Comparison of Computational Results with a Low-g, Nitrogen Slosh and Boiling Experiment

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Outline

• Background and Motivation:
  • Cryogenic fluid behavior in flight conditions
  • Long-term, in-space storage of cryogenic propellants for future exploration missions

• Problem Setup:
  • Geometry & grid
  • Fluent settings
  • Fluid properties (N₂): temperature, pressure dependent?
  • UDF for condensation / evaporation
  • UDF for non-inertial reference frame
  • Time-dependent acceleration and Bond number
  • Boundary conditions
  • Procedure for initial conditions

• Comparison with experimental data:
  • Initial thermal profile
  • Visual comparison with high-speed movie
  • Pressure data: balance of evaporation and condensation
  • Net heat transfer/boiling heat transfer rate
  • Comparison with temperature sensor data
Background & Motivation

• Background:
  • LN2 tank in 2010 low-g parabolic aircraft campaign
  • Significant condensation, evaporation, & boiling
  • Simulation compared to one low-g parabola

• Motivation:
  • Cryogenic fluid behavior in flight conditions
  • Long-term, in-space storage of cryogenic propellants for future exploration missions
Geometry & Grid

- 3-Dimensional grid, 360 degree sector
- Fluid Grid: 569,110 Cells
  - In interior, uniform, structured grid
  - 1 mm resolution
- Solid Grid: 685,858 Cells
  - Unstructured grid
  - Variable resolution
- Thermal isolation at joint, sealing gasket
- Post mounted temperature sensors, not simulated
- Currently, no refinement
- Partitioned for 16 or 32 processors

- Fluid tank dimensions:
  - Radius: ~3 cm
  - Height: ~10 cm
- Slosh frequency:
  - Observed ~4 Hz
  - Calculated 5.0 Hz
Geometry & Grid

- Joint (Thermally Insulated)
- Sapphire Window
- Lid Surface
- Aluminum Lid
- Cryo Cooler
Fluent Setup for Simulations

- Simulations performed using ANSYS Fluent version 13;
- 3D grid of fluid and solid regions
- Mass, momentum, energy, turbulence PDEs
- Compressible, ideal gas; Boussinesq liquid
- Fluid properties of nitrogen for fluid viscosity, thermal conductivity, specific heat, latent heat of vaporization, surface tension at 77.244K, 1 bar from webbook.nist.gov/chemistry/fluid
- Solid: temperature dependent density, specific heat, and thermal conductivity from CNES for inox (stainless steel), aluminum, and sapphire
- Volume of Fluid (VOF) for 2-phase flow
- k-ω SST turbulence model of Menter et. al. (turbulent damping = 10)
- UDF for mass transfer at liquid/ullage interface, boiling, and gas phase condensation
- UDF for non-inertial acceleration,
- Boundary conditions on later slide,

- Second order upwind scheme was used for discretization of the mass, momentum, energy, and turbulence, (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)
- PRESTO! scheme was used for the pressure interpolation (face values)
- First order implicit time discretization was used, also bounded second order implicit
- Time step = 1e-04 seconds
- Extensive instrumentation of the simulation
Temperature & Pressure Dependence of Fluid Properties

- Initially used constant properties for $\mu$, $\kappa$, $C_p$, at 77.244K, 1 bar, but ~10% error
- Range of temperature and pressure: 70-110 K; 1 – 3 bar
- Well represented by simple polynomial in temperature:
  - Viscosity $\mu$, (vapor & liquid)
  - Thermal conductivity $\kappa$, (vapor & liquid)
  - Surface tension, $\gamma$
  - $C_p$ liquid
- Varies with both temperature and pressure:
  - $C_p$ gas
  - Heat of vaporization / condensation
  - $Z$ varies ~8% (Ideal gas assumption)
Evaporation/Condensation UDF

- Mass transfer and heat of vaporization/condensation

- Based on Hertz-Knudsen-Schrage equation:
  \[ \dot{m}_{net} = \frac{2}{2 - \sigma_{cond}} \sqrt{\frac{MW_{vap}}{2\pi R_u}} \left( \sigma_{evap} P_{sat}(T_{liq}) - \sigma_{cond} P_{vap} \right) \]
  kg/s-m²  Evaporation is +ve

- Assume: \( \sigma_{cond} = \sigma_{evap}; \) \( T_{vap} = T_{liq}; \)
- \( \text{Constant}(\sigma) \times (P_{sat}(T) - P)/\sqrt{T}/\text{length\_scale} \) for local P, T
  - Enforces saturation conditions on interface

- UDF Define_Adjust() calculates mass transfer; UDF Define_Mass_Transfer() applies
- Requires kg/s-m³, hence length_scale = sqrt(1/|grad c|²), c is VOF fraction

- Different situations, different accommodation coefficients:
  - Interface condensation, \( \sigma = 1.0 \times 10^{-4} \) is ‘best’ fit
  - Interface evaporation, \( \sigma = 1.0 \times 10^{-4} \) is ‘best’ fit
  - Boiling (liquid phase evap), \( \sigma = 5.0 \times 10^{-3} \) is ‘plausible’ fit
  - Gas phase condensation, \( \sigma = 1.0 \times 10^{-4} \) is used

- Boiling—vaporization away from a liquid/vapor interface:
  - Superheat criteria in each cell: \( T_{\text{max}} - T_{\text{sat}}(P) > 5 \text{ K} \) \( T_{\text{max}} \) is max in cell (walls too)
  - Dry boiling cut-off
- \( P_{\text{sat}}(T) \) by curve fit from Reynolds, *Thermodynamic Properties in SI*
- \( T_{\text{sat}}(P) \) curve fit to NIST data
Non-Inertial Reference Frame UDF

- Non-inertial reference frame accounts for:
  - Linear acceleration of aircraft, \( \mathbf{a} \)
  - Angular rotation, \( \mathbf{\omega} \), and angular acceleration, \( \mathbf{\alpha} \) (not present)

\[
\hat{\mathbf{a}}_{cg} + 2\mathbf{\omega} \times \mathbf{v} + \dot{\mathbf{\omega}} \times \mathbf{r} + \mathbf{\omega} \times (\mathbf{\omega} \times \mathbf{r})
\]

- In general, piece-wise linear fit to \( \mathbf{a}, \mathbf{\omega}, \mathbf{v}_r \) samples

- Here, acceleration, \( \mathbf{a} \), sampled at 2 Hz, 10 Hz
  - Two components: \( a_x, a_z \); assume \( a_y = 0 \)
  - Piece-wise linear fit to supplied \( a_x, a_z \)
  - Initial conditions: steady acceleration
    \( a_x = -16.5 \text{ m/s}^2, \ a_y = 0, \ a_z = -1.93 \text{ m/s}^2 \)

- UDF Define_Source adds terms to RHS of momentum equations as \( \rho \mathbf{a} \), (kg m\(^2\)/s\(^2\)), and RHS of energy eqn. as \( \rho \mathbf{a} \cdot \mathbf{v} \), (kg m\(^3\)/s\(^3\))

- Fluent has trouble with microgravity
  - Issues at \( O(\ a/g ) \sim 10^{-6} \)
  - No issues at \( O(\ a/g ) \sim 10^{-5} \)
Simulation Conditions: Bond Number

Bond number:
- Range \([ 0.3, 6. ]\)
- Mean 2.
- \(O(1)\) for 10 s
- Surface tension forces/body forces
- Eötvös number

Acceleration due to gravity at 10 Hz supplied by CNES
- 2 components: \(g_x, g_y\)
Boundary Conditions

- Heat fluxes total ~4 W
- Assumed constant on surface of each part
- Due to radiation & conduction
- Liquid-to-vapor contact angle: 5 degrees
- Initial constant acceleration:
  - $a_x = -16.4993 \, \text{m/s}^2$; $a_x/g = -1.682$
  - $a_y = 0$.
  - $a_z = -1.9325 \, \text{m/s}^2$; $a_z/g = -0.197$
- Initial interface
  - Position: ~60 mm from bottom
  - Angle: from initial acceleration
Initial Thermal Conditions

- Initial conditions by transient fluid-thermal simulation
  - Constant gravity
  - 90 s with time step of $4.0 \times 10^{-4}$ s
- Thermal isolation at joints
Vapor and sealing gasket create insulation (high temperature gradient)

- Inox lid heats up in high-g interval with vapor at top
- With low-g, re-orientation, liquid impinges on hot lid, and boils
- Heat Transfer: surface boiling, departure of bubble, condensation
- Heat transferred into well-mixed liquid with high heat storage capacity
Section 2: Comparison with Experimental Data

• Initial temperature profile
• Visual comparison with high-speed movie
• Pressure data: balance of evaporation and condensation
• Net heat transfer/boiling heat transfer rate
• Comparison with temperature sensor data
Initial Thermal Conditions

| Top Lid Center | t12a | 30.4 | 0.3 |
| Top Lid Edge | t12b | 15.2 | 3.4 |
| Top Lid Side | t12c | 4.4 | 0.9 |
| t12d | 4.2 | 0.9 |
| t12e | 3.5 | 0.0 |
| t12f | 3.4 | -0.1 |
| t12g | 3.3 | -0.2 |
| t12h | 3.3 | -0.2 |
| t12i | 3.2 | -0.2 |
| t12j | 3.0 | -0.3 |
| t12k | 2.6 | -0.1 |
| t12l | 2.6 | 0.4 |

- Discrepancy near t12b in high temperature gradient: gasket modeling?
- Discrepancy near t12l and lower lid: specified heat fluxes?
Initial Re-orientation of Surface

- 00:14 in data
- T=93.5 s in CNES_5C_7
Heavy Boiling Phase with Condensation and Transit

00:26 in data

T=96.75 s in CNES_5C_7
Condensation and Evaporation: Both Large, Almost Cancel
Pressure Evolution

\[ \sigma_{\text{evap}} = \sigma_{\text{cond}} = 1 \times 10^{-4} \]

\[ \sigma_{\text{evap}} = \sigma_{\text{cond}} = 2 \times 10^{-4} \]
Internal Energy: A Measure of Heat Transfer

Is Boiling Heat Transfer Rate Correct?

\[ \int_{\text{vol}} \rho_{\text{liq}}(T - T_{\text{ref}}) C_{\text{v liq}} \nu_{\text{liq}} d\text{Vol} \]

- Liquid Delta Internal Energy
- Vapor Delta Internal Energy
- Ax/g

Estimated \( \Delta \text{Internal Energy from Experiment: 1050 J} \)
Results: Wall Temperatures
Results: Temperature Sensor T12G

![Graph showing temperature changes over time for T12G, CNES T12G, and Ax/g.]
Fluid Temperature on Midplane

Time = 89.994
Results: Temperature Sensor T12A
Temperature Sensors: Dry-to-Wet, Wet-to-Dry

- Diode sensors time constant: $\tau = 0.1$ s
- 95% in 3 time constants, $\tau$
- Hot gas exposure duration is 0.3 – 0.5 s (one-way)
- Wet-to-dry transition includes a liquid film that must vaporize, before gas
- Wet-to-dry time delays observed experimentally
Sensors: Wet-to-Dry With Drainage

- Temperature discrepancy between T12a sensor (top) and simulation
- After low gravity phase (final re-orientation), as lid should be heating vapor to create a stable thermal stratification
- Experimental geometry is different: fill line and valve
- Wet-to-dry transition complicated by drainage?
- Drainage of liquid visible, in experiment, 2 s after final re-orientation
- Some simulations show waves in thermal stratification, others do not
Summary

- Presentation: setup of Fluent and comparison with experimental results
  - Initial temperature profile
  - Visual comparison with high-speed movie
  - Pressure data
  - Net heat transfer/boiling heat transfer rate
  - Comparison with temperature sensor data

- Generally, good agreement with experimental data

- Evidence for low sensitivity of wet-to-dry temperature sensors

- Limitations of boiling model

- Limitation in prediction of condensation / evaporation

- Future work:
  - Further analysis of thermal layers near fluid/vapor interface
  - Grid resolution studies