Pressurization of a Flightweight, Liquid Hydrogen Tank: Evaporation & Condensation at a Liquid/Vapor Interface

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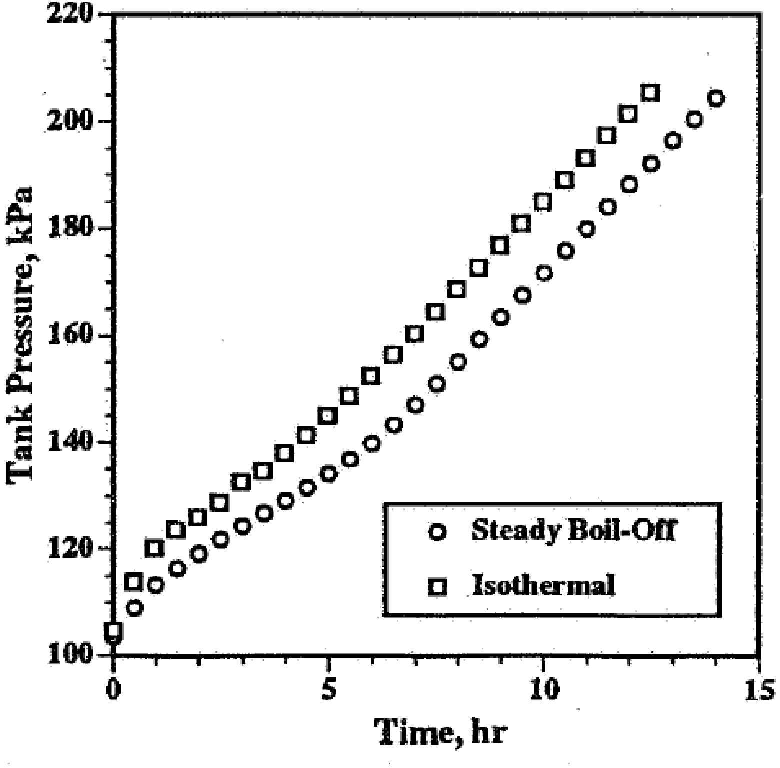
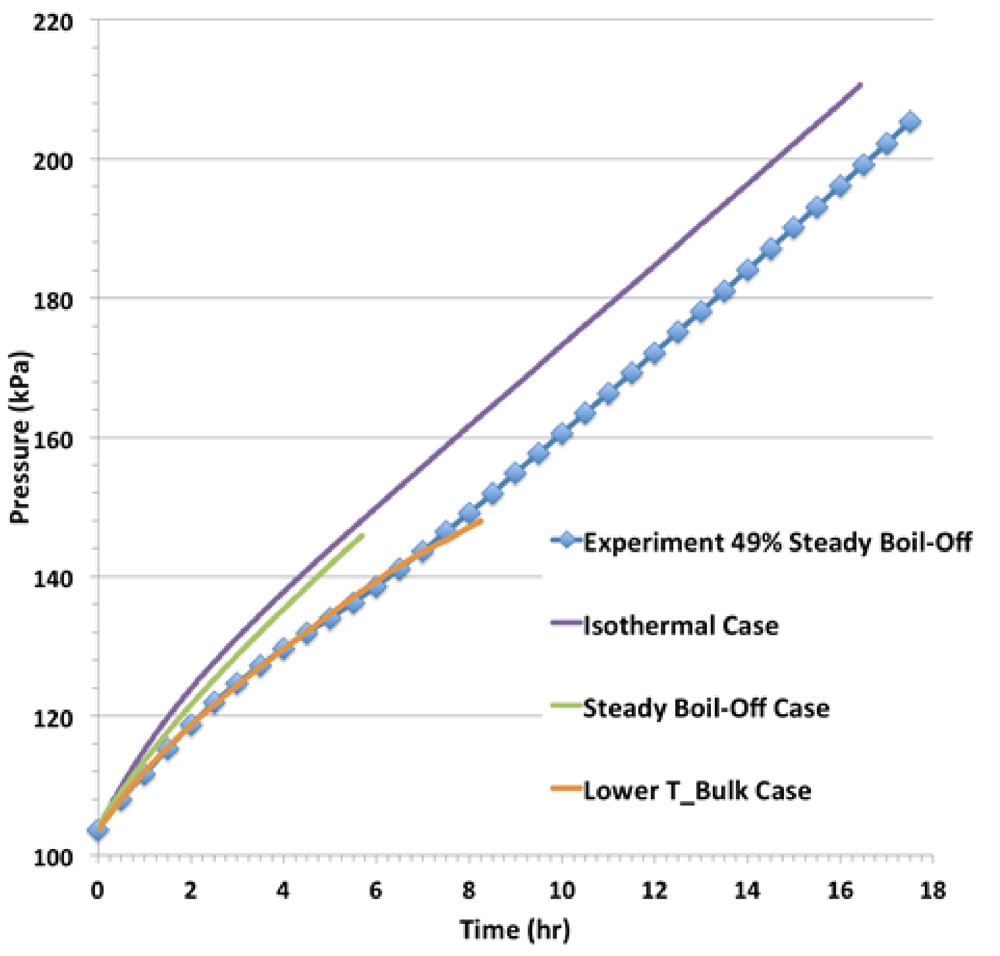
Outline

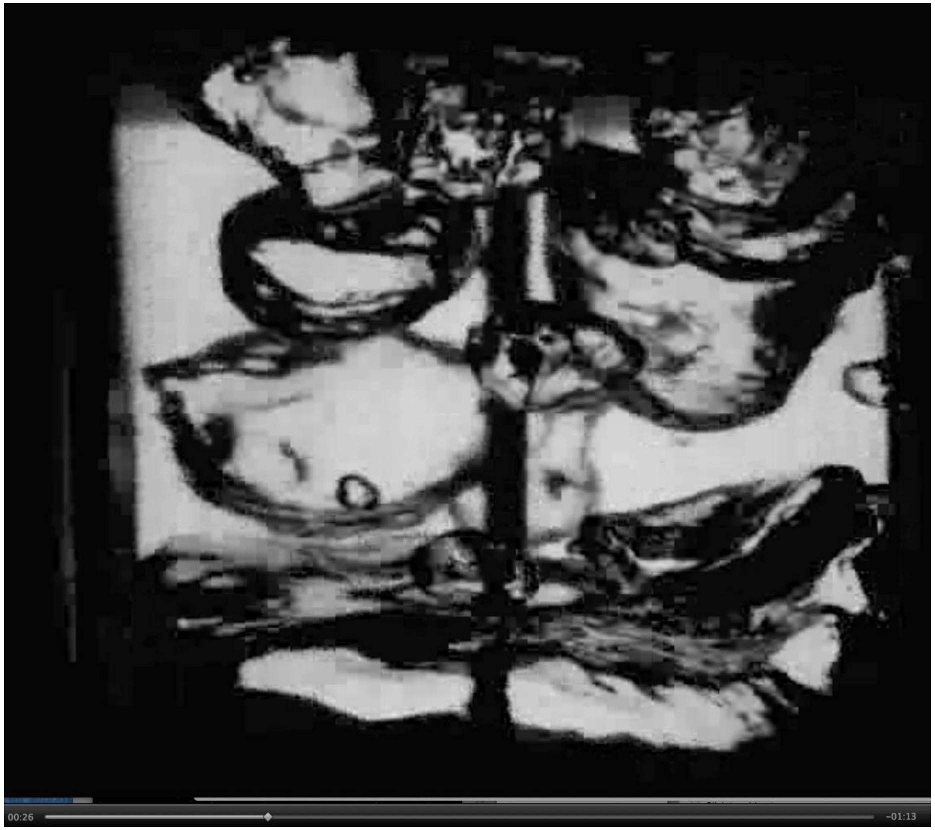
- Issues with evaporation/condensation at interface
- Temperature jumps at an interface—sharp gradients
- Interface physics: mass and *energy* transfer
- Model equation: solved two ways
- Numerical methods: subgrid model & coupling
- Results: practical demonstration of method

K-Site: Slow Self-Pressurization Captures Pressure Evolution





CNES Low-g Slosh: Heavy Boiling Phase with Condensation and Transit



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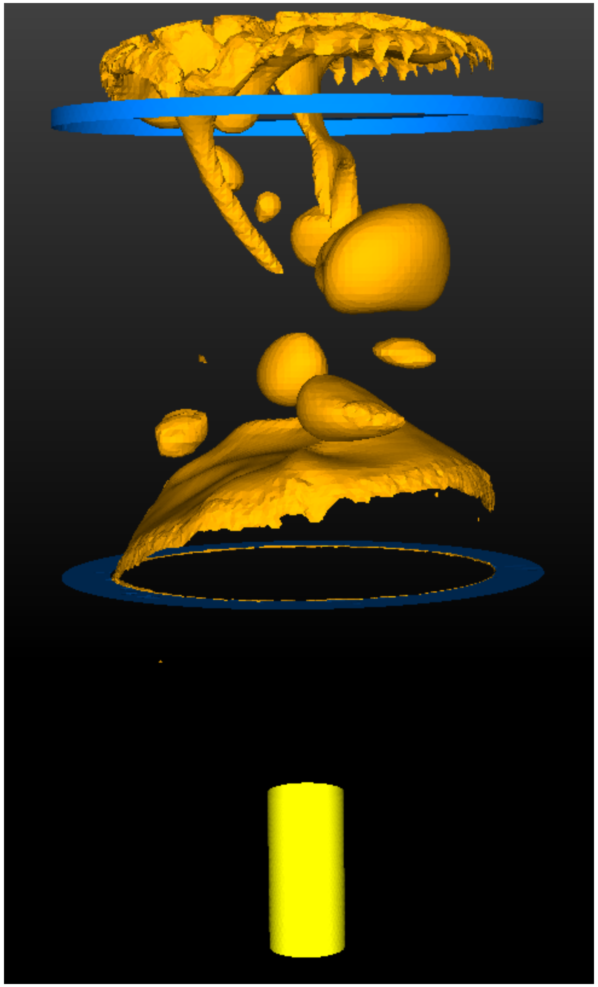
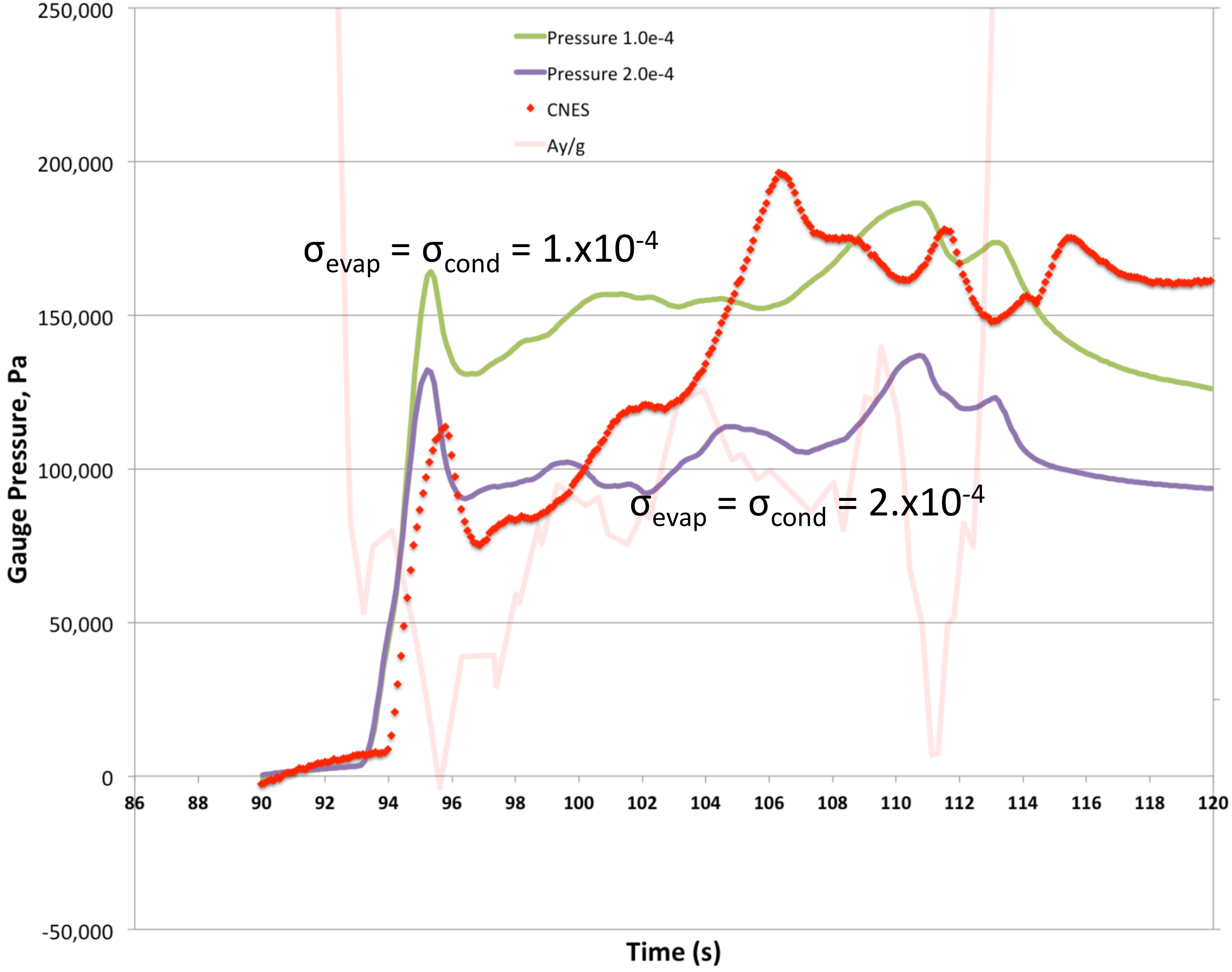


T=96.75 s in CNES_5C_7

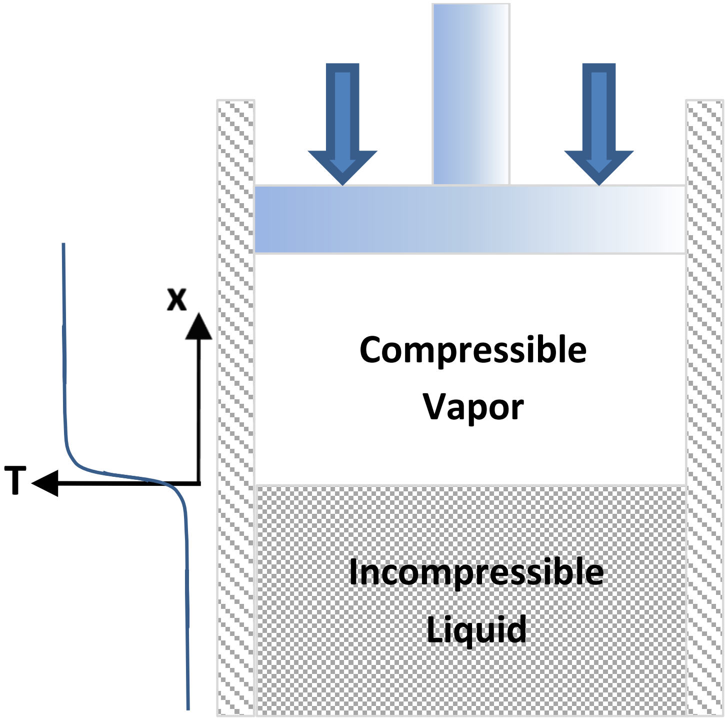
CNES Low-g Slosh: Pressure Evolution



Temperature “Jumps” at the Interface

$$W = -\int p \, dV$$

Work done on the vapor phase



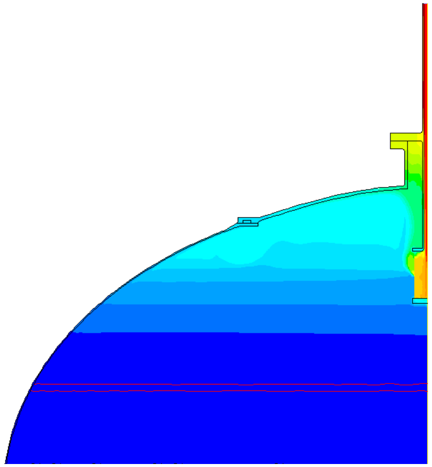
Pressurization caused by:

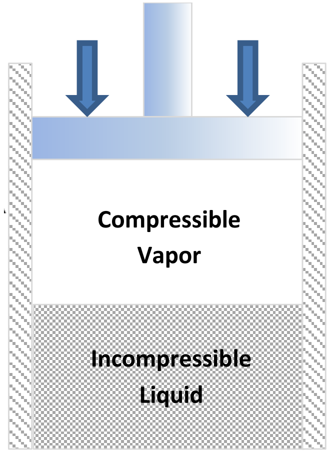
- Pressurant
- Boiling liquid
- Clouds rise/fall
- Temperature gradients

Temperature gradient established

Pressurization of a Compressible Gas

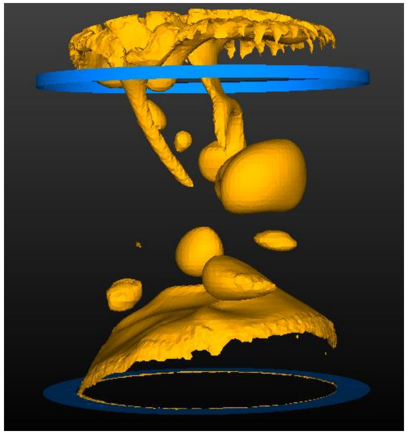
	Latent Heat ΔH_{vap} (J/kg)	**T_{sat} (K)**	**$\Delta T_{compress}$ 1->2 atm (K)**	**Vapor $\Delta H_{vap}/C_p$ (K)**	**Liquid $\Delta H_{vap}/C_p$ (K)**	**Vapor α**	**Liquid α**
Helium	20,752.	4.2304	1.342	2.3	3.9	5.95E-05	2.82E-05
Methane	510,830.	111.67	20.433	230.3	146.7	2.88E-03	1.25E-04
Nitrogen	199,178.	77.355	16.942	177.2	97.6	1.45E-03	8.86E-05
Oxygen	213,050	90.188	19.752	219.5	125.4	1.93E-03	7.82E-05
Parahydrogen	445,440.	20.277	4.441	36.4	46.1	1.04E-03	2.81E-06
Water	2,256,440.	373.12	70.019	1084.9	535.3	2.02E-02	1.68E-04





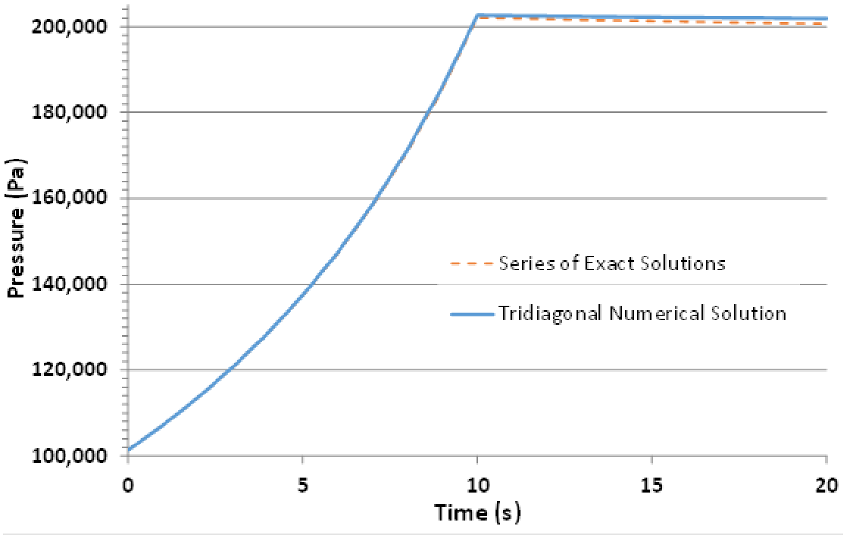
Compressible Vapor

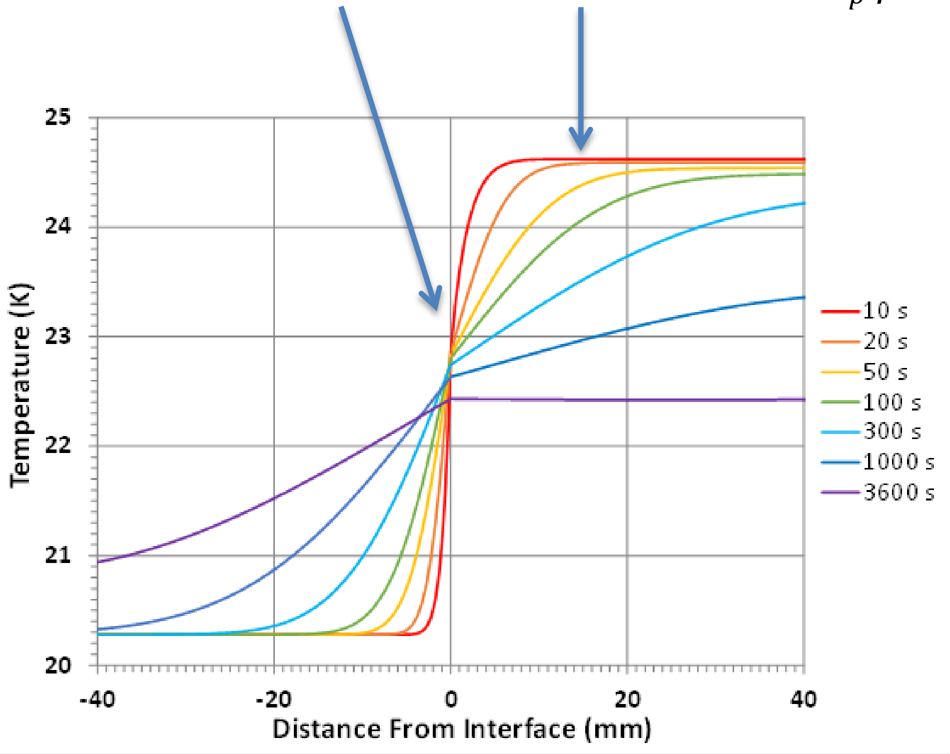
Incompressible Liquid



Energy/Heat Equation

$$\rho C_p \frac{\partial T}{\partial t} - k\frac{\partial^2 T}{\partial x^2} = \dot{q}_{interface} + \dot{q}_{vap} \qquad \alpha = \frac{k}{C_p\,\rho}$$





Negligible:

- Fluid motion
- Temperature variation in interface plane

Heat Equation: Series of Exact Solutions

$$\rho C_p \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} = \dot{q}_{interface} + \dot{q}_{vap}$$

$$T^{vap}(x,t) = T_{\infty}^{vap}(t) + \sum_{j=1}^{t_j \le t} \frac{Q_j^{vap}}{(4\pi\alpha_{vap}(t-t_j))^{1/2}} \, e^{\frac{-x^2}{4\alpha_{vap}(t-t_j)}}, \quad x \ge 0$$

$$T^{liq}(x,t) = T_{-\infty}^{liq} + \sum_{j=1}^{t_j \le t} \frac{Q_j^{liq}}{(4\pi\alpha_{liq}(t-t_j))^{1/2}} \, e^{\frac{-x^2}{4\alpha_{liq}(t-t_j)}}, \quad x \le 0$$

$T_{-\infty}^{liq}$, is assumed constant

$T_{\infty}^{vap}(t)$, from isentropic compression $\quad \frac{T_1}{T_0} = e^{\frac{dS}{C_p}} \left(\frac{V_0}{V_1}\right)^{\gamma-1}$

$$\left(-k_{liq}\frac{dT}{dx}\right)_{interface-liq} - \left(-k_{vap}\frac{dT}{dx}\right)_{interface-vap} = \dot{q}_{flux} = \dot{m}_{flux}\left(p_{interface}, T_{interface}\right) \Delta H_{vap}\left(T_{interface}\right)$$

Heat Equation: Numerical Solutions

$$\rho C_p \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} = \dot{q}_{interface} + \dot{q}_{vap}$$

$$D(T_i^+ - T_i^-) - (T_{i+1}^+ - T_i^+) + (T_i^+ - T_{i-1}^+) + \frac{(\omega - 1)}{\omega}(T_{i+1}^- - T_i^-) - \frac{(\omega - 1)}{\omega}(T_i^- - T_{i-1}^-) = \frac{\Delta x^2}{\omega\, k}\dot{q}_{vap}$$

$$D = \frac{\rho C_p \Delta x^2}{\omega k \Delta t}$$

Solved as a tridiagonal matrix

$T_{-\infty}^{liq}$, is assumed constant

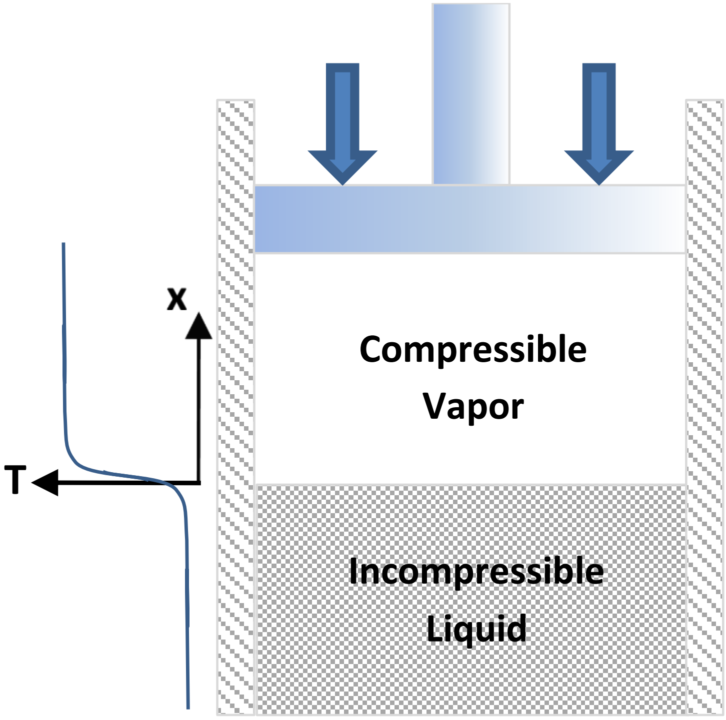
$T_{\infty}^{vap}(t)$, from isentropic compression

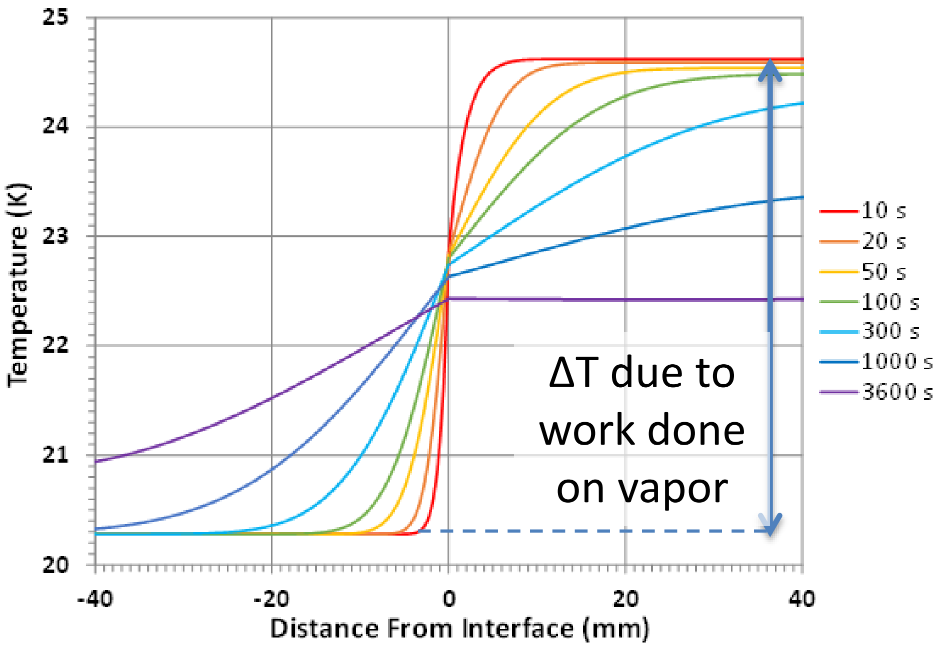
$$\frac{T_1}{T_0} = e^{\frac{dS}{C_p}} \left(\frac{V_0}{V_1}\right)^{\gamma - 1}$$

$$\left(-k_{liq} \frac{dT}{dx}\right)_{interface-liq} - \left(-k_{vap} \frac{dT}{dx}\right)_{interface-vap} = \dot{q}_{flux} = \dot{m}_{flux}\left(p_{interface}, T_{interface}\right) \Delta H_{vap}(T_{interface})$$

Temperature "Jumps" at the Interface

$$W = -\int p\, dV$$





ΔT due to work done on vapor

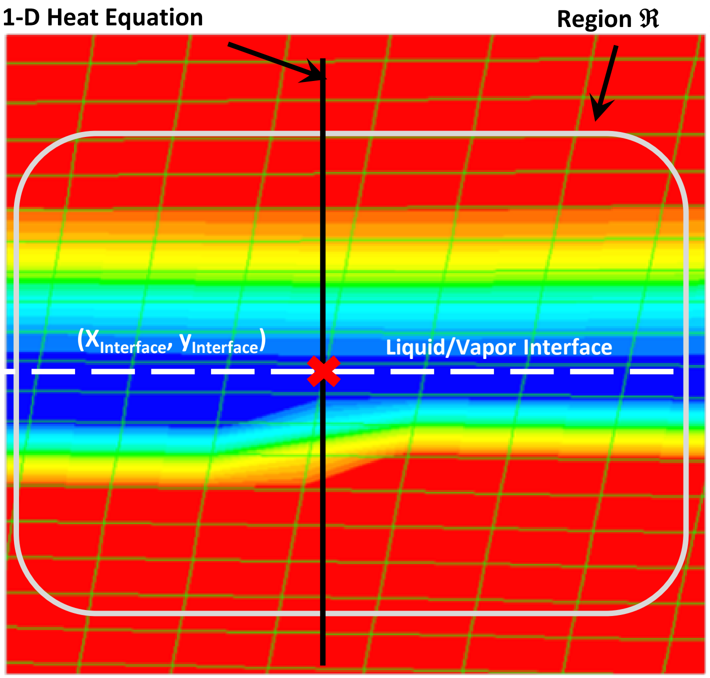
~~Intermission~~ Mid-Review

- Thermal Layers: role of heat near the interface
- Exact & numerical solutions: verification
- Evaporation/Condensation rates:
  - Temperature gradients at interface, O(1 mm)
  - Heat transfer near interface is important-- if not rate limiting
- From Physics, application to CFD simulation ---➔

CFD: Subgrid Model for Interface

- Fine grid needed to resolve thermal layers ~1mm
- Interface can move and curve
  - grid generation nightmare, even unstructured, adaptive grid
- Subgrid model moves with the interface
- Solves the 1-D heat equation normal to interface
- Four couplings between subgrid model and Fluent
- Energy & mass source terms in liquid/vapor equations

Coupling Between Subgrid Model and Simulation



Coupling 1:

$$x_{interface} = \frac{\sum_{\mathfrak{R}} x\,\varphi(1-\varphi)}{\sum_{\mathfrak{R}} \varphi(1-\varphi)}$$

$$y_{interface} = \frac{\sum_{\mathfrak{R}} y\,\varphi(1-\varphi)}{\sum_{\mathfrak{R}} \varphi(1-\varphi)}$$

Coupling 2:

$$p_{interface} = \frac{\int_{\mathfrak{R}} p\,\varphi_{vap}\,dV}{\int_{\mathfrak{R}} \varphi_{vap}\,dV}$$

Coupling 3: Fluent Source Term (liquid & vapor) $\dot{m}_{interface}$

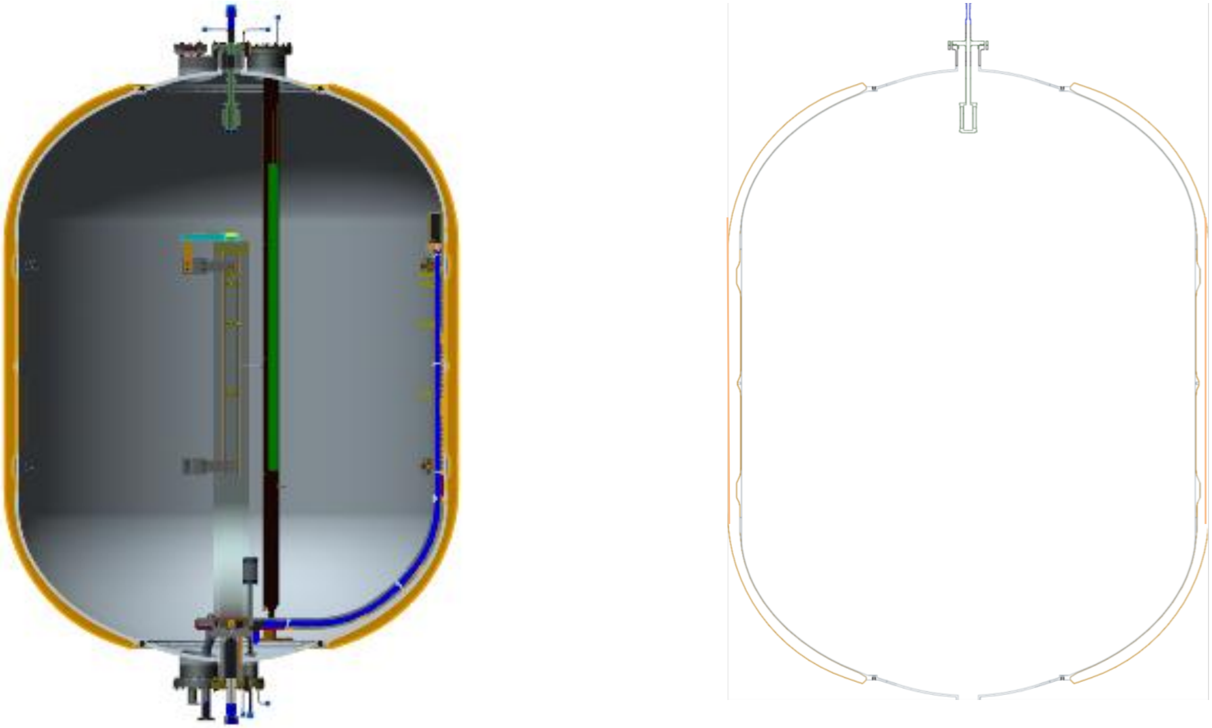
Coupling 4: Fluent Source Term (liquid & vapor) $\dot{q}_{interface}$

Mass and Energy are conserved
Must be careful about sizing Fluent source terms!!

EDU Tank

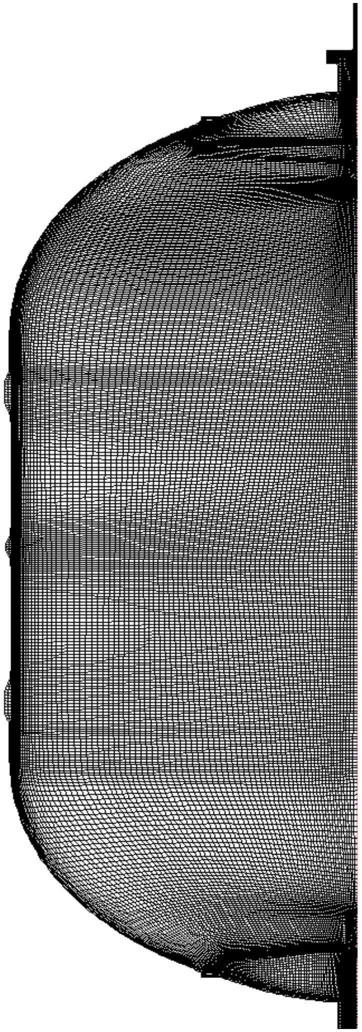
- 2219 Aluminum; Volume 4.34 m^3; I.D. 1.70 m; I. H. 2.33 m
- 1.25” SOFI, 60 layers MLI; 2.54 mm wall thickness

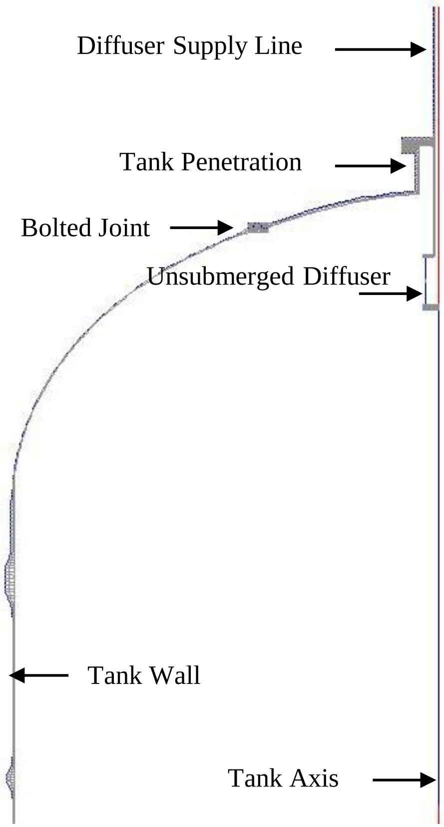
EDU CAD Geometry



- Axisymmetric geometry/grid

EDU CAD Geometry





Diffuser Supply Line

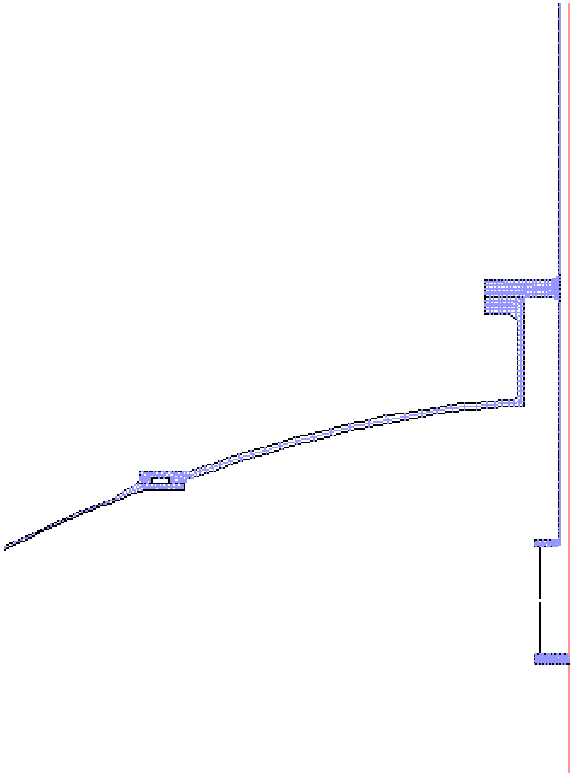
Tank Penetration

Bolted Joint

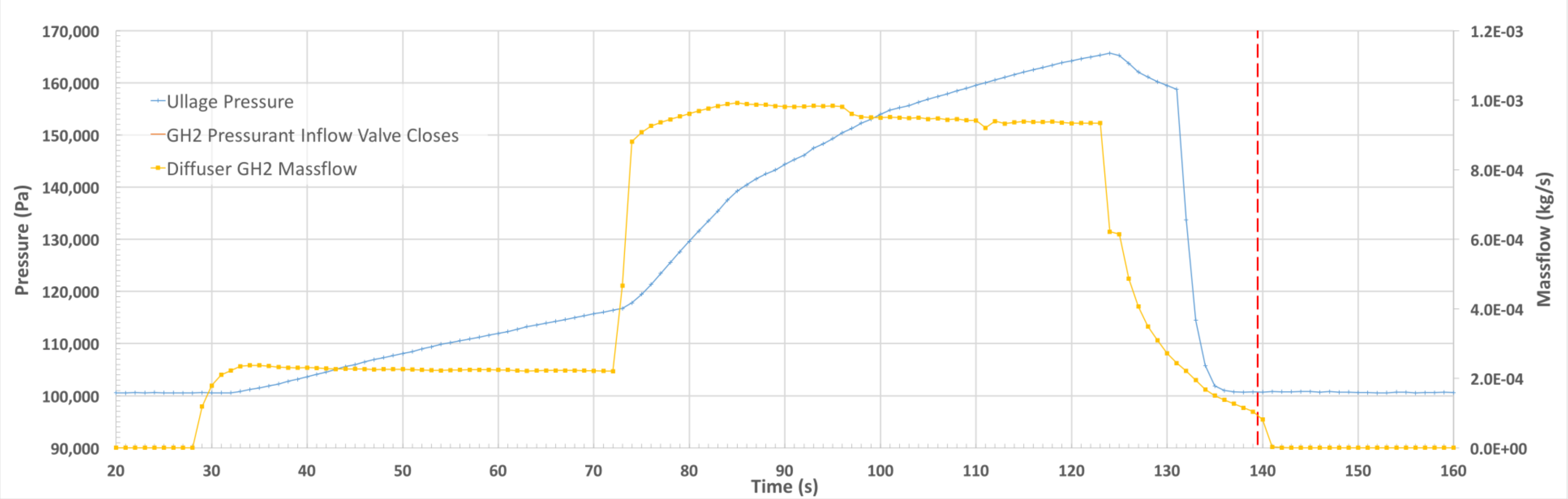
Unsubmerged Diffuser

Tank Wall

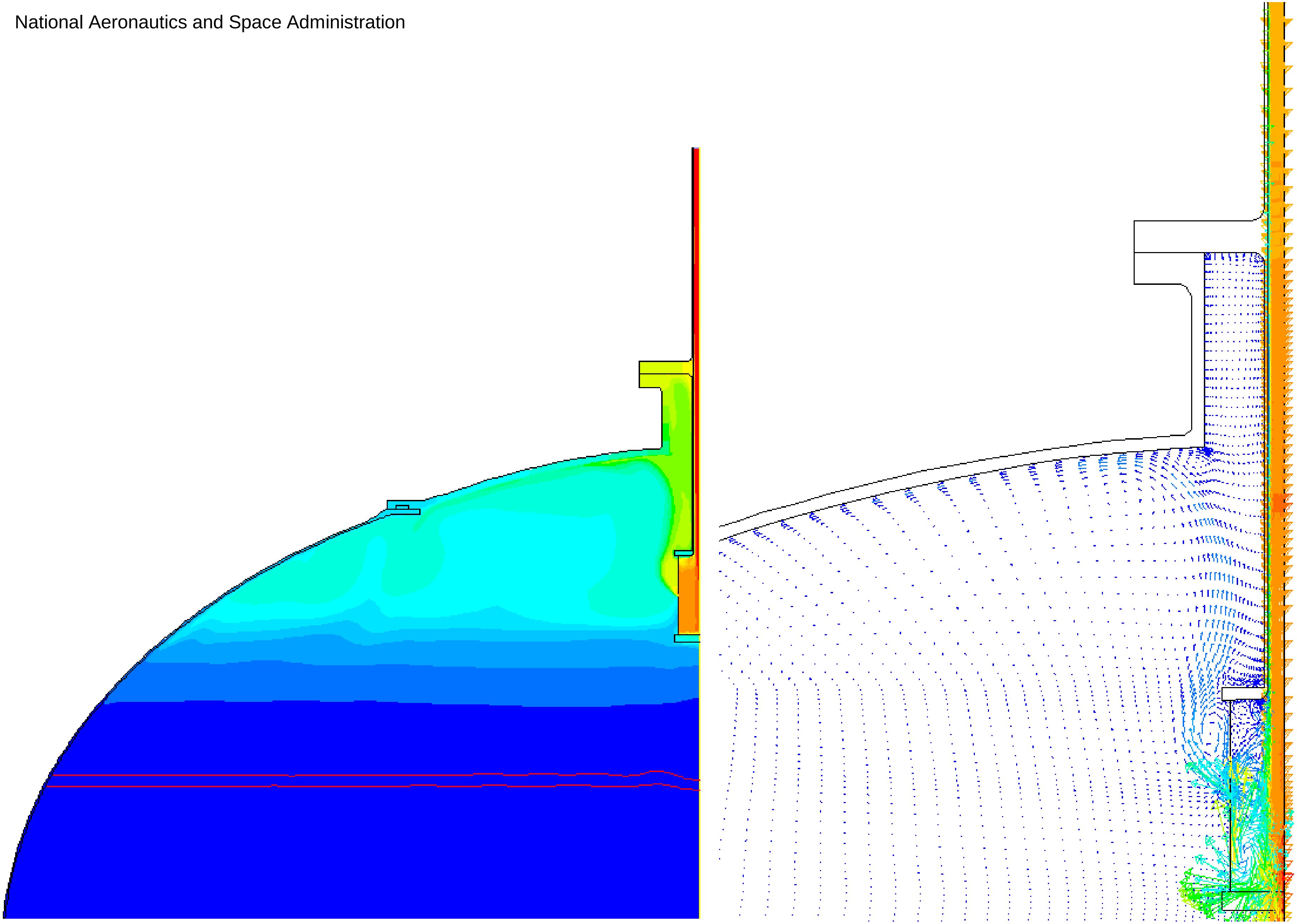
Tank Axis

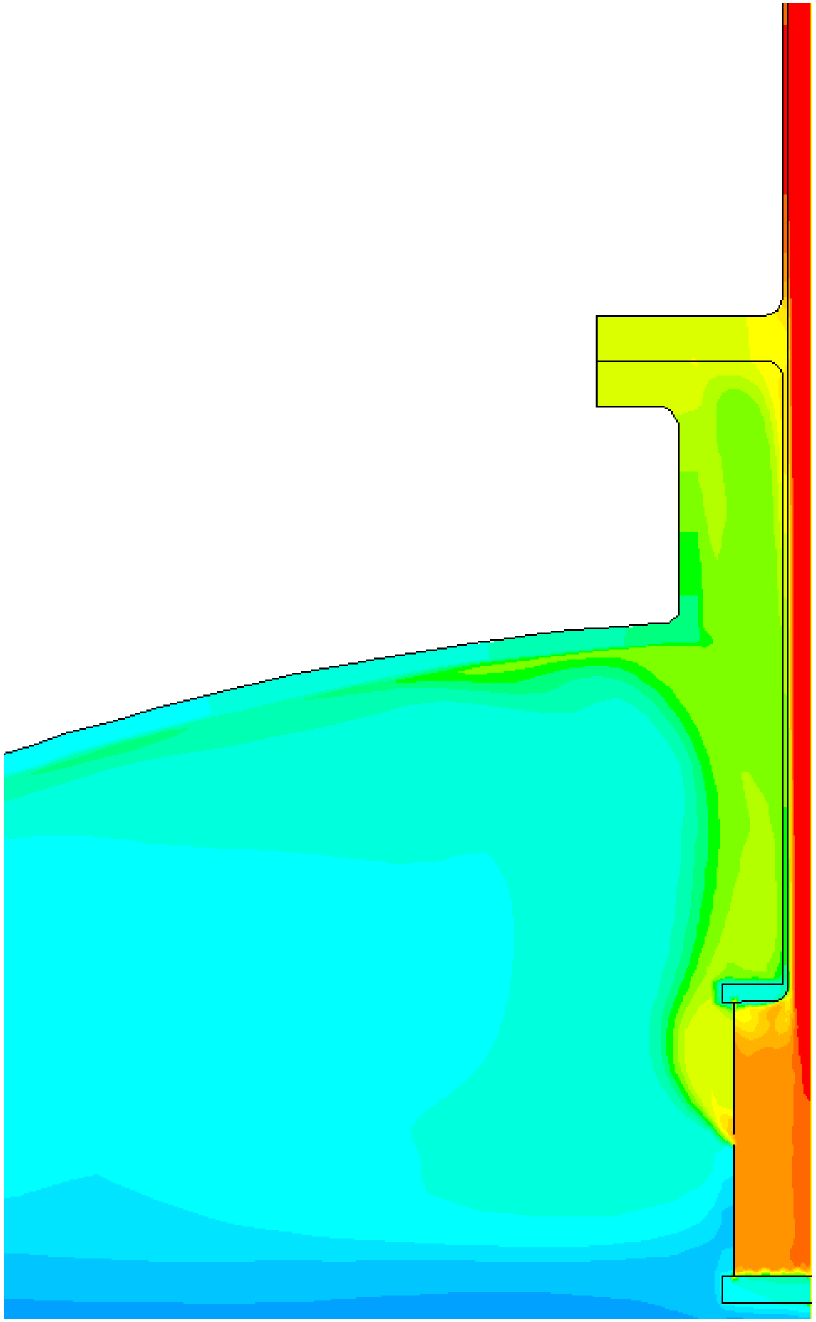


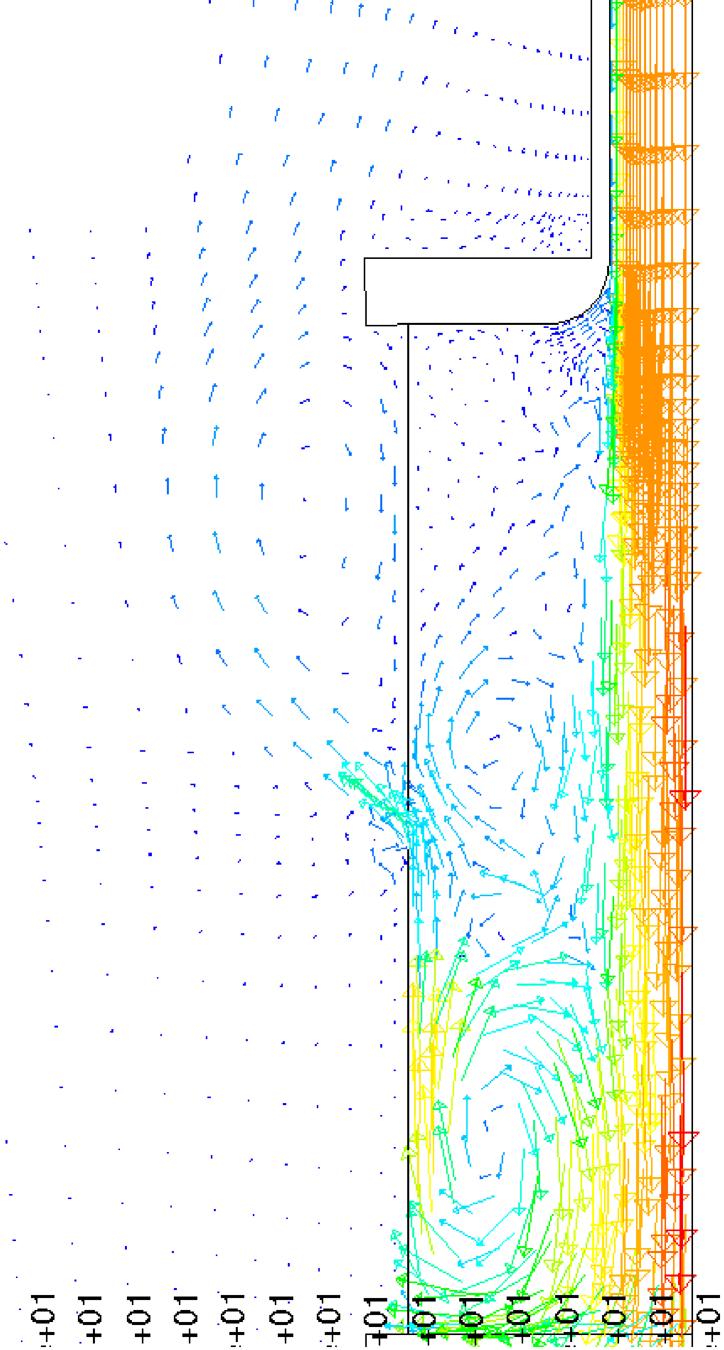
Phase A Test Data



- Test HT-15, 16 on day 3 of Phase A testing
- 90% Fill level
- Pressurant gas at 290 K through the unsubmerged diffuser supply line
- Small drain flow, less than 1% of volume



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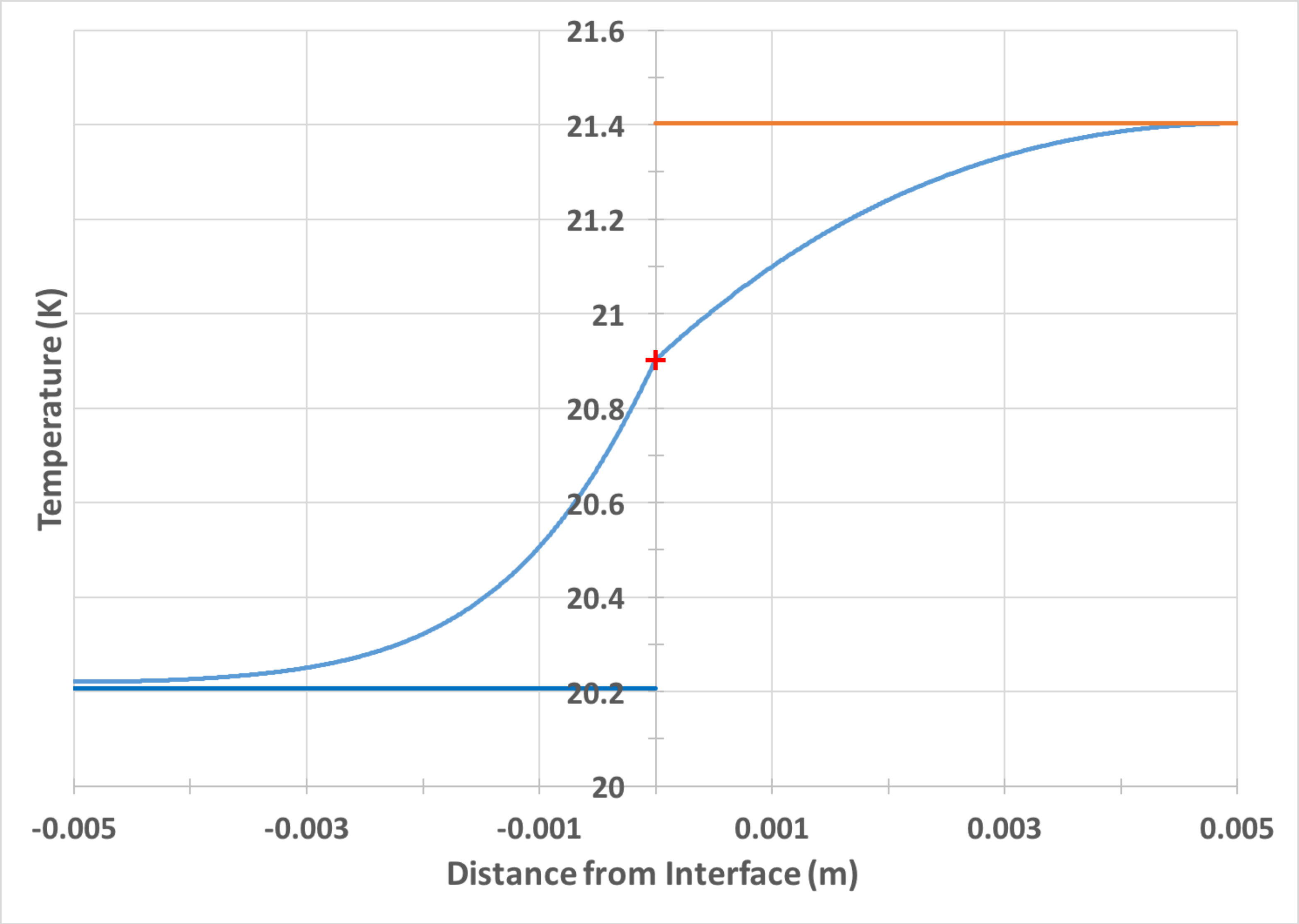
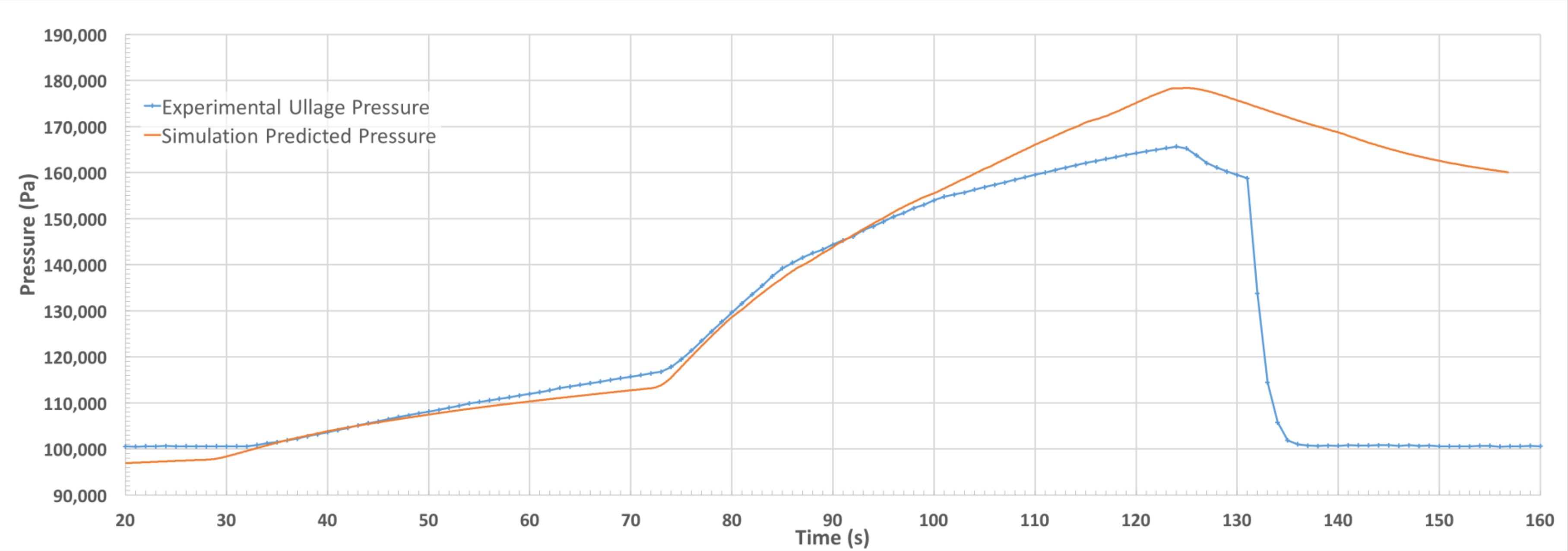
Press_11 at 87.23 seconds



Q_{vapor} -4.04 W/m^2; Q_{liquid} -54.03 W/m^2;

Condense Heat Flux 52.7 W/m^2; Condense Mass Rate -1.13e-4 kg/m^2-s;

Results



- Good measure of condensation rate?
- For duration, pressurant inflow to condensation is between 1.5:-1 and 2:-1
- After 123 s, pressurant declines
- Assuming pressure release after 131 s

Conclusions

- Proof of concept for improved interface mass & energy transfer
- Accommodation coefficient of 1.0
- Extension to curved surfaces, multiple surfaces
- Need to examine other problems in the context of this result

Mass & Heat Equations

$$\rho C_p \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} = \dot{q}_{interface} + \dot{q}_{vap}$$

$$\dot{m}_{flux}\left(p_{interface}, T_{interface}\right) = \frac{2}{2 - \sigma_{cond}} \sqrt{\frac{MW}{2\pi R_u}} \left(\sigma_{evap} \frac{p_{sat}\left(T_{liq}\right)}{\sqrt{T_{liq}}} - \sigma_{cond} \frac{p_{vap}}{\sqrt{T_{vap}}}\right)$$

$$\dot{q}_{flux} = \dot{m}_{flux}\left(p_{interface}, T_{interface}\right) \Delta H_{vap}\left(T_{Interface}\right)$$

$$\frac{T_1}{T_0} = e^{\frac{dS}{C_p}} \left(\frac{V_0}{V_1}\right)^{\gamma - 1} = e^{\frac{dS}{C_p}} \left(\frac{p_1}{p_0}\right)^{1 - \frac{1}{\gamma}}$$