SLOSHING OF CRYOGENIC LIQUIDS IN TANKS

Multiphase Workshop 2017, Cachan

Philipp Behruzi, Diana Gaulke, Dennis Haake,

Yannick Jego, Martin Konopka

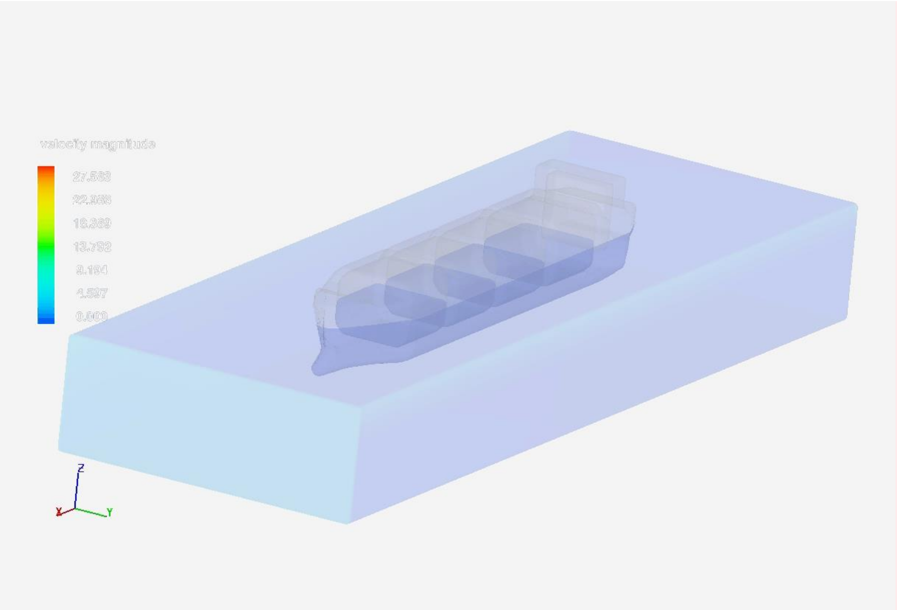
In cooperation with DLR Institute of Space Systems, Bremen, Germany

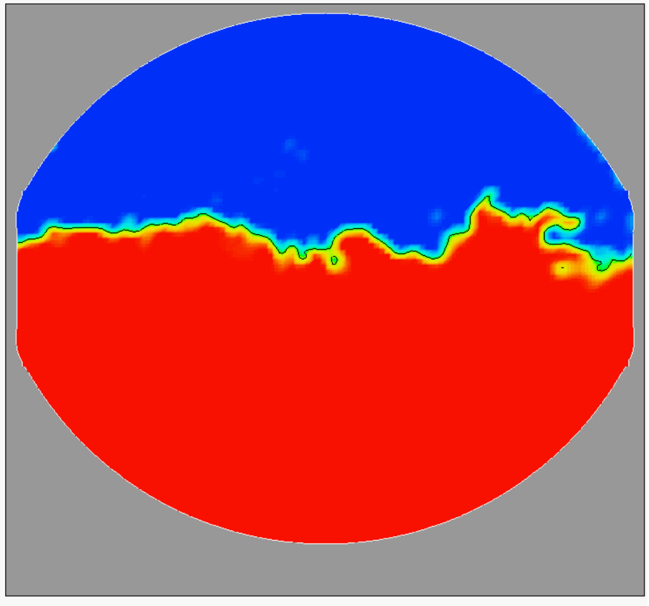
01

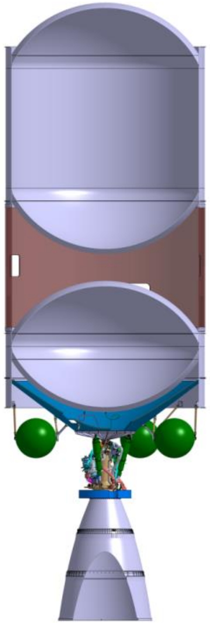
INTRODUCTION

COMMON PROBLEMS IN SHIPPING & SPACE INDUSTRIES

Cryogenic sloshing … a common problem in shipping & space industry





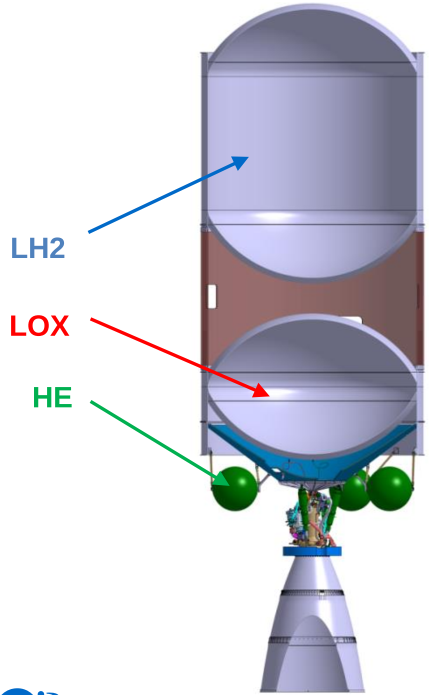


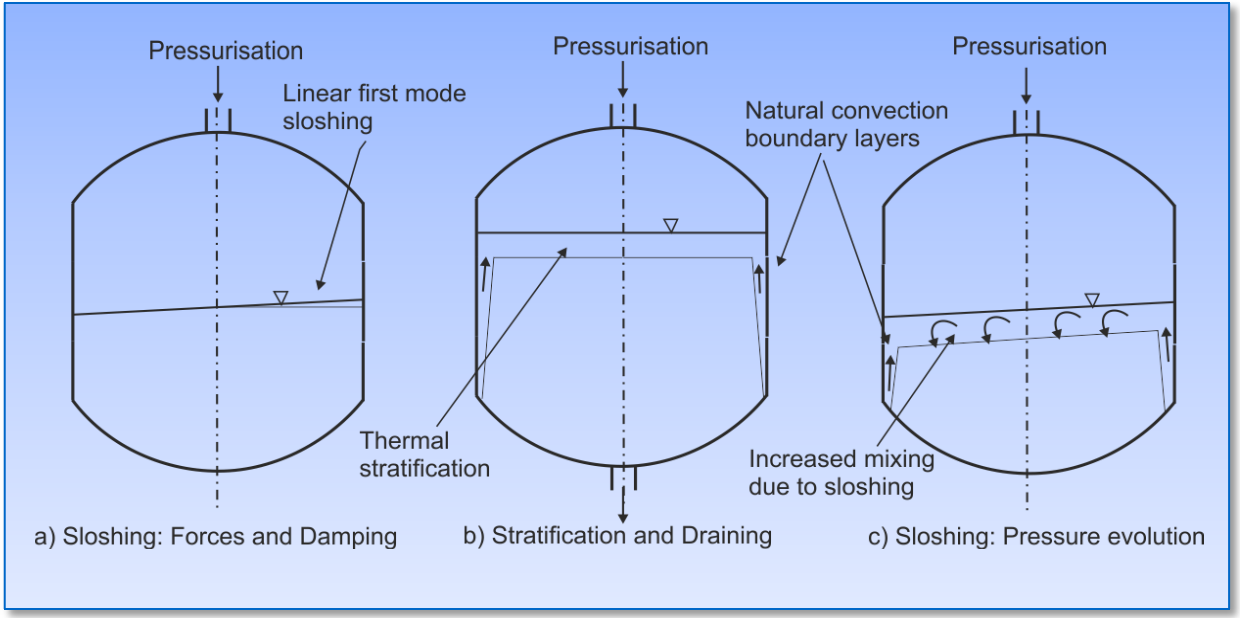
LNG ship

Ariane 6

MOTIVATION

- Typical phenomena which occur in rockets with cryogenic tanks at accelerated phases are
  - Sloshing (aerodynamic forces & stage/booster separations)
  - Stratification and draining



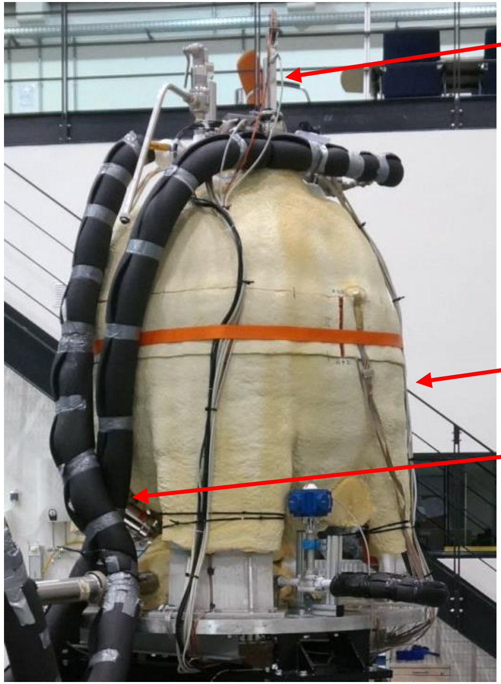


02

LN2 SLOSHING EXPERIMENT SETUP

LN2 EXPERIMENTAL SETUP

DLR Hexapod system with LN2 tank



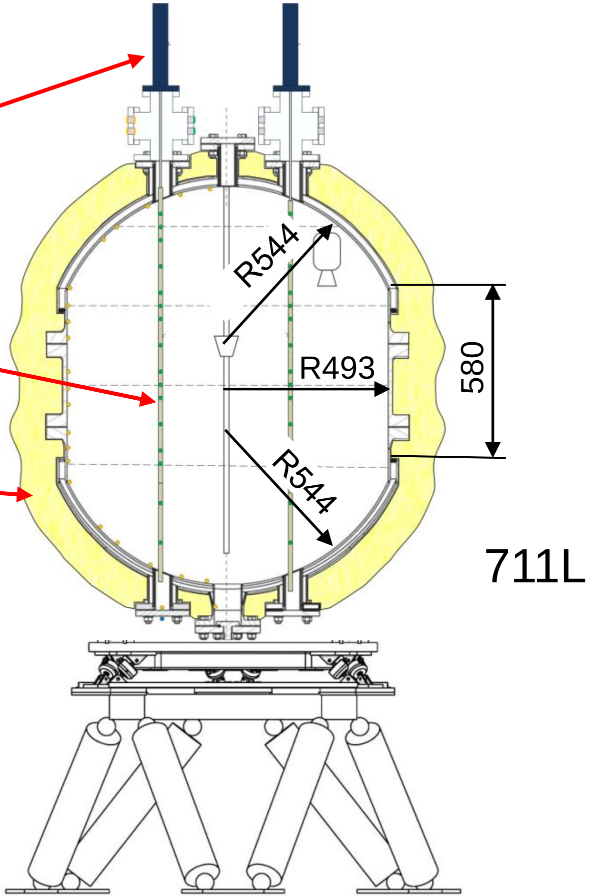
Measurement rod drive system

Measurement rods (16 silicon diodes each)

PU - foam insulation

Pressurisation lines

74 Temperature sensors



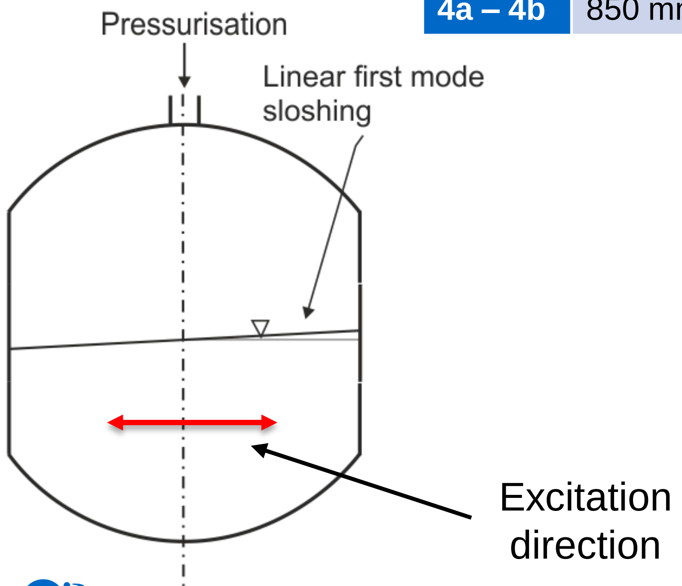
03

ISOTHERMAL SLOSHING EFFECTS EXPERIMENT VS. CFD

SLOSHING – FORCES AND DAMPING

Comparing isothermal effects

Case	Fill level	Type	Experiment/Flow solver	Grid	Turbulence Model
1	600 mm	Isothermal sloshing	Experiment	-	-
1a – 1d	600 mm	Isothermal sloshing	Flow-3D v11.0.4	1 – 4	-
1e – 1g	600 mm	Isothermal sloshing	Flow-3D v11.0.4	2 - 4	k-ω
4	850 mm	Isothermal sloshing	Experiment	-	-
4a – 4b	850 mm	Isothermal sloshing	THETA	5 - 6	-



Acceleration of the tank $\ddot{x}(t) = -\omega_c^2 x_a \sin(\omega_c t)$

Excitation parameters

Case	Excitation frequency f	Excitation amplitude x_a
1 - 1h	0.7 Hz	10 mm

NUMERICAL METHODS – SLOSHING COMPUTATIONS

- Numerical methods of Flow-3D and the DLR Theta Code for the sloshing computations

Flow-3D

- Volume of fluid method
- Incompressible solution of the Navier-Stokes equations
- GMRES algorithm for the pressure solution
- Second order accurate discretization for inviscid and viscous terms
- Constant fluid properties
- laminar flow / *k*-ω turbulence models

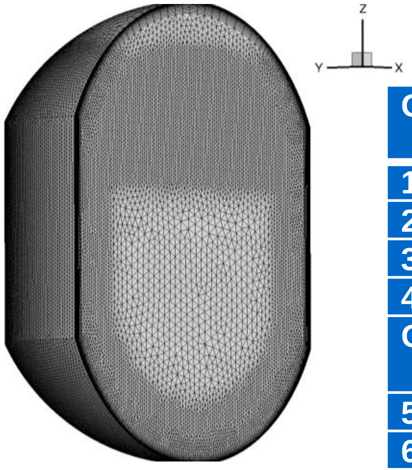
DLR Theta Code

- Volume of fluid method, VOF transport by the CICSAM method
- Incompressible solution of the Navier-Stokes equations
- Second order accurate scheme
- Multigrid
- Constant fluid properties

CICSAM = ”Compressive Interface Capturing Scheme for Arbitrary Meshes”

MESHING – SLOSHING COMPUTATIONS

DLR Theta

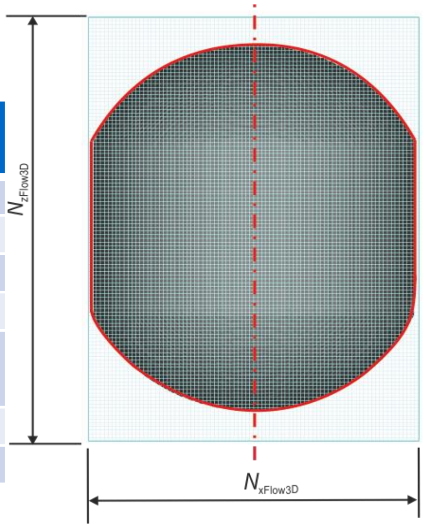


Hybrid grid

Grid parameters

Grid	Number of grid points	Minimal grid spacing ΔxΔyΔz	Wall normal grid spacing
1	800000	0.97 cm × 0.97 cm × 0.97 cm	$\Delta n^{+}_{max} = 100$
2	1600000	0.76 cm × 0.76 cm × 0.76 cm	$\Delta n^{+}_{max} = 90$
3	3200000	0.61 cm × 0.61 cm × 0.61 cm	$\Delta n^{+}_{max} = 80$
4	6400000	0.48 cm × 0.48 cm × 0.48 cm	$\Delta n^{+}_{max} = 62$
Grid	Number of grid points	Wall normal distance to first mesh node	
5	1000000	0.10 mm	$\Delta n^{+}_{max} = 1.7$
6	1840000	0.05 mm	$\Delta n^{+}_{max} = 0.9$

FLOW-3D

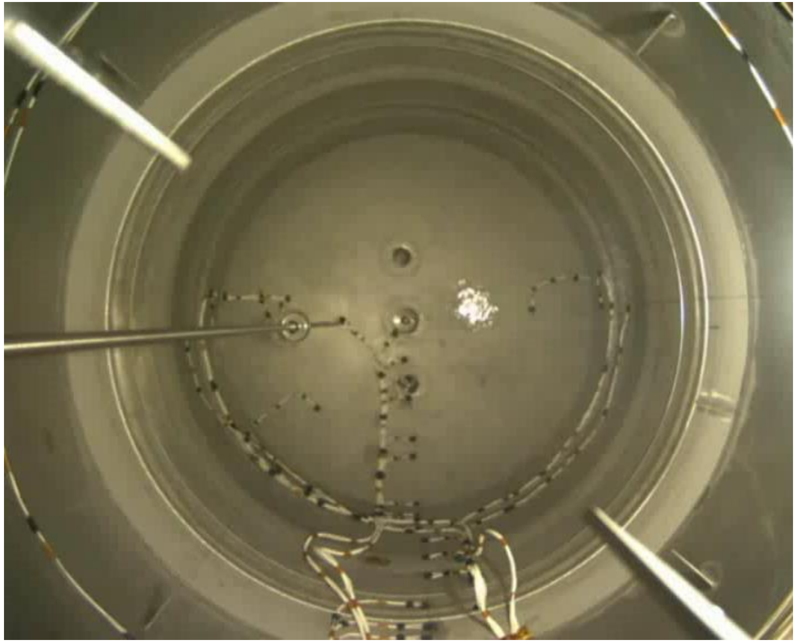


Cartesian grid

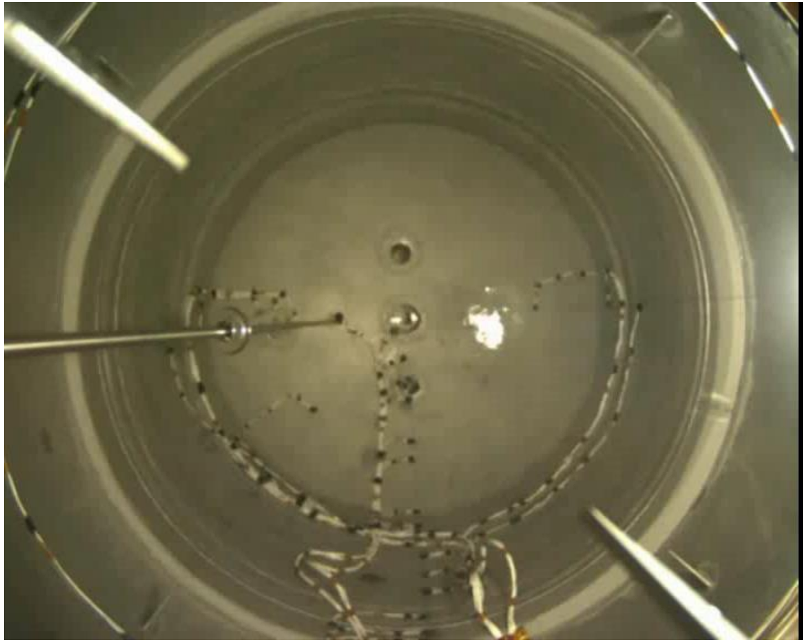
Grids used for Flow-3D and the DLR Theta Code

No-slip boundary conditions at tank walls

SLOSHING – EXPERIMENT VIDEOS



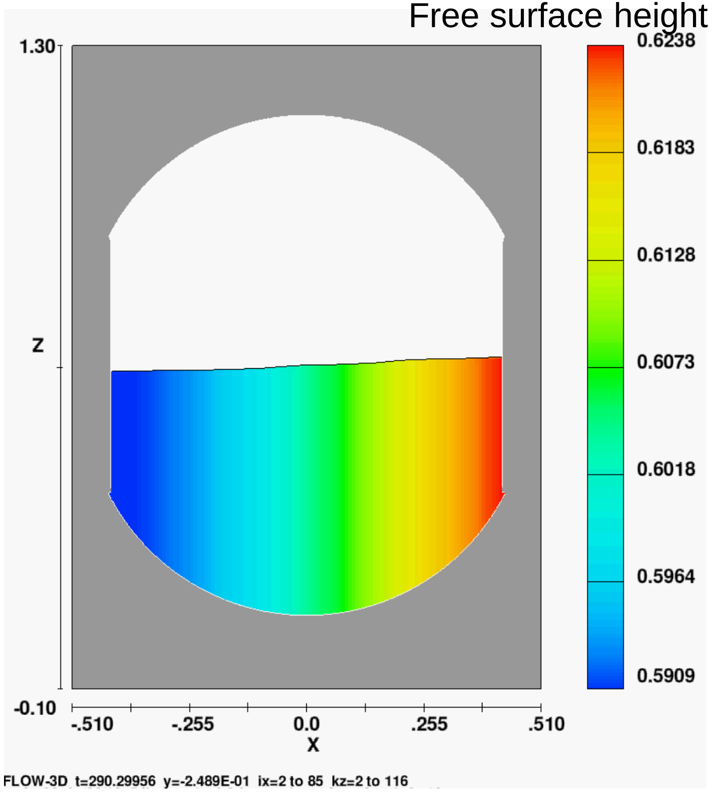
Case 1, sloshing video



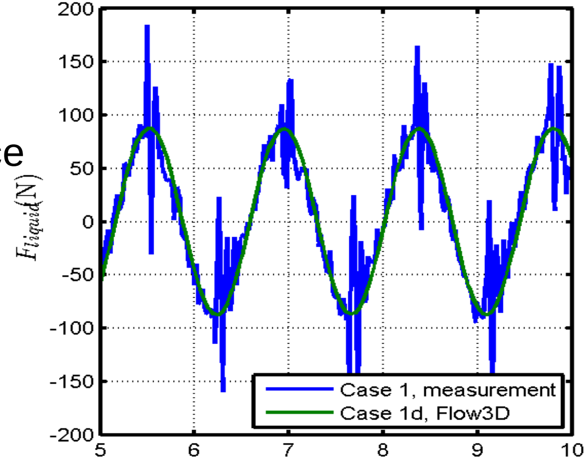
Case 4, sloshing video

SLOSHING – FORCE HISTORY FLOW-3D

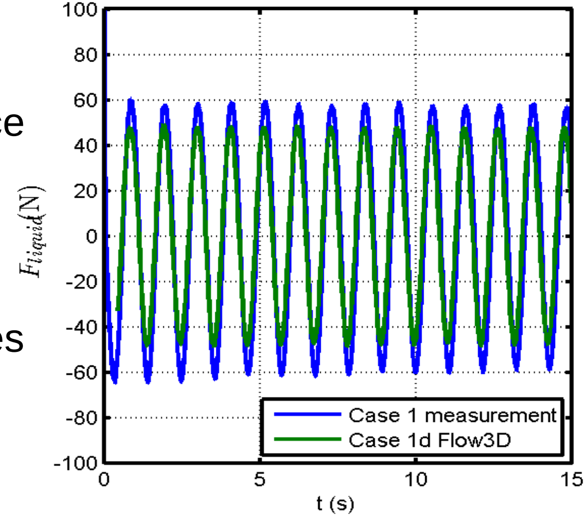
Case 1b, exited sloshing phase



Case 1b, liquid force evolution **during excitation**



Case 1b, liquid force evolution **during damping (no exciatation)**



FLOW-3D computes 16% lower force amplitudes

arianeGROUP

SLOSHING – DAMPING RESULTS

$$Ga = \frac{aR^3}{\nu^2}$$

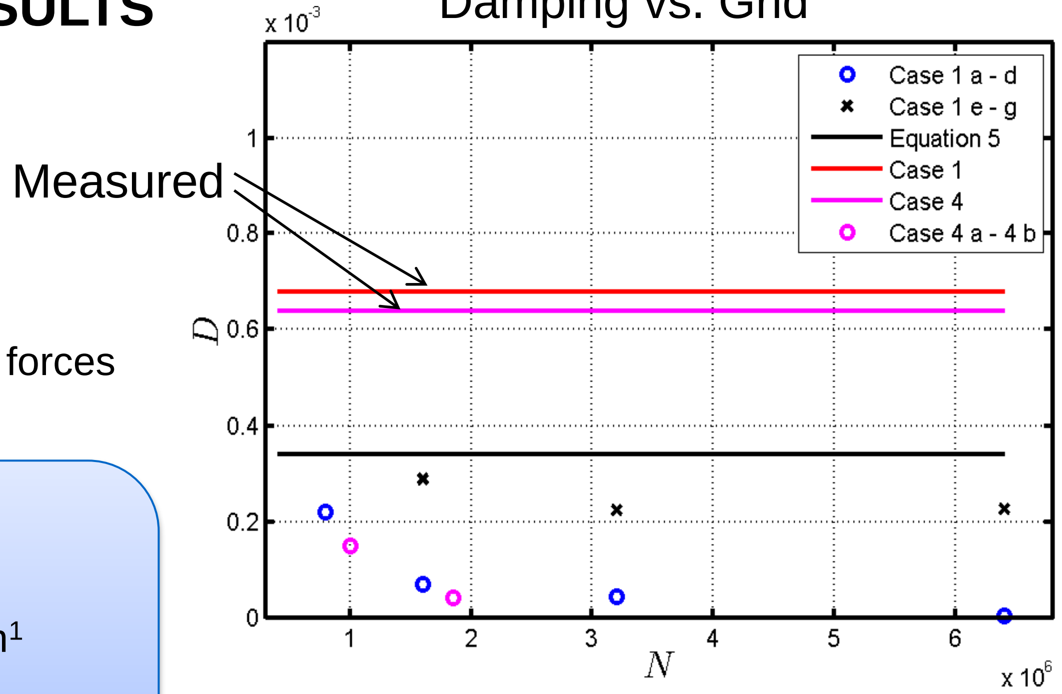
Galilei number, ratio of product of gravity and inertia forces with viscous forces

$$D = 0.79\, Ga^{-\frac{1}{4}} f\left(\frac{Z}{R}\right).$$

Semi-empirical damping correlation[1]

[1]Stephens, D. G., Leonard, H. W., Perry, T. W., "Investigations of the Damping of Liquids in Right Circular Cylindrical Tanks, Including the Effects of a Time-Variant Liquid Depth", Nasa Langley Research Center, TN-D-1367, Hampton, VA, 1962

Damping vs. Grid



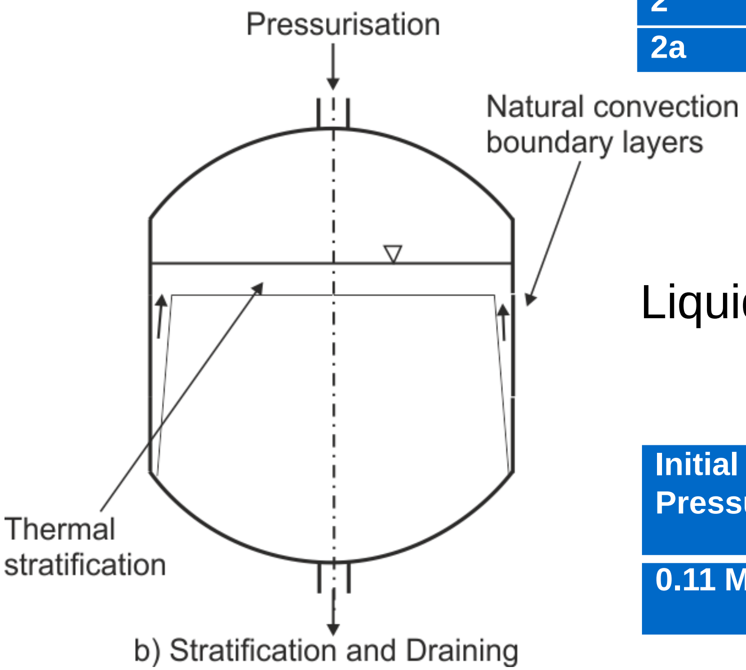
Damping coefficients

- Cases 1 a – d (FLOW-3D laminar, grid study)
- Case 1 e – g (FLOW-3D turbulet, grid study)
- Case 4 a – b (TETHA laminar, grid study)

04

DRAINING EXPERIMENT

Draining – Experiment and computation



Case	Fill level	Type	Experiment/ Flow solver	Grid	Turbulence Model
2	1080 mm	Draining	Experiment	-	-
2a	1080 mm	Draining	Flow-3D v.11.1	7	*k*-ω

Flow parameters

Liquid saturated at 1.1 bar → pressurized to 4 bar

Initial Pressure	Pressure	Draining volume flow rate	GN2 pressurisation flow rate	GN2 temperature
0.11 MPa	0.4 MPa	1.4 l/s	approx. 0.015 kg/s	235 K ≤ T ≤ 252 K

Flow parameters

GRID, BOUNDARY AND INITIAL CONDITIONS

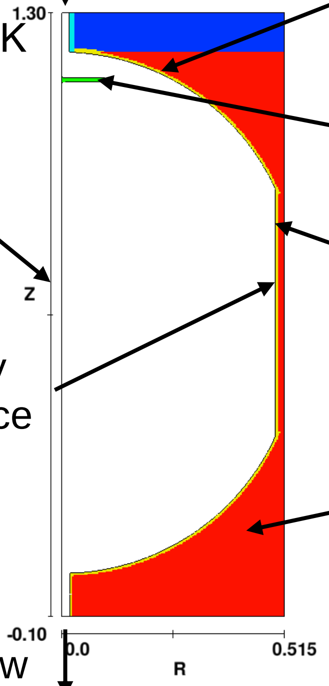
Constant pressure boundary

235 K ≤ T ≤ 252 K

Symmetry

No-slip boundary at the tank surface

Prescribed outflow velocity

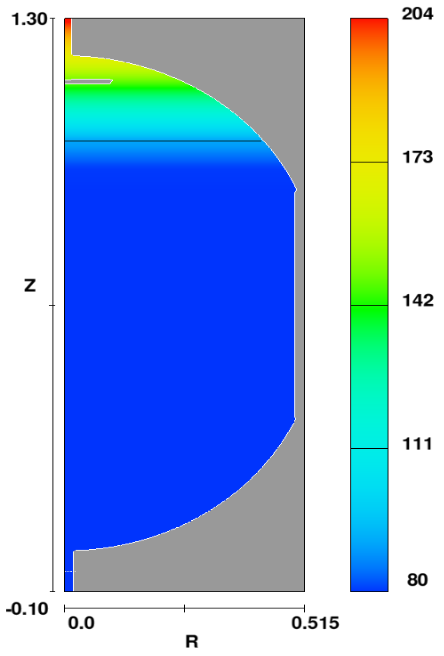


6 mm steel inner tank shell with conduction

Simplified baffle

$$\dot{q} = h(T_{wall,inner} - T_{wall,outer})$$

300 K constant reference

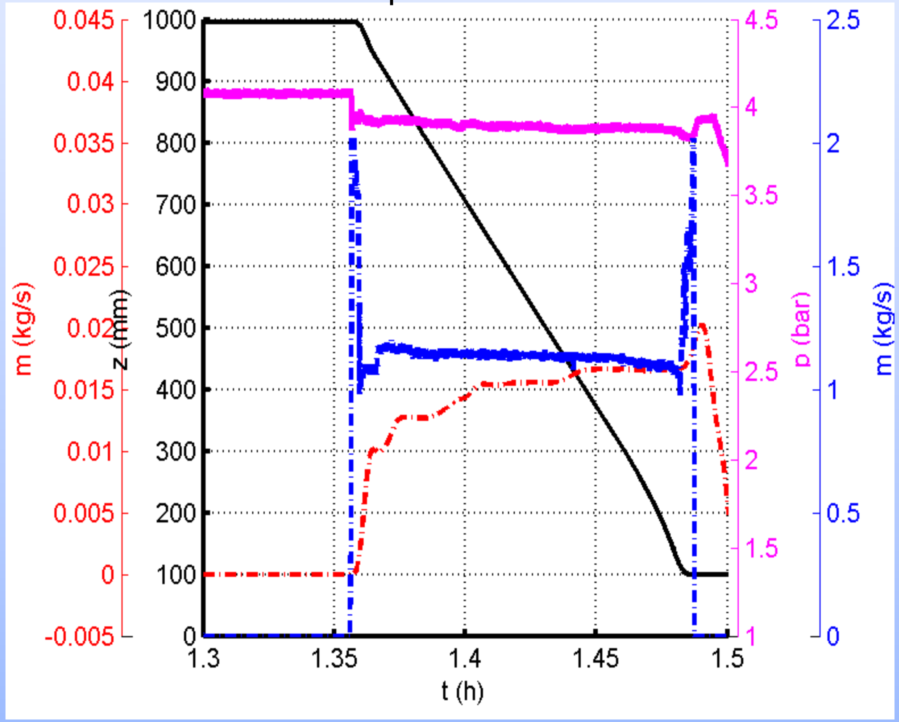


Initial fluid temperature contours

Gr id	Number of grid points	Minimal grid spacing ΔxΔyΔz
7	80234	0.3 cm × 0.3 cm

RESULTS OF THE DRAINING EXPERIMENT AND COMPUTATIONS

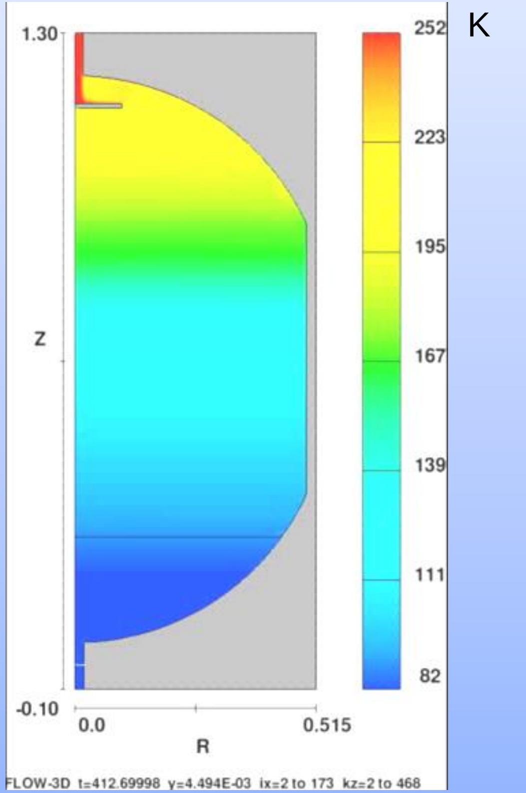
Experiment



Fill level (black), pressure (magenta), vapor flow rate (red), and liquid flow rate (blue) for filling experiment case 2 a

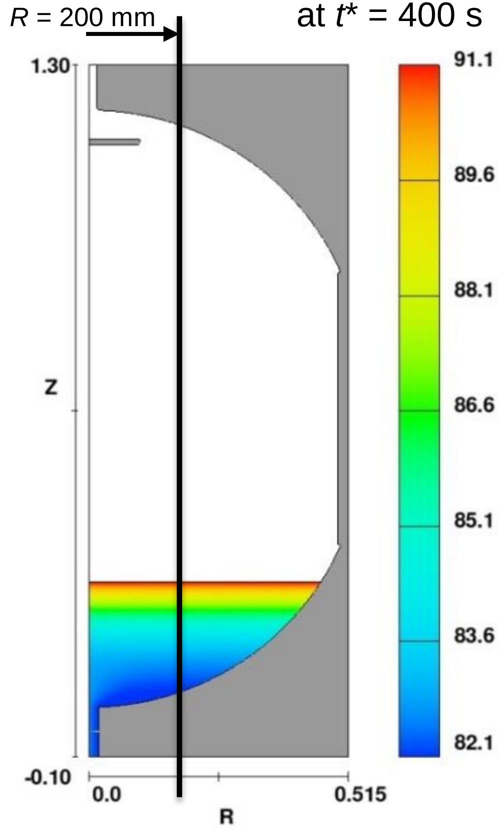
CFD (Flow-3D)

Temperature contours at case 2 a

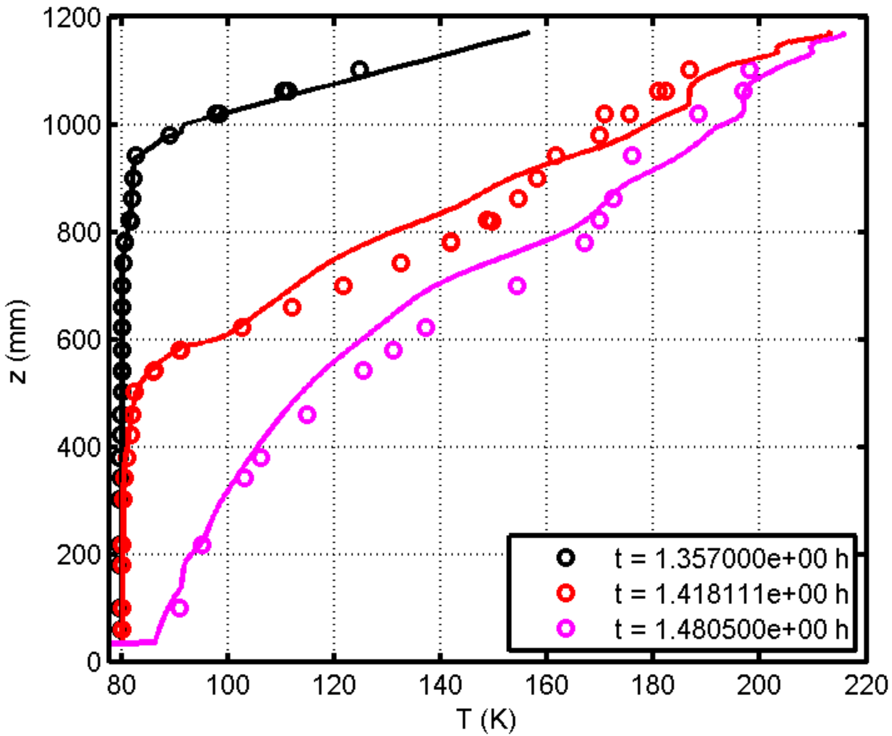


RESULTS OF THE DRAINING EXPERIMENT AND COMPUTATIONS

Flow-3D temperature contours at t^* = 400 s



Comparison of measured and computed fluid temperature contours cases 2 and 2 a

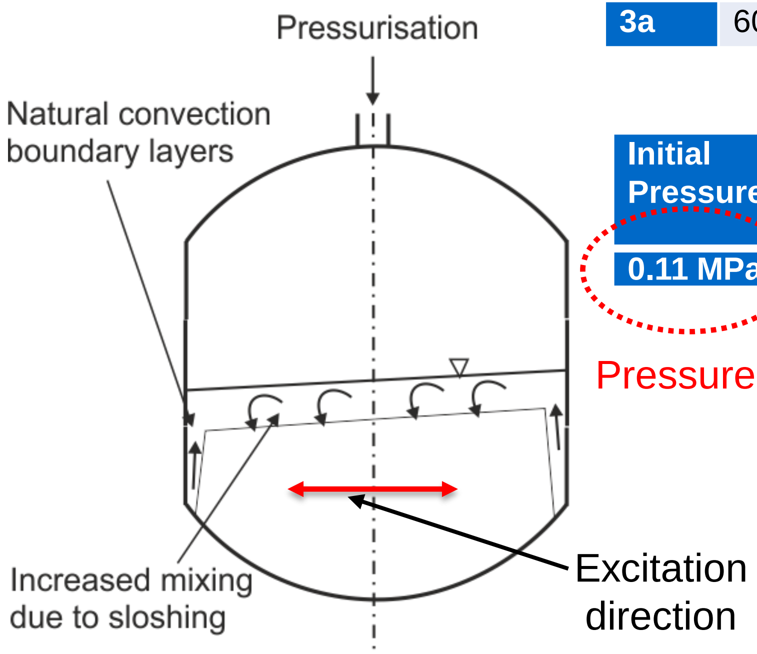


- t^* = 0 s
- t^* = 220 s
- t^* = 444 s

05

SLOSHING & STRATIFICATION EXPERIMENT VS. ANALYSIS

SLOSHING – STRATIFICATION EXPERIMENT



c) Sloshing: Pressure evolution

Case	Fill level	Type	Experiment/Flow solver	Grid
3	600 mm	Non-isothermal sloshing	Experiment	-
3a	600 mm	Non-isothermal sloshing	Ullage pressure solver	8

Parameters of sloshing computations and experiments

Initial Pressure	Pressure	Draining volume flow rate	GN2 pressurisation flow rate	GN2 temperature
0.11 MPa	0.4 MPa	-	approx. 0.018 kg/s	approx. 210 K

Pressure at saturation

Flow parameters

$$\ddot{x}(t) = -\omega_c^2 x_a \sin(\omega_c t)$$

Acceleration of the tank

Case	Excitation frequency f	Excitation amplitude x_a
1 - 1h	0.7 Hz	10 mm

Excitation parameters

NUMERICAL METHOD OF THE ULLAGE PRESSURE SOLVER

Simplified 1-D modeling

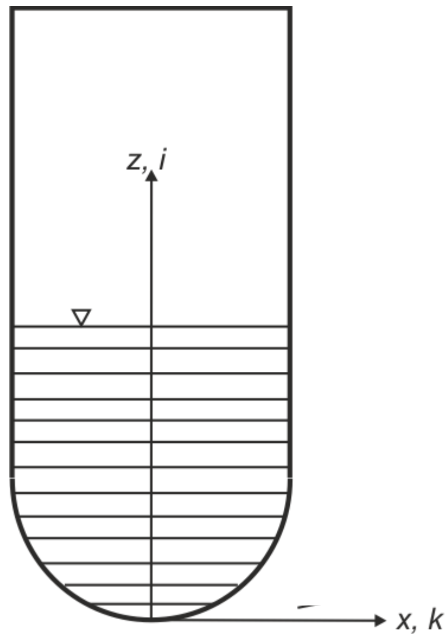
Second order accurate discretization of the energy equation in the liquid

Single-node approximation of the ullage assuming the ideal gas law is valid

Energy equation is solved with heat and mass transfer

Constant transport properties in the liquid and ullage

Increased heat transfer in the liquid to model sloshing



Example-schematic of the ullage pressure solver

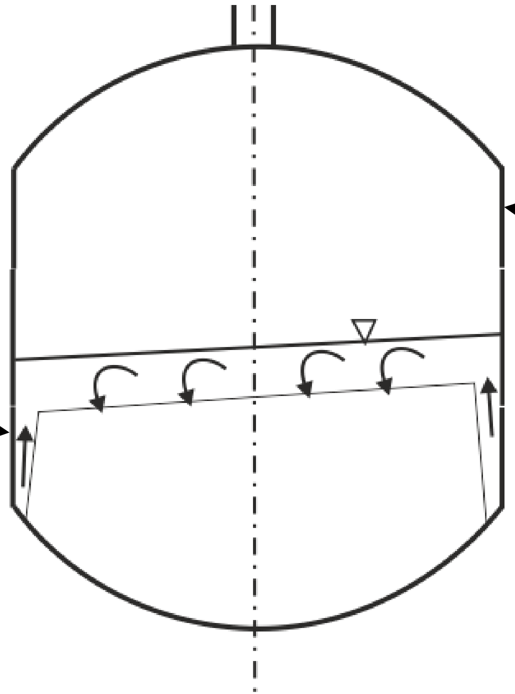
SLOSHING & PRESSURE EVOLUTION

Grid, boundary and initial conditions

Prescribed GN2 mass flow and temperature

Grid	Number of grid points	Minimal grid spacing Δz
8	1000	6 mm

Grid parameters

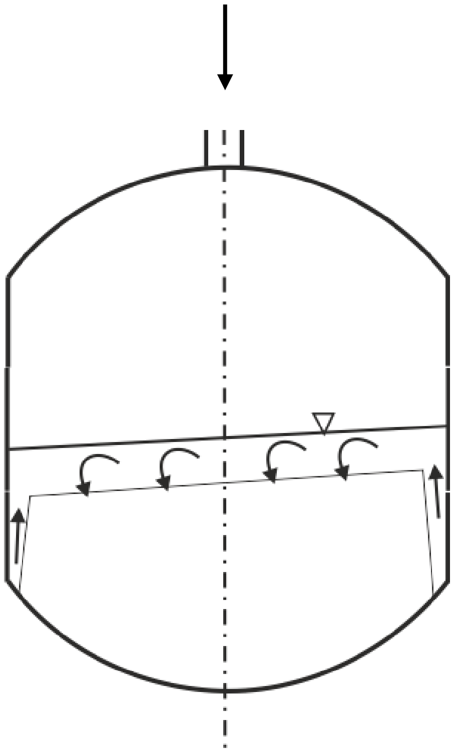


Ullage vapor heat transfer

$$\dot{q} = hA(T_{ullage} - T_{wall})$$

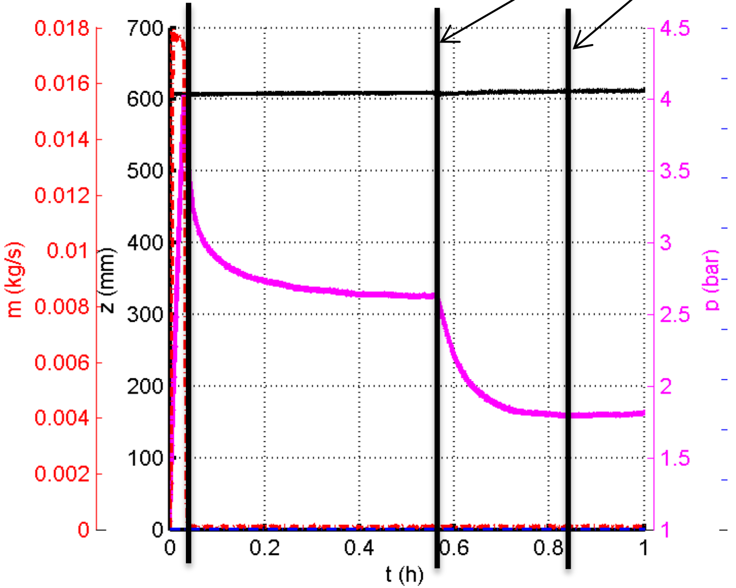
Prescribed heat transfer into the liquid

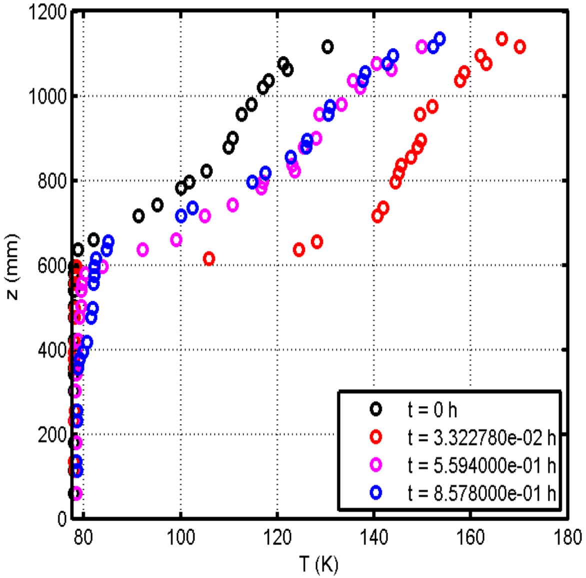
SLOSHING & PRESSURE EVOLUTION



Sketch of the LN2 tank during sloshing

Experiment results

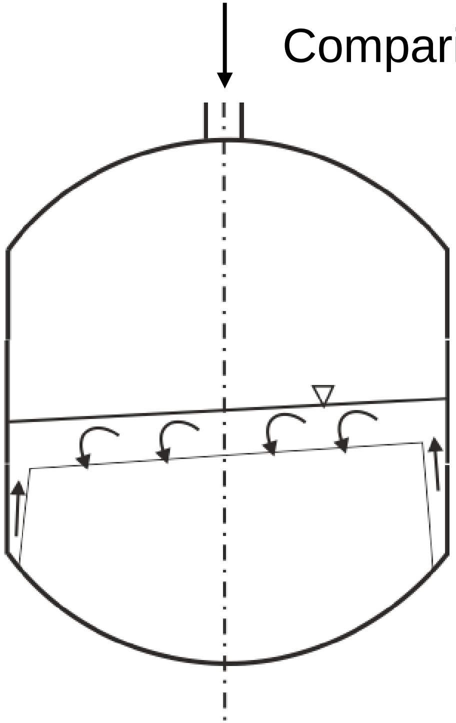


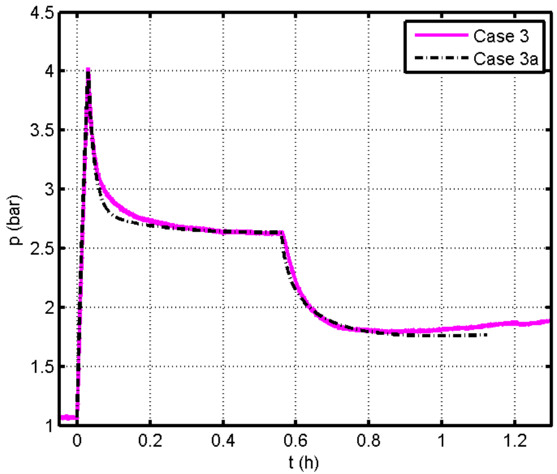


Fill level (black), pressure (magenta), and vapor flow rate (red)

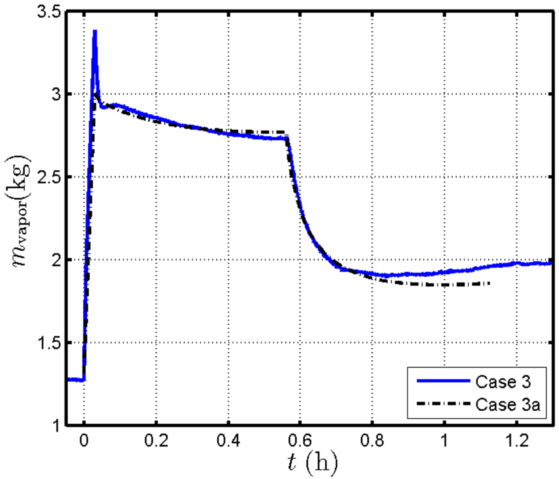
SLOSHING & PRESSURE EVOLUTION

Comparison of the ullage pressure solver with the experiments





Pressure evolution of the experiment and computation

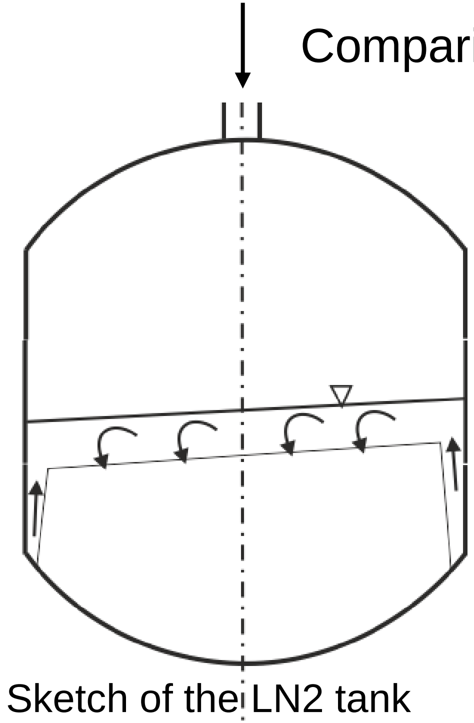


Vapor mass evolution of the experiment and computation

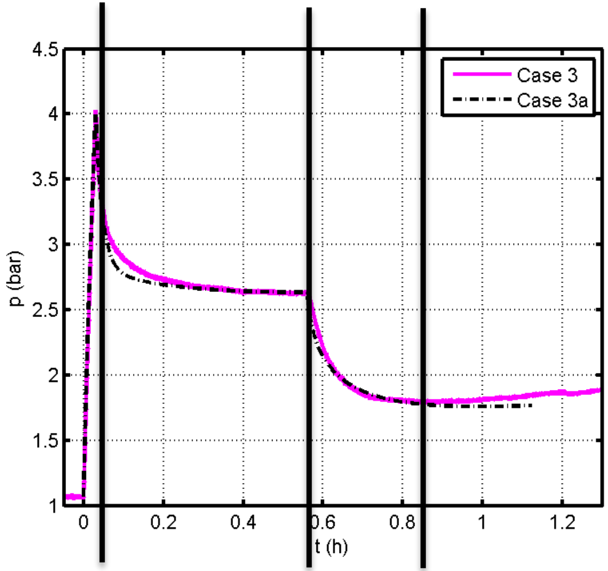
Sketch of the LN2 tank during sloshing

SLOSHING & PRESSURE EVOLUTION

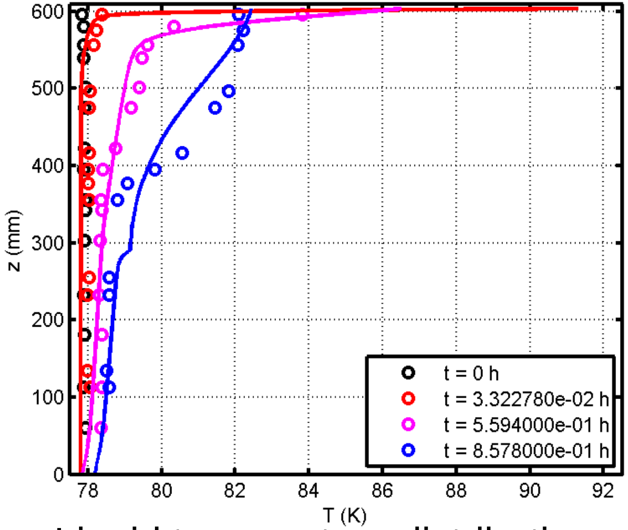
Comparison of the ullage pressure solver with the experiments



Sketch of the LN2 tank during sloshing



Pressure evolution of experiment and computation



Liquid temperature distribution of the experiments (circles) and computation (solid lines)

06
CONCLUSION

CONCLUSION

Comparisons between Experiment & Numerics

- Sloshing: Forces and Damping
- Draining: Stratification
- Sloshing: Pressure evolution

Valuable results were obtained with cryogenic sloshing experiments

→ Improving CFD model
→ Enhancing CFD phase change model for VoF methods
→ Validating simplified phase change models tuned with sloshing experiments
→ Simplified modelling approach predicting pressure evolution appears to be a good choice

Lessons learned valuable for future LNG sloshing experiments

- Experiment set-up → measurement rods beneficial
- Experiment / CFD + analysis comparisons

REFERENCE

M. Konopka et al., “Analysis of LN2 Filling, Draining, Stratification and Sloshing Experiments”, 46th AIAA Fluid Dynamics Conference, AIAA 2016-4272, 2016