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THERMAL ANALYSIS OF THE CRYOGENIC PROPELLANT TANK IN LAUNCH VEHICLES

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ABSTRACT

Cryogenic propellants that have been sub-cooled are placed into cryogenic tanks utilized for space applications. A heated layer of liquid forms close to the liquid-vapor interface during the protracted periods of time before launch when heat from outside sources escapes into the tank. Thermal stratification is the term for this process.

A transient, two-phase, thermodynamic model of thermal stratification in a cryogenic tank was constructed in this work. The model considers the flow of the propellant boundary layer caused by nearby natural convection. MATLAB was used to solve equations relating to continuity, momentum, energy, and mass transfer.

Studies were then conducted to ascertain the impact of stratified mass liquid temperature and liquid Pressure profile on liquid sub-cooling in the propellant tank. According to the study, sub-cooling the cryogenic tank results in a higher stratified mass.

The findings of this study can be applied to enhance cryogenic tanks' operation and design for space applications.

Specific Objective-

- *To establish the variation of temperature and pressure with the heat radiant on the outside wall of the tank.*
- *To identify any factors affecting the relationship between temperature, pressure, and radiant heat.*

KEYWORDS- *Cryogenic Tank, Insulation, Thermal Stratification, Liquid Hydrogen.*

1. NOMENCLATURE

A -Surface area (m2)
Cp -Specific heat (J/Kg-K)
D -Tank diameter (m)
d -Port diameter (m)
g -Gravity (m/s2)
H -Enthalpy (J/kg)
h -Heat transfer coefficient (W/m2 -K)
h_fg -Latent heat of vaporization (J/K)
k -Thermal conductivity (W/m-K)
m -Resident mass (Kg)
Nu -Nusselt number
Pr -Prandtl number
Gr -Grashof number
P -Pressure (Pa)
Q -Heat (J)
Ra -Rayleigh number
Re -Reynolds number
T -Temperature (K)
t -Time (s)
U -Boundary flow velocity (m/s)
x -Tank height (m)

Subscripts

a -Ambient conv Convection
int -Liquid-vapor interface
l -Liquid
s -Tank outer surface

u -Ullage
v -Vapor
w -Inner wall

2. INTRODUCTION

Many technical applications, including the storage of rocket propellant, liquefied fuel, and air separation systems, typically employ cryogenic fluids such as liquid nitrogen (LN2), liquid hydrogen (LH2), liquid oxygen (LOX), and liquefied natural gas (LNG) in tanks. When there are thermal demands from the environment, the temperature of these storage containers rises. the tank used to store petrol. Before the combustion chamber is opened in cryogenic launch rockets, fluid travels through the propellant tank through a turbo pump. when the fluid used in the pump's intake warms up the potential for pump cavitation to exceed the "limiting temperature" or cavitation limit. As a result, the liquid inside the tank that is warmer than the limitation threshold cannot be utilized for burning, rendering the stratified mass of propellant useless. Stratified propellant mass is considered when calculating the launch vehicle's payload penalty but, in this paper, we won't consider the stratified mass. Highly effective insulation is employed to lessen the stratified mass and decrease heat leakage into the tank. A crucial factor in the design of the propellant tank and the effectiveness of the launch vehicle systems is the temperature of the liquid. To build the cryogenic fluid system utilized in launch vehicles, it is crucial to accurately estimate how temperature and pressure will change over time in the propellant tank. engine with unstable cryogenic combustion.

Although there are many books on stratification, relatively few of them investigate the stratification process for various liquid sub-cooling conditions. The estimation of temperature under various sub-cooling levels is crucial because cryogenic launch vehicle systems demand sub-cooled propellant at the intake of its turbo-pump. LH2 is used as the working fluid in the current study to evaluate the temperature stratification phenomena. The development of a two-phase thermal stratification model considers the liquid's inherent convection currents caused by heat leaks. The experimental data published in the literature [1] are used to validate the numerical model, and the data are also used to compare the rate of increase in liquid temperature over time.

3. MODEL DESCRIPTION

A typical liquid hydrogen tank, having a diameter of 4m, length of 7m, wall thickness of 4mm, and various foam-insulation thicknesses of 10mm, 20mm, 30mm, and 40mm, consider the whole wall thickness as a summation of insulation thickness and tank wall to ease the calculation and liquid level filled up to 80% of the total height.

In an axis-symmetric tank, thermal stratification is brought on by a complicated two-dimensional boundary layer phenomenon that occurs near the tank wall. To predict the development of pressure and bulk fluid temperatures when various thermodynamic transients in the tank occur. It is presumed that the temperature differential between the interface and the bulk liquid is not large enough, thus making it simpler to predict how the temperature of the bulk fluid will change over time.

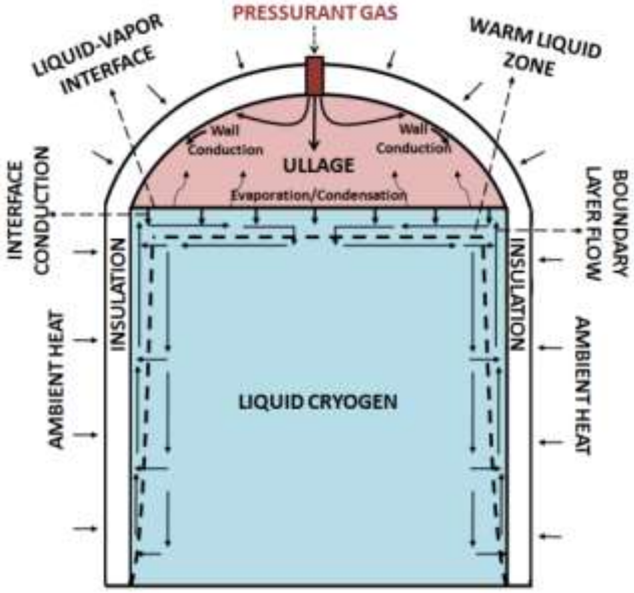

Figure 1: Actual model of cryogenic propellant tank

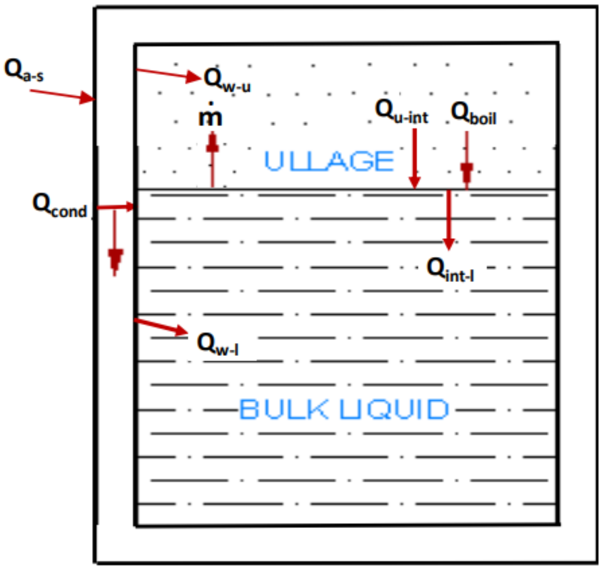

Figure 2: An approximated model of a cryogenic propellant tank

4. SOLUTION METHODOLOGY

Since utilizing the nodal approach to solve the problem, divide the tank capacity into two sections and treated the liquid portion as the first node while treating the ullage portion as a second node. And consider wall thickness as another node to find the temperature variation at the inside wall's surface with different heat radiant at the outside. Now apply the Continuity, momentum, energy, mass transfer equations, and equation of state to solve the problem. At the wall thickness, use the Transient heat conduction equation to evaluate the variation of temperature.

Mathematical equations used for the calculation of the parameter of tank capacity-

4.1 Conservation of Mass

The rate of change of mass in the control volume is equivalent to the net mass flow from a fluid node, as shown below.

$$\dot{m}_{up} - \dot{m}_{down} = \frac{dm}{dt}$$

4.2 Conservation of Momentum

A more complicated version of Newton's second law serves as the governing equation for flow connections. The following is how to write the momentum conservation equation for a fluid connector.

$$\frac{dm}{dt} = \frac{A_c}{L} \cdot \left[\left(P_{up} - P_{down} \right) - f \cdot \frac{1}{2\rho {A_c}^2} \cdot \left(\frac{dm}{dt} \right)^2 \right]$$

The Churchill formulation is used to compute the viscous coefficient 'f'. Momentum conservation is imposed on the fluid connectors that join the fluid nodes.

4.3 Conservation of Energy

The first law of thermodynamics serves as the foundation for the expression of the energy conservation equation. The difference between the rate of energy transport into the control volume and the rate of energy transport out of the control volume equals the rate of increase of internal energy in the control volume. Thus, the enthalpy-based energy conservation equation may be expressed as follows:

$$\frac{dU}{dt} = \left(H_{up}\dot{m}_{up} - H_{down}\dot{m}_{down}\right) + \frac{dQ}{dt}$$

Where:

$$\frac{dQ}{dt} = hA\left(T_w - T_{l,u}\right)$$

where Q, shown below, represents heat in-leak from ambient at boundary fluid nodes with heat transfer coefficient (h).

4.4 Equation of State

Thermodynamic variables at a particular fluid lump are calculated using a real fluid state equation with compressibility factor, Z, being input from the NIST database.

$$P = Z.\frac{m}{V}.\frac{R}{M}.T$$

Now, discuss each part of the tank capacity one by one

5. COMPONENTS OF NODES

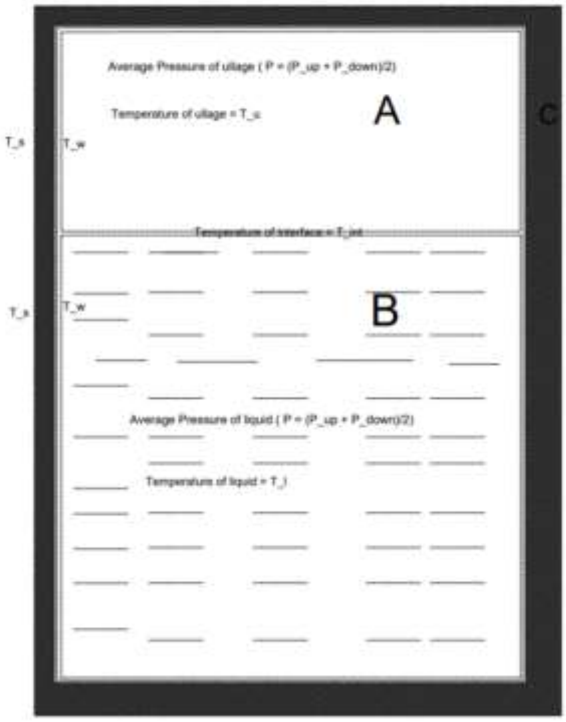

Figure 3: Distribution of nodes within the capacity of the tank and on the wall

Where A is the first node for the ULLAGE part, B is the second node for the Liquid part, and C is the node for the tank metal with insulation. Now analyze each node separately:

5.1 For the tank walls and insulation

Consider the whole tank and insulation as a single node as shown in Figure 3, and apply a transient heat conduction equation on the tank thickness to estimate the variation of inside wall temperature(T_w). the steady-state temperature of the inner wall is determined by the heat flux and the thermal conductivity of the wall material.

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} - q$$

Where the ‘q’ is the constant heat flux applied on the outer surface of the tank. And atmospheric temperature is maintained at 298.15 K. Equations that will be used for the Tank wall and fluid parts are decoupled. assume that:

- q= 2600 W/m^2
- k/rho*Cp) = 4.96 * 10^-7 m^2/s
- L = 3.3cm
- K= 0.02 W/mk
- Initial temp. = 20K

then the result of the variation of inside wall temperature will look like:

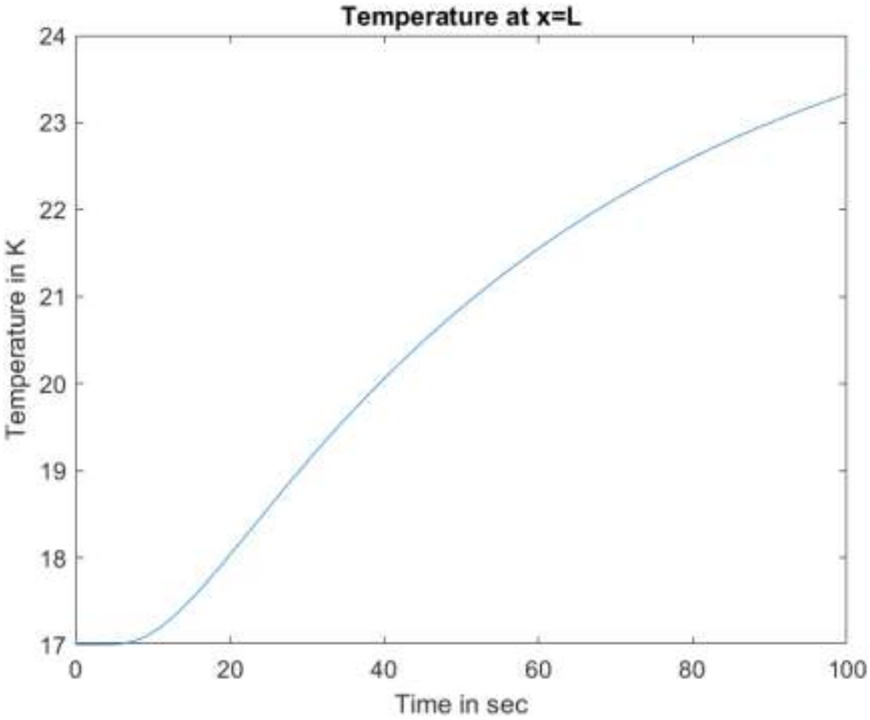

Figure 3: Variation of inner wall temperature with the time

The graph shows that the temperature of the inner wall initially increases rapidly as the heat flux is applied. This is because the heat flux is transferred to the inner wall through conduction, which is a relatively slow process. However, the temperature eventually reaches a steady state after very long time, where the rate of heat transfer through the wall is equal to the rate of heat loss from the wall to the cryogenic fluid. The steady-state temperature of the inner wall is determined by the heat flux and the thermal conductivity of the wall material. The higher the heat flux, the higher the steady-state temperature. The higher the thermal conductivity of the wall material, the lower the steady-state temperature.

5.2 For the liquid part

In a similar way for the liquid part, consider a single node to the whole liquid volume and apply the conservation equations and equation of state to find the variables. Where we need to estimate the variation of “Pressure (P_up and P_down)” and “Temperature(T_u)” of liquid.

So, assume the following properties of liquid hydrogen:

- Specific heat(Cp_l)= 16.403+0.878*(T_l-17)
- Heat transfer coefficent= 0.11 * ((9.8*17*10^(-3)*(T_wT_l)*L_l^3)/((v_l)^2))^(0.25)*(k_l/L)
- dm/dt = volume flow rate * density
- Enthalpy = Cp_l*(T_l-17)

- Density= 234.91/(1+(17*10^(-3)*(T_l-17)))
- Height of liquid (L_l)= 0.8*L (this approx. relation came from a previous experiment performed)
- Friction factor= 0.0075
- Molecular mass=2
- A_l=3.14*D*L_l • Ac=3.14*(D/2)*(D/2)
- Mass flow rate downstream (m_down_l)= 0

Note: all the above-assumed values came from the NIST datasheet
Then the variation of temperature and pressure will look like:

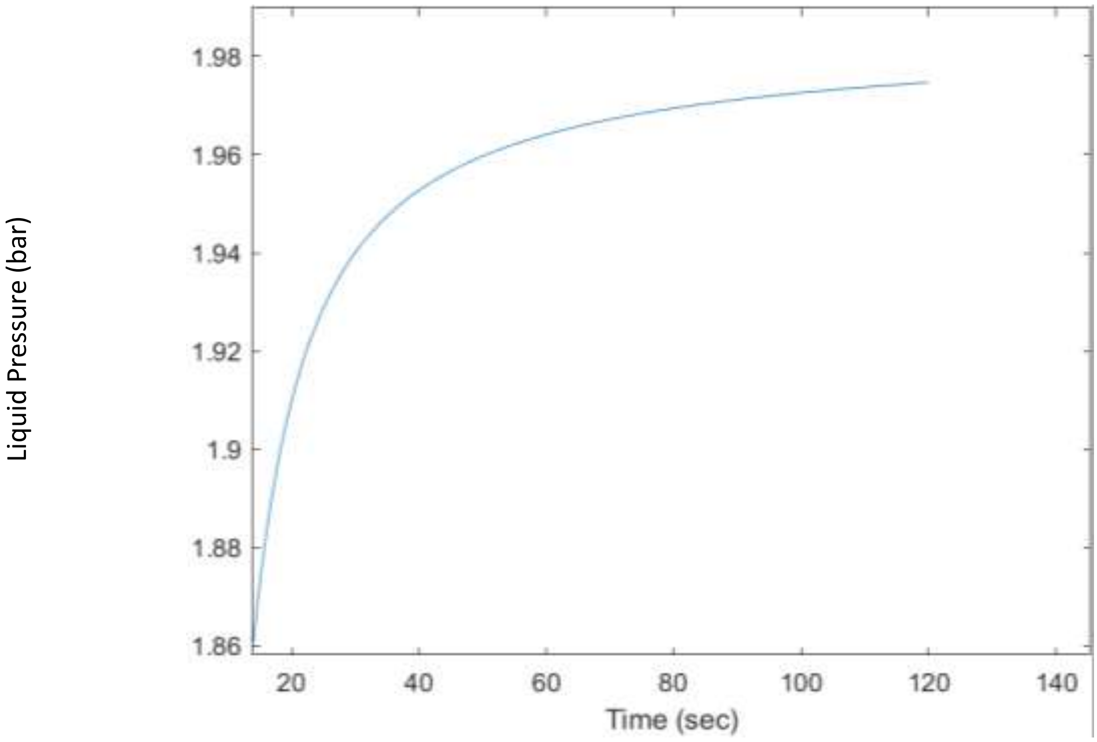

Figure 5: Liquid bulk Pressure Vs time of LH2

The graph shows the liquid pressure inside a cryogenic tank of liquid hydrogen as a function of time. The x-axis of the graph shows the time in seconds, and the y-axis shows the liquid pressure in the bar. The initial liquid pressure in the tank is about 1.5 bar. After 20 seconds, the liquid pressure increased to about 1.9 bar. After 40 seconds, the liquid pressure increased to about 1.94 MPa.

The liquid pressure continues to increase relatively steadily until about 120 seconds when it starts to level off. This is because the rate of evaporation of the liquid hydrogen slows down as the temperature of the liquid hydrogen decreases. the maximum liquid pressure in the tank is about 1.98 bar.

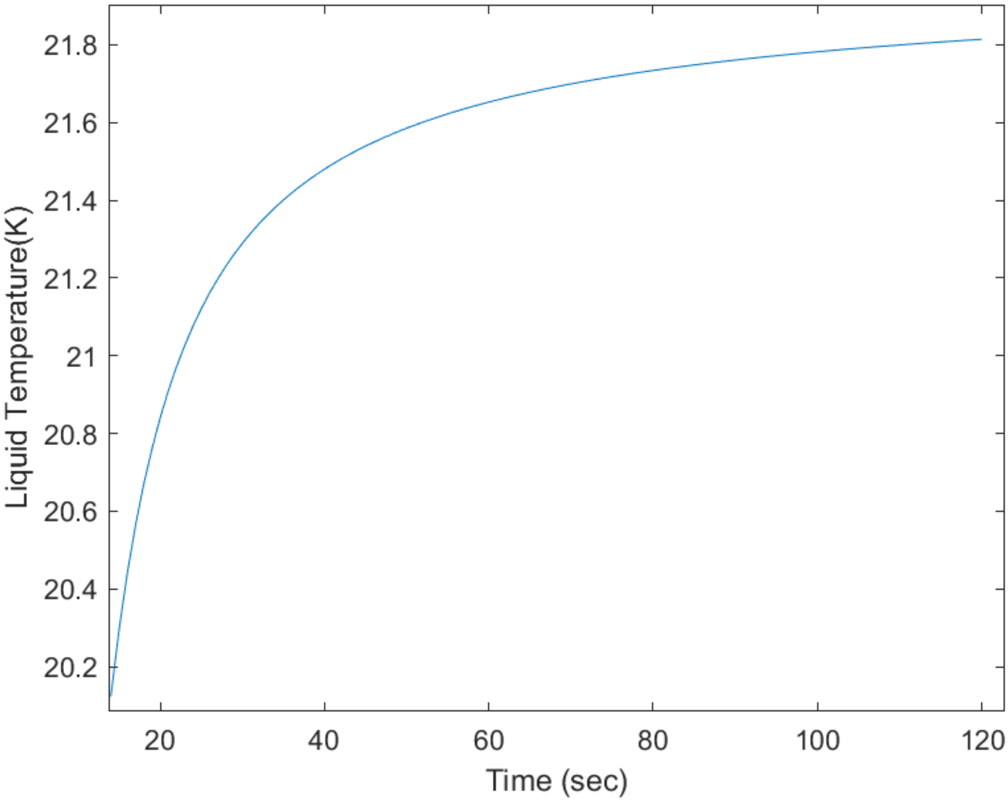

Figure 6: Liquid Bulk Temperature Vs time of LH2

The temperature starts at around 20 K and gradually increases to around 22 K(B.P.). The graph also shows that the rate of temperature increase is not constant. The graph you sent me shows the liquid temperature of a substance as a function of time. The x-axis of the graph shows the time in seconds, and the y-axis shows the liquid temperature in Kelvin (K). The data points on the graph show that the liquid temperature decreases as time goes on. This is because the liquid is being heated, and the heat is causing the liquid to vaporize.

The initial liquid temperature in the tank is about 20 K, After 20 seconds, the liquid temperature increased to about 20.4 K, After 40 seconds, the liquid temperature increased to about 21.4 K and after 120 sec. the temperature will steady at 21.8 K because the liquid hydrogen boiling point is at 22 K.

5.3 For the Ullage part

Similarly, consider another node for the whole ullage part to estimate the variation of temperature and pressure of hydrogen gas. Assume that:

- Height of ullage=0.2*L
- Friction factor= 0.015
- Molecular mass=2
- A_u=3.14*D*L_u
- Ac=3.14*(D/2)*(D/2)
- m_up_u= 0
- Density= 234.91/(1+(17*10^(-3)*(T_u-17)))
- Enthalpy= Cp_u*(T_u-17) = Hdown
- Specific heat(Cp_u)= 25.313+1.1*(T_u-17)
- Heat transfer coefficent= 0.024*T_u^(0.5)*P_u^(-0.5)
- dm/dt = volume flow rate * density

Note: All the above-assumed values came from the NIST datasheet
The variation of pressure and temperature of gas will look like:

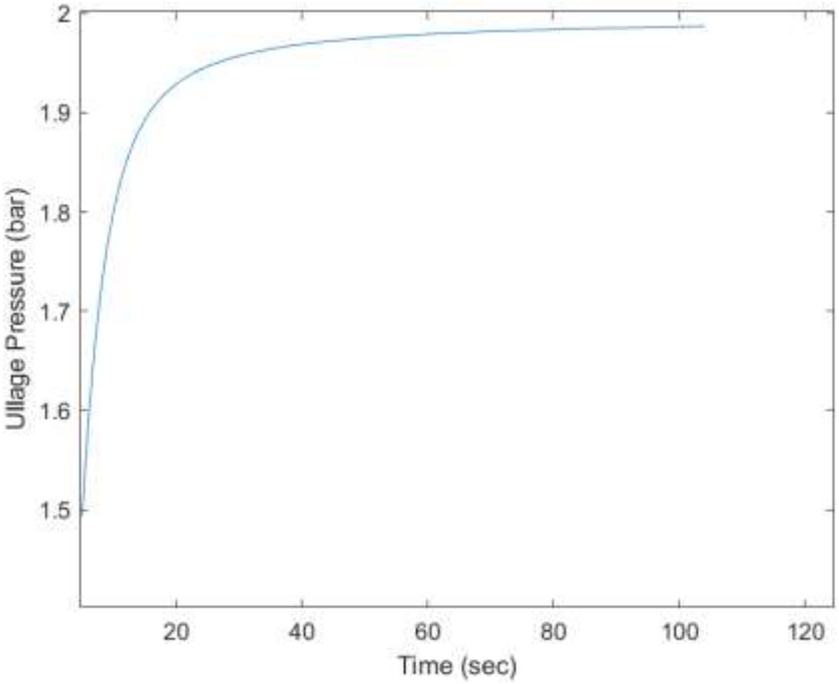

Figure 7: Ullage Pressure Vs time of LH2

The graph shows the ullage pressure vs. time of a cryogenic propellant tank. The ullage pressure is the vapor pressure above the liquid hydrogen in the tank. The graph shows that the ullage pressure increases over time as the liquid propellant is consumed. The initial ullage pressure is about 1.5 bar. The ullage pressure then increases rapidly to about 1.9 bar in the first 20 seconds. The ullage pressure then increases gradually to about 2 bar over the next 100 seconds. This is because the liquid propellant temperature is near to its steady value so the rate of evaporation will slow down.

The variation of ullage temperature with respect to time shown below

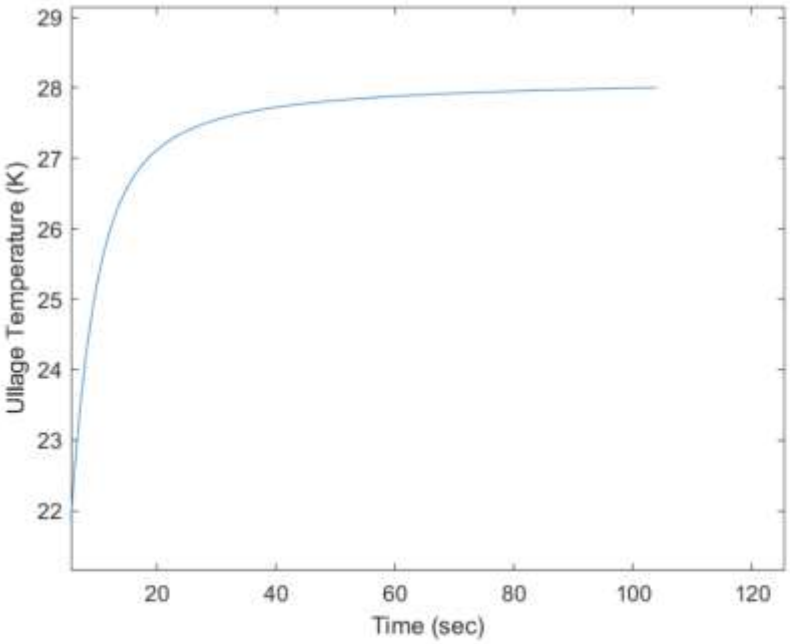

Figure 8: Liquid Temperature Vs time of LH2

The graph shows the ullage temperature vs. time of a cryogenic propellant tank. The ullage temperature is the vapor temperature above the liquid hydrogen in the tank. The graph shows that the ullage temperature increases over time as the liquid propellant is consumed. The initial ullage pressure is about 22 K. The ullage temperature then increases rapidly to about 25K in the first 20 seconds. The ullage temperature then increases gradually to about 28K over the next 100 seconds. This is because the liquid propellant temperature is near to its steady value so the rate of evaporation will slow down.

6.CONCLUSION AND RESULT

To understand how insulation thickness affects the development of the tank's pressure and temperature, a transient, two-phase thermodynamic model of a liquid hydrogen cryogenic propellant tank utilized in a typical launch mission is built. As time passes temperature and pressure of the cryogenic tank increase till their steady value but not exceeding 2 degrees Celsius except for the ullage temperature profile.

Following are the salient conclusions drawn from the analyses:

- Lower insulation thickness above cryogenic tanks causes a larger heat infiltration into ullage gas, which considerably raises tank pressure.
- The development of the stratified mass is significantly influenced by tank pressure, which affects interface temperature. A higher tank pressure results in a greater mass of liquid stratified.
- Propeller tanks used in launch vehicles suffer a payload penalty because of the increased temperature because of higher liquid heat infiltration from the environment when tank insulation is thinner.
- Due to a larger ullage heat in-leak, thinner tank insulation reduces the amount of pressuring mass needed to pressurize the tank. After pressurization, a larger ullage mass must thus be released in order to maintain consistent tank pressure.
- The solar flux and ambient temperature have an impact on the tank's outer surface temperature, which in turn impacts the heat in-leak and ultimately the tank pressure.

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