CFD Modeling of the Multipurpose Hydrogen Test Bed (MHTB) Self-Pressurization and Spray Bar Mixing Experiments in Normal Gravity: Effect of Accommodation Coefficient on the Tank Pressure

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Overview

- Problem Description
- Computational Model Description
- Results
  - Self-Pressurization of MHTB Tank
  - Cooling of MHTB Tank using Spray
- Conclusions
- Future Work
Introduction

- Affordable and reliable cryogenic storage for use in propellant systems is essential to meeting NASA’s future exploration goals.

- Cryogen mass loss occurs when heat leaks into the tank from the surroundings.

- Heat is carried to the interface by natural convection currents $\rightarrow$ evaporation $\rightarrow$ vapor compression $\rightarrow$ rise in tank pressure.

- Pressure control is necessary to keep tank pressure within design limits (venting or active control)

- Predicting self-pressurization and depressurization rates is important for designing future tanks and pressure control systems.
Problem Description: MHTB Self-Pressurization and Spray Bar TVS Ground-Based Experiment

Tank Internal volume 37.5 m³

Cylindrical midsection with:

height = 3.05 m
diameter = 3.05 m

2:1 elliptical end caps

Tank is enclosed in a vacuum shroud

4 spray bar tubes attached to center tube heat exchanger

NASA TM-212926, 2003

Goal of this work is to simulate first self-pressurization and then cooling of the tank via spraying cold liquid into the vapor using ANSYS Fluent Lagrangian Spray model combined with in-house developed UDFs
Problem Description: Modeling Approach

2D axisymmetric

Before starting spray run, 2D-axi results interpolated to 3D grid and self-pressurization continued for a short time to ensure no problems.

3D 90° sector

Self-pressurization simulation performed on 2D-axisymmetric grid. Spray Bar Mixing simulation will use 3D 90° sector grid. Spray-Bar/Heat Exchanger assembly is approximated as lying along centerline.
Computational Model Description: Equations Solved

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

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

Energy: \[
\frac{\partial}{\partial t} (\rho E) + \nabla (\rho (E + p)) = \nabla (k_{\text{eff}} \nabla T) + S_h
\]

Volume of Fluid (VOF) model:

Energy and Temperature are defined as mass average scalars: \[
E = \sum_{q=1}^{2} \alpha_q \rho_q E_q
\]

Properties: \[
\rho = \sum_{q=1}^{2} \alpha_q \rho_q, \quad \mu_{\text{eff}} = \sum_{q=1}^{2} \alpha_q \mu_{\text{eff} q}, \quad k_{\text{eff}} = \sum_{q=1}^{2} \alpha_q k_{\text{eff} q}
\]

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

Continuum Surface Force (Brackbill et al.): \[
F_{\text{vol}} = \sum_{\text{pairs } i, j, i < j} \sigma_{ij} \frac{1}{2} \left( \rho_i + \rho_j \right) \frac{\alpha_i \rho_i h_i \nabla \alpha_j + \alpha_j \rho_j h_j \nabla \alpha_i}{h_i}
\]

where \( h_i = \nabla \cdot \hat{n} \)

Interfacial mass transfer per unit volume: \[
S_{\alpha_q} = \vec{m}_i \cdot A_i \left[ \frac{kg}{m^3 \cdot \text{sec}} \right]
\]

where \( A_i = |\nabla \alpha| \), is an interfacial area density in 1/m, \( \vec{m}_i \) is a mass flux vector in kg/(m^2·sec).

where \( \alpha \) is a volume fraction of the primary phase
Schrage’s Relation: \[ |\dot{m}| = \left( \frac{2\sigma}{2 - \sigma} \right) \left( \frac{M}{2\pi R} \right)^{1/2} \left( \frac{P_i}{T_i^{1/2}} - \frac{P_v}{T_v^{1/2}} \right) \]

where
- \(\sigma\) – accommodation coefficient
- \(M\) – 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 \(T_i = T_v \approx T_{sat}\) at the interface)

Particle Energy Equation:
\[ m_p c_p \frac{dT_p}{dt} = h \cdot A_p (T_\infty - T_p) - L \dot{m}_p \]

UDFs used:
- VOF (DEFINE_MASS_TRANSFER)
  - Calculate mass transfer using Schrage relation and supply it to Fluent for phase interaction at the interface
- Lagrangian spray (DEFINE_DPM_SCALAR_UPDATE, DEFINE_SOURCE)
  - Perform particle tracking in the vapor, remove particles from the vapor domain when they reach the interface and add their contributions to the liquid through source terms.
  - Define sources for the spray bar liquid jets.
  - Model heat and mass transfer between particles (droplets) and vapor
Computational Model Description: Numerical Methods

- Simulations performed using ANSYS Fluent version 16
- **2D-**Axisymmetric formulation for self-pressurization; **3D 90°** sector for Spray cooling study
- Compressible ideal gas
- Laminar or k-ω SST turbulence model of Menter et. al
- Temperature dependent properties for vapor and liquid viscosity and thermal conductivity; vapor specific heat
- Interfacial mass transfer and mass transfer between droplets and continuous phase (vapor) is modeled based on Schrage’s relation via user’s subroutine
- Surface tension effects via Continuum Surface Force method of Brackbill et al.
- Contact angle for hydrogen 0°

- Second Order Upwind scheme was used for discretization of the Turbulence, Energy and Momentum 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
- Bounded Second Order Implicit temporal discretization was used with implicit VOF model; First Order Implicit scheme was used with explicit VOF model
Computational Model Description: Grid

3D 90° sector (184400 hex cells)

- First row: 0.0094 m
  - Growth Factor: 1.05
  - Number of Rows: 17

- First row: 0.002 m
  - Growth Factor: 1.2
  - Number of Rows: 14

- First row: 0.002 m
  - Growth Factor: 1.2
  - Number of Rows: 10

- Number of Intervals on the Vapor Side: 136
  - Average Interval size: 0.02 m

- Number of Intervals: 151
  - Average Interval size: 0.025 m

- Number of Intervals: 64
  - Interval size: 0.02 m

- Number of Intervals on the Liquid Side: 97
  - Average Interval size: 0.03 m

- Number of Intervals: 20
  - Interval size: 0.12 m

On all tank walls $y^+ < 5$
Computational Model Description: Initial Conditions

Self-Pressurization
- \( T \) field from experimental data
- Velocity = 0.0 m/s
- Turbulent Kinetic Energy (in a turbulent run) = \( 1.0 \times 10^{-6} \) m\(^2\)/s\(^2\)
- Specific Dissipation Rate = 100 l/s
- Interface initialized at 50% or 90% liquid fill level
- 2D axisymmetric

Spray
- \( T, V, \text{vof} \) fields from the end of self-press simulation interpolated on to 3D 90 degree sector mesh
Self-Pressurization and Spray
- Tank centerline: Axis

Spray
- Spray Bar Wall: Adiabatic
- 21 spray injections: Plain Orifice Atomizer with 4 particle streams; with constant $T = 21.088 \, \text{K}$
- 22 liquid jets: Point sources for mass, momentum and energy

Self-Pressurization and Spray
- 0° contact angle for hydrogen

Spray
- Pump: Area averaged sink for mass, momentum and energy

Tank Walls: Uniform heat flux:
- 15.35 W (0.89873 W/m²) – vapor
- 35.65 W (2.0841 W/m²) - liquid

Computational Model Description:
Boundary Conditions

0.03175 m
Injection type: **plain-orifice atomizer** with 4 particle streams per injection

- **Inert particle** (coupling with continuous phase for mass transfer done in the UDF)

- **Standard parcel release method** (releases one parcel per injection stream, calculates number of particles based on the mass flow rate of the particle stream)

- Injection material is **liquid hydrogen** with constant properties at T=21.088K

- **Two-way coupling** with continuous phase; unsteady particle tracking with flow time step

- Particle **breakup** model

- **Spherical** drag law model

- **Variable flow rate** based on experimental data

- Injector inner diameter = 0.001702 m

- Orifice length = 0.000711 m

- Turbulent dispersion of particles: **Discrete Random Walk model**
CFD Results:
MHTB Tank Self-Pressurization
CFD Results: MHTB Tank Self-Pressurization - Accommodation Coefficient Effect

Medium Grid: 9,246 cells
CFD Results: MHTB Tank Self-Pressurization - Accommodation Coefficient Effect

Implicit VOF

Explicit VOF
CFD Results:
Cooling of MHTB tank using Spray
CFD Results: Cooling of MHTB Tank using Spray - Effect of Turbulence Modeling
CFD Results: Cooling of MHTB Tank using Spray - Results of the Turbulent VOF Model

Time [s] = 1.00
CFD Results: Cooling of MHTB Tank using Spray - Results of the Turbulent VOF Model
CFD Results: Cooling of MHTB Tank using Spray - Results of the Turbulent VOF Model

Droplet and temperatures at the center plane of injections
CFD Results: Cooling of MHTB Tank using Spray - Results of the Turbulent VOF Model

Droplet and vapor temperatures and streamlines at the center plane of injections
Temperature at the horizontal plane in the vapor
CFD Results: Cooling of MHTB Tank using Spray - Results of the Turbulent VOF Model

Location of the spray bar relative to the temperature measurement rake
CFD Results: Cooling of MHTB Tank using Spray - Results of the Turbulent VOF Model

![Graph showing distance from the tank bottom vs. temperature (K) for experimental and CFD results.]

- **Laminar 34 seconds**: Temperature distribution for laminar conditions after 34 seconds.
- **Turbulent 34 seconds**: Temperature distribution for turbulent conditions after 34 seconds.

![Graph showing temperature vs. time after beginning of spray for experimental and CFD results.]

- **TD1**
CFD Results: Cooling of MHTB Tank using Spray - Results of the Turbulent VOF Model
CFD Results: Cooling of MHTB Tank using Spray - Results of the Turbulent VOF Model
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[Graph showing pressure over time after the beginning of spray, with different lines representing different models and a legend indicating experimental data and various model configurations.]
Conclusions

Self-Pressurization

- A CFD model was developed for modeling self-pressurization of MHTB tank using **compressible VOF** model with custom model for **mass transfer** between liquid and vapor phases.
- Varying accommodation coefficient from 0.1 to 0.0001 had very little effect on the tank pressure predictions. Explicit VOF model allowed use of larger value of accommodation coefficient with a need to reduce time step size when the highest value was used.

Spray Cooling

- A CFD model was developed for simulating spray cooling of MHTB tank using **compressible VOF** with **Lagrangian Spray** model.
- The laminar and turbulent VOF models resulted in very similar tank pressures that agree well with experimental data.
- The droplets reduce temperature and promote mixing in the vapor region via heat and mass exchange during spray. Temperature of the droplets increases when they travel in the vapor towards the interface. Passage of the droplets creates a hot spot in the areas of higher droplet concentration in the middle of the vapor region.
- Droplet accommodation coefficient had significant effect on the tank pressure decrease with the higher values resulting in faster pressure drops.
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