# ABSTRACT

An efficient way of handling and storing cryogenic propellant is required for future space exploration. In rocketry applications, propellants are stored at subcooled conditions in foam-insulated tanks. Any kind of heat infiltration may lead to stratification and self-pressurization of the tank.in this study the Computational Fluid Dynamic (CFD) was used to simulate Loss of Vacuum scenarios for studying the safety performance of high-pressure cryogenic storing vessels for various storage applications. For these simulations, the real gas equations of state (EoS) for hydrogen based on the Leachman's NIST reference model and a modified van der Waals model were used. And also studied about the pressure and temperature rise in the tank with various volume of fraction of liquid cryogen with different heat flux conditions. The problem coming under multiphase flow so the solution was done by volume of fluid method (VOF.)

Keywords: Cryogenic storage, Loss of vacuum , Computational fluid dynamics, self pressurization.

## 1.INTRODUCTION

Future space missions required prolonged storage of cryogenic propellant. Now a days propellant are stored in foam of insulated tank But due to loss of vacuum scenarios , Heat from outside would enter into the vacuum region which will enhance gas conduction and convection. This will cause Continuous increase in pressure and temperature inside product domain which will cause loss of product stored in cryogenic tank through safety valve and chances of Blast.so the study of vacuum loss and consequences are very important . The Computational Fluid Dynamic (CFD) was used to simulate Loss of Vacuum scenarios for studying the safety performance of high-pressure Nitrogen vessels. here we are doing three cases ,first one exact heating model solution, simulation of total vacuum loss case and lastly outside loss of vacuum with the ambient air leaking into the annulus In the above all case the product container contains gas state only and this can also simulate in Nitrogen liquid storage Dewar by using ANSYS (Fluent) Multiphase VOF Transient condition.

## 1.1 Literature Review

(Travis et al., 2012) In this paper the Computational Fluid Dynamic (CFD) code GASFLOW was used to simulate Loss of Vacuum scenarios for studying the safety performance of high-pressure hydrogen vessels for vehicular storage applications. they have simulated three cases , such as the outer steel shell of the vessel is removed and the Carbon-Fiber-Epoxy (CFE)(adjacent layer to vacuum layer) surface is directly exposed to ambient air. and the second one the outer shell is intact, but there is outside loss of vacuum with the ambient air leaking into the annulus and the last case is outer shell is intact, but there is inside loss of vacuum with hydrogen leaking from the tank into the annulus and they have made conclusion that Bare tank situation is the situation which large pressure rise occurs with a small time and consequences of inside loss of vacuum is more than outside loss of vacuum case.

(Xie et al., 2012) The influence of SCLIV (sudden catastrophic loss of insulating vacuum) on storage performance for a HVMLI(High-vacuum-multilayer-insulation) cryogenic tank is experimentally studied in this paper. A test rig was built up and experiments were conducted using LN2 as the test medium. The cryogenic tank was tested in the conditions of various combinations with different initial liquid level and number of insulation layers. Concluded that the storage process of a SCLIV cryogenic tank can be divided into three stages: no-loss storage stage, safety valve steady operation stage and safety valve unsteady operation stage, The thermal stratification in the liquid, as well as the liquid subcooling goes through an increasing firstly and then a decreasing process in the storage process after SCLIV and The initial liquid level of the cryogenic tank has important effect on the liquid subcooling and thermal stratification in the liquid. The numbers of insulation layers and the initial liquid level of the tank have important influence on the storage time.

(Pomeroy et al., 2019) Determine liquid nitrogen evaporation rates of intact liquid nitrogen storage tanks and tanks with their vacuum removed. Donated storage tank performance (LN2 evaporation) was evaluated before and after induced vacuum failure. Vacuum of each tank was removed by drilling through the vacuum port. Temperature probes were placed 2 in. below the bottom of the Styrofoam cap/plug, and tanks were weighed every 3 h. Evaporation rate and time from failure to the critical temperature was determined and find the conclusions as for the first time, we have data on how liquid nitrogen storage tanks behave when their vacuum is removed. These findings are conservative; each lab must consider starting volume, tank size/capacity, function (storage or shipping), age, and pre existing evaporation behaviour in order to develop an emergency response to critical tank failure. Times to complete failure/ evaporation and critical warming temperature after vacuum loss are different; these data should be considered when evaluating tank alarm systems.

(Ovidi et al., 2019) In this paper , Computational Fluid Dynamics (CFD) is used to investigate the pressurisation behaviour of cryogenic storage tanks by applying the Volume-Of-Fluid method and taking into account vaporization-condensation phenomena. The boundary conditions are estimated from a 1-dimensional model to solve the heat transfer through the tank insulation layers, eventually taking into account accidental damages. The tank CFD model is preliminary validated against small-scale experimental data obtained for cryogenic nitrogen and then extended to the simulation of an industrial cylindrical tank, whose volume is $100m^3$. The effect of fluid, i.e. ethylene and LNG (modelled as pure methane), filling level and possible insulation damage, on natural convection driving liquid stratification and ultimately tank pressurisation is analysed. and It was found that pressurisation and vapour heat-up are faster for ethylene than methane. The liquid thermal stratification was observed to be wider for methane than ethylene due to a more efficient natural convective flow.

(Vishnu & Kuzhiveli, 2019) Any kind of heat infiltration may lead to stratification and self-pressurization of the tank. The supply of warm propellant beyond the cavitation limit to a turbo-pump is dangerous and hence additional propellant has to be loaded, which affects the payload capacity. The evolution of stratification during lift-off and accelerated conditions and coast phase will be different from those during normal ambient conditions. During lift-off the gravity value can reach up to 6g and microgravity (lg) conditions at the coast phase. Hence, accurate prediction of the state of propellant at all stage is required for the successful mission planning. A multiphase axis-symmetric CFD model is developed, which can simultaneously account for heat transfer from the ambient and heat exchanges within the fluids during different gravity conditions. The results show that the self-pressurisation in microgravity condition is due to phase change rather than thermal stratification. The flow velocity will be maximum during lift-off and accelerated condition. Hence, greater self-pressurisation happens during the initial period and reduction in pressure rise rate is noticed later, which is due to turbulence of the fluid.

(Chen et al., n.d.) In order to predict the pressure and investigate the interrelation among the physical processes in cryogenic propellant tanks, a 2D axial symmetry Volume-of-Fluid (VOF) computational fluid dynamic (CFD) model including a liquid propellant phase and a mixture real gas phase is established. The propellant phase change model is based on the assumption of thermodynamic equilibrium. Two comparisons between the simulation results and the self-pressurization tests of two different liquid hydrogen tanks are made to validate the model. And the deviations of pressure in the tanks are 2.7%~6.1%. The results indicate that the evaporation induced by the initial overheat is the key factor of the pressure rising in the liquid hydrogen tank at the beginning of self-pressurization, but has less influence when the tank becomes saturated.

(Jazayeri & Khoei, 2008) The growth of natural circulation and thermal stratification inside LOx ,LN2 storage tanks due to heat transfer from surroundings is investigated using a non equilibrium ,two-domain , mathematical model .the two dimensional model is considered for the liquid domain in two cases and a lumped. thermodynamic model is utilized for vapour domain. the vapour is assumed to behave like an ideal gas. the developed mathematical model for liquid domain consists of conservation of mass, momentum, energy equations with boussineq approximation. An implicit finite volume technique with a uniform mesh for liquid domain is used to predict the velocity and temperature field.

# 2. PROJECT PROGRESS

## 2.1 Exact Heating Model Solution

Exact heating model solution for nitrogen gas was found, the idea behind the exact heating solution is that in a loss of vacuum situation, the insulation of the tank is no longer functioning because ambient air leaks in the vacuum space. In time, no matter what the heat transfer, the tank will warm to ambient temperature 300K.

NIST equation of state can be used to compute an exact solution for constant volume heating. present the solution in the following manner

1. Select an initial temperature
2. Select a range of initial pressures
3. Compute the gas densities for the selected initial temperature and each pressure value by inverting the NIST pressure equation

   $$P=(\rho,T)$$
4. Select a final temperature; for example, 300 K, or select a final pressure; for example 40.1 MPa (when the mechanical safety vent opens )
5. Compute the final pressure using the selected final temperature or compute the final temperature using the selected final pressure.

6. Here validated and plotted two exact heating model solution

The plots are made after validation of the data provided in GASFLOW simulations for cryogenic tank loss of vacuum scenarios**[2]**

## 2.2 Results and discussion

***1.Validation:***

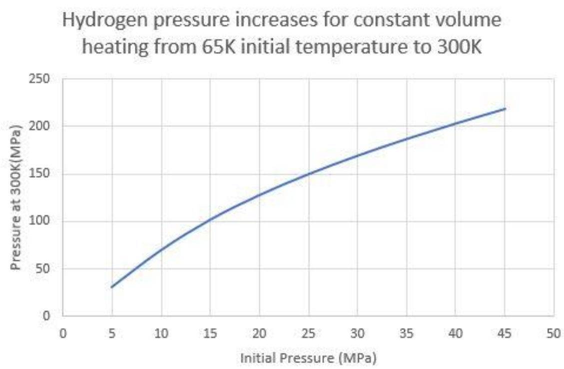



*Figure 1. 1 An exact pressure solution for hydrogen constant volume heating from a given initial temperature and pressure to the final temperature at 300 K*

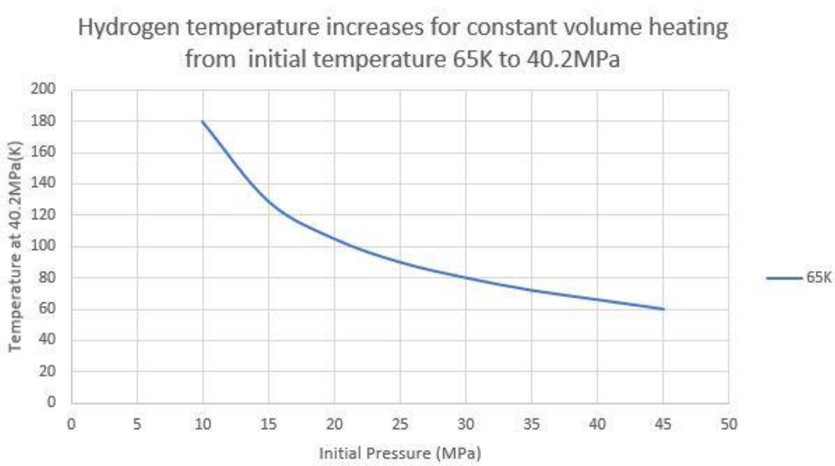



*Figure 1. 2An exact temperature solution for hydrogen constant volume heating from a given initial temperature and pressure to the final pressure at 40.2 MPa.*

.

The above two graph are validated against the graphs shows in GASFLOW simulation in paper[1]

***2. Results***

Exact heating Model solution for Nitrogen gas stored in various initial temperature and pressure are plotted.

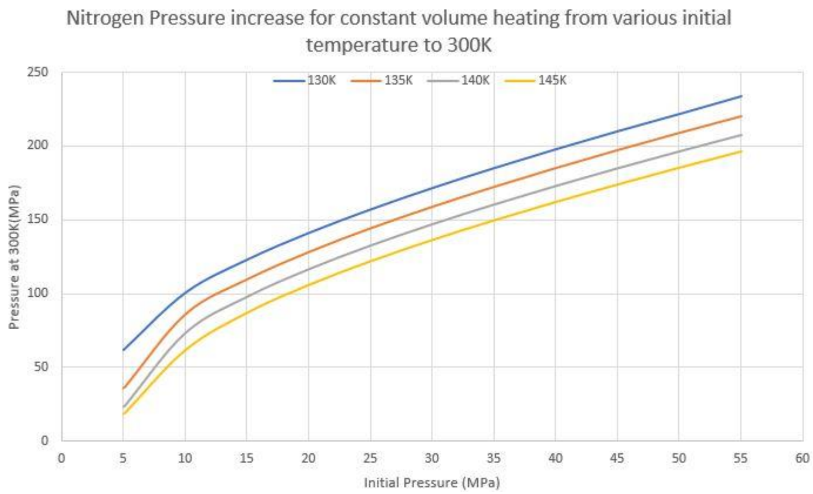



*Figure 1. 3An exact pressure solution for Nitrogen constant volume heating from a given initial temperature and pressure to the final temperature at 300 K.*

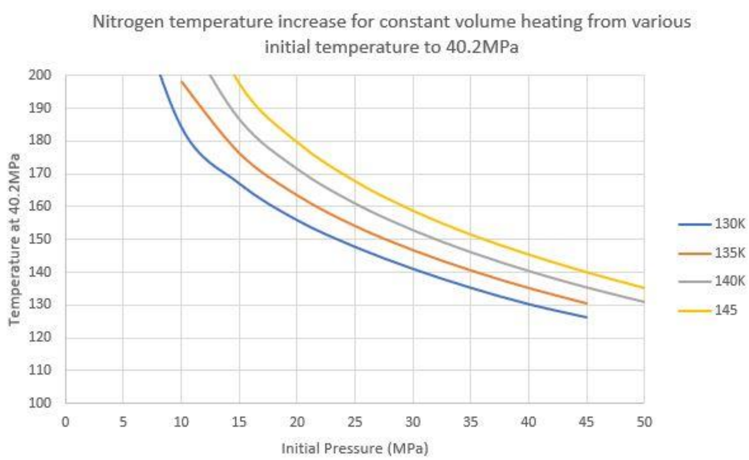



*Figure 1. 4 An exact temperature solution for hydrogen constant volume heating from a given initial temperature and pressure to the final pressure at 40.2 MPa. (Safety valve designed pressure)*

**Conclusion from the two graphs are:**

1. For a particular initial temperature ,Final pressure(at 300K) increases with increase in initial Pressure
2. For a particular initial pressure ,Final pressure (For 300K) decreases with increasing in initial temperature
3. In four cases of Nitrogen , Maximum Pressure is developed for initial temperature 130K

4. Final pressure is depends on Both initial temperature and Pressure
5. For a particular initial temperature ,Final Temperature(For 40.190MPa) increases with decrease in initial Pressure
6. For a particular initial pressure ,Final Temperature  (For 40.190MPa) Increases with increasing in initial temperature
7. In four cases of Nitrogen, Maximum Pressure is developed for initial temperature 145K
8. Final Temperature for a particular final pressure  is dipends on Both initial temperature and Pressure

# 3. SIMULATION WORK PROGRESS

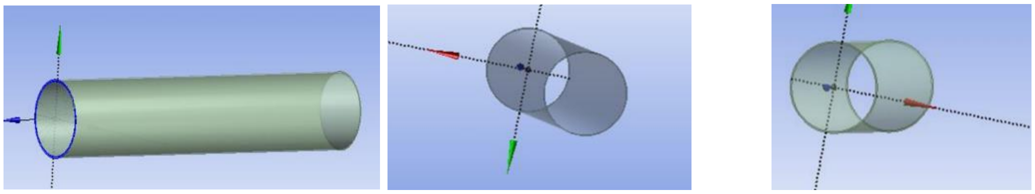
**PROBLEM DEFINITION**

## 3.1 Numerical simulation of BARE Tank(Validation)

For the First case where the outer steel shell is removed, the tank wall is a composite structure with 4.0 mm aluminum and 9.5 mm carbon-fiber epoxy directly exposed to temperature. Numerical simulation is done by using Ansys (Fluid Fluent) Software.

### 3.1.1 Geometry

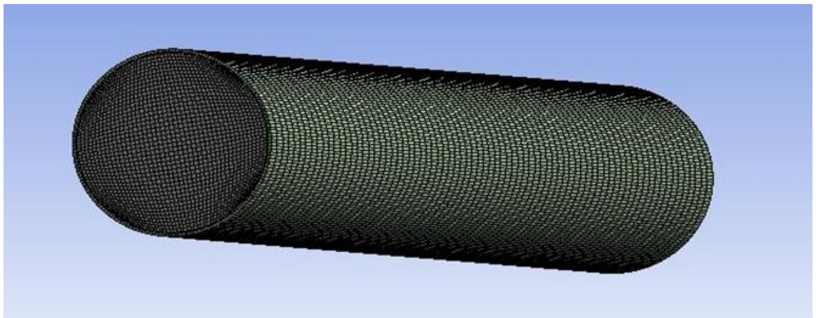
Diameter fluid domain 279mm,AL shell of thickness 4mm thickness and 9.5mm CFE and length is 1872.9mm



Fluid domain Al shell CFE Shell

*Figure 2. 1Fluid domain (left), insulation layer(Center) and CFE layer (right)*

### 3.1.2 Meshing



No of element :177485  No of Node :186186

*Figure 2. 2Complete grid form for computational domain*

In order to generate a good quality mesh, three mesh metrics are considered.

1. Orthogonality

2.Aspect Ratio

3. Skewness

All the metrics pointed the mesh being of good quality

### 3.1.3 Mathematical formulation

A) Assumptions

1. Fluid is taken as compressible
2. Domain is considerd as Three dimensional
3. Contribution in heat transfer through Radiation is negligible.

B) Governing equations for flow of fluid and heat transfer are as follows:

Conservation of mass

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Equation of energy conservation

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \frac{\partial T}{\partial x} + \rho c_p v \frac{\partial T}{\partial y} + \rho c_p w \frac{\partial T}{\partial z} = k \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right] + q$$

### 3.1.4. Boundary conditions

1. Outside surface maintained at 300K
2. Cryogenic domain is filled with hydrogen at 65K 30MPa
3. Top and bottom of storage tank are insulated
4. Real gas soave Redlich kwong Equation is used for the hydrogen density, and this is a density based solver problem.

### 3.1.5. Solution methodology

The equations of mass conservation, and energy conservation are solved using finite volume method with the help of commercial Ansys Fluent software. The coupling between pressure and velocity is prevailed by the SIMPLE algorithm .To discretize the momentum and energy equations, 2nd order upwind scheme was used. The criteria for convergence of mass and momentum conservation equation were $10^{-3}$, whereas for energy conservation equation was $10^{-6}$. The other details corresponding to flow solver are available in [18].

### 3.1.6 Results and discussion

Initial contour of Cryogenic domain

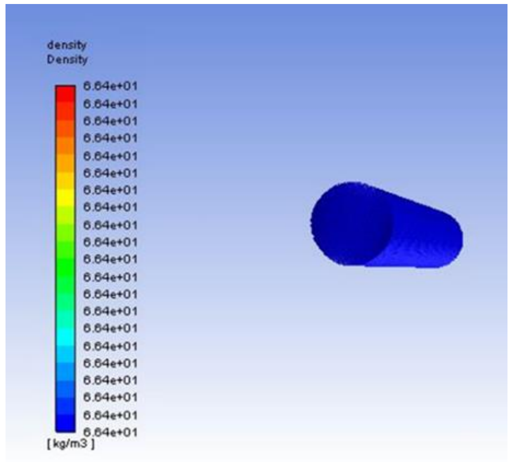



*Figure 2. 3Density contour at t=0sec,66.2kg/m3, they value same as in paper [1]*

## Simulated Results for 30 seconds (0.01 time step)

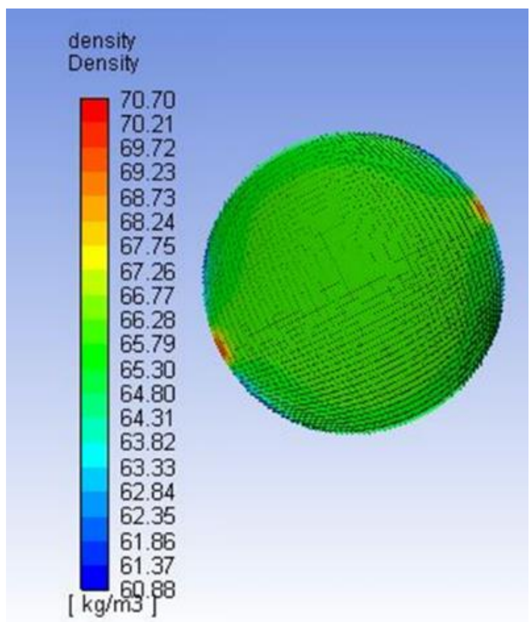



*Figure 2. 4 Density contour after 6sec*

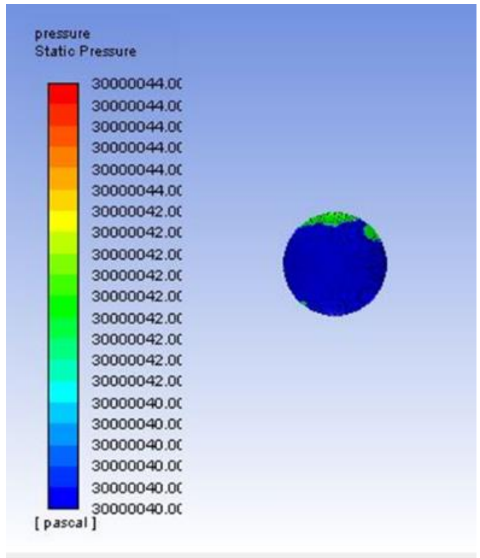



*Figure 2. 5 Pressure contour*

Temperature variation inside the cylindrical Tank

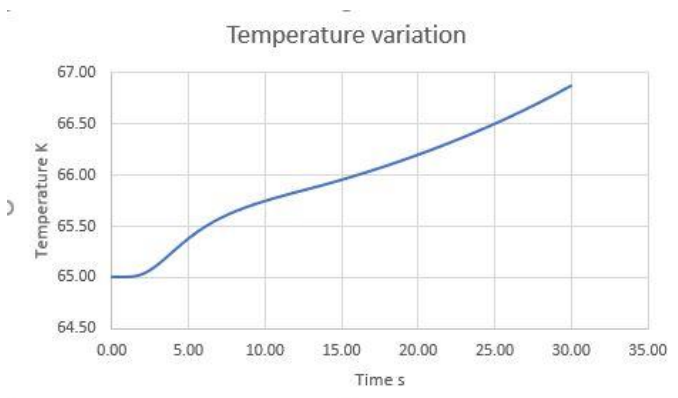



*Figure 2. 6 Temperature variation*

Density variation inside the cylindrical tank

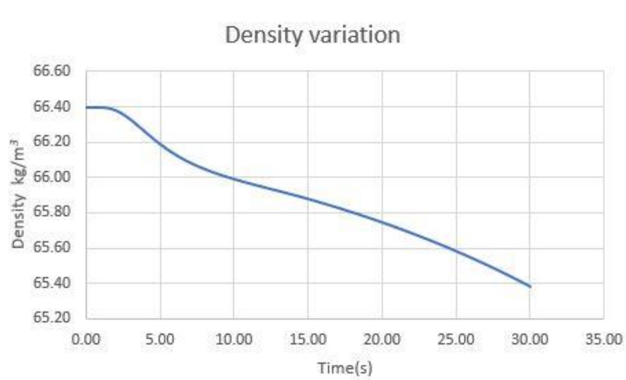



*Figure 2. 7 Density variation*

Pressure variation inside the cylindrical tank

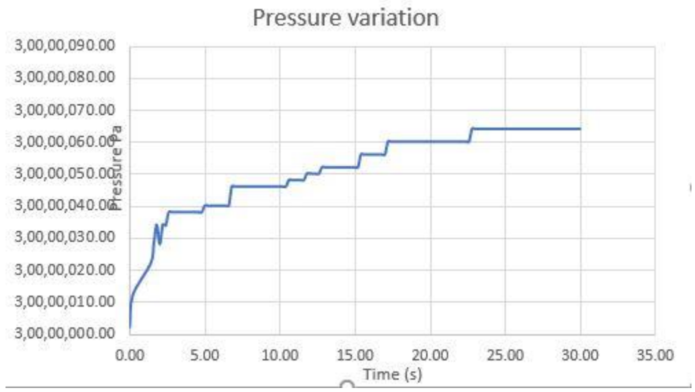



*Figure 2. 8 Pressure variation*

### 3.1.7 Conclusions from simulation

- Validated the current simulation with NIST Reference equation of state**.**
- From simulation ,We get pressure after 6 sec as 30.124835MPa at a temperature 65.6K
- From NIST table corresponding to 65.6K and density 65.8kg/m$^3$ is pressure is 30.1447965MPa

## 3.2 Numerical simulation of Rectangular tank filled with liquid nitrogen

### 3.2.1 Problem definition (Prob.2)

Validation of the numerical model is required to consider the self-pressurization of the cryogenic tank. The results obtained from the numerical model are validating with the experimental results obtained by Seo and Jeong [9]. The experimental set-up consists of a cylindrical tank with a diameter of 0.201 m and height 0.213 m. The cryogen used was liquid nitrogen with 50% fill level. A constant heat flux of 1.2 W was applied on the left sidewall. The liquid and vapour were at an initial pressure of 99 kPa and temperature corresponding to the saturation value. The self-pressurization for a time period of 100 s was capturing and comparing to numerical results.

### 3.2.2 Geometry

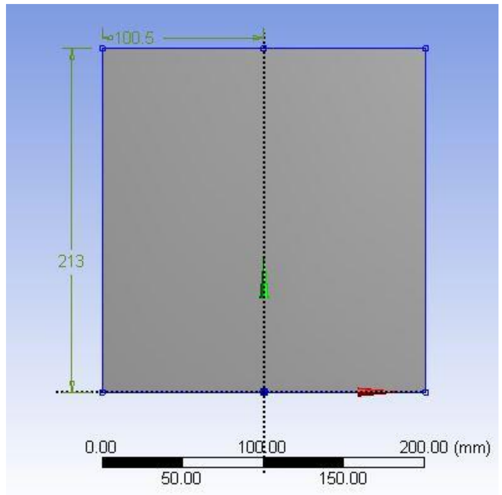



*Figure 3. 1 Fluid domain prob.2*

### 3.2.3 Mesh

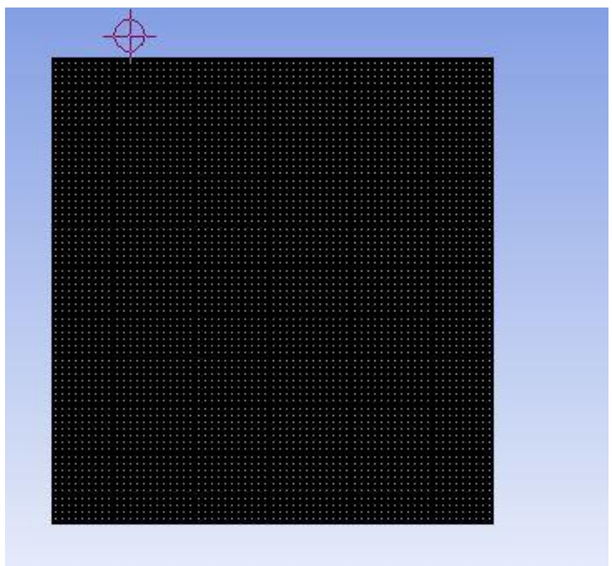


*Figure 3. 2 Complete grid form for computational domain prob.2*

43014 Node 42600 Element

In order to generate a good quality mesh, three mesh metrics are considered.

1. Orthogonality

2.Aspect Ratio

3. Skewness

All the metrics pointed the mesh being of good quality

### 3.2.4. Mathematical formulation

A) Assumptions

1. 2D Domain is used
2. Fluid is taken as incompressible
3. Contribution in heat transfer through Radiation is negligible.

B) Governing equations for flow of fluid and heat transfer are as follows:

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\vec{v}) = 0$$

Conservation of momentum

$$\frac{\partial}{\partial t}(\rho\bar{v}) + \nabla \cdot (\rho\overline{v\bar{v}}) = -\nabla p + \nabla \cdot [\mu(\nabla\bar{v} + \nabla\bar{v}^T)] + \rho\vec{g} + \vec{F}$$

Conservation of energy

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \left(\bar{v}(\rho E + p)\right) = \nabla \cdot \left(k_{eff}\nabla T\right) + S_h$$

### 3.2.5.Boundary conditions

a) 50% of Tank filled with liquid nitrogen
b) Constant Heat flux 8.7W/m2 is applied on both sides (Side thickness 0.001m-steel)
c) Top and Bottom of the tank are insulated

### 3.2.6. Solution methodology

CFD package Ansys 15 is used for solving the conservation equations.2 Dimensional multi phase VOF method is used and k-e turbulence model with enhanced wall function is applied. The pressure–velocity coupling algorithm selected is SIMPLEC (Semi-Implicit Method for Pressure-Linked Equation-Consistent). The converged solution is easy to achieve by this method than by a SIMPLE algorithm. The body-force-weighted average scheme is used for solving the momentum equation. For tracking the liquid–vapour interface, the Geometric Reconstruction Scheme is applied. Since the problem is transient in nature, a time step of 0.01 s is selected.In each cell, volume fraction is defined in such a way that the sum of both liquid and vapour volume fractions becomes unity. approach is applied

### 3.2.7 Results and discussion

Initial volume fraction of Liquid Nitrogen

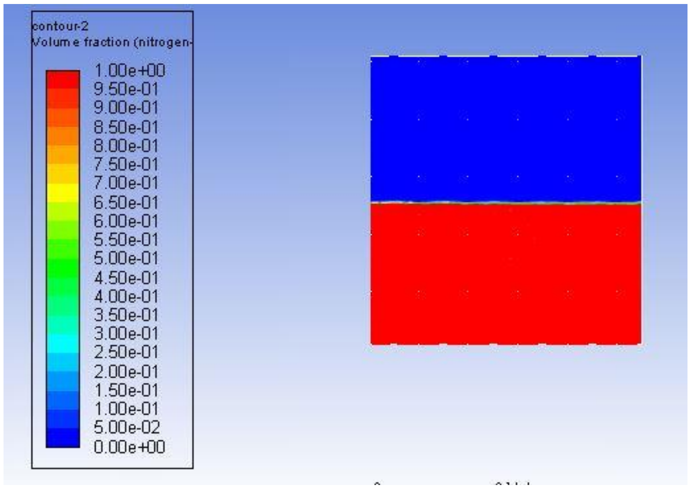



*Figure 3. 3 Volume fraction at t=0 sec prob.2*

Result obtained after simulation of 60 sec

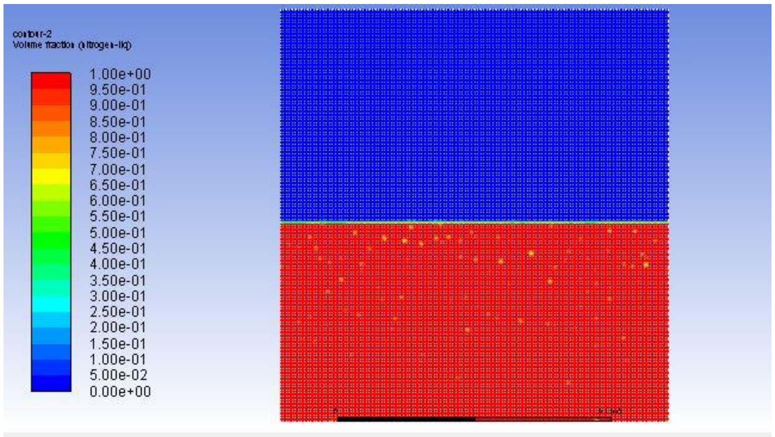



*Figure 3. 4 Volume fraction contour prob.2*

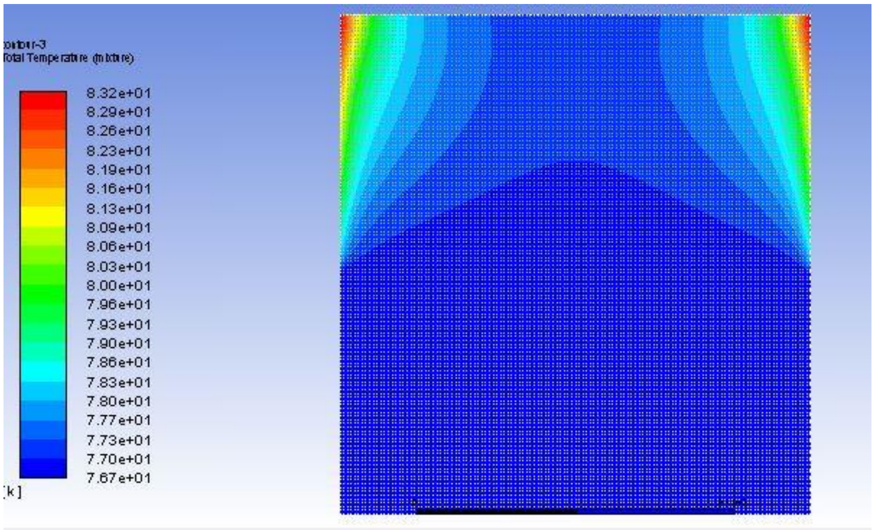



*Figure 3. 5 Temperature contour prob.2*

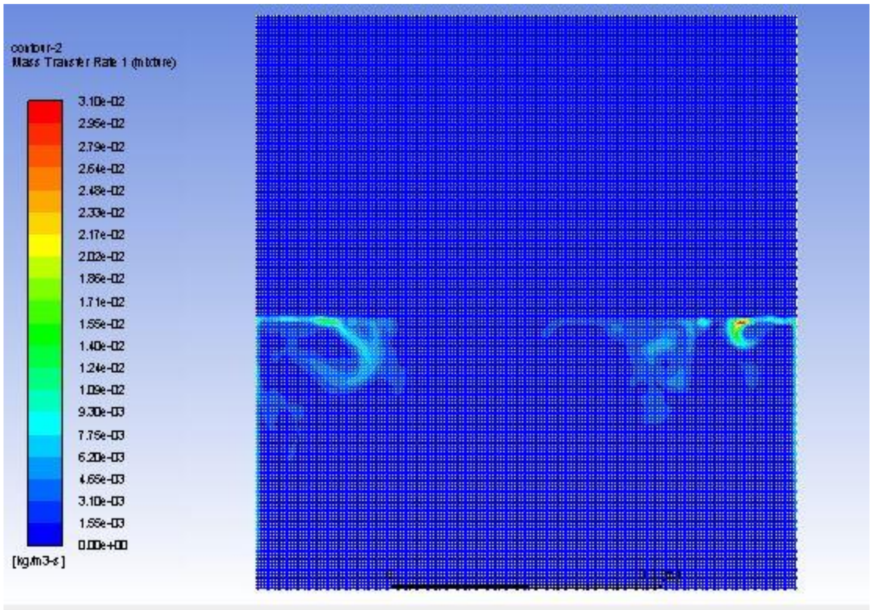



*Figure 3. 6 Mass flow (Phase) prob.2*

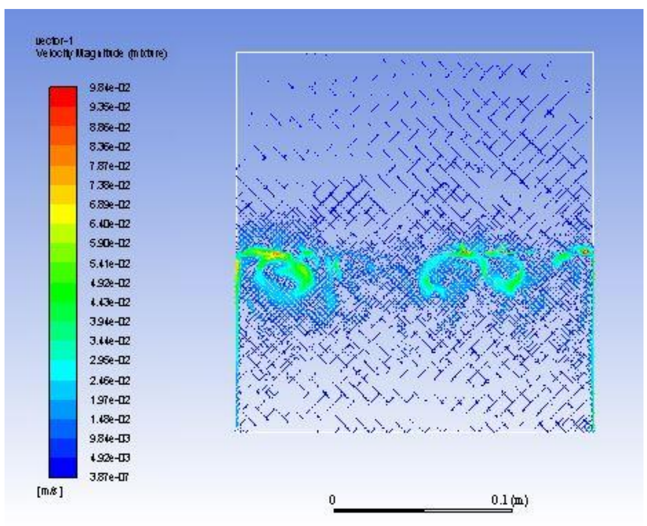



*Figure 3. 7 Velocity Magnitude (Mixture) prob.2*

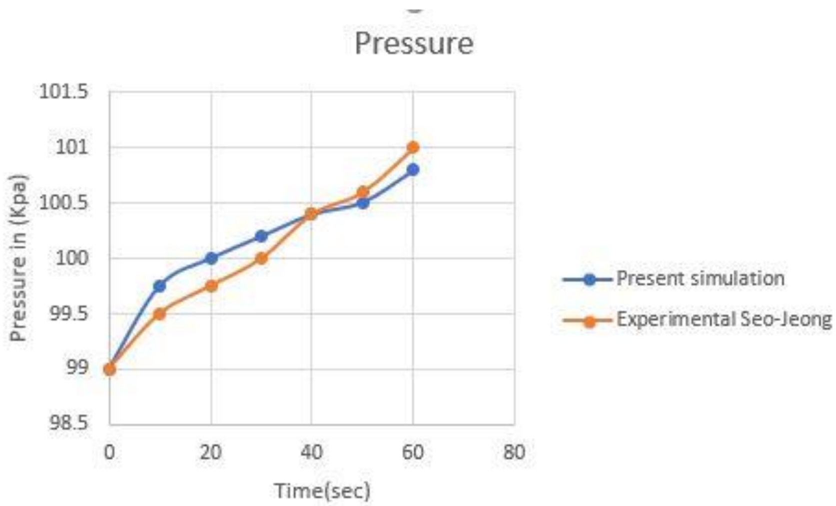



*Figure 3. 8 Pressure variation prob.2*

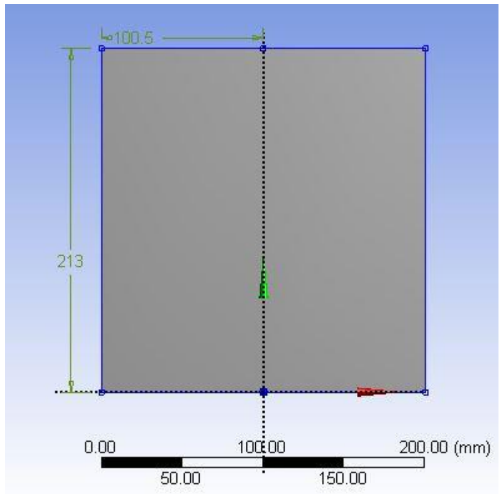
### 3.2.8. Conclusions from simulation prob.2

1. The temperature rise in gaseous Phase is faster than liquid phase region
2. Heat is transferred to the tank, the liquid near the sidewall is heated up and a boundary layer develop. the warm fluid inside the boundary layer move upwards and is reaching at the liquid–vapour interface
3. For the simulation work i have used 0.001sec time step , simulated result is matching with Soe and Jeong work

## 3.3 Numerical simulation of tank with various filling condition and Various heat flux condition

The experimental set-up consists of a cylindrical tank with a diameter of 0.201 m and height 0.213 m. The cryogen used was liquid nitrogen with 25%, 50% and 75% fill level. A constant heat flux of 10W/m$^2$ was applied on sidewall. The liquid and vapour were at an initial pressure of 99 kPa and temperature corresponding to the saturation temperature. The self-pressurization ,temperature and volume fraction change for a time period of 60 s was capturing and plotted.

## Geometry




## METHODOLOGY

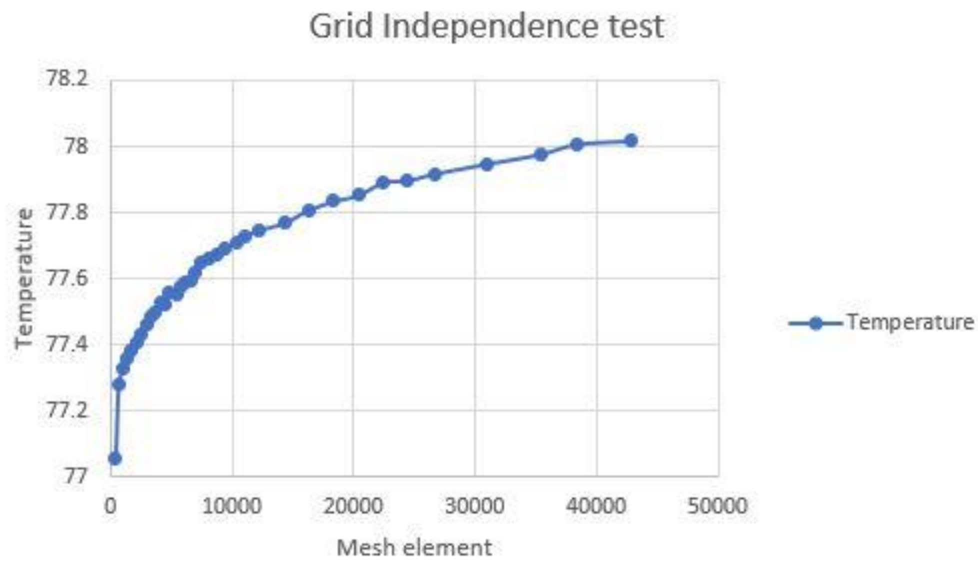
Same as validation work

## BOUNDARY CONDITION

- Case1: Liquid $N_2$ filled 25% in tank and constant heat flux 10w/$m^2$ is exposed to side surfaces. top and bottom of the tank are insulated.
- Case2: Liquid $N_2$ filled 50% in tank and constant heat flux 10w/$m^2$ is exposed to side surfaces. top and bottom of the tank are insulated.
- Case3: Liquid $N_2$ filled 75% in tank and constant heat flux 10w/$m^2$ is exposed to side surfaces. top and bottom of the tank are insulated.
- Case4: Liquid $N_2$ filled 50 % tank and constant heat flux 10w/$m^2$ is exposed to side surfaces. top and bottom of the tank are insulated.
- Case5: Liquid $N_2$ filled 50 % tank and constant heat flux 20w/$m^2$ is exposed to side surfaces. top and bottom of the tank are insulated.
- Case6: Liquid $N_2$ filled 50 % tank and constant heat flux 30w/$m^2$ is exposed to side surfaces. top and bottom of the tank are insulated.
- Case 7: Liquid $O_2$ filled 50% tank and constant heat flux 10W/$m^2$ is exposed to side surfaces. top and bottom of the tank are insulated

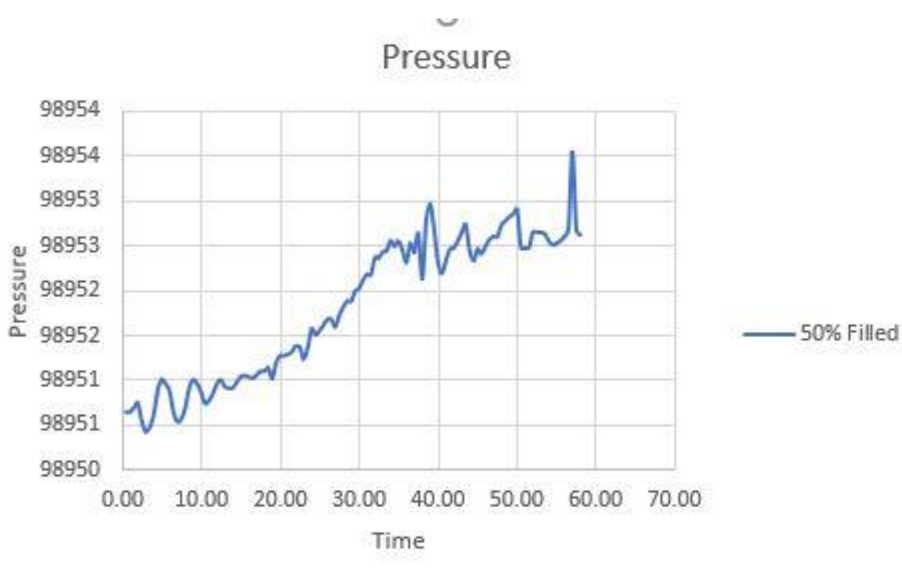
## RESULT AND DISCUSSION

### *Grid independent Test*

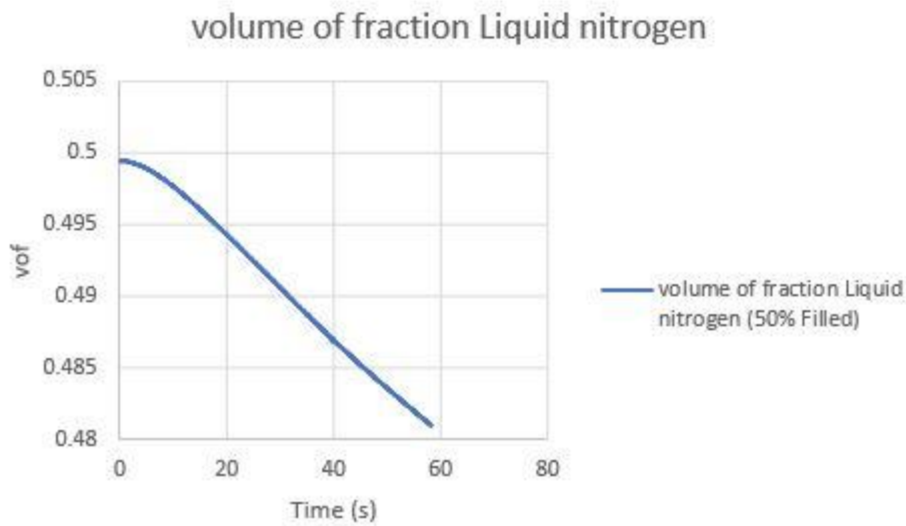



So from the analysis it was found that for Mesh element 40000, the plot is become parallel to x axis.so I chose a mesh element greater than 40000 for better result.

**Case 1**: Liquid N2 filled 25% in tank and constant heat flux 10w/m2 is exposed to side surfaces.top and bottom of the tank are insulated.

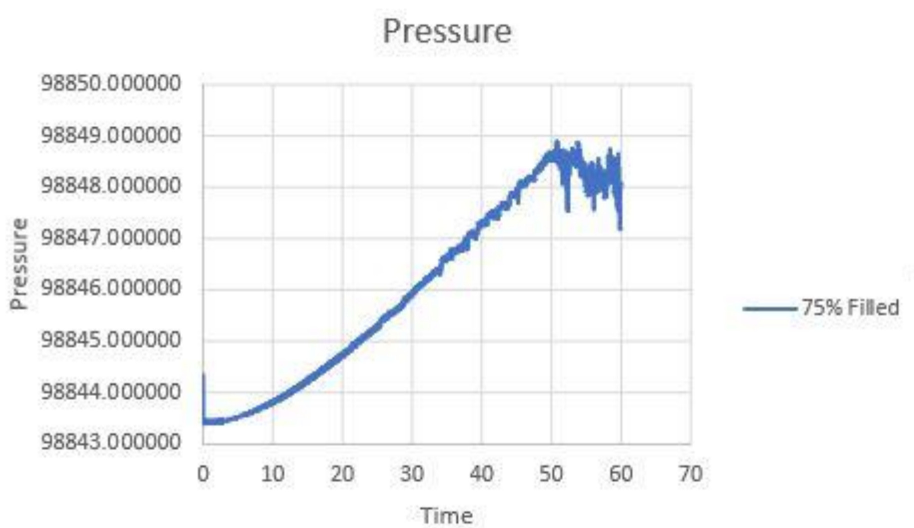



*Pressure inside domain*

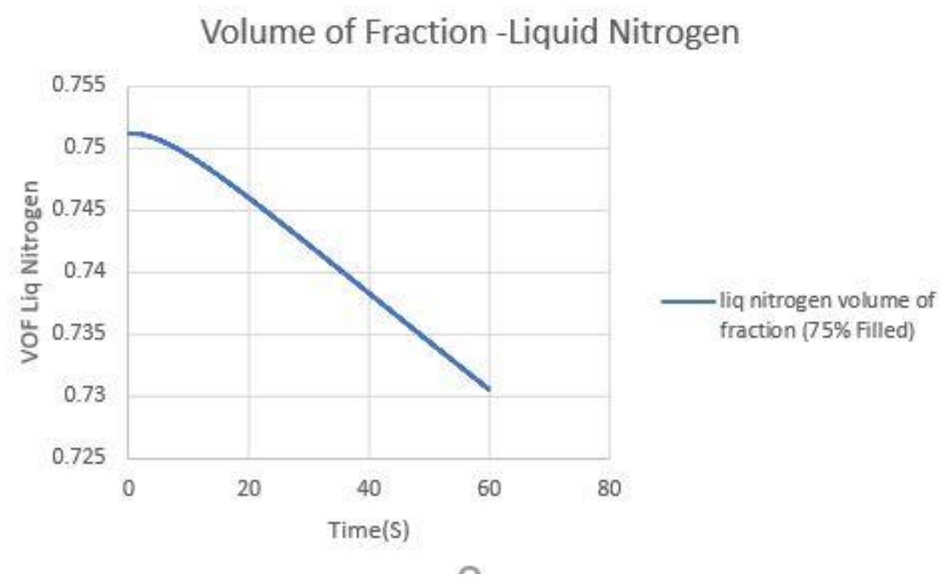



*Volume fraction change in domain*

**Case 2**: Liquid N2 filled 50% in tank and constant heat flux 10w/m2 is exposed to side surfaces.top and bottom of the tank are insulated.

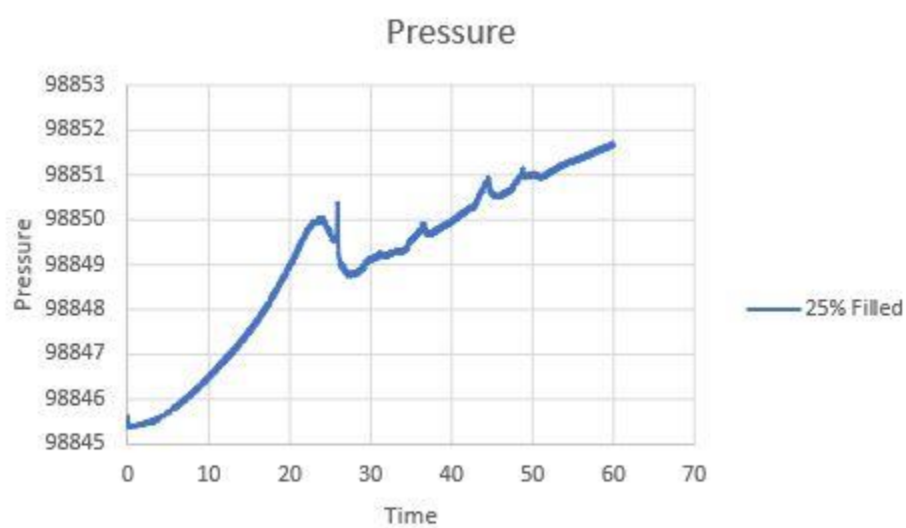



*Pressure inside domain*

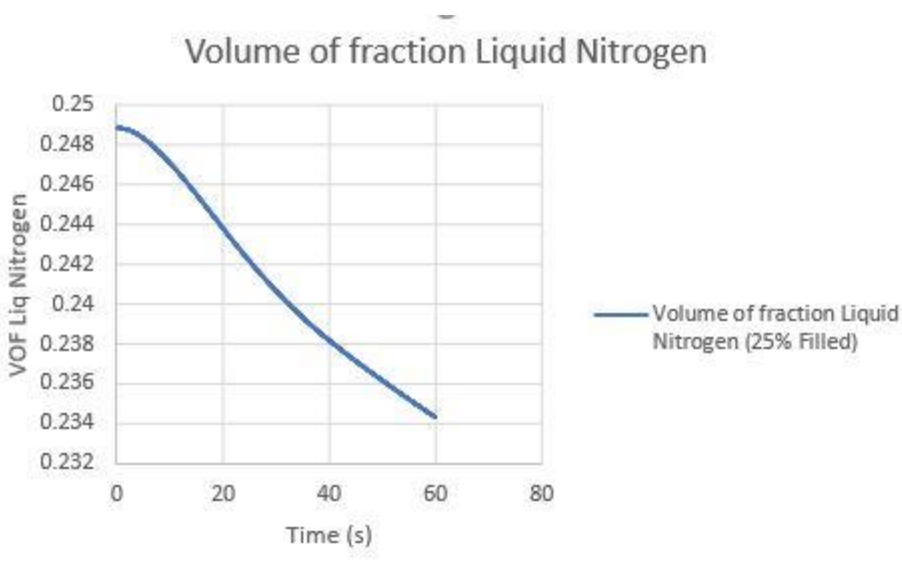



*Volume fraction change in domain*

**Case 3**: Liquid N2 filled 75% in tank and constant heat flux 10w/m2 is exposed to side surfaces. top and bottom of the tank are insulated.



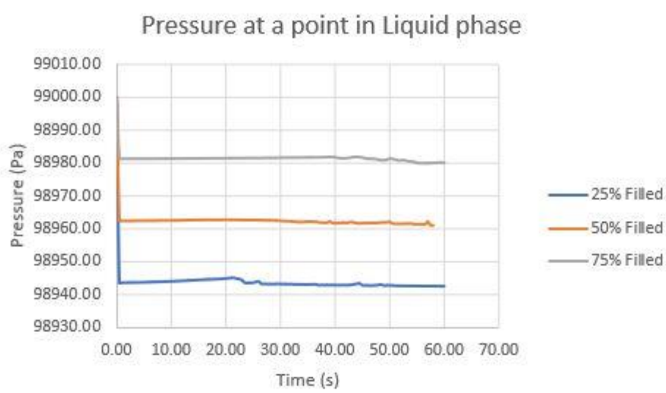

*Pressure inside domain*



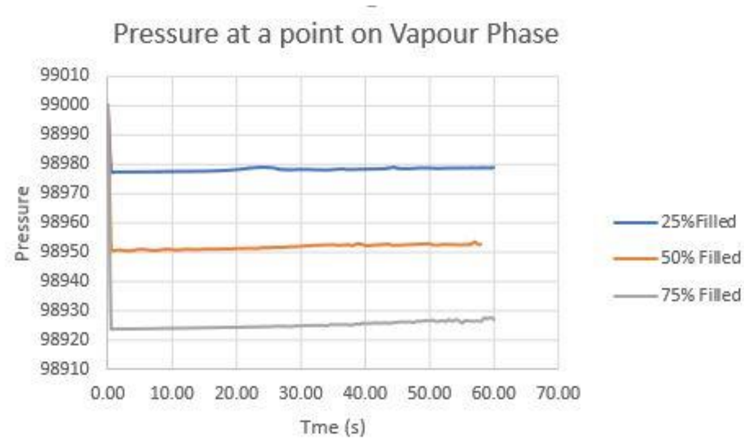

*Volume fraction change in domain*

**Comparing the above three cases**

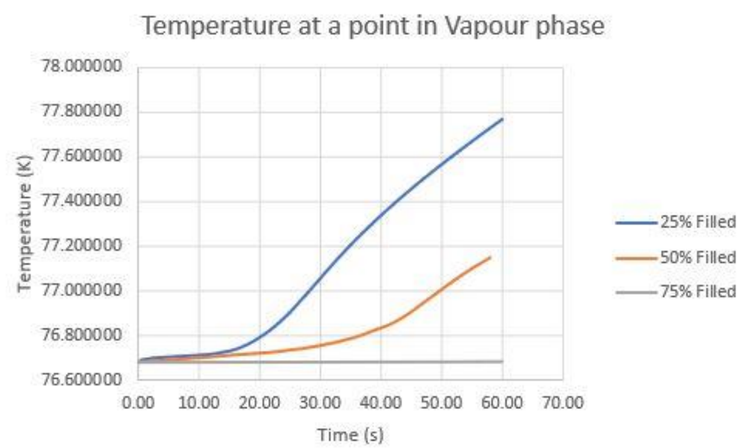
Pressure at a point in liquid phase



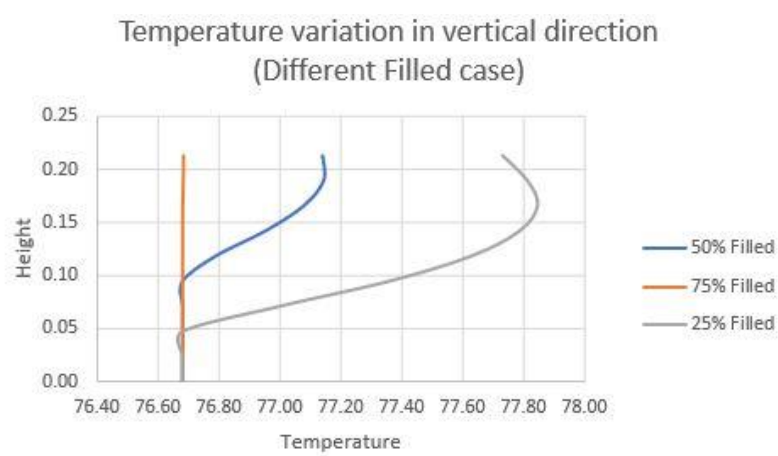

Pressure at a point in vapour phase



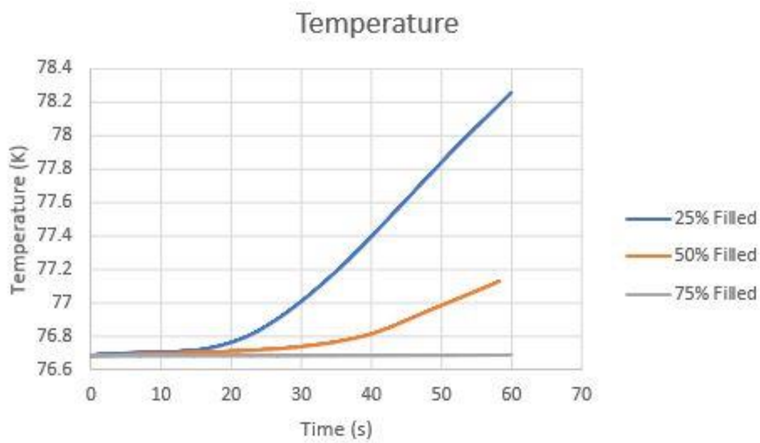

Temperature at a point in Vapour phase



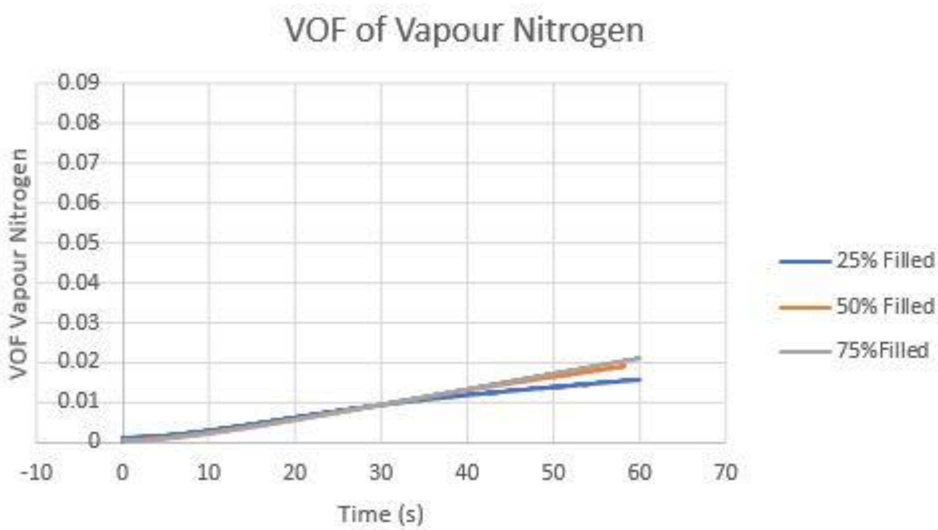

Temperature variation in vertical direction



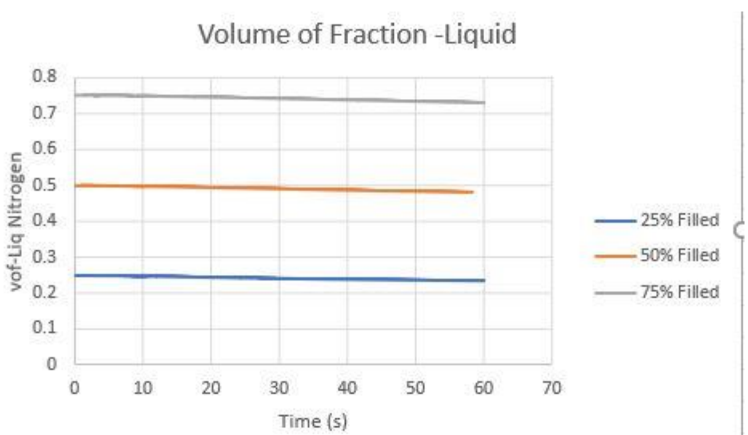
Temperature inside domain




Volume of fraction -formation of vapour nitrogen

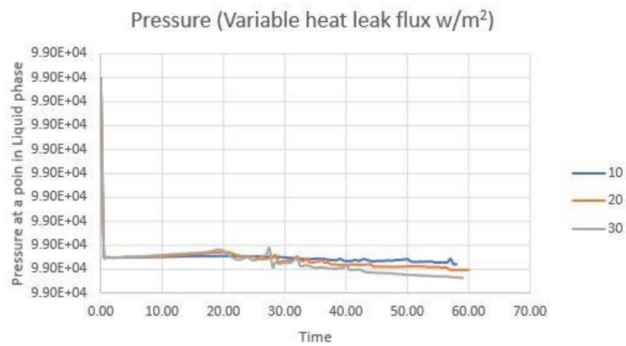



Volume of fraction -formation of vapour nitrogen

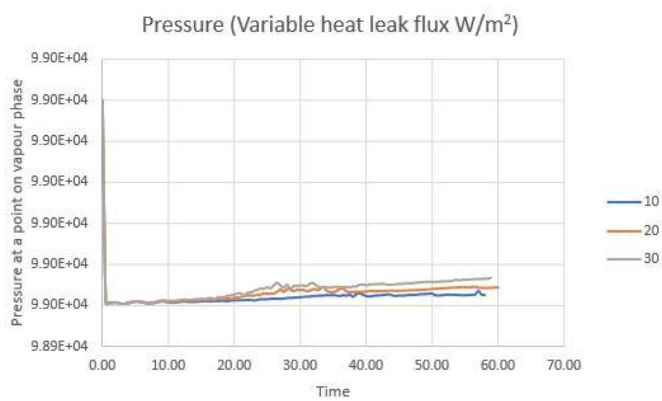


**Comparing variable heat flux condition for same initial volume of fraction**

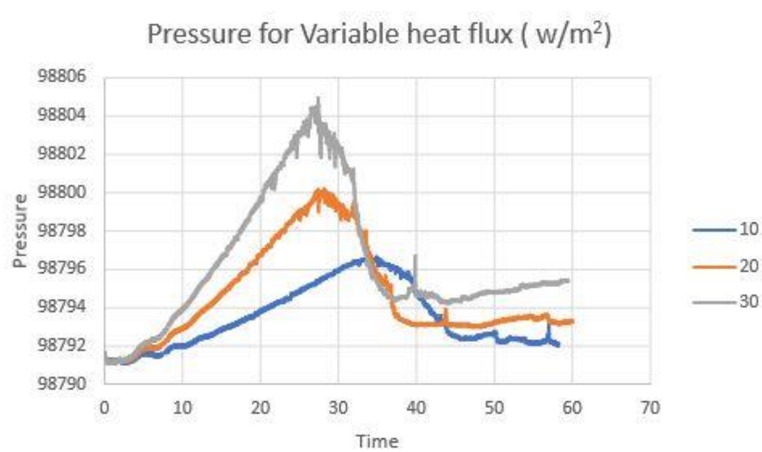
Pressure in liquid phase of tank for variable heat flux



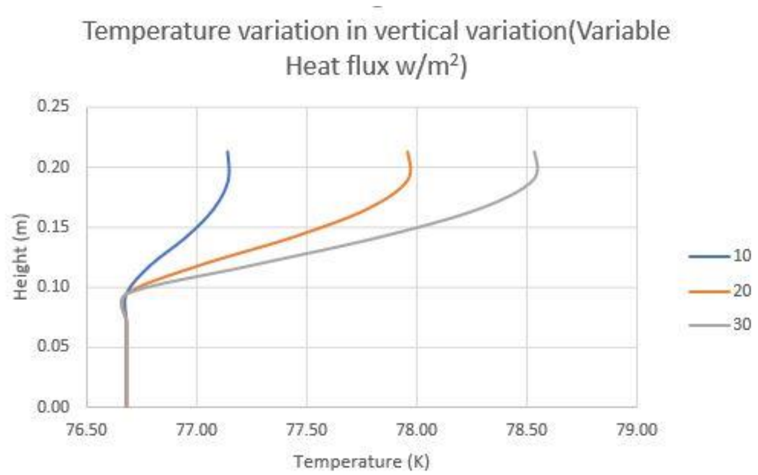

Pressure in vapour phase of tank for variable heat flux



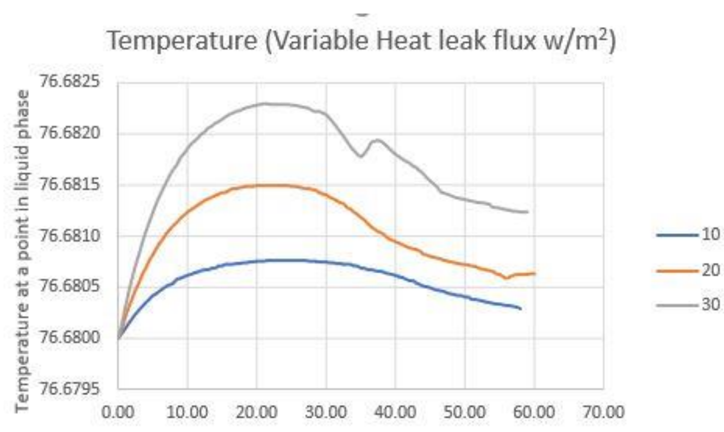

Pressure in tank for variable heat flux



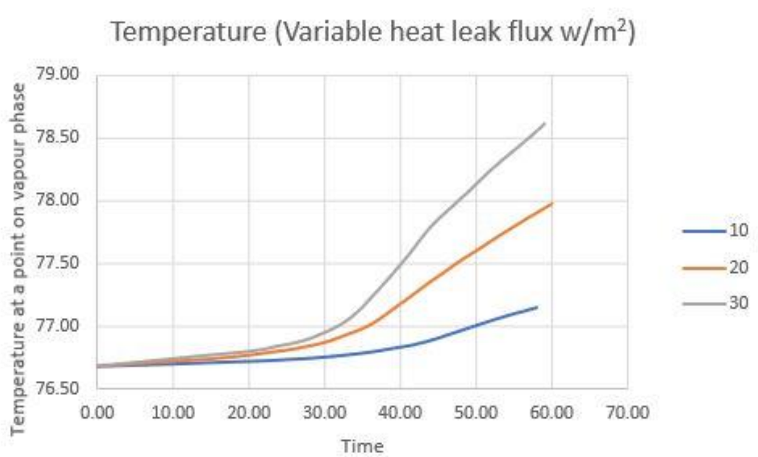
Temperature variation in tank (vertical direction)



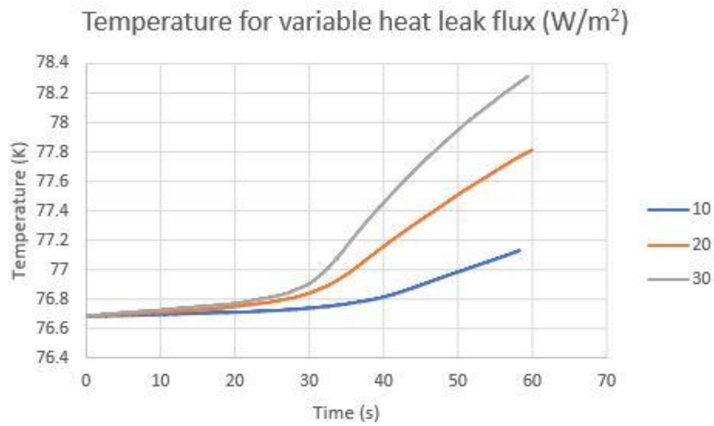

Temperature at a point in liquid phase



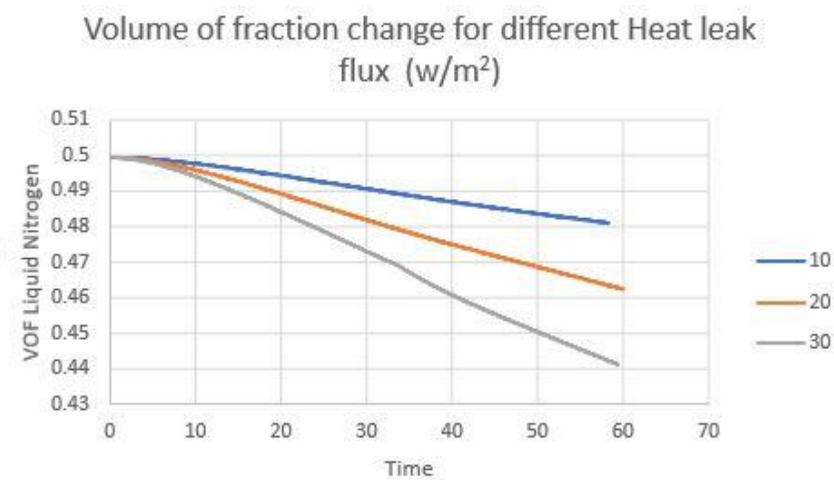

Temperature at a point in vapour phase



Avg temperature in domain



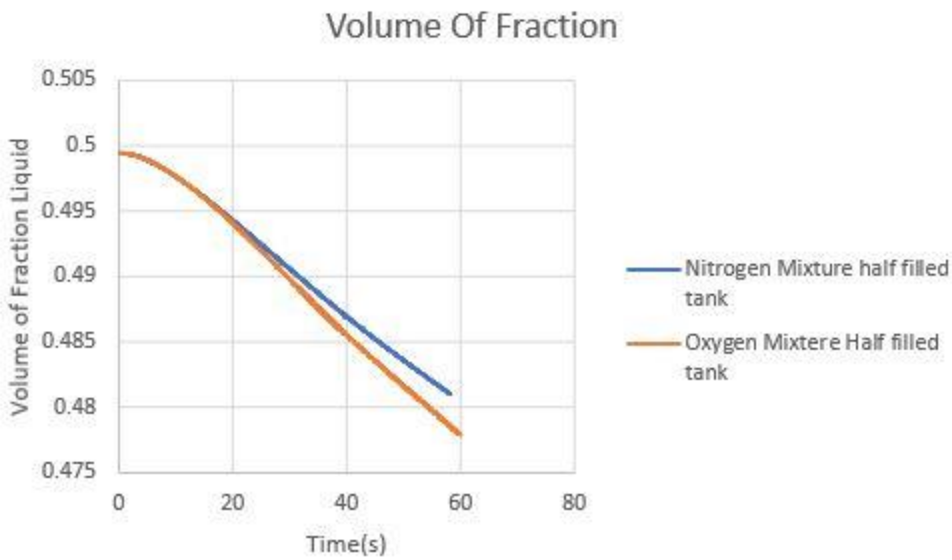

Volume of fraction change for different heat flux



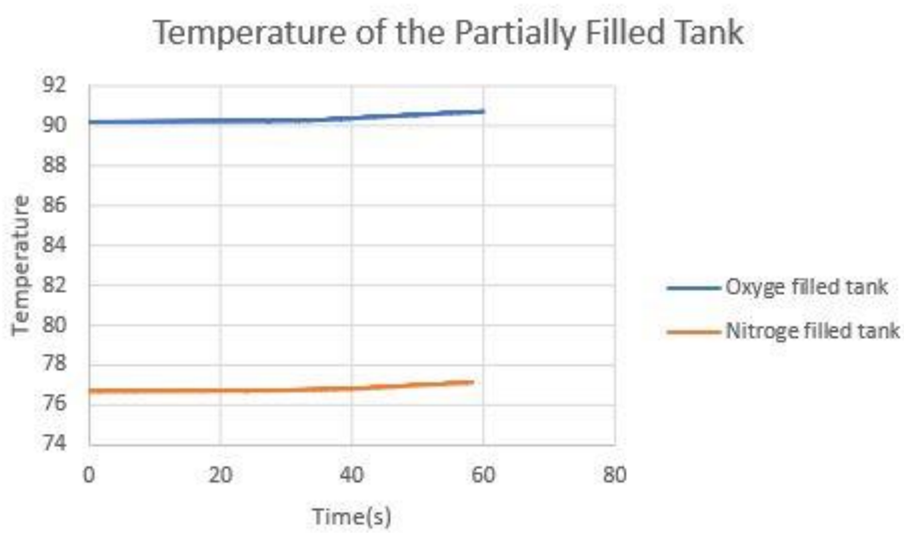

*Volume of fraction change for different heat flux*

**Case 7**: Liquid $O_2$ filled 50% tank and constant heat flux 10W/$m^2$ is exposed to side surfaces. top and bottom of the tank are insulated

Volume fraction comparison between Oxygen and Nitrogen




*Temperature comparison between oxygen and Nitrogen*




*Temperature comparison between oxygen and Nitrogen*

# RESULT AND CONCLUSIONS

- The temperature rise in gaseous Phase is faster than liquid phase region
- Heat is transferred to the tank, the liquid near the sidewall is heated up and a boundary layer develop. the warm fluid inside the boundary layer move upwards and is reaching at the liquid–vapour interface.

- Boil rate  is more faster with liquid filling condition
- The temperature and pressure rise is increasing with Heat flux leak
- Temperature and pressure rise in tank is depends on Fraction of liquid filled and Heat leak into the tank.
- Temperature at a point in gas phase is proportional to Heat leak and inversely proportional to Liquid fraction in Tank
- The pressure rise increases with decreasing filling condition.
- Volume fraction change in oxygen filled tank is larger compared to Nitrogen filled tank.

# 5 REFERANCES


1. Chen, L., Ai, B., Chen, S., & Liang, G. (n.d.). *Simulation of self-pressurization in cryogenic propellant tank*. 1068–1073.

2. Jazayeri, S. A., & Khoei, E. M. H. (2008). Numerical comparison of thermal stratification due natural convection in densified LOX and LN2 tanks. *American Journal of Applied Sciences*, *5*(12), 1773–1779. https://doi.org/10.3844/ajassp.2008.1773.1779

3. Ovidi, F., Pagni, E., Landucci, G., & Galletti, C. (2019). Numerical study of pressure build-up in vertical tanks for cryogenic flammables storage. *Applied Thermal*

4. *Engineering*, *161*(July), 114079. https://doi.org/10.1016/j.applthermaleng.2019.114079

5. Pomeroy, K. O., Reed, M. L., LoManto, B., Harris, S. G., Hazelrigg, W. B., & Kelk, D. A. (2019). Cryostorage tank failures: temperature and volume loss over time after

6. induced failure by removal of insulative vacuum. *Journal of Assisted Reproduction and Genetics*, *36*(11), 2271–2278. https://doi.org/10.1007/s10815-019-01597-5

7. Travis, J. R., Piccioni Koch, D., & Breitung, W. (2012). A homogeneous non-equilibrium two-phase critical flow model. *International Journal of Hydrogen Energy*, *37*(22), 17373–17379. https://doi.org/10.1016/j.ijhydene.2012.07.077

8. Vishnu, S. B., & Kuzhiveli, B. T. (2019). Effect of micro- and elevated gravity condition on the evolution of stratification and self-pressurization in a cryogenic propellant tank. *Sadhana - Academy Proceedings in Engineering Sciences*, *44*(3), 1–8. https://doi.org/10.1007/s12046-018-1034-4

9. Xie, G. F., Li, X. D., & Wang, R. S. (2012). Experimental study on the storage

performance of high-vacuum-multilayer- insulation tank after sudden, catastrophic loss of insulating vacuum. *Heat and Mass Transfer/Waerme- Und Stoffuebertragung*, *48*(5), 757–766. https://doi.org/10.1007/s00231-011-0928-z

10 Mansu Seo, Sangkwon Jeong *Analysis of self-pressurization phenomenon of cryogenic fluid storage tank with thermal diffusion model* Cryogenics 50: 549–555

11 Reference Equation of State for the Thermodynamic Properties of Nitrogen-NIST Website

12 ANSYS Fluent Theory Guide. ANSYS Fluent Theory Guide. ANSYS Inc., USA 15317, 724–746 (2013).