# Analysis of Thermal Stratification During Initial Active Pressurization in a Cryogenic Propellant Tank

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## ABSTRACT

The prediction of thermal stratification in a cryogenic propellant tank is necessary for the successful execution of space missions. For the reduction of pressuring gas mass, high-temperature gas is used for pressuring which may lead to thermal stratification and hence self-pressurization. The rise in propellant temperature may also lead to cavitation in a pump which has to be avoided. So modeling of stratification in the cryogenic tank is essential as the liquid propellant must meet the pump inlet condition. A CFD model is created which can simultaneously account for the heat exchanges within the propellant tank and also heat transferred from ambient during initial active pressurization phase. The amount of ullage gas required, Effect of ullage gas temperature on the development of stratification, variation of pressure inside the tank etc is found out. The results show that there will be a reduction in pressure at the end of active pressurization which is due to phase change and reduction in vapor temperature. A MATLAB code has been developed to investigate thermal stratification during initial active pressurization. It is found that there is a fair agreement between the results obtained from the MATLAB code and CFD simulation.
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## NOMENCLATURES

Cp = Specific heat at constant pressure, J/kg K
g = Local gravitational acceleration, m/s$^2$
h = Heat transfer coefficient, W/m$^2$K
H = Tank height, m
A = Area, m$^2$
Nu = Nusselt number
P = Pressure, N/m$^2$
Pr = Prandtl number
R = Tank radius, m
Ra = Rayleigh number
T = Time, s
x = Characteristic dimension, m
Greek symbols
α = Thermal diffusivity, m$^2$/s
β = Volumetric thermal expansion coefficient, 1/K
Δ = Thickness of stratified layer, m
δ = Boundary layer thickness, m
θ = Temperature difference, K

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## INTRODUCTION

Thermal stratification inside the cryogenic storage tank is a well-known phenomenon. For space mission, the heat infiltration into the cryogenic tank is mainly due to aerodynamic heating. When heat leakage into the system occurs through the side wall, a free convective boundary layer is developed along the side wall. It gives rise to convection current and warm fluid will move upward and accumulates at the top. A warm layer of fluid will develop at the liquid-vapor interface and this warm layer of fluid is known as a thermally stratified layer.
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## THERMAL STRATIFICATION

Need for predicting stratification

- Self pressurization of the tank
- Reduces lock up time
- Causes cavitation in pump
    - The warm propellant beyond pump cavitation limit is unusable. So excess liquid mass ( stratified mass ) has to be loaded which is a liability to the payload capacity of launch vehicle.

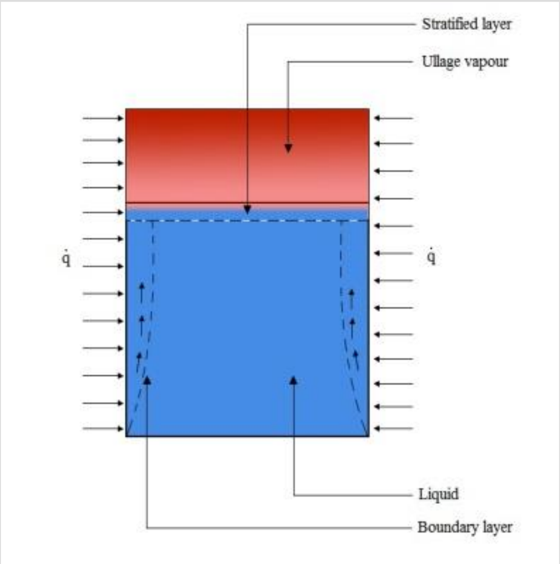
Turbo pump cavitation:

$P_t = P_{sat}\,(T_s) + NPSP + NPSP_{margin} + \Delta P - P_{acc}$

$P_t$ - Tank pressure

NPSP – Net positive suction pressure

$P_{acc}$ – Static pressure due to vehicle acceleration




Thermal stratification

## MATHEMATICAL MODELING

Turbulent flow:

Rayleigh number, $Ra = Gr\,\mathrm{Pr} = \frac{g\beta\theta_w x^3}{\upsilon^2}\frac{\mu Cp}{k}$

Velocity profile, $u(y) = u_1(\frac{y}{\delta})^{\frac{1}{7}}(1-\frac{y}{\delta})^4$

Where, $u_1 = 1.185\frac{\upsilon}{x}(Gr)^{\frac{1}{2}}[1+0.49(Pr)^{\frac{2}{3}}]^{\frac{-1}{2}}$

Temperature profile, $\theta(y) = \theta_w[1-(\frac{y}{\delta})^{\frac{1}{7}}]$

Boundary layer mass flow $\dot{m}_{bl} = \pi R^2\rho\left(\frac{d\Delta}{dt}\right) = \frac{8\pi hR}{C_p}(H-\Delta)$

Development of stratified layer, $\frac{\Delta(t)}{H} = 1 - e^{\frac{-8ht}{Rc_p\rho}}$

Transient analysis:

Average Nusselt number, $Nu_{av} = 0.0210(GrPr)^{\frac{2}{5}}$

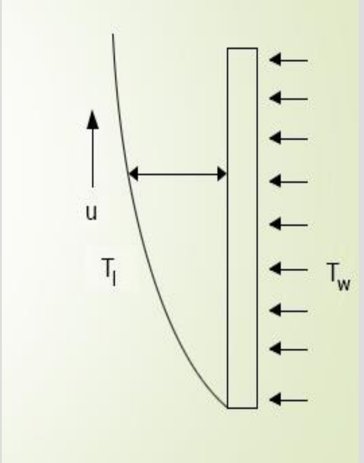
Temperature at stratum, $T_s = (\theta_w + T_b) - \theta_w^{\frac{-2Hht}{R\Delta C_p\rho}}$

## HEAT AND MASS TRANSFER

Heat transfer from ambient

Assuming constant wall temperature,

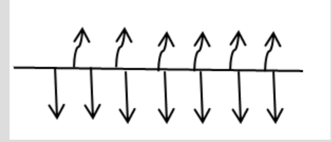
- Boundary layer thickness, $\delta = \frac{3.04\upsilon Gr_x^{0.250}}{[g\beta(Tw-Tl)\upsilon]^{1/3}}$
- Grashoff number, $Gr_x = \frac{g\beta(Tw-Tl)x^3}{\upsilon^2}$
- Velocity, $U = 0.210Gr_x^{0.125}\,[g\beta(Tw-Tl)\upsilon]^{1/3}$




Heat transfer from ullage to interface

- $\frac{dQ_{u-int}}{dt} = h_{u-int}A_{int}\frac{d\Delta T_{u-int}}{dt} + H\frac{dm}{dt}$
- $\frac{dm}{dt} = \frac{[h_{int-l}A_{int}\frac{d\Delta T_{int-l}}{dt} - h_{u-int}A_{int}\frac{d\Delta T_{u-int}}{dt}}{H}$
- Heat transfer coefficient, $h = K_H C\frac{k_l}{l_s}Ra^n$
- $Gr_x = \frac{g\beta(Tw-Tb)l_s^3}{\upsilon^2}$

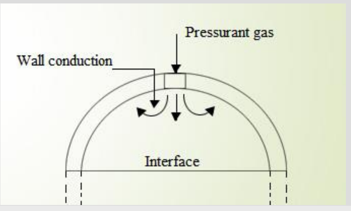
Ullage



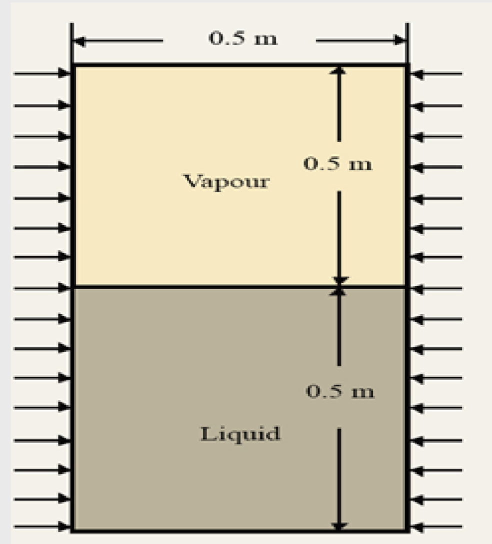
Liquid

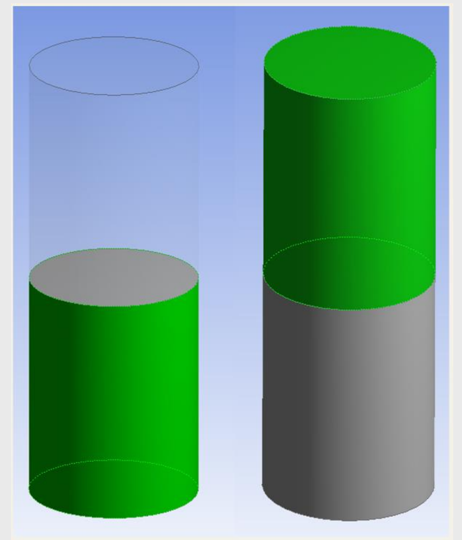
Heat transfer during pressurization

- $Nu_x = 0.56Re_d^{0.67} + 0.104Ra^{0.352}$
- $h = \mu_l(\frac{\Delta T}{h_{fg}})^2(\frac{g(\rho_l-\rho_v)}{\sigma})^{\frac{1}{2}}[\frac{Cp_l}{0.01Pr_l}]^3$

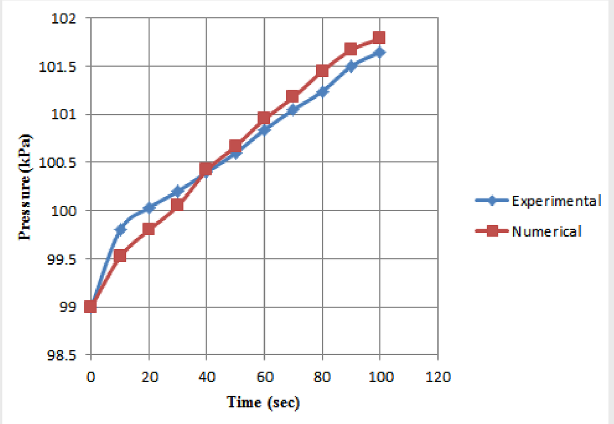


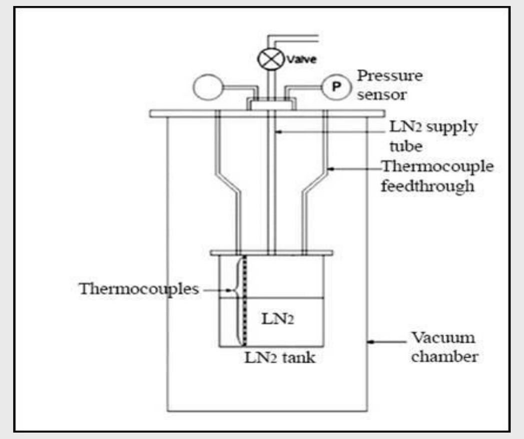

## FORMULATION



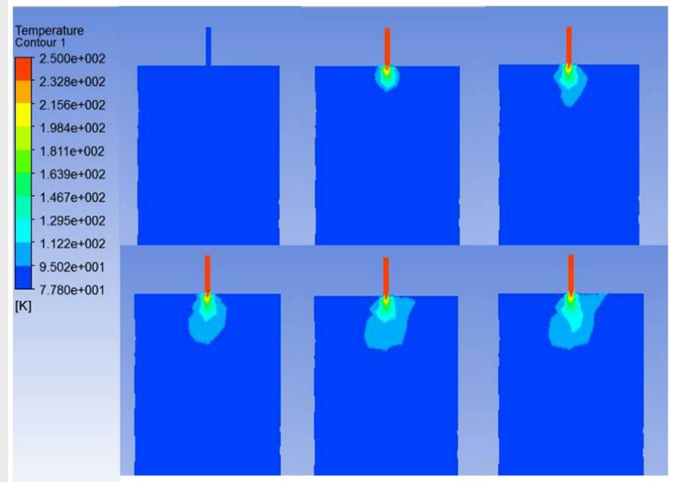
Liquid and vapour domain

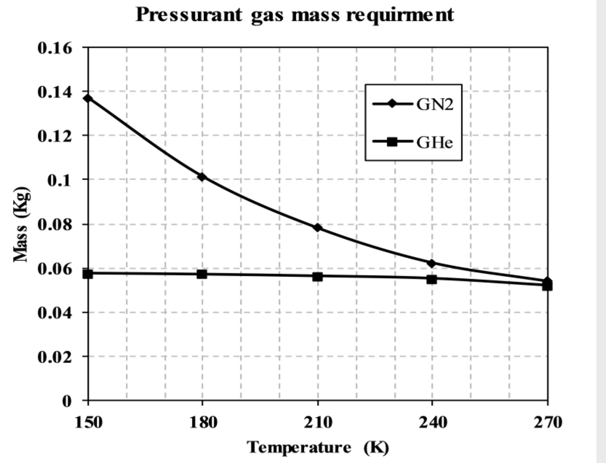


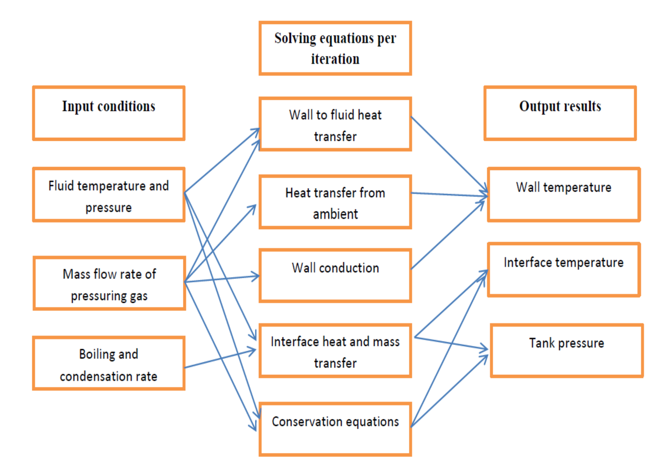



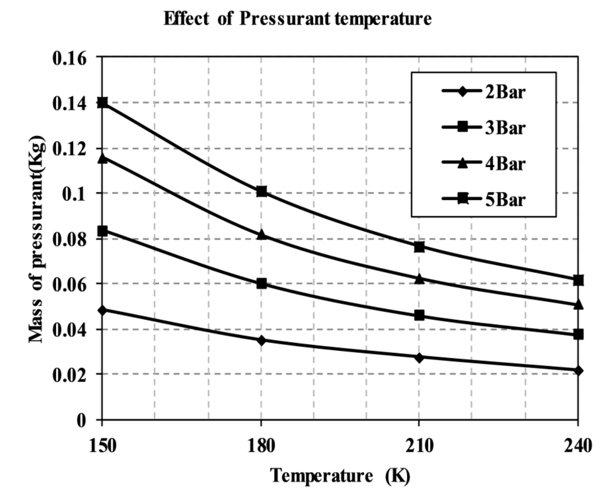

Validation of the model

## ACTIVE PRESSURIZATION



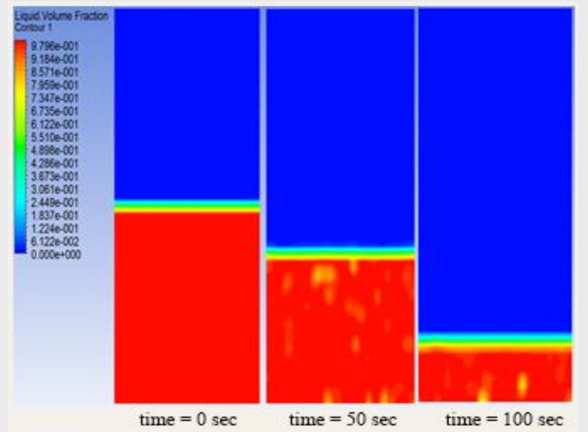


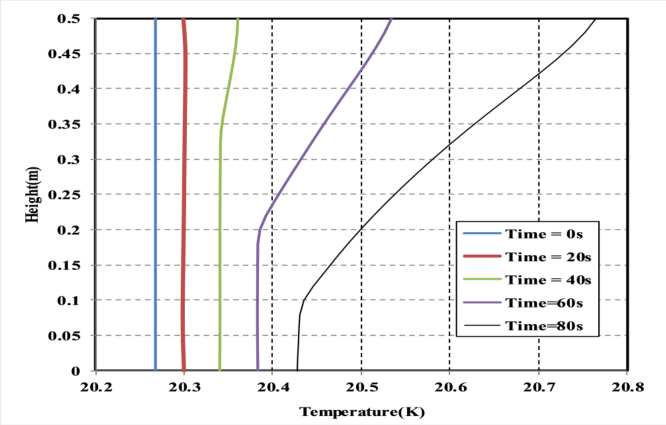




Effect of gas temperature on active pressurization

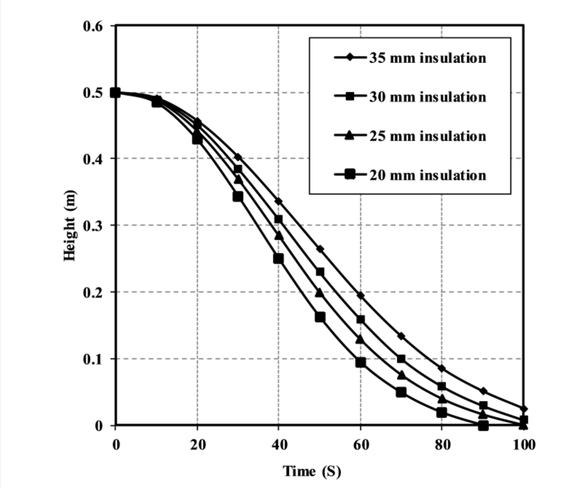
## EVOLUTION OF STRATIFICATION



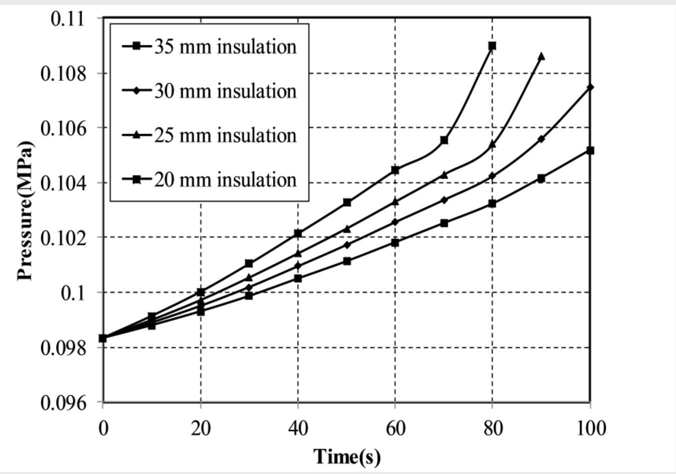

Self pressurization




Evolution of stratification




Variation of interface with different insulation thickness




Tank pressure with different insulation thickness

## CONCLUSIONS

- Increasing the insulation thickness reduces the heat inleak and thereby decreases the tank pressure rise.
- For gaseous nitrogen pressurization, an increased gas temperature reduces the required pressuring gas mass.
- The use of He as pressuring gas is very advantageous as it cannot condense and has low molecular weight and density.
- Less amount of He gas is required for active pressurization and hence overall weight can be reduced.
- The present numerical model can be improved by incorporating stratification on isogrid construction on tank inner surface instead of plain inner wall.

## REFERENCES

[1]C. Ludwig, M. E. Dreyer, and E. J. Hopfinger, “Pressure variations in a cryogenic liquid storage tank subjected to periodic excitations,” International Journal of Heat and Mass Transfer, vol. 66, pp. 223–234, Nov. 2013.

[2]Jeswin Joseph, Gagan Agarwal. “Effect of insulation thickness on pressure evolution and thermal stratification in a cryogenic tank”. Applied thermal Engineering 2016