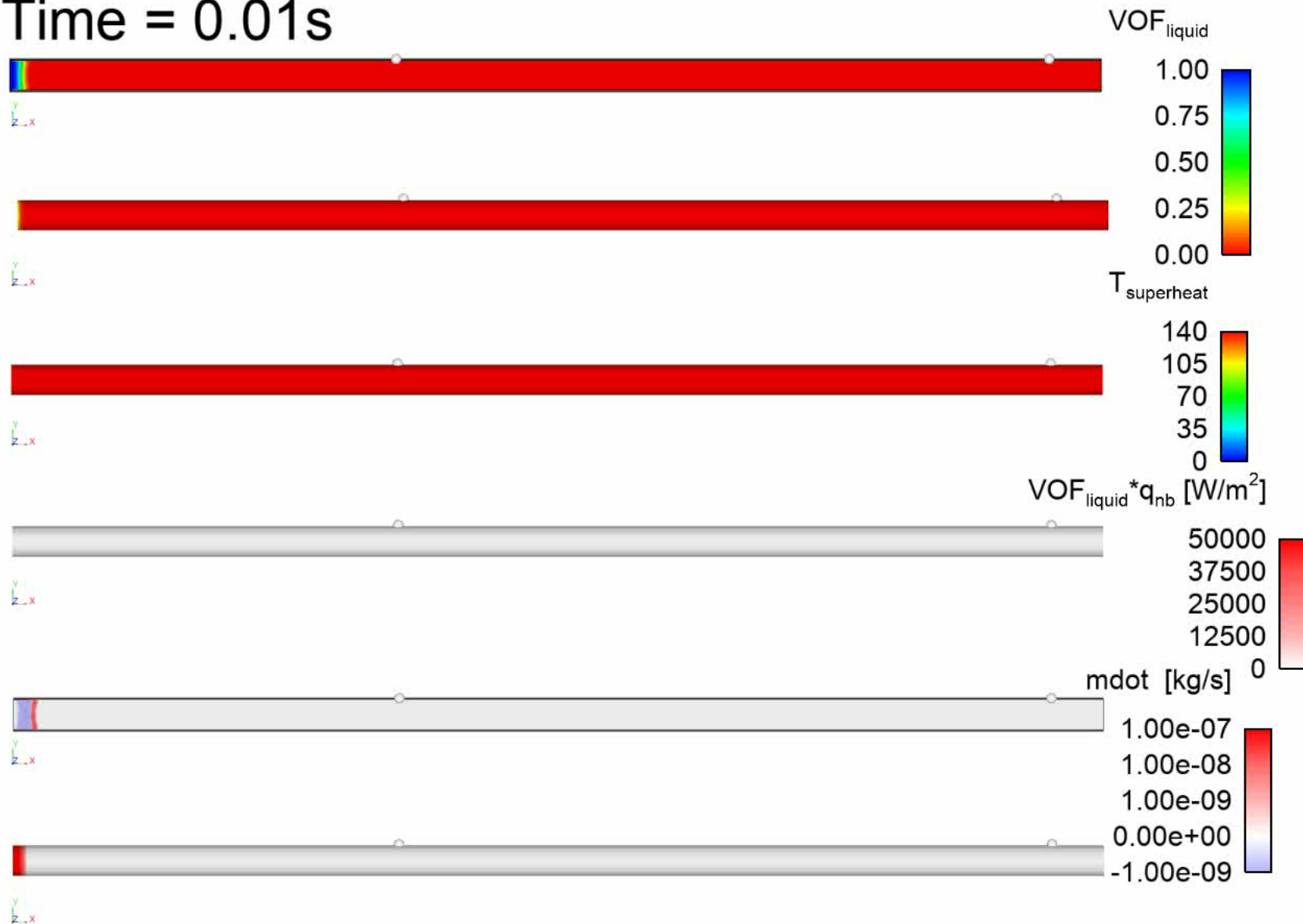
Different sets of equal Lee evaporation & condensation coefficients are required to correctly predict the nucleate chilldown times at the upstream and downstream locations:

- TC1-3: Lee Evap & Cond Coeffs = 30 1/sec
- TC4-6: Lee Evap & Cond Coeffs = 15 1/sec



3D CFD-Coupled-Subgrid Model Simulation Results: LN2 Test 40 (Darr 2016)

Time = 0.01s



[Contour Animations](#)
Central Axial Plane
Cross-section View

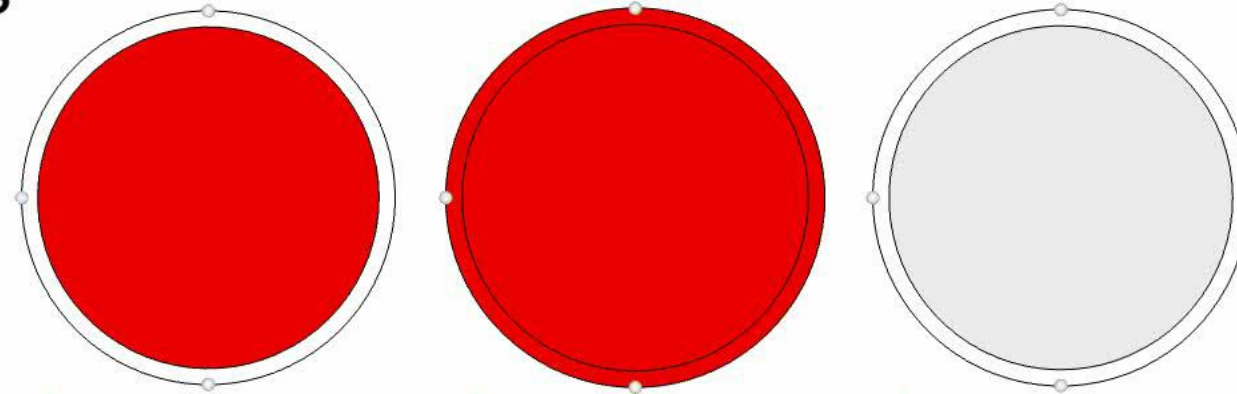
- $T_o = 288.54$ K
- $T_i = 88.61$ K
- $P_{out} = 325.900$ Kpa
- $Ts_i = Ts (P_i) = 88.44$ K
- $\dot{m}_i = 0.0346$ Kg/s
- $\alpha_{l,i} = 1$
- $Re_{in} = 35,626$.

$$C_{\tau, evap} = C_{\tau, cond} = 2000 \text{ s}^{-1}$$

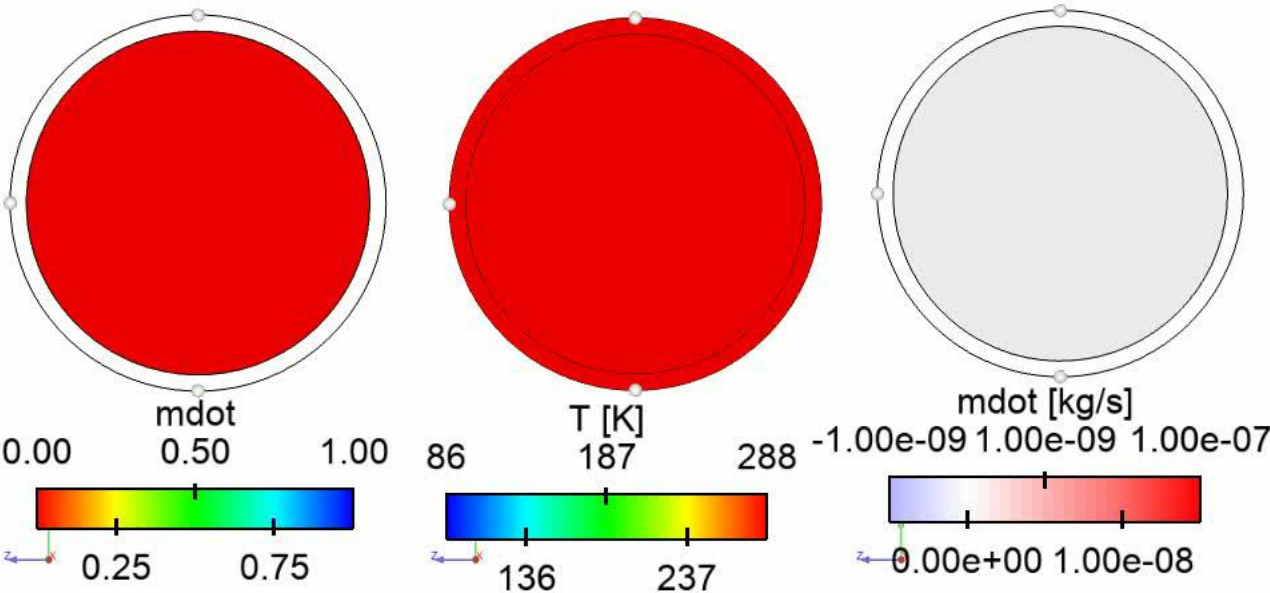
3D CFD-Coupled-Subgrid Model Simulation Results: LN2 Test 40 (Darr 2016)

Time = 0.01s

TC1-3



TC4-6



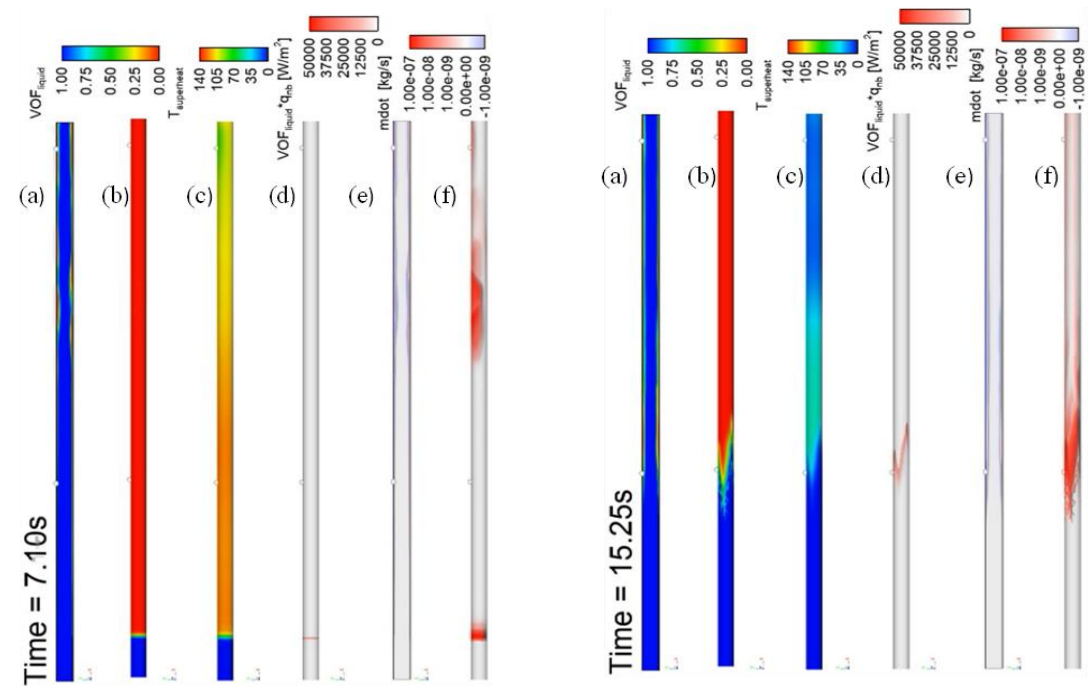
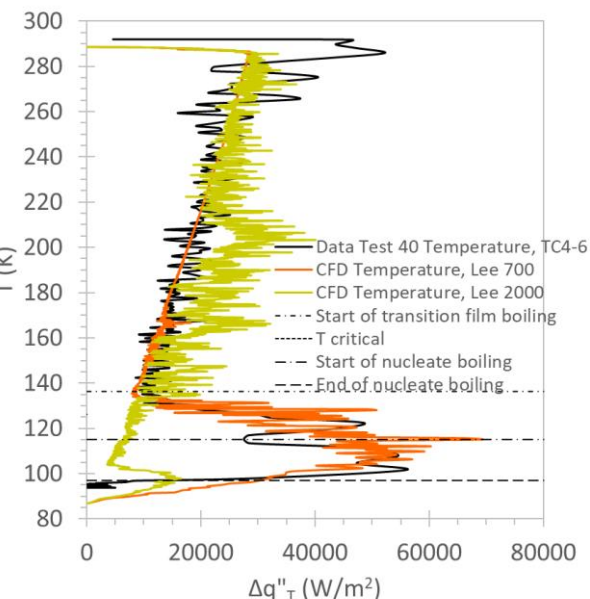
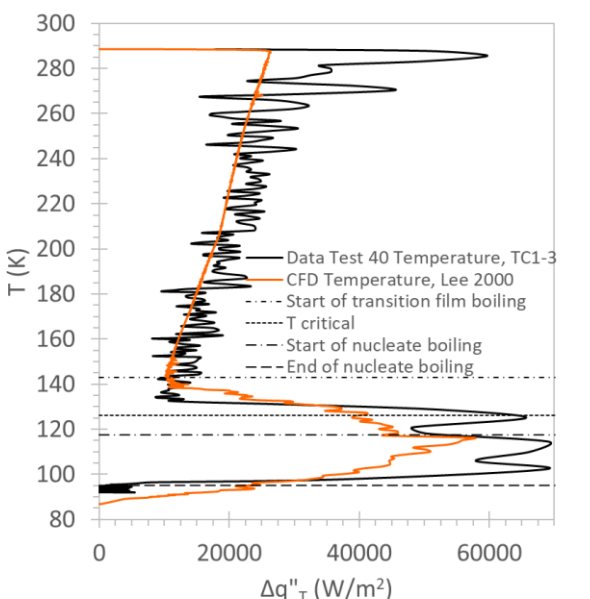
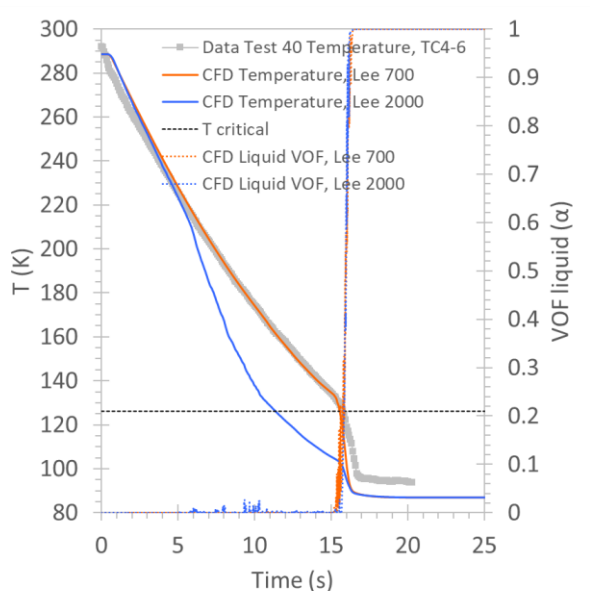
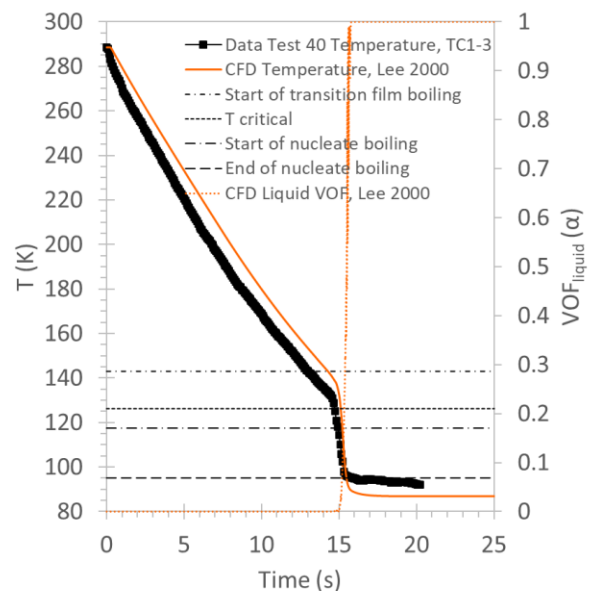
Contour Animations
 Radial Plane Cross-Section
 Views at TC-1-3 & TC4-6
 Axial Locations

- $T_o = 288.54$ K
- $T_i = 88.61$ K
- $P_{out} = 325.900$ Kpa
- $Ts_i = Ts (P_i) = 88.44$ K
- $\dot{m}_i = 0.0346$ Kg/s
- $\alpha_{l,i} = 1$
- $Re_{in} = 35,626$.

$$C_{\tau, evap} = C_{\tau, cond} = 2000 \text{ s}^{-1}$$



3D CFD-Coupled-Subgrid Model Simulation Results: LN2 Test 40 (Darr 2016)

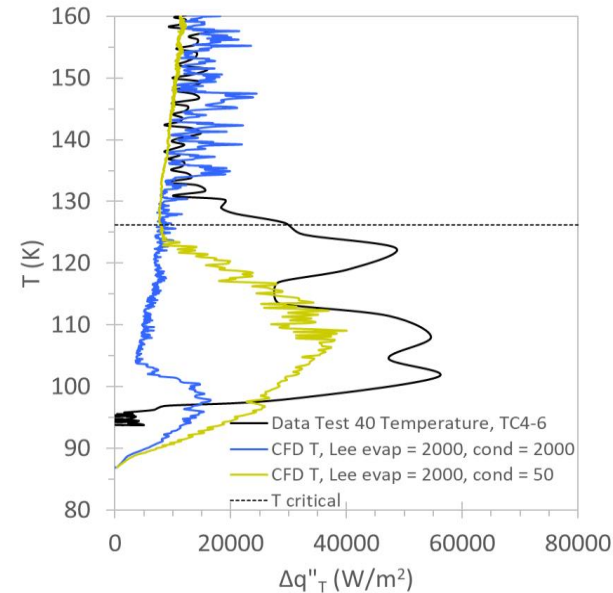
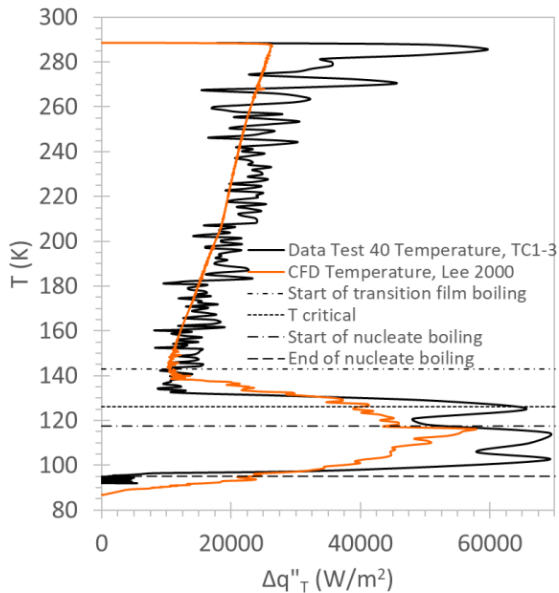
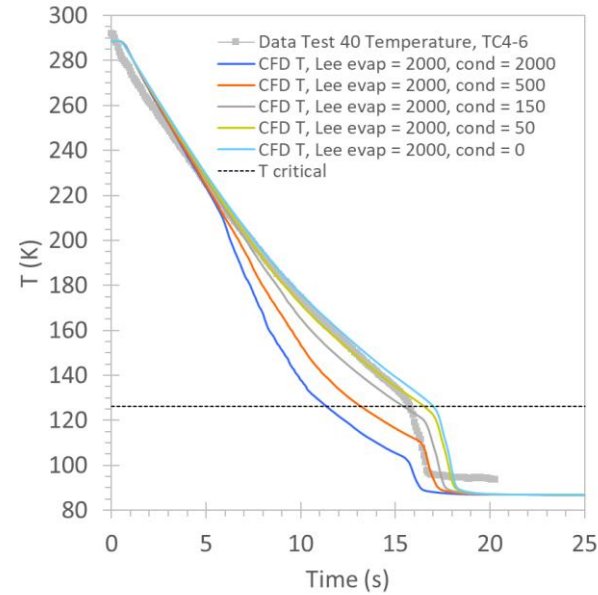
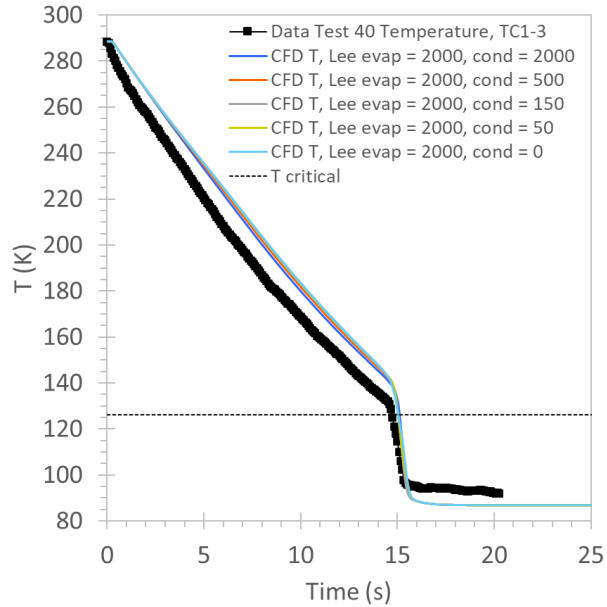


Larger CFD Cell Size at The Wall
 Different sets of equal Lee evaporation & condensation coefficients are required to eliminate premature downstream cooldown of the transfer line:

- TC1-3: Lee Evap & Cond Coeffs = 2000 1/sec
- TC4-6: Lee Evap & Cond Coeffs = 700 1/sec



3D CFD-Coupled-Subgrid Model Simulation Results: LN2 Test 40 (Darr 2016)



Larger CFD Cell Size at The Wall
Simulation with one set of unequal Lee evaporation & condensation coefficients can predict the correct timing of the upstream and down stream chilldown simultaneously:

- Lee Evaporation Coeff = 2000 1/sec
- Lee Condensation Coeff = 50 1/sec



- A Two-Phase model for line chilldown was developed by coupling:
 - A conjugated Eulerian Mixture model for the fluid that captures the film boiling using a Lee model for phase change
 - A sub-grid model that captures bubble nucleation, growth, and departure during nucleate boiling
- Validation of 3D model predictions against 1g LN2 experimental results proved for the first time that transition from film to nucleate boiling to single phase flow during line chilldown operations can be successfully and directly captured by CFD with only the Lee mass transfer coefficient as the single adjustable parameter.
- The numerical case studies, however, pointed towards important questions regarding both the experimental results and the computational findings that needs to be resolved in future work:
 - A more general model for phase change mass transfer calculations that allows for a changing mass transfer rate along the transfer line must be implemented..
 - A mechanistic formulation for the buildup of the liquid volume fraction at the wall is needed for capturing the transition from stable to unstable film boiling with enhanced numerical and physical fidelity.
 - The dampening of turbulence effects by the liquid-vapor interface during film boiling can directly affect interfacial mass transfer. This effect may be quite important and must be addressed in future model development.



Funding and programmatic support from the NASA Microgravity Biological and Physical Sciences (BPS) Division and from the Space Technology Mission Directorate (STMD) at NASA Headquarters through the ZBOT Experiment science investigations and the Cryogenic Portfolio Projects at NASA GRC are gratefully acknowledged.



Backup Slides I