Evolution of stratification in a cryogenic propellant tank at reduced gravity environment

Vishnu S.B, Biju T Kuzhiveli
Centre for Advanced Studies in Cryogenics
National Institute of Technology Calicut, Kerala, India, 673601
E-mail:vishnusb90@gmail.com

Abstract. The prediction of thermal stratification in a cryogenic storage tank is necessary for the successful execution of space mission. The working fluid may be stored in the sub-cooled conditions and possibility of heat infiltration may lead to the increase of temperature as well as the pressure of the cryogenic fluid. The rise in fluid pressure may also lead to cavitation in the turbo pump which has to be avoided. Commonly used stratification models are based on temperature and velocity correlation developed for flow over a flat plate. An experimental cryogenic test tank is designed, fabricated and stratification is studied using nitrogen as the model propellant. The effect of gravity on the evolution of stratification is studied by using a CFD model. The results show that the fluid velocity will be lesser at microgravity condition which causes the boundary layer fluid to absorb a large amount of heat and the nature of the heat transfer changes from convection to evaporation.

1. Introduction
Prolonged storage of cryogens is very much essential in conducting advanced space missions. To reduce the overall weight of the structure, the cryogens are stored in foam insulated tanks. So there will be heat infiltration from the surrounding to the cryogen. Since the cryogens are stored at their near boiling temperature, a very small amount of heat in leak may affect its state. Due to the heat in leak from the ambient or through the support structures, the liquid near the tank wall will heat up and a boundary layer will form (figure 1). The warm fluid inside the boundary layer will move up due to the density difference and deposited the heat energy at the liquid-vapour interface. So a high-temperature fluid layer will be developed at the liquid-vapour interface which is known as a thermally stratified layer and this phenomenon is known as thermal stratification.

The stratification phenomena inside a cryogenic tank lead to self-pressurization. Because the temperature at the liquid-vapour interface determines the pressure inside the tank. In order to maintain the tank pressure within a limit, successive venting is required. It leads to cryogen loss and additional cryogen has to be loaded which is a liability. For cryogenic engines, the state of propellant at the inlet of turbo pump or propellant feed system is very much important. If the stratum fluid is allowed to enter into the turbo pump, there is a great possibility that the fluid temperature will be above the cavitation limit which leads to mission failure.

Since the storage and transfer of cryogen involves complexity, a number of efforts have been made to study the self pressurization and fluid temperature distribution. For past 60 years, Tatom et al. [1] conducted experimental studies to find out the evolution of stratification in a liquid hydrogen tank. The effect of bottom heating on self pressurization was studied by Fan et al. [2] and concluded that controlled bottom heating can reduce the stratification. C. Ludwig et al. [3] conducted experiments using liquid nitrogen to study the effect of periodic lateral forces on tank pressure. The effect of insulation thickness, wind velocity and sub cooling on stratification was investigated by Jeswin Joseph et al [4] by developing
a computational model using SINDA/FLUINT package. Zhan Liu et al [5] developed a CFD model to investigate thermal stratification at different microgravity condition and compared the CFD results with two theoretical models ie, Reynolds [6] and Tellep [7].

2. Experimental set up
A schematic representation and actual experimental set up used for stratification studies are shown in figure 2 and figure 4 respectively. A high-pressure stainless steel test tank which is capable of handling internal pressure up to 8 bar is designed and fabricated for the experimentation (figure 3). Multilayer insulation and vacuum insulation is used for preventing heat infiltration from the surrounding. Liquid nitrogen is filled inside and allowed to stratify. The cryogen reservoir and ambient is separated by vacuum chamber for insulation purpose. The vacuum maintained inside the chamber is of the order of $10^{-6}$ Torr. Such degree of vacuum will reduce the gas conduction heat load from vacuum jacket (at room temperature) to the cryogen vessel. A turbo molecular vacuum pump coupled with the rotary pump is used for evacuating the vacuum chamber. A custom-made vacuum jig is used for the simultaneous evacuation and sealing purpose. Both Pirani and ionization gauges are used for the vacuum measurement. To measure the self-pressurization inside the tank, Unik 5000 series pressure transducer is used. To measure the stratification inside the tank, temperature at different liquid height is to be noted. For that purpose, 16 numbers of PT100 sensors are placed inside a small stainless steel tube and these sensors are separated vertically by 80 mm. The outputs from the sensors are connected to the data acquisition system provided by National Instruments in which readings are stored at an interval of 5 seconds.

The test tank for this set up is made of SS 304 with an aspect ratio of approximately 14. The cryogen reservoir and vacuum jacket are the important components of the vessel. The reservoir is having an inner diameter of 108.2 mm and height 1400 mm. The thickness of the wall is 3 mm which is designed to operate an internal pressure of 8 bar. Two pressure relief valves are provided at the top side of the vessel to relieve the pressure inside the cryogen reservoir in case of any vacuum and internal leak (figure 5). Any sort of vacuum or vessel leak may lead to the direct contact between the liquid cryogen and surrounding air which leads to over pressurization. Relief valves will operate if the internal pressure exceeds the design pressure of 8 bar. Two NW40 vacuum ports are provided for the evacuation and vacuum measurement purpose. 20 layers of multilayer insulation which consist of alternate layers of fibre glass papers and aluminium foil are wrapped around the inner vessel to reduce the radiation heat infiltration.
3. CFD Model
A 2D axis symmetric multiphase model is developed to study the evolution of stratification at normal and microgravity conditions. Commercial CFD package Ansys 15 is used for the simulation. The tank considered is cylindrical with a 0.5m diameter, 1m height and 0.003m thickness. Since the flow is turbulent in nature, k-ε turbulence model with enhanced wall function is applied. A constant heat flux of 10W/m² is applied at the side wall and top and bottom as adiabatic.

SIMPLEC (Semi Implicit Method for Pressure Linked Equation- Consistent) pressure-velocity coupling algorithm is selected because of easiness to achieve converged solution than by using SIMPLE algorithm. The momentum equation is solved by body forced weighted average scheme and tracking of the liquid-vapour interface is done with Geometric Reconstruction Scheme. The time step selected is 0.001s because the problem is unsteady and Courant number should be less than 0.1.

Figure 3. Experimental tank with locations of temperature sensors.

Figure 4. Experimental set up

Figure 5. Top side of test tank
The VOF (Volume Of Fluid) method helps to predict the movement of the liquid-vapour interface. The term volume fraction is defined in each cell in such a way that the summation of both liquid and vapour volume fraction gives unity. The CFD model is validated with the experimental result available in the literature [8]. It was found that the model developed over predicts the pressure value for an initial period, but after that was in good agreement.

4. Results and Discussion

4.1 Experimental results

After carrying out the evacuation of the vacuum chamber, liquid nitrogen is poured into the test tank. A large amount of fumes are generated inside the tank and it is allowed to escape to atmosphere through the vent valve provided. After carrying out the initial chilling, the level correction operation is carried out and the final liquid level set is 0.5m from the bottom of the tank. The vent valve is closed and the tank is allowed to self-pressurize. The temperature of liquid and vapour at different elevation is recorded. The measured liquid temperature near the interface is shown in figure 6. A temperature gradient towards the interface is visible and this gradient is known as thermal stratification. The ullage (the additional volume provided inside the cryogenic container to account for the thermal expansion of the cryogen) temperature history is depicted in figure 7. The temperature is increasing along the height of the container in the ullage area. But the temperature history of each sensor shows almost constant value for a time period of 1700 s.

![Figure 6. Evolution of stratification.](image)

![Figure 7. Ullage temperature.](image)
4.2 CFD results
A detailed stratification and fluid motion can be studied by using the CFD model. The simulation is carried out for 150 s and two gravity conditions were simulated. Normal \((g = g_0 = 1)\) and micro gravity \((g = 10^{-3}g_0)\) conditions. The evolution of stratification can be found out from figure 8a. A higher temperature layer is visible near the interface as well as the left side wall. The warm layer at the interface is due to stratification and the left side wall is due to the heat flux applied. From velocity contours (figure 8b), it is clear that there will be lower fluid velocity at microgravity condition and some localized hot spots are visible inside the fluid. This slow heat absorption nature will retard self pressurization initially, but when the local fluid enthalpy value exceeds the required energy for phase change, localized boiling takes place. It can be identified in the forms of bubbles (figure 8c) and transfers heat to the ullage due to buoyancy and surface tension effects.

Figure 8. Simulation results at normal and micro gravity conditions (a) Evolution of Stratification at normal gravity, (b) Velocity contour, (c) Volume fraction.

5. Conclusions
In this paper, a study of the evolution of stratification at different gravity condition is presented. An experimental test tank is fabricated and stratification is studied using nitrogen as the model propellant. The effect of reduced gravity is studied by developing a CFD model. Under microgravity conditions, the fluid velocity is smaller and it causes the boundary layer fluid to absorb more amount of heat. Small vapour regions are developed which indicates the change of heat transfer mode from convection to evaporation which will aid self-pressurization.

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