SLOSHING OF CRYOGENIC LIQUIDS IN TANKS

Multiphase Workshop 2017, Cachan
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Yannick Jego, Martin Konopka

In cooperation with DLR Institute of Space Systems, Bremen, Germany
INTRODUCTION
COMMON PROBLEMS IN SHIPPING & SPACE INDUSTRIES

Cryogenic sloshing … a common problem in shipping & space industry

LNG ship

Ariane 6

SLOSHING OF CRYOGENIC LIQUIDS IN TANKS - 16/10/2017
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

SLOshing of CRYOGENIC LIQUIDS IN TANKS - 16/10/2017
03 ISOTHERMAL SLOSHING EFFECTS EXPERIMENT VS. CFD
### SLOSHING – FORCES AND DAMPING

Comparing isothermal effects

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

Pressurisation

Linear first mode sloshing

Acceleration of the tank

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

Excitation parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>Excitation frequency f</th>
<th>Excitation amplitude x_a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 1h</td>
<td>0.7 Hz</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

Comparing isothermal effects

\[\dot{x}(t) = -\omega_c^2 x_a \sin(\omega_c t)\]
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"
Grids used for Flow-3D and the DLR Theta Code

No-slip boundary conditions at tank walls

### Grids

<table>
<thead>
<tr>
<th>Grid</th>
<th>Number of grid points</th>
<th>Minimal grid spacing</th>
<th>Wall normal grid spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>800000</td>
<td>0.97 cm × 0.97 cm × 0.97 cm</td>
<td>Δn⁺max = 100</td>
</tr>
<tr>
<td>2</td>
<td>1600000</td>
<td>0.76 cm × 0.76 cm × 0.76 cm</td>
<td>Δn⁺max = 90</td>
</tr>
<tr>
<td>3</td>
<td>3200000</td>
<td>0.61 cm × 0.61 cm × 0.61 cm</td>
<td>Δn⁺max = 80</td>
</tr>
<tr>
<td>4</td>
<td>6400000</td>
<td>0.48 cm × 0.48 cm × 0.48 cm</td>
<td>Δn⁺max = 62</td>
</tr>
<tr>
<td>5</td>
<td>1000000</td>
<td>0.10 mm</td>
<td>Δn⁺max = 1.7</td>
</tr>
<tr>
<td>6</td>
<td>1840000</td>
<td>0.05 mm</td>
<td>Δn⁺max = 0.9</td>
</tr>
</tbody>
</table>

**Grids**

- **DLR Theta**
- **Hybrid grid**

**Grid parameters**

- **Cartesian grid**
- **FLOW-3D**
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 excitation)

FLOW-3D computes 16% lower force amplitudes
SLOSHING – DAMPING RESULTS

\[ Ga = \frac{aR^3}{v^2} \]

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


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

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<th>Grid</th>
<th>Turbulence Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1080 mm</td>
<td>Draining</td>
<td>Experiment</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2a</td>
<td>1080 mm</td>
<td>Draining</td>
<td>Flow-3D v.11.1</td>
<td>7</td>
<td>k-ω</td>
</tr>
</tbody>
</table>

Flow parameters

Liquid saturated at 1.1 bar → pressurized to 4 bar

<table>
<thead>
<tr>
<th>Initial Pressure</th>
<th>Pressure</th>
<th>Draining volume flow rate</th>
<th>GN2 pressurisation flow rate</th>
<th>GN2 temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11 MPa</td>
<td>0.4 MPa</td>
<td>1.4 l/s</td>
<td>approx. 0.015 kg/s</td>
<td>235 K ≤ T ≤ 252 K</td>
</tr>
</tbody>
</table>

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

\[ \dot{q} = h(T_{\text{wall, inner}} - T_{\text{wall, outer}}) \]

300 K constant reference

Initial fluid temperature contours

<table>
<thead>
<tr>
<th>Grid</th>
<th>Number of grid points</th>
<th>Minimal grid spacing ΔxΔyΔz</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>80234</td>
<td>0.3 cm × 0.3 cm</td>
</tr>
</tbody>
</table>
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 2a

CFD (Flow-3D)

Temperature contours at case 2a

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RESULTS OF THE DRAINING EXPERIMENT AND COMPUTATIONS

Flow-3D temperature contours

$R = 200 \text{ mm}$

at $t^* = 400 \text{ s}$

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

- $t^* = 0 \text{ s}$
- $t^* = 220 \text{ s}$
- $t^* = 444 \text{ s}$

SLOSHING OF CRYOGENIC LIQUIDS IN TANKS - 16/10/2017
05
SLOSHING & STRATIFICATION EXPERIMENT VS. ANALYSIS
SLOSHING – STRATIFICATION EXPERIMENT

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<tbody>
<tr>
<td>3</td>
<td>600 mm</td>
<td>Non-isothermal sloshing</td>
<td>Experiment</td>
<td>-</td>
</tr>
<tr>
<td>3a</td>
<td>600 mm</td>
<td>Non-isothermal sloshing</td>
<td>Ullage pressure solver</td>
<td>8</td>
</tr>
</tbody>
</table>

Parameters of sloshing computations and experiments

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<tr>
<th>Initial Pressure</th>
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<th>Draining volume flow rate</th>
<th>GN2 pressurisation flow rate</th>
<th>GN2 temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11 MPa</td>
<td>0.4 MPa</td>
<td>-</td>
<td>approx. 0.018 kg/s</td>
<td>approx. 210 K</td>
</tr>
</tbody>
</table>

Flow parameters

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

Acceleration of the tank

Excitation parameters

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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

<table>
<thead>
<tr>
<th>Grid</th>
<th>Number of grid points</th>
<th>Minimal grid spacing Δz</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1000</td>
<td>6 mm</td>
</tr>
</tbody>
</table>

Prescribed heat transfer into the liquid

Ullage vapor heat transfer

\[ \dot{q} = hA(T_{\text{ullage}} - T_{\text{wall}}) \]
SLOSHING & PRESSURE EVOLUTION

Experiment results

Sloshing initiated
Minimum pressure

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

Sketch of the LN2 tank during sloshing

SLOSHING OF CRYOGENIC LIQUIDS IN TANKS - 16/10/2017
SLOSHING & PRESSURE EVOLUTION

Comparison of the ullage pressure solver with the experiments

Sketch of the LN2 tank during sloshing

Pressure evolution of the experiment and computation

Vapor mass evolution of the experiment and computation
**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