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Validation of a Two-Phase CFD Model for Predicting Propellant Tank Pressurization and Pressure Collapse in The Ground-Based K-Site Hydrogen Slosh Experiment

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Test description

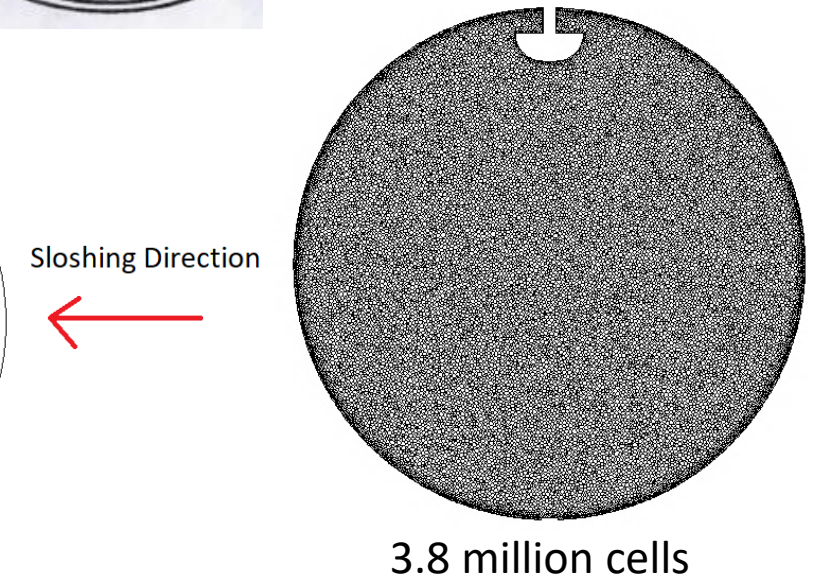
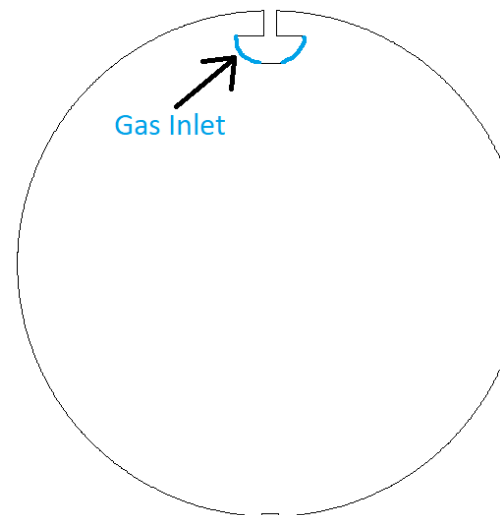
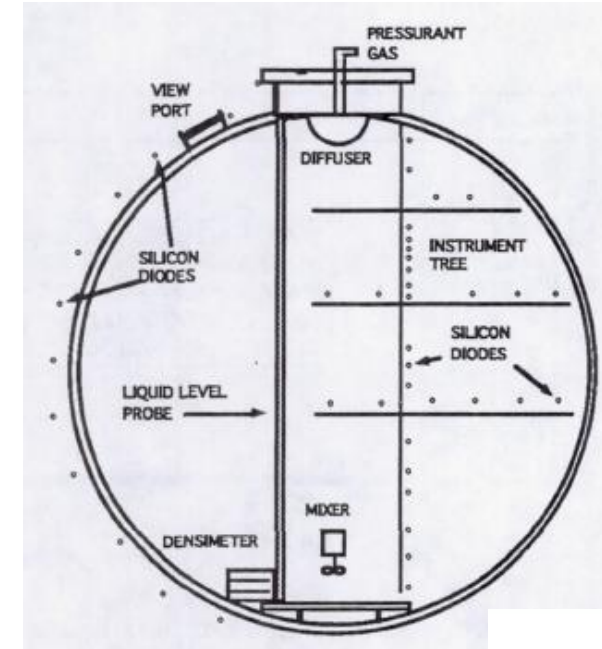


Experiment

- Testing conducted at the K Site facility
- Tank D = 1.79 m;
- Gaseous H₂ flown through a diffuser at the top of the tank during pressurization. Pressurization is followed by sloshing in the lateral direction.
- Temperature sensors on a vertical rake, horizontal rake and on the tank wall.

CFD

- 3D geometry with tank wall included
- VOF Model
- Temperature dependent LH₂ properties
- Experimental T profile used as Initial Conditions for pressurization
- 64% fill level considered
- Measured values of mass flow rate and temperature applied uniformly at the surface of the injector as B.C.
- Sloshing cases **870** (frequency of 0.75 Hz and amplitude of ± 1.5 in), **869** (frequency of 0.95 Hz and amplitude of ± 0.5 in) modeled



Computational Model: Equations Solved



Continuity: $\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = 0$

Momentum: $\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla(\rho \vec{v} \vec{v}) = -\nabla p + \nabla[\mu_{eff}(\nabla \vec{v} + \nabla \vec{v}^T)] + \rho \vec{g} + \vec{F}_{vol}$

Energy: $\frac{\partial}{\partial t}(\rho E) + \nabla(\vec{v}(\rho E + p)) = \nabla(k_{eff} \nabla T) + S_h$

Schrage's Relation : $|\dot{\mathbf{m}}| = \left(\frac{2\sigma}{2 - \sigma} \right) \left(\frac{M}{2\pi R} \right)^{1/2} \left(\frac{P_i}{T_i^{1/2}} - \frac{P_v}{T_v^{1/2}} \right), \left[\frac{kg}{m^2 \cdot sec} \right]$

where σ – accommodation coefficient (value of 0.001 was used)
 M – molar mass of hydrogen
 R – universal gas constant (8.314472 J/mol K)
 P_i and P_v – interfacial and vapor pressures, Pa
 T_i and T_v – interfacial and vapor temperatures, K (assumed that $T_i = T_v \cong T_{sat}$ at the interface)

Computational Model: Equations Solved



Volume of Fluid (VOF) model:

Energy and Temperature are defined as mass average scalars:

$$E = \frac{\sum_{q=1}^2 \alpha_q \rho_q E_q}{\sum_{q=1}^2 \alpha_q \rho_q}$$

Properties: $\rho = \sum_{q=1}^2 \alpha_q \rho_q$, $\mu_{eff} = \sum_{q=1}^2 \alpha_q \mu_{eff\ q}$, $k_{eff} = \sum_{q=1}^2 \alpha_q k_{eff\ q}$

Continuity of Volume Fraction of the q -th phase: $\frac{1}{\rho_q} \left[\frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) \right] = S_{\alpha_q}$

Continuum Surface Force (Brackbill et al.):

$$F_{vol} = \sum_{\text{pairs } ij, i < j} \sigma_{ij} \frac{\alpha_i \rho_i h_j \nabla \alpha_j + \alpha_j \rho_j h_i \nabla \alpha_i}{\frac{1}{2} (\rho_i + \rho_j)}$$

where $h_i = \nabla \cdot \hat{n}$

Interfacial mass transfer per unit volume: $S_{\alpha_q} = \dot{\mathbf{m}}_i \cdot \mathbf{A}_i \left[\frac{kg}{m^3 \cdot sec} \right]$

$\mathbf{A}_i = |\nabla \alpha|$, is an interfacial area density in $1/m$, $\dot{\mathbf{m}}_i$ is a mass flux vector in $kg/(m^2 \cdot sec)$.

where α is a volume fraction of the primary phase

UDFs used:

VOF (DEFINE_MASS_TRANSFER)

- ❖ Calculate mass transfer using Schrage relation and supply it to Fluent for phase interaction at the interface

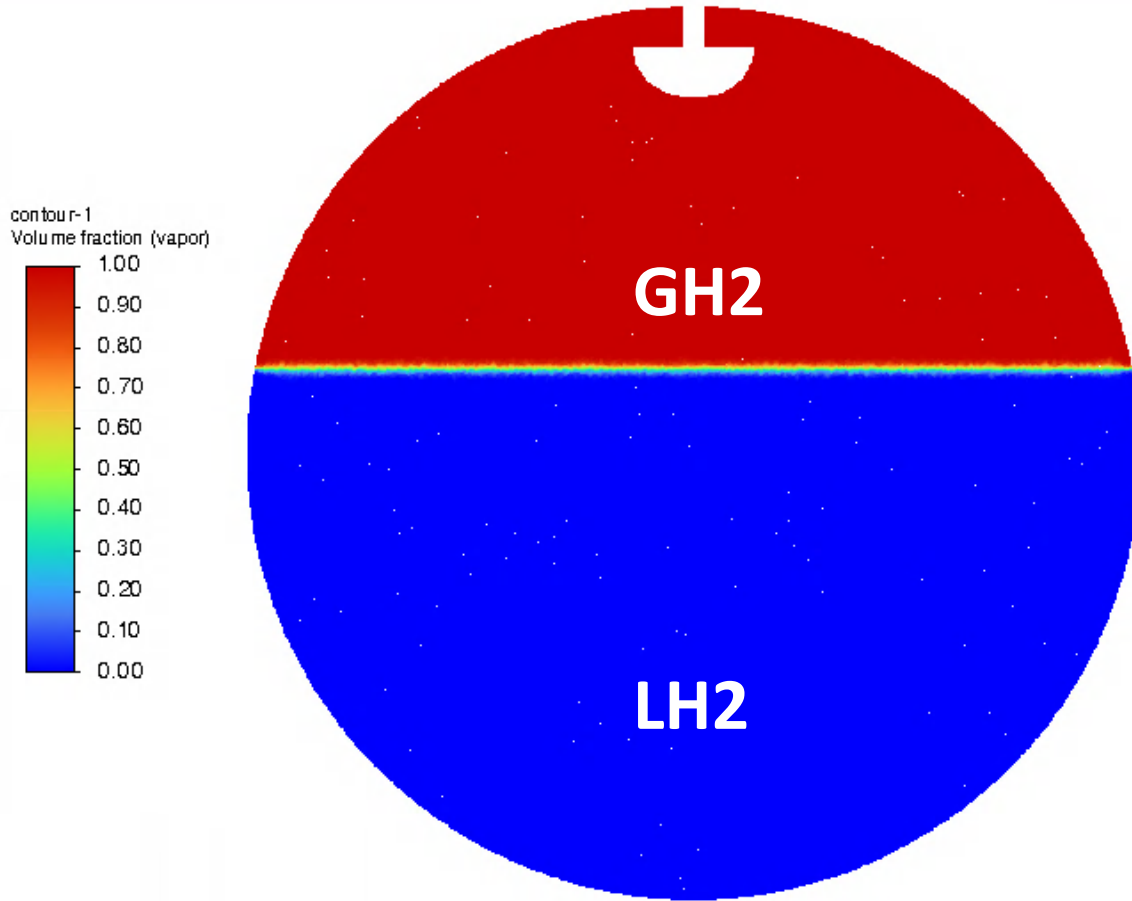
Computational Model: Numerical Methods



- Simulations performed using ANSYS Fluent version 23.1
- **3D** geometry was modeled
- Compressible ideal gas
- Surface tension effects via Continuum Surface Force method of Brackbill et al.
- Contact angle 0°

- Second Order Upwind scheme was used for discretization of the Energy, Momentum and Turbulence equations (cell values)
- PISO scheme was used for the Pressure-Velocity coupling (cell values)
- Least Squares Cell Based scheme was used for the gradient calculations (face values)
- Body Force Weighted scheme was used for the Pressure interpolation (face values)
- Point Implicit (Gauss-Seidel) linear equation solver with Algebraic Multi-Grid (AMG) method was used for solving linearized systems of equations
- First Order Implicit temporal discretization was used with explicit VOF model with $\Delta t = 0.04$ s for pressurization and 0.001 s for sloshing simulations

Problem description - Pressurization



Pressurization

Initial Conditions before Pressurization (Ramp):

- 36% initial ullage volume (64% liquid fill level)
- $P_{init} = 14.6 \text{ psia} = 100660.0 \text{ Pa}$
- T_{init} (at the interface and in the liquid) = $T_{sat}(P_{init}) = 20.249 \text{ K}$
- Vapor temperatures from experimental values (axial profile)
- Wall temperatures match fluid temperatures at the same axial position

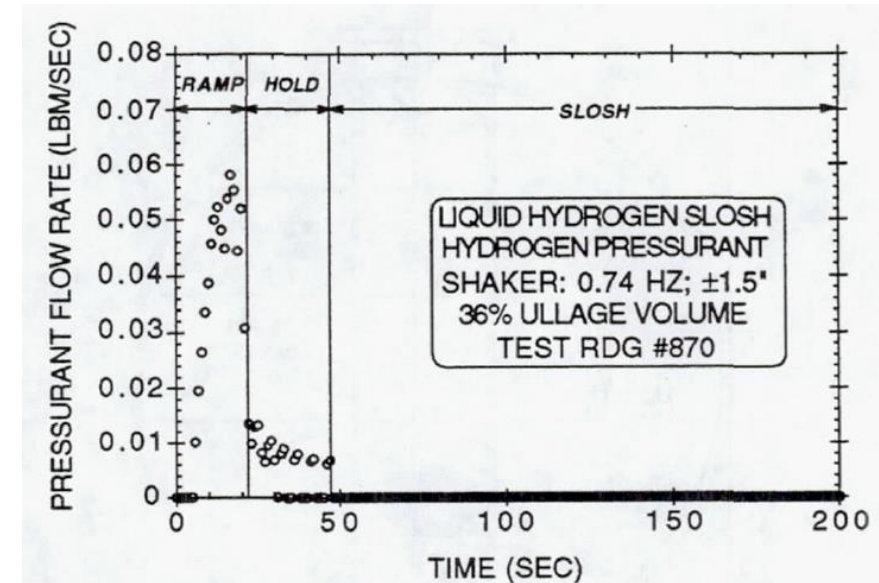
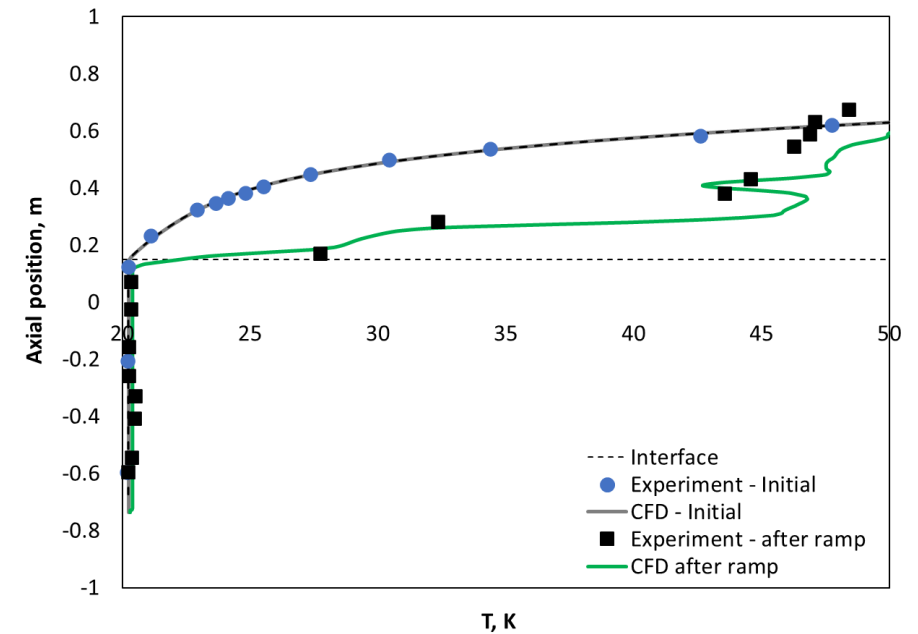
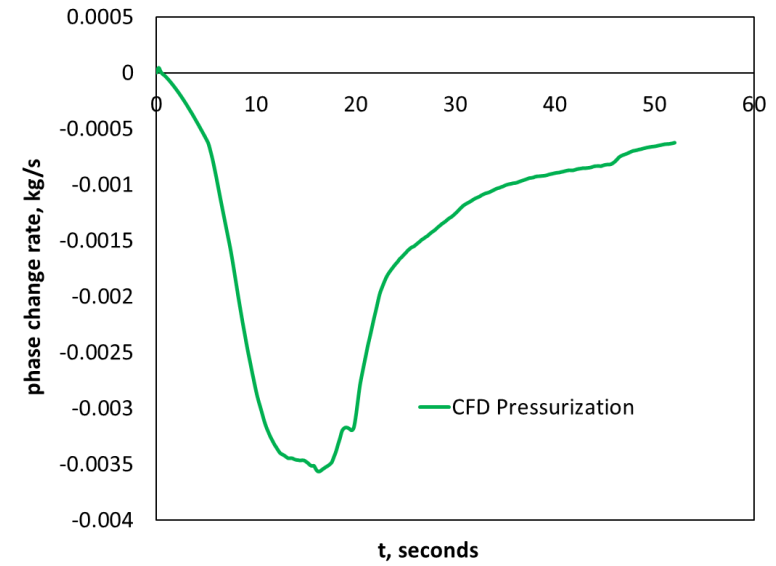
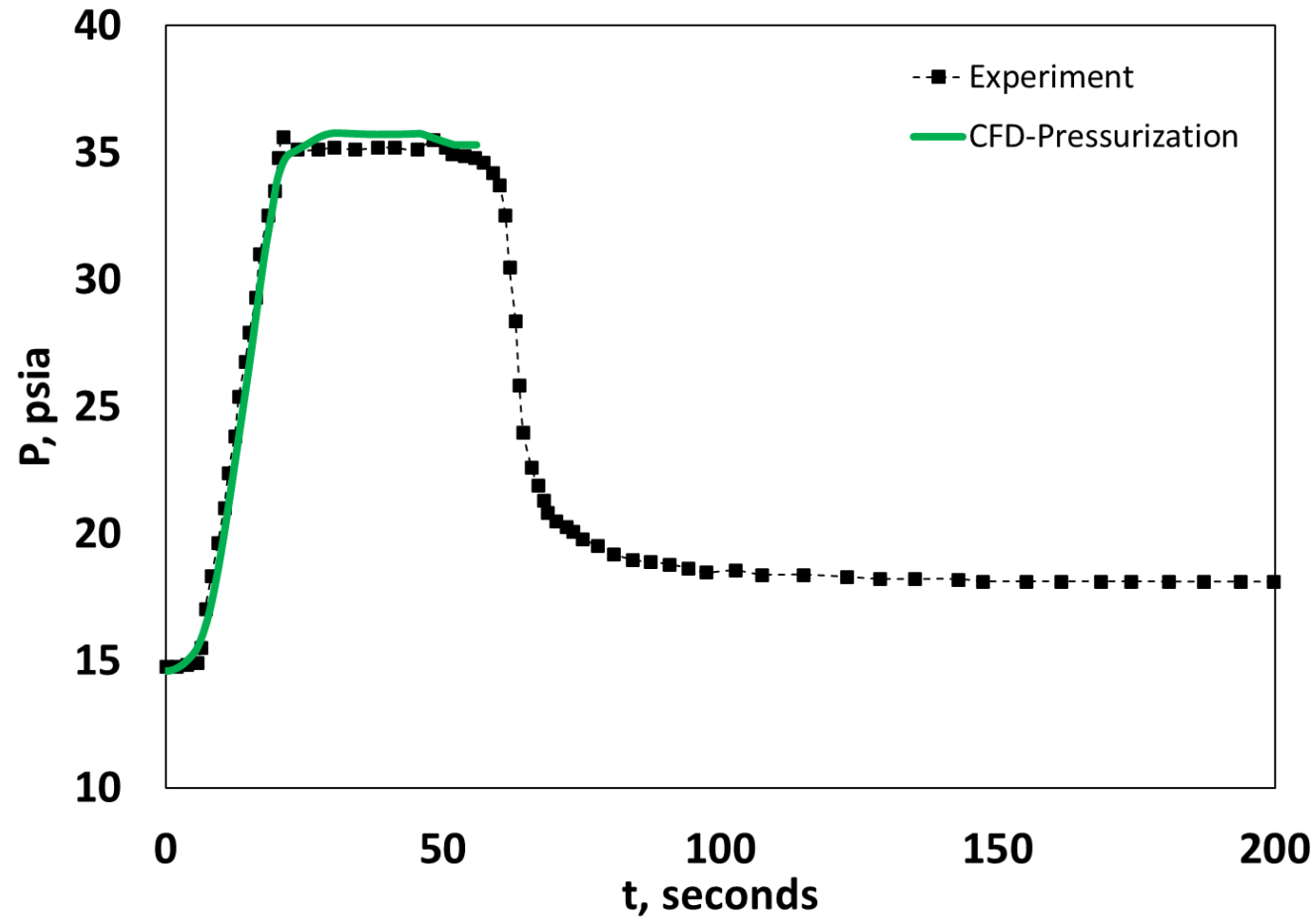


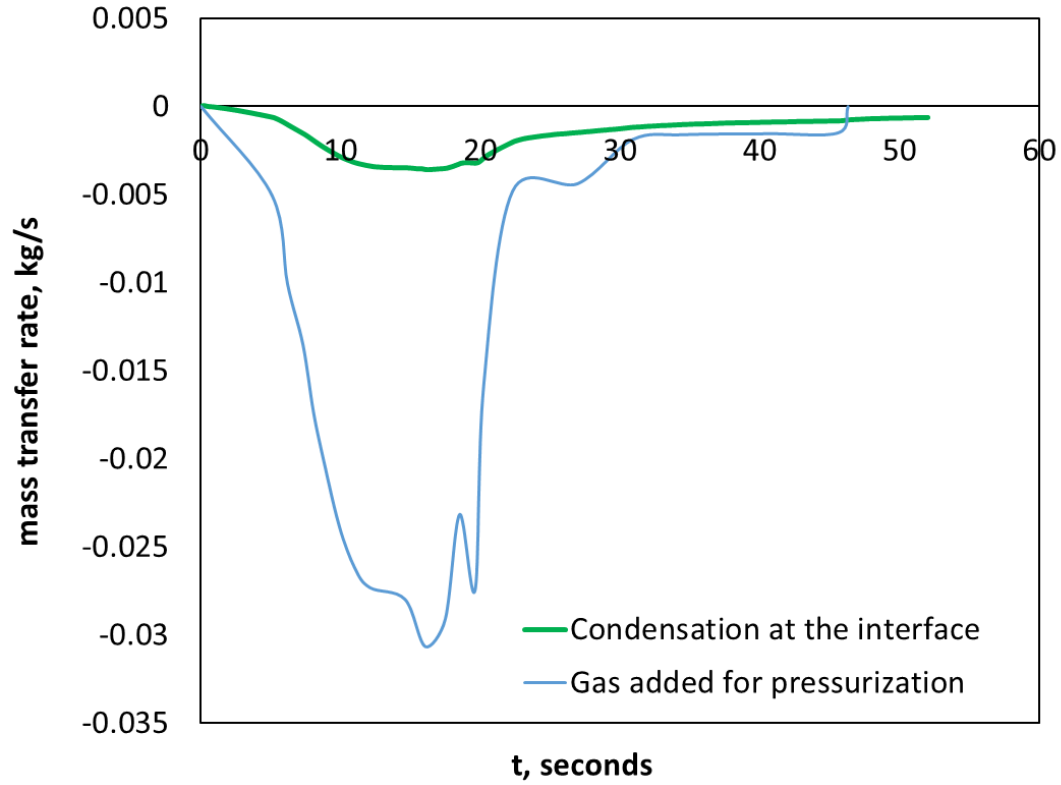
Fig. 6. Injected pressurant mass flow as a function of time for a liquid hydrogen slosh test.

Moran, M. E., McNelis, N. B., Kudlac, M. T., Haberbusch, M. S., Satorino, G.A., "Experimental Results of Hydrogen Slosh in a 62 Cubic Foot (1750 Liter) Tank," NASA TM-106625, 1994

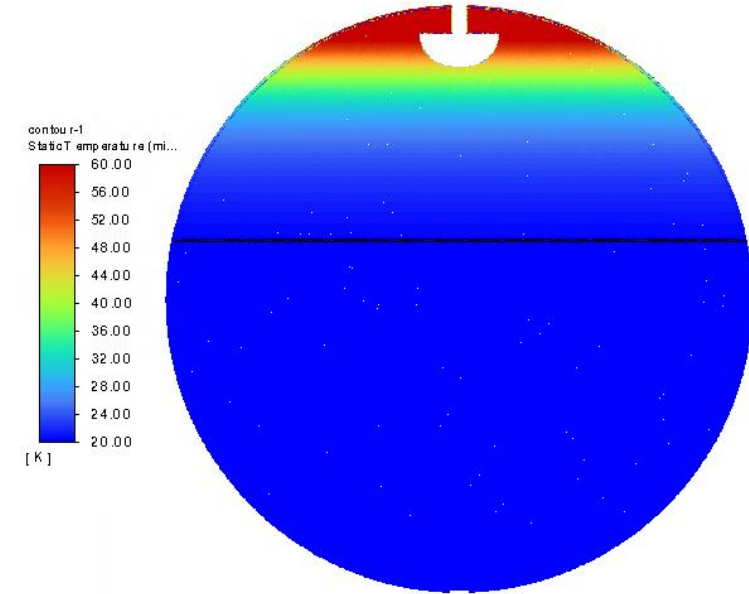
CFD Results - Pressurization



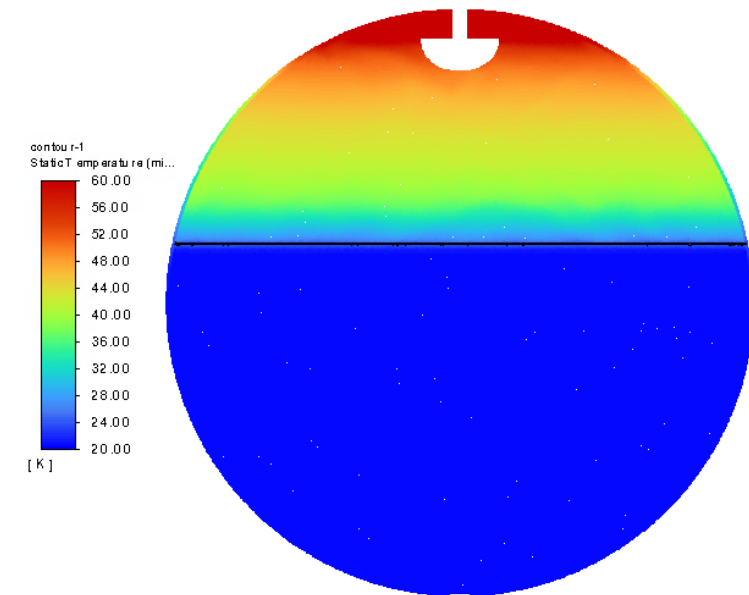
CFD Results - Pressurization



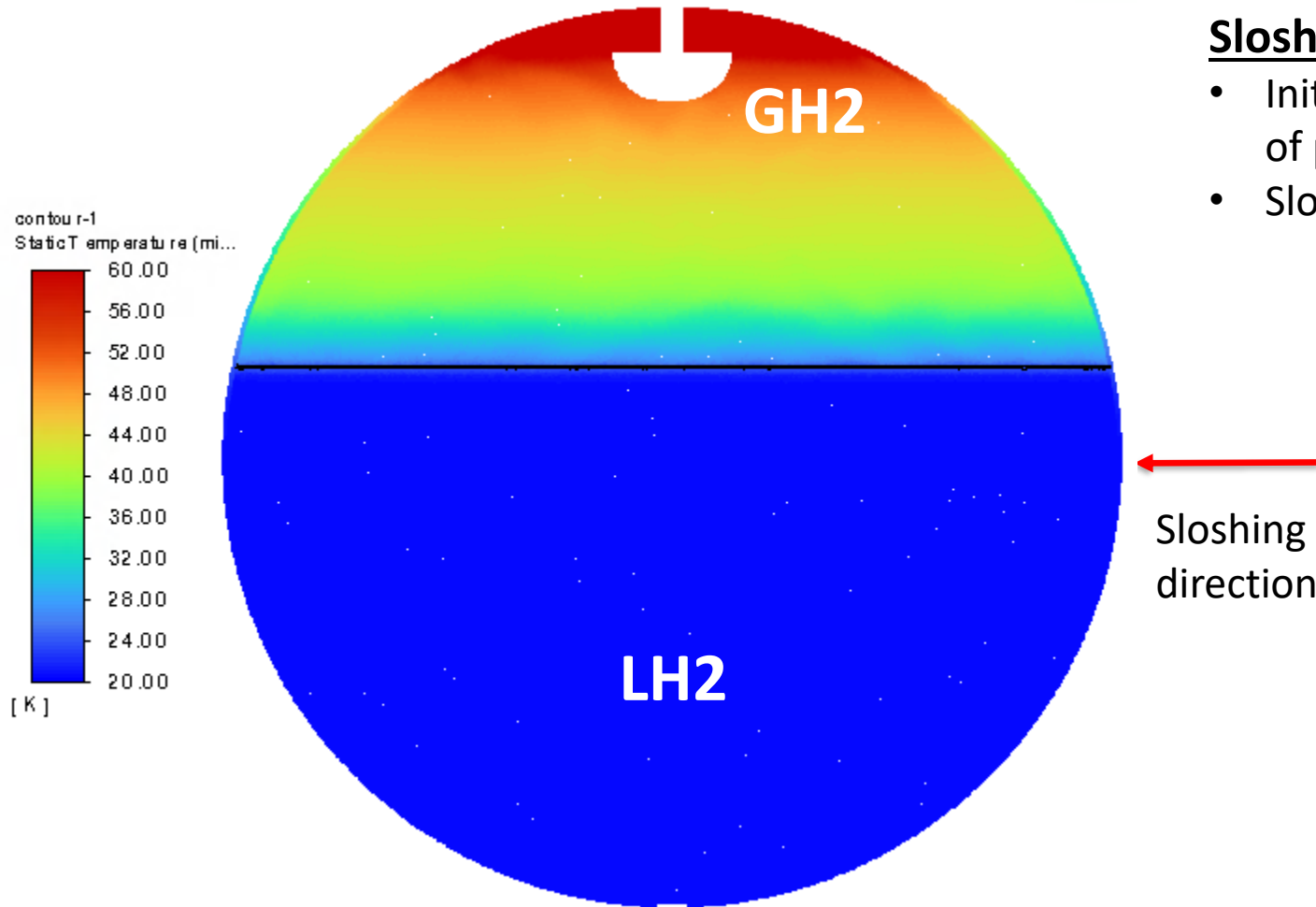
Beginning



End



Problem description - sloshing

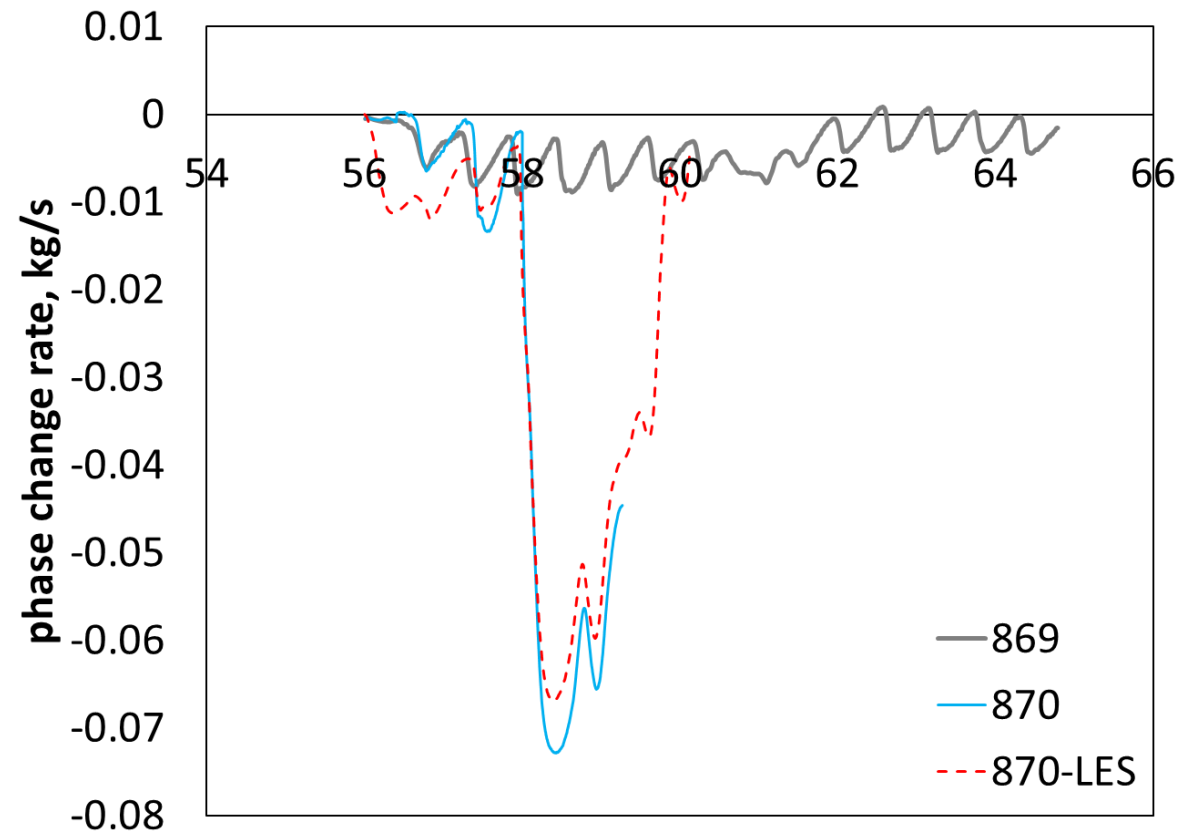
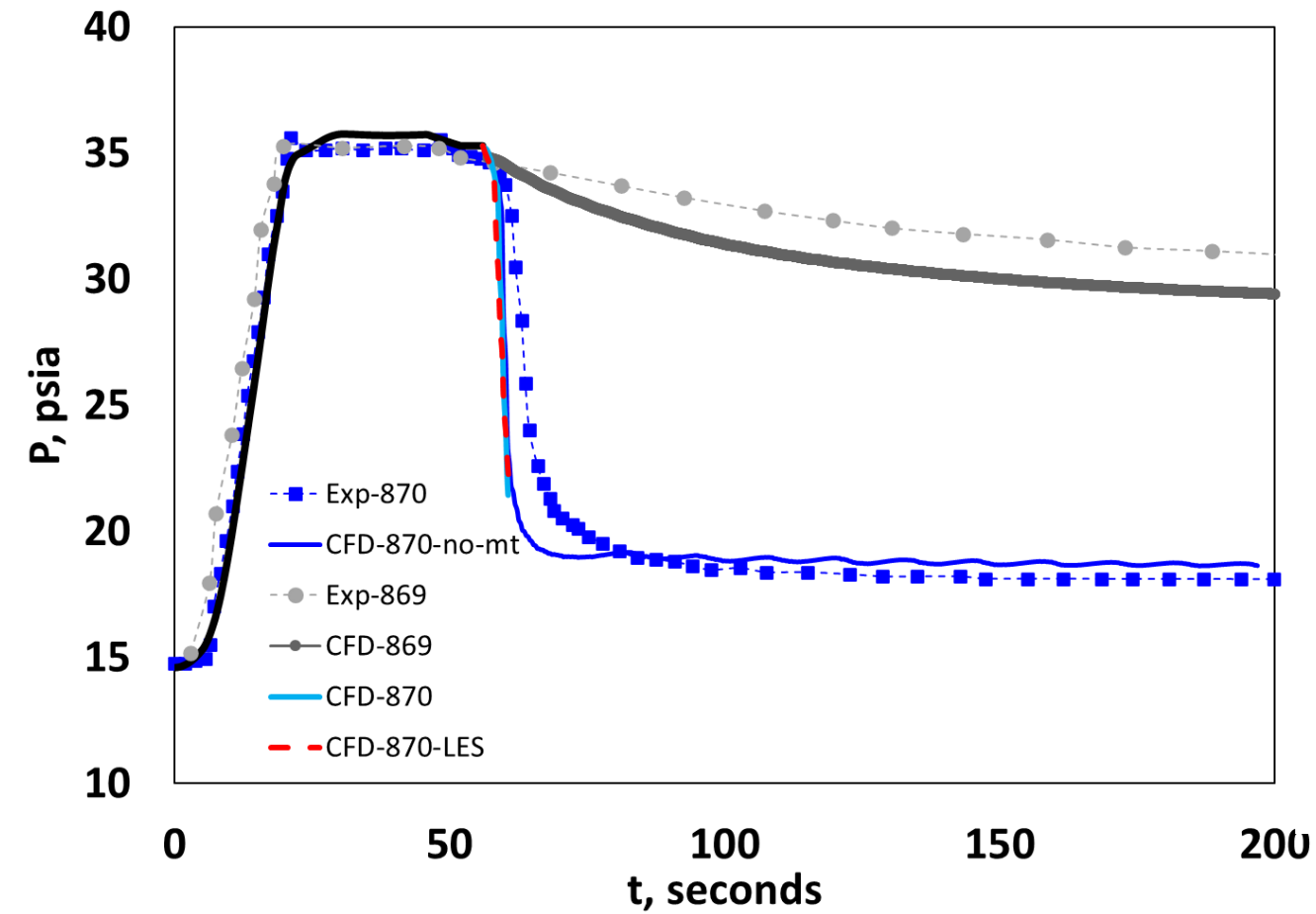


Sloshing

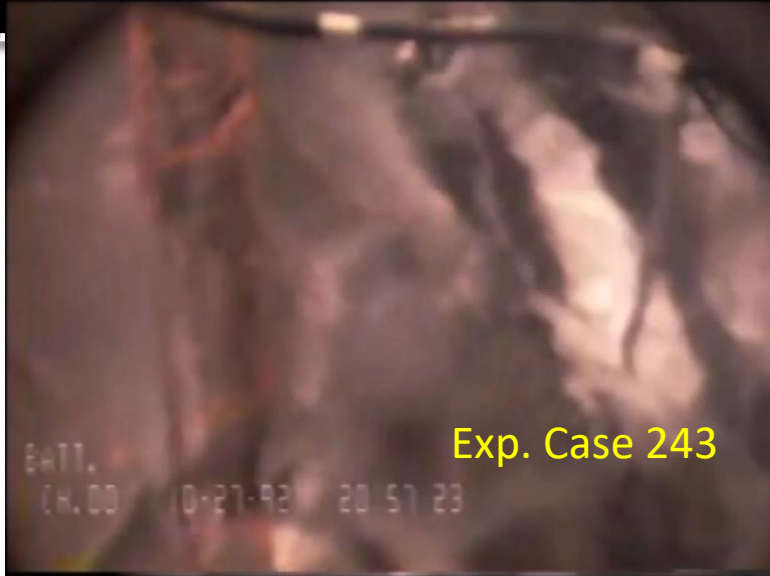
- Initial conditions before sloshing: CFD results at the end of pressurization
- Sloshing frequency and amplitude: from experiment

Test Case	Freq&Ampl	Ullage Volume, %	Pressure Collapse, %
869	0.95Hz; 0.5 ±in	33	29
870	0.74Hz; 1.5 ±in	36	84

CFD Results - Sloshing



CFD Results - Sloshing



Exp. Case 243

Test Case	Freq&Ampl	Ullage Volume, %	Pressure Collapse, %
869	0.95Hz; 0.5 $\pm$ in	33	29
242	0.95Hz; 0.5 $\pm$ in	49	30
870	0.74Hz; 1.5 $\pm$ in	36	84
243	0.74Hz; 1.5 $\pm$ in	49	68



Exp. Case 242

Case 870 – fine mesh, no MT

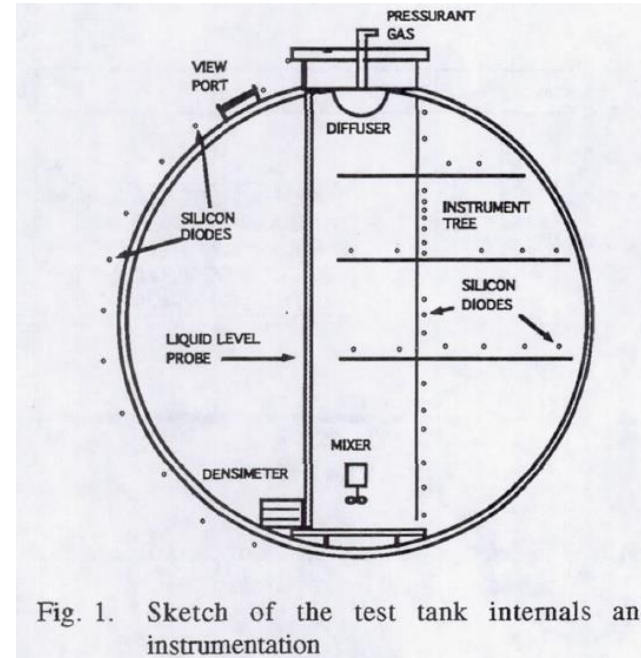
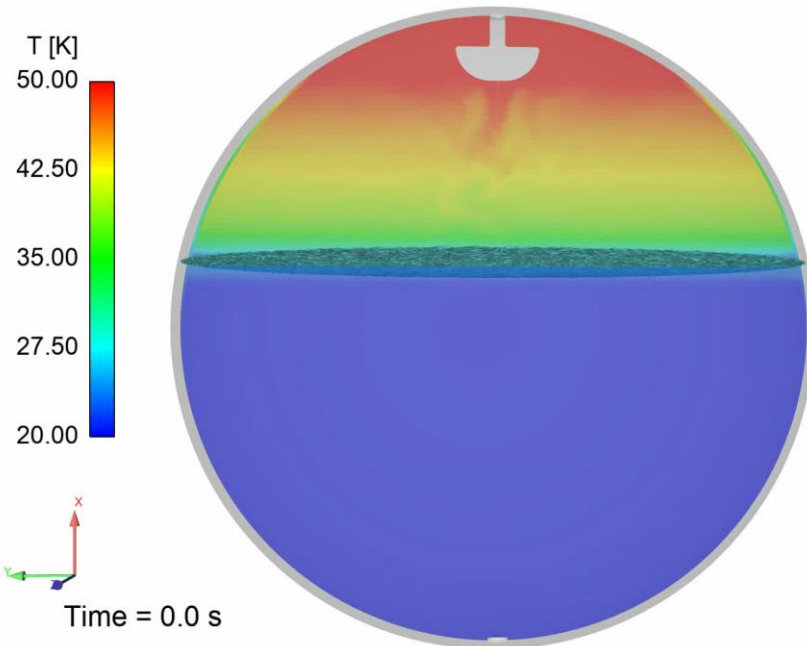
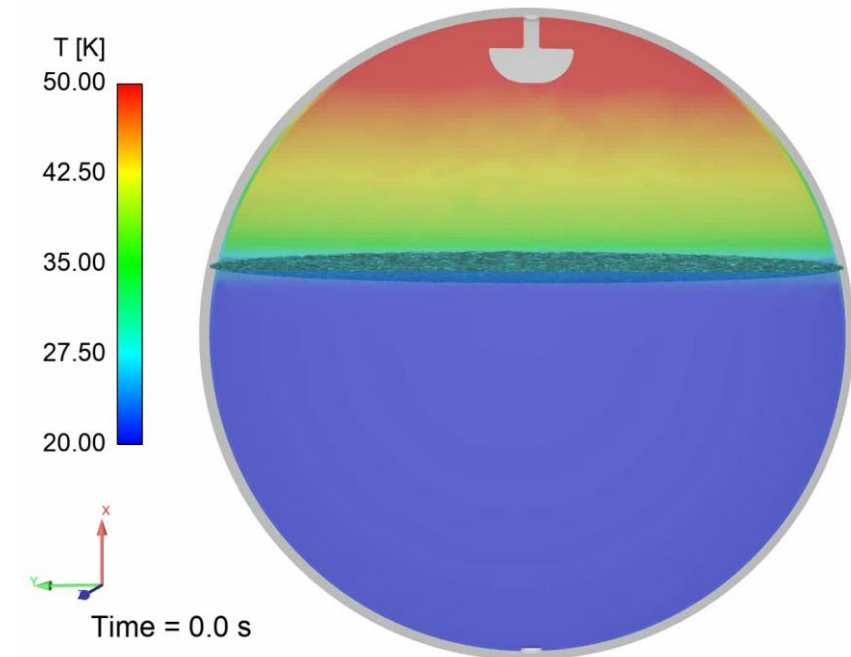
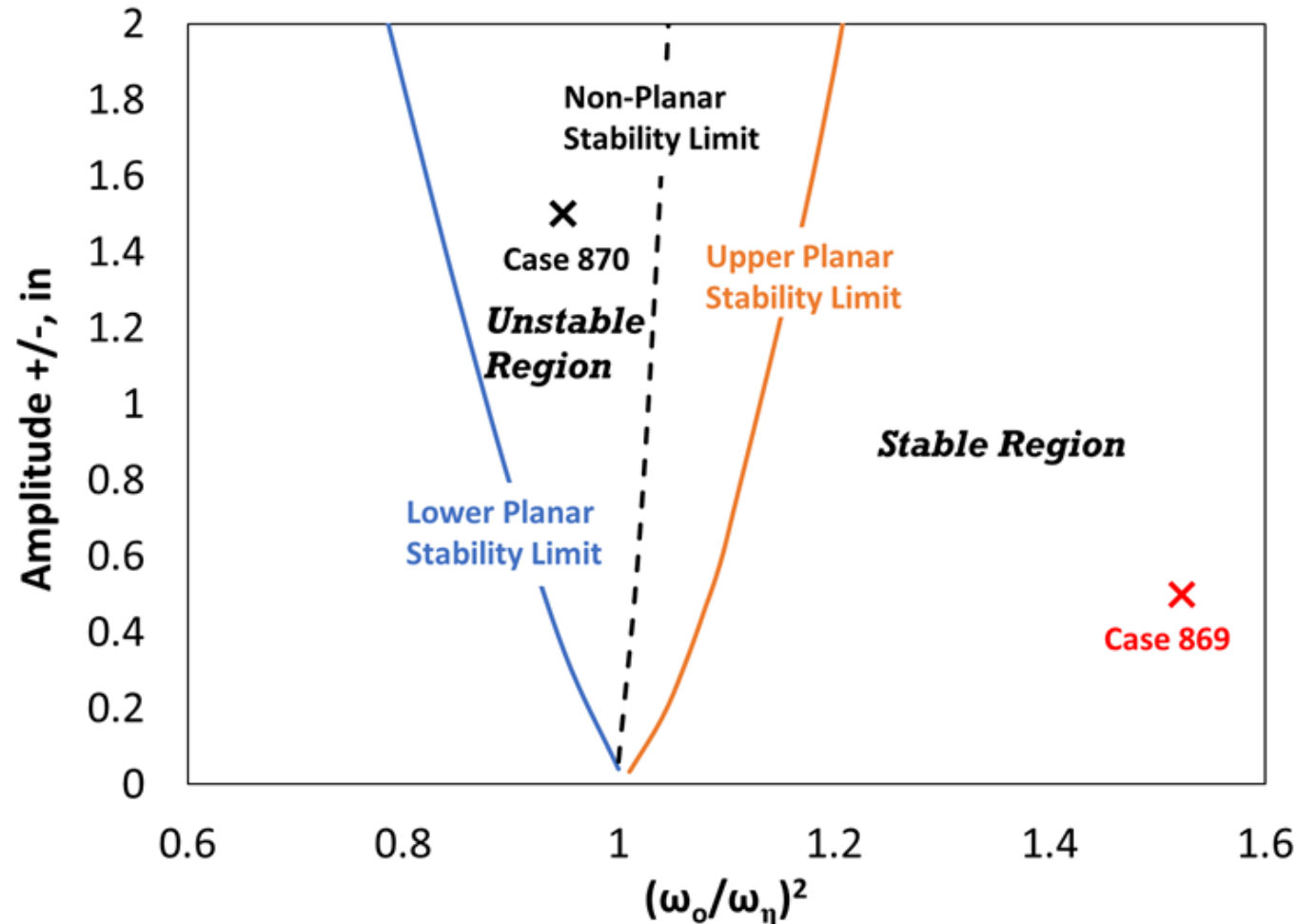


Fig. 1. Sketch of the test tank internals and instrumentation

Case 869 – fine mesh, with MT



Slosh stability map for cases 869 and 870



$$\omega_n = \frac{1}{2\pi} \sqrt{\frac{\lambda g}{R}} \quad (2)$$

where: ω_n = natural frequency

g = gravitational acceleration

R = tank radius

λ = empirical constant based on
liquid height and tank radius
(see Table II)

Using the calculated natural frequency, stability boundaries for both planar and nonplanar motion can be estimated from another experimentally derived relation (Sumner)²:

$$\left(\frac{\omega_o}{\omega_n}\right)^2 = K_1 + K_2 \left(\frac{X_0}{2R}\right)^{\frac{2}{3}} \quad (3)$$

where: ω_o = excitation frequency

X_0 = excitation amplitude

$K_{1,2}$ = empirical constants

Conclusions:



- Autogenous pressurization and sloshing CFD model was developed and validated against K-Site Hydrogen sloshing data
- Autogenous pressurization results showed good agreement with measured tank pressure and temperatures
- Sloshing results compared reasonably well with measured tank pressures for both sloshing cases considered. Both CFD and experimental results followed the same trend, showing much faster and larger pressure drop in the case with the high amplitude sloshing.
- CFD showed that phase change did not play a significant role in the high amplitude sloshing case (870). This case with phase change had convergence difficulties past 4 seconds of sloshing.

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