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Investigating the Effects of Heat Ingress and Tank Motion on the Ullage Space of a Partially Filled Liquid Hydrogen Tank Using CFD

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ABSTRACT

Cryogenic fuel tanks used in ships are continuously subjected to heat ingress and motions which affect the thermal behavior of the fluid inside the tanks. In this study, the ullage space of a liquid hydrogen (LH2) tank subjected to heat ingress and periodic rolling motion is analyzed using Computational Fluid Dynamics (CFD). A two-dimensional transient model utilizing the dynamic mesh approach is created to represent the ullage space of a partially filled LH2 tank. Three cases are studied where the properties of the thermal insulation of the tank model are varied, resulting in a different heat ingress for each case. A low-frequency motion is applied to the model domain, which induces mixing of temperature layers and cooling due to vapor contact with wetted walls. After 60 s of tank motion, most mixing is observed in the case with the smallest heat ingress, whereas in the cases with larger heat ingress and, consequently, larger thermal and density gradients, separation into a warmer and colder vapor region can be observed. The model developed in this work can be used to gain insight into how liquid hydrogen tanks used on ships are affected by heat ingress and ship motions.

Keywords: Computational Fluid Dynamics, Hydrogen, Heat Ingress, Tank Motion, Cryogenic Fuel Tank

INTRODUCTION

Hydrogen is considered a potential fuel in the shipping industry to mitigate greenhouse gas emissions from the propulsion system. Like natural gas, hydrogen can be liquefied to increase its energy density and stored in cryogenic tanks; this requires cooling down the hydrogen to temperatures around 20 K. Even with efficient thermal insulation, LH2 tanks are affected by heat ingress leading to boil-off and thermal stratification [1, 2]. Ship motions, on the other hand, can cause mixing and destratification of the fluid, which affects e.g. the tank pressure. Understanding fluid behavior under such conditions is crucial for safe operation and design of the fuel tanks.

Various studies have been conducted on fluid behavior in cryogenic tanks. Kang et al. [3] used Finite Element Analysis to investigate thermal stratification in liquid cryogen tanks and the effects of thermal aspect ratio. S B et al. [4] conducted experiments on thermal stratification and pressurization in a partially filled liquid nitrogen (LN2) tank and developed a CFD model to predict fluid behavior in the tank. Jeon et al. [5] performed experiments on the thermal behavior and generation of boil-off gas in a Type C LN2 tank and conducted numerical simulations using CFD.

Furthermore, Jeon et al. [6] conducted experiments on the Type C LN2 tank subjected to rolling motions and presented a multiphase CFD model using the volume of fluid (VOF) method and a phase change model to predict the effects of liquid sloshing in the tank, while Liu et al. [7] implemented the VOF method to investigate the effects of intermittent external excitations on the thermal performance in a liquid oxygen tank.

Most of these studies implemented two-phase models and either simulated the thermal stratification phenomenon in stationary tanks or the response to motions in tanks with initially uniform fluid temperatures. However, not many studies have been conducted on the effects of tank motions on an initially thermally stratified ullage space of a cryogenic fuel tank through

computational methods.

In this study, CFD modelling with dynamic mesh is used to simulate the fluid behavior in the ullage space of an LH2 tank subjected to external heat input and rolling motion. The vapor phase is modelled exclusively for detailed prediction of thermal behavior in the ullage while limiting the required mesh size and avoiding additional computational costs from including the liquid phase. The resulting model is used to demonstrate how mixing affects the thermal behavior of the vapor phase in an LH2 tank with different heat ingress and temperature gradients. Furthermore, the modelling approach in the present work is validated against experimental cases and datasets sourced from previous studies. Thermal stratification in the ullage is validated against experiments in a stationary LN2 tank [8], while the effect of tank motion is validated against experiments performed in a pressurized hot water-water vapor tank [9].

METHODOLOGY

Model LH2 Tank Concept and System Boundary Conditions

A Type C cryogenic storage tank with double-walled vacuum insulation filled with perlite powder is used as the tank concept and visualized in Figure 1. The design choices made here are assumptions and estimates based on literature findings for LH2 tanks [1, 2, 10].

The tank has an inner length and diameter of 1500 mm and 500 mm, respectively. Stainless steel of the grade 316L is used as wall material for both the inner and outer wall, which both have a thickness of 3.5 mm, while the thickness of the annular space between the walls is 100 mm. The liquid filling level of the tank is 50%, with the pressure inside the tank at 4 bar and liquid temperature as well as initial gas temperature at 26 K, while the temperature of the outer wall is set at 288 K. In the CFD simulations, the tank is modelled using a two-dimensional representation.

In total, three cases are considered in this work, where the thermal boundary conditions are varied for each case by adjusting the thermal conductivity of the insulation. Ratnakar et al. [10] investigated the effective thermal conductivity of various insulation materials for cryogenic storage tanks and considered different vacuum levels in their study. The conductivity values used for the tank insulation in this work are taken within the ranges presented in the study for perlite powder vacuum insulation. Here, the thermal conductivity of the insulation is assumed to be varied by adjusting the vacuum level in the annular space.

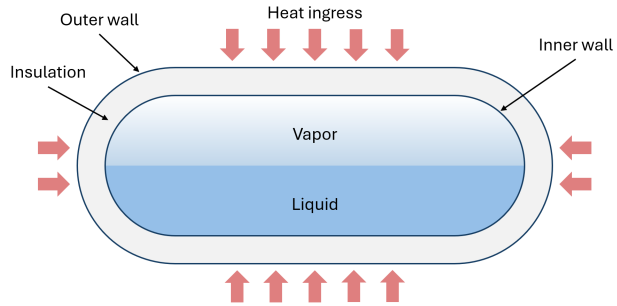


Figure 1. Design concept of the model LH2 tank.

The thermal conductivity of the walls and insulation, as well as the total thermal conductivity for the entire wall structure in each case are summarized in Table 1. The heat transfer rates into the liquid zone and the boil-off rates are given in Table 2. These are calculated based on the heat conduction through the walls to the liquid zone with inner wall temperature of 26 K.

Table 1: Thermal conductivity of the inner and outer walls (k_w), insulation (k_{ins}) and the total thermal conductivity (k_{tot}).

	Case 1	**Case 2**	**Case 3**
k_w [W/(m²•K)]	15	15	15
k_{ins} [W/(m²•K)]	0.0005	0.001	0.002
k_{tot} [W/(m²•K)]	0.000535	0.00107	0.00214

Table 2: Heat transfer rate into liquid (Q_l) and boil-off rate at the liquid surface (m_{evap}).

	Case 1	**Case 2**	**Case 3**
Q_l [W]	2.3	4.7	9.4
m_{evap} [kg/s]	$5.2 \cdot 10^{-6}$	$1.0 \cdot 10^{-5}$	$2.1 \cdot 10^{-5}$

For the tank motion simulations, a periodic rolling motion is applied to the model domain to simulate the motions of a moving ship. In each case, the amplitude is 10° and the period is 12 s. The liquid surface remains flat throughout the motion. This can be seen as an approximate representation of a tank with floating baffles to mitigate sloshing. Furthermore, the tank motion causes wetting of wall surfaces, where wetted surfaces are assumed to have the same temperature as the gas-liquid interface (26 K). Figure 2 shows the ullage at different stages of the tank motion and the direction of gravity perpendicular to the liquid surface. This approach for modelling the ullage and gravity during tank motion allows for simpler implementation of the dynamic mesh while maintaining realistic domain geometry and gravity conditions.

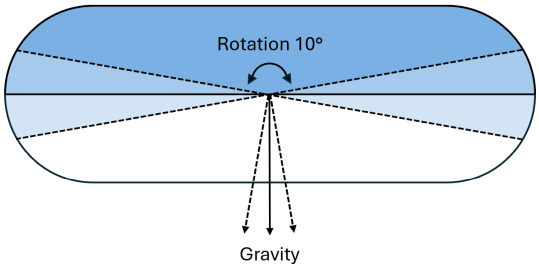


Figure 2. Ullage position at different points of the tank motion.

Numerical Model

CFD analyses of the three cases are conducted using the Ansys Fluent 2024 R1 software. A two-dimensional transient model with dynamic meshing is created to represent the vapor phase inside the tank. The simulations are performed in two parts: Part 1: the formation of the thermal gradient in the ullage due to heat ingress and natural convection, and Part 2: the tank motion and its effect on the thermal gradient is investigated.

Part 1: Thermal Gradient

The fluid domain consists of hydrogen gas surrounded by the tank walls and the liquid surface at the bottom. For the first part of the simulations, the domain is not moving, and the liquid surface is modelled as a wall with a mass source term to represent boil-off. A pressure outlet of the size 10 mm is set at the middle of the top wall to maintain the tank pressure close to 4 bar. The boundary conditions for the walls and liquid surface for each case are set as described in the previous section for computing the thermal gradient.

In the first part, the thermal gradient in the ullage for the static tank is computed. This is conducted by first calculating the thermal gradients for steady state conditions for a low Rayleigh value by reducing gravity and, subsequently, switching to a transient model and incrementally increasing gravity to normal conditions. This approach is to prevent the solution from diverging. The simulations are run until the temperature gradients become stable, using a time step of 0.01 s.

Part 2: Tank Motions

Results from the first part of the simulations are then used as the initial conditions for the tank motion simulations. The dynamic mesh method with user-defined functions for the mesh motion is applied to represent the motion and change in shape of the vapor domain over time, see Figure 2. The direction of gravity is also set to follow the motion so that it is always perpendicular to the liquid surface. For the tank motion simulations, the domain is closed. The mass source term for the liquid surface is set to zero, which means that the vapor mass will remain constant. Furthermore, the wetted parts of the walls are set at the same temperature as the liquid surface. The time step used here is 0.005 s.

Solver Settings

The effects of heat ingress and buoyancy are considered by enabling the energy equation and using the ideal gas law for fluid density to solve the thermal gradients. The governing equations used in the model are continuity, momentum and energy conservation. Species transport is also used to account for the mass source term at the liquid surface, and the fluid flow is modelled using the k-ω SST turbulence model with near-wall treatment. Furthermore, the pressure-based transient solver with PRESTO! pressure discretization scheme and PISO algorithm are used for the solver settings. The convergence conditions for the residuals are set as 10^{-6} for energy and 10^{-5} for continuity and transport equations.

METHOD VALIDATION

Before modelling the LH2 cases, the model was validated against experimental data from the literature. Firstly, the model for developing the thermal gradient in the static ullage was validated using experiments reported by Singh et al. [8], where they measured the vertical temperature gradient inside an LN2 tank at atmospheric conditions with liquid filling levels of 57%, 69% and 77%, with heat ingress of 0.27 W, 0.26 W and 0.29 W into the vapor phase, respectively, as well as a heat ingress of 2.03 W into the liquid for all cases. The tank used in the study consisted of an inner and outer vessel made of aluminum sheets with vacuum multi-layer insulation in between. The inner height of the tank was 360 mm, and the diameter was 300 mm [8]. In the present work, two-dimensional meshes with a mesh size of 5 mm were used to model the vapor phase of each validation case. In Figure 3, results from the simulations are compared to the experimental data from the study by Singh et al. [8].

Secondly, the tank motion model was applied to one of the experiments conducted in the study by Grotle and Æsøy [9]. In their study, they measured the thermal response in a pressurized hot water tank subjected to rolling motions using an amplitude of 3° and various frequencies. The tank used in their study was an insulated cylindrical pressure tank with spherical tank heads and supplied with a heating element. The length of the cylindrical part was 0.89 m, the diameter was 0.35 m, and the tank had a liquid filling level of 50%. Before the tank motion tests, the liquid was heated to 393 K, most of the air was removed and the tank pressure was increased to 4.0254 bar [9]. The tank motion model with the dynamic mesh used in the present work was applied to the hot water tank experiment case with a frequency of 0.13 s^{-1}, where the liquid surface remains flat [9]. A two-dimensional mesh with a mesh size of 5 mm was used to model

the vapor phase of the hot water tank case. In Figure 4, the simulation results using the tank motion model are compared to the experimental data of the pressure reduction in the hot water tank.

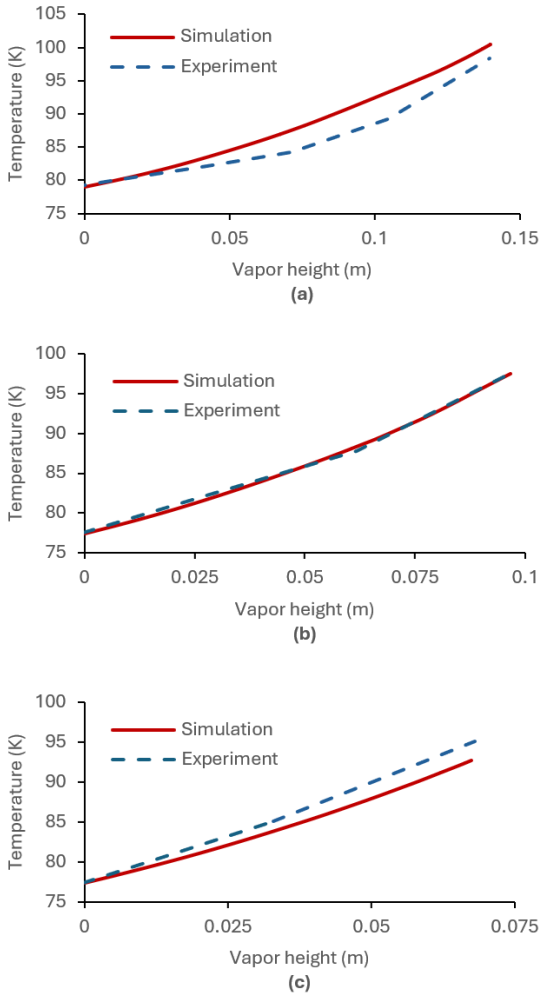


Figure 3. Simulation results for the vertical thermal gradient validated against experimental data for liquid filling levels of (a) 57%, (B) 69% and (c) 77% [8].

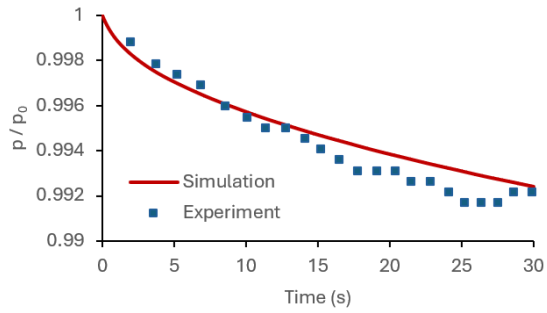


Figure 4. Simulation results for the tank motion model validated against experimental data [9]. Results are for tank pressure over time.

RESULTS FOR LH2 TANK CASES

Mesh Sensitivity Analysis

A mesh sensitivity analysis was conducted to determine the required mesh size for the LH2 tank ullage model. Three different mesh sizes were compared against each other: cell sizes of 2.5 mm, 5 mm and 10 mm with corresponding minimum cell sizes of 0.5 mm, 1 mm and 2 mm around the pressure outlet. The heat transfer rates at the tank walls and the vertical temperature gradients for the different mesh sizes were investigated for Case 2, see Table 1 and 2. The difference between the heat transfer rates was less than 1% between all cases and Figure 5 reveals that the temperature gradients were almost identical. A mesh size of 5 mm is chosen for this study to balance accuracy and computational costs.

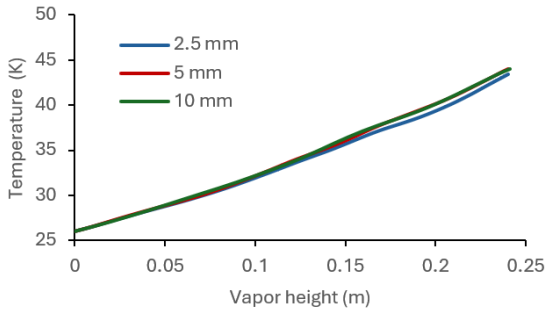


Figure 5. Vertical temperature gradient in LH2 tank ullage computed for mesh sizes 2.5 mm, 5 mm and 10 mm.

LH2 Tank Ullage Simulations

The initial temperature gradients for Case 1, 2 and 3 at stationary conditions were established using the method described earlier. In each case, the transient run was 120 s in total, at which point the gradients had reached a steady state. The temperature contours of the ullage for Case 1, 2 and 3 with the initial thermal gradients are shown in Figure 6(a1), (b1) and (c1), respectively. The time is marked as 0 s to indicate the initial state for the tank motion runs. Furthermore, the corresponding vertical thermal gradients for each case are shown in Figure 7(a). The sizes of the thermal gradients are 10.9 K, 18.7 K and 29.6 K for Case 1, 2 and 3, respectively. These are dependent on the total thermal conductivity values of the tank walls and the associated heat ingress into the tank.

Once the initial thermal gradients were computed, the dynamic mesh method was applied and the tank motion cases were computed for a total run time of 60 s, or five complete oscillations of 12 s periods. The temperature distribution in the ullage for each case at the start and the end of the moving tank runs are shown in Figure 6(a2), (b2) and (c2), and the corresponding vertical temperature gradients are shown in Figure 7(b).

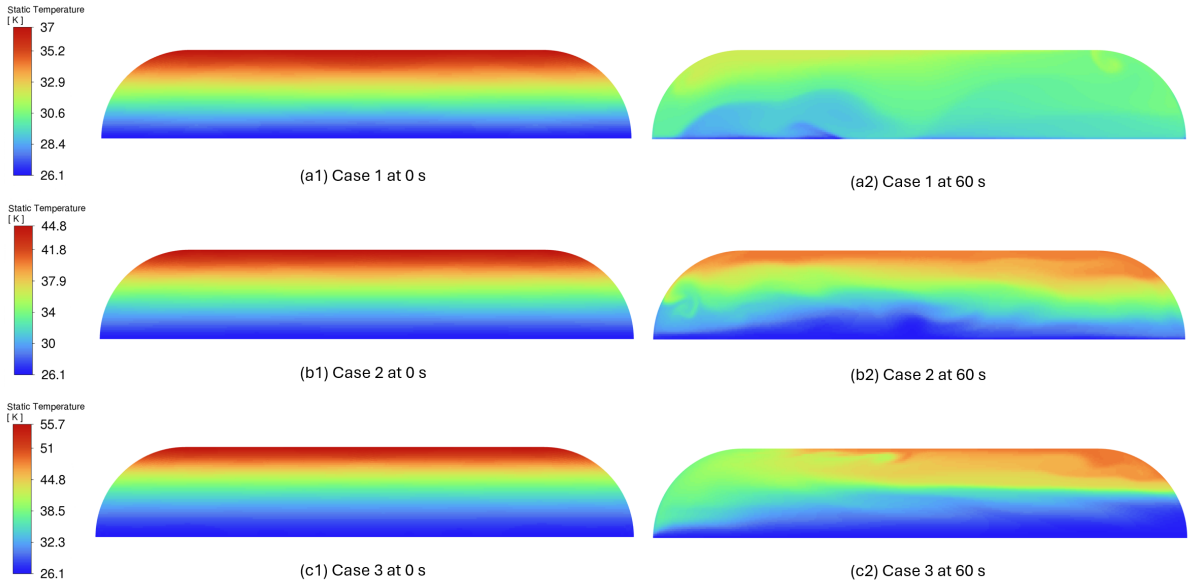


Figure 6. Temperature profile of the ullage at stationary conditions ((a1), (b1) and (c1)), and after 60 s of tank motion ((a2), (b2) and (c2)).

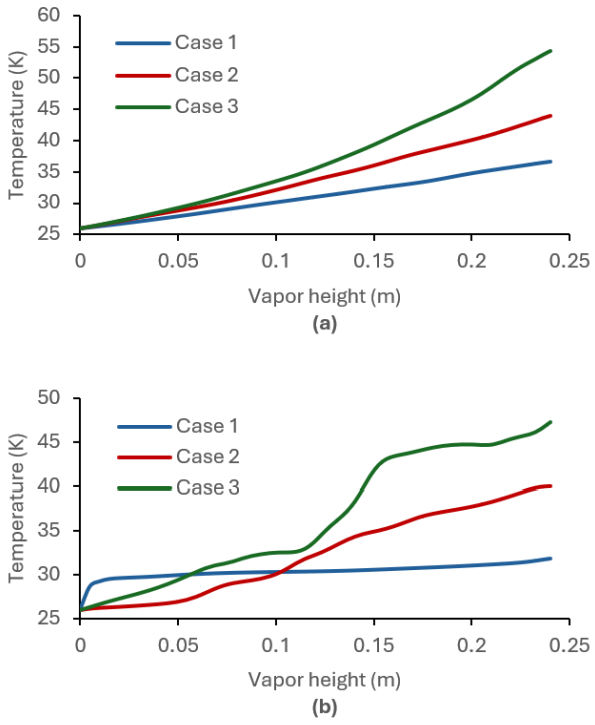


Figure 7. Vertical thermal gradient in the ullage for Case 1, 2, and 3 with (a) initial thermal stratification and (b) after 60 s of tank motion.

After 60 s of tank motion, there is a significant reduction in overall temperature and some mixing of temperature layers in all cases. Most mixing can be observed for Case 1, which also has the smallest initial temperature gradient. This is expected behavior, as a smaller temperature difference also means a smaller difference in density between fluid layers, which enhances mixing. For Case 3, on the other hand, the thermal gradient can be seen separating into two fluid layers around the middle of the domain: the denser cold zone at the bottom and the warmer zone with lower density on top. Case 2 also shows separation between fluid layers, although not as clearly as Case 3 and it still has moderate mixing between cold and warm zones.

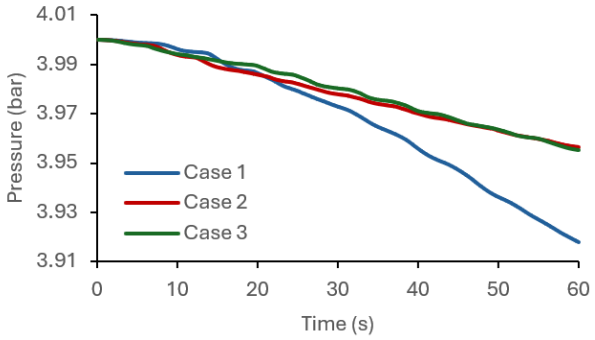


Figure 8. Tank pressure over time for Case 1, 2, and 3.

Furthermore, the vapor cooling also causes a reduction in the domain pressure, as shown in Figure 8. Case 1 has a significantly larger pressure reduction compared to Case 2 and 3, which have a similar pressure evolution to each other over time. The mixing and destratification of fluid layers in Case 1 allows warmer fluid to come into

contact with wetted walls and the liquid surface, resulting in more efficient heat transfer from the vapor to the liquid, and consequently, a larger pressure reduction. Both in Case 2 and 3, the fluid separation into two density layers hinders the mixing of the fluid and the subsequent heat transfer from vapor to liquid, slowing down the pressure reduction rate.

CONCLUSIONS

A numerical investigation on the effects of heat ingress and ship motions on the thermal behavior in the ullage of an LH2 tank was conducted using CFD modelling with dynamic meshing. Three cases were studied, where the thermal conductivity value of the tank insulation was varied and the subsequent response to the thermal gradient and destratification effect due to rolling motion was analyzed. Varying the thermal conductivity value of the insulation affected the size of the temperature gradient. It was observed that for the case with the smallest temperature gradient, the tank motion resulted in destratification and an almost uniform temperature profile in the ullage within five complete oscillations. In the other two cases, the larger difference in density between fluid layers caused separation into cold and warm fluid regions. The results of this work demonstrate the effects of heat ingress and ship motion on the ullage space of an LH2 fuel tank by varying the properties of the thermal insulation. The developed model can be used for further investigations of similar effects in cryogenic tanks.

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