Thermal stratification in LH2 tank of cryogenic propulsion stage tested in ISRO facility

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Abstract. Liquid oxygen and hydrogen are used as oxidizer and fuel respectively in cryogenic propulsion system. These liquids are stored in foam insulated tanks of cryogenic propulsion system and are pressurized using warm pressurant gas supplied for tank pressure maintenance during cryogenic engine operation. Heat leak to cryogenic propellant tank causes buoyancy driven liquid stratification resulting in formation of warm liquid stratum at liquid free surface. This warm stratum is further heated by the admission of warm pressurant gas for tank pressurization during engine operation. Since stratified layer temperature has direct bearing on the cavitation free operation of turbo pumps integrated in cryogenic engine, it is necessary to model the thermal stratification for predicting stratified layer temperature and mass of stratified liquid in tank at the end of engine operation. These inputs are required for estimating the minimum pressure to be maintained by tank pressurization system. This paper describes configuration of cryogenic stage for ground qualification test, stage hot test sequence, a thermal model and its results for a foam insulated LH2 tank subjected to heat leak and pressurization with hydrogen gas at 200 K during liquid outflow at 38 lps for engine operation. The above model considers buoyancy flow in free convection boundary layer caused by heat flux from tank wall and energy transfer from warm pressurant gas etc. to predict temperature of liquid stratum and mass of stratified liquid in tank at the end of engine operation in stage qualification tests carried out in ISRO facility.

1. Introduction

Liquid Propulsion Systems centre of Indian Space research organization successfully completed in November 2007 the qualification tests of Cryogenic Upper Stage (CUS) which was designed and developed for Upper Stage propulsion of Geosynchronous Satellite launch vehicle-GSLV MkII. This stage uses liquid oxygen and hydrogen as oxidizer and fuel respectively and is powered by a cryogenic engine delivering a nominal thrust of 73 kN in vacuum. Flight testing of CUS was accomplished in GSLV D5 and GSAT 14 mission on 5-1-2014. Prior to the realisation of flight stage, a ground test stage was realised to carry out development tests viz propellant fill and drain, liquid hydrogen expulsion test, stage hot tests envisaged for stage qualification.

The ground test stage was filled with 13300 kg of LOX and 2400 kg of LH2 for stage hot test to ensure operation of cryogenic engine for 720 s. One of the objectives of stage hot test is to measure the temperature of stratified liquid layer in LH2 tank during LH2 outflow of 38 lps for engine operation in stage hot test under the conditions of heat flux of about 200W/m² to tank wall and heat...
transfer from warm pressurant gas supplied at 200 K for tank pressure maintenance at 0.2 MPa. To predict the temperature of liquid stratum and mass of stratified liquid in tank during stage hot test, a thermal model is developed considering buoyancy flow in free convection boundary layer caused by heat flux from tank wall and energy transfer from warm pressurant gas to stratified layer. Model results and test data show a close match. This paper outlines configuration of ground test stage, Stage hot test sequence, analytical model for liquid stratification, comparison of test data with model results and conclusion.

2. Configuration of Cryogenic stage for ground test

Figure 1 shows the overall configuration of ground test stage which was subjected to development and qualification tests.

It consists of propellant tanks for storing LOX and LH2, inter-tank structure for mechanically interconnecting the tanks, LOX and LH2 umbilical connector units, fluid circuits, cryogenic gas bottles, command system, thermal insulation, cryogenic engine, control system etc.

![Figure 1. Overall configuration of ground test stage](image)

LOX fluid circuits are interfaced between LOX tank and its umbilical connector unit to facilitate filling and temperature conditioning of LOX, venting of oxygen vapour during the test. Similar systems are interfaced between LH2 tank and its umbilical connector unit for carrying out filling of LH2, liquid level maintenance, venting of hydrogen vapour etc.
Independent vent and relief systems are provided in LOX and LH2 tanks for protecting from over-pressurization. Pneumatic command system provides regulated pressure of 5 MPa to the electrically actuated command valves for the actuation of pneumatic valves of engine and stage systems.

A regulator based pressurization system is provided for LH2 tank pressure maintenance at 0.2 MPa during LH2 outflow of 38lps during cryogenic engine operation. Hydrogen gas at 200 K and 8 MPa is tapped from regenerative coolant outlet manifold of cryogenic engine and is supplied to the inlet of regulator unit for LH2 tank pressurization. For LOX tank pressure maintenance at 0.17 MPa, cryogenic helium gas stored in gas bottles at 22 MPa is regulated through a regulator module before being supplied to tank.

Cryogenic engine operating on staged combustion cycle is integrated to the stage through thrust frame. This engine delivers 73 kN thrust in vacuum burns LOX and LH2 at a flow rate of about 14 and 2.4 kg/s respectively.

Propellant tanks and fluids lines are thermally insulated to reduce heat leak to the system. This hardware is instrumented to acquire additional data during testing compared to flight stage.

3. Stage hot test sequence

As per the test sequence shown in figure 2, LOX tank is chilled down using LOX supplied through LOX fill and drain umbilical port at low flow rate. After ensuring liquid collection at tank bottom, flow rate of LOX is increased to 3.5 kg/s for filling the tank. Then, temperature conditioning of LOX is initiated by simultaneously filling sub cooled LOX at 76-77 K and draining the warm LOX from the tank. This operation continued for about 4200 s to achieve bulk mean temperature of LOX at 77.8 K.

![Figure 2. Stage hot test sequence](image)

Similarly, LH2 tank is chilled down using LH2 supplied through LH2 fill and drain umbilical port at low flow rate. After chilling the tank bottom to 20 K, LH2 supply flow rate is increased to 1 kg/s for filling the tank. Then, the filled level was replenished to compensate evaporation loss of LH2 until thermal conditioning of LOX is completed. Subsequently, LH2 tank is vented to 0.115 MPa to achieve liquid temperature of 20.8 K. Later both the tanks are filled at lower flow rate to reach final level corresponding to loading of 13300 kg of LOX and 2400 kg of LH2 using capacitance level sensor. During this period, engine chilling is carried out initially with cold helium gas at 40-50 K and later using respective propellants. After reaching the specified temperature in LOX and LH2 pumps employed in cryogenic engine, hot test is authorized and engine operation started as per start sequence and propellant tanks are pressurized and maintained the specified pressure throughout the hot test.

4. Influence of stratified layer temperature in the design of LH2 tank pressurization system.

Propellant tanks are pressurized to meet the Net positive suction pressure (NPSP) requirement of pumps employed in cryogenic propulsion system. NPSP is the pressure head required at the pump inlet...
above the saturation pressure of the liquid. Design of pressurization system requires temperature of stratified layer which reaches the pump inlet towards the end of engine operation. Following expression shows the influence of stratified layer temperature, $T_s(t)$ in the design of LH2 tank pressurization system.

$$P_t = P_{sat}(T_s) + NPSP + NPSP_{margin} + \Delta P - P_{acc} \tag{1}$$

Since stratified layer temperature is higher than bulk liquid temperature $T_b$ during engine operation, saturation pressure corresponding to stratified layer temperature is to be considered for determining tank pressure to be maintained by the pressurization system.

5. Thermal stratification in cryogenic tanks

Thermal stratification in cryogenic tank refers to non-uniform temperature in the liquid column of a tank caused by the migration of heated fluid from boundary layer to liquid free surface and forming a stratum at a temperature higher than the bulk liquid. Figure 3 depicts boundary layer and stratified layer formed in the liquid column, ullage volume of a cryogenic tank.

![Figure 3 Schematic of stratification](image)

6. Non-dimensional numbers for buoyant flows

A non-dimensional Rayleigh number $Ra$ is used to classify buoyancy induced boundary layer flow. Rayleigh number, is a product of Grashof number $Gr$ and Prandtl number, $Pr$

Buoyancy driven free convective flow along the tank inner wall can be laminar or turbulent.

$$Ra = Gr \cdot Pr = \frac{g \beta \theta_w x^3 \mu \bar{C}_p}{v^2} \cdot \frac{\mu \bar{C}_p}{K} \tag{2}$$

Equation 2 is applicable for constant wall temperature condition.

$$Ra^* = Gr^* \cdot Pr = \frac{g \beta q_w x^4 \mu \bar{C}_p}{K v^2} \cdot \frac{\mu \bar{C}_p}{K} \tag{3}$$
Equation (3) gives a relation for modified Rayleigh number, \(Ra^*\) which is a product of modified Grashof number, \(Gr^*\) and Prandl number for constant heat flux condition. Transition from laminar to turbulent region takes place when \(Ra^*\) is around \(10^{11}\).

7. Analytical model for stratification

Modeling of thermal stratification in propellant tanks employed in cryogenic propulsion system requires an understanding of mass and energy transportation in the buoyancy induced boundary layer caused by tank wall heating.

The system analyzed is a foam insulated cylindrical tank filled with LH2 to a height, \(H\) and is subjected to wall heat flux and no vent condition. For the given conditions in tank, Rayleigh number is calculated and thereby boundary layer flow is identified as either laminar or turbulent. Stratification analysis is based on integration of liquid mass flow rate taking place in the natural convection boundary layer along the inner wall of tank.

Following assumptions are considered for analysis

1. Initial liquid temperature is in equilibrium with vapour pressure and is uniform in the entire liquid bulk.
2. Warm liquid molecules present in boundary layer migrate towards liquid free surface and forms a warm liquid stratum.
3. Heat leak through tank wall appears as sensible heat in the free convection boundary layer adjacent to tank wall.
4. There is no mixing between warm liquid stratum and bulk liquid.
5. The warm stratum at liquid surface is uniformly mixed.

The growth of stratified layer is governed by the rate at which warm fluid in the boundary layer flows in to the stratified layer. The mass flow rate in the boundary layer is given in equation (4).

\[
m_{bl} = \rho 2\pi R \int_{0}^{\delta} u(y) \, dy
\]  

(4)

For constant tank wall temperature condition, the velocity and temperature profiles with in a turbulent boundary layer caused by free convection are given by equation (5) and (7) respectively.

\[
u(y) = u_{t}\left(\frac{y}{\delta}\right)^{7/4} \left(1 - \frac{y}{\delta}\right)^{4}
\]  

(5)

\[
u_{t} = 1.185 \frac{V}{x} \left[1 + 0.49(Pr)^{2/3}\right]^{1/2}
\]  

(6)

\[
\theta(y) = \theta_{w} \left[1 - \left(\frac{y}{\delta}\right)^{1/7}\right]
\]  

(7)

Applying energy balance between heat entering the tank wall below the stratum, \(H-\Delta(t)\) and heat exiting the boundary layer at the stratum interface, we get

\[
q_{w}^{-1}(H-\Delta(t)) = h \theta_{w} \left(\frac{H-\Delta(t)}{\rho Cp \int_{0}^{\delta} \theta(y) u(y) \, dy}
\]  

(8)

Combining equation (4) and (8) with the appropriate expression for a turbulent boundary layer, we get
\[ m_{bl} = \rho \pi R^2 \left( \frac{d\Delta}{dt} \right) = \frac{8m_{liq}}{Cp} \left( H - \Delta(t) \right) \] (9)

Based on the measured wall temperature and liquid temperature in the vicinity of tank wall during hot test and the heat flux through foam insulation of tank wall, \( h_{liq} \) is computed.

Integrating equation (9), yields an expression for the growth of the stratified layer \( \Delta(t) \) for turbulent boundary layer as given below.

\[ \Delta(t) = \left[ H - \Delta(t) \right] \left[ 1 - e^{-\frac{8h_{liq}t}{RCp\rho}} \right] \] (10)

The stratified layer temperature increase with time is computed as given in equation (11)

\[ T_s(t) = T_w - \theta_w - \frac{2Hht}{R \Delta(t) \rho Cp} + \Delta T_{gas} \] (11)

\( \Delta T_{gas} \) is caused by heat transfer from ullage gas to stratified layer and is computed using equation (12)

\[ Q_g = Kh_g A_{sur} (T_g - T_s) \] (12)

where K is a correction factor and is obtained from experimental data. Heat transfer coefficient is computed by the following relation

\[ h_g = \frac{0.27k_g}{D} \left[ \frac{D^3 \rho_g^2 g \beta_g (T_g - T_s)}{\mu_g^2 \left( \frac{Cp_g \mu_g}{k_g} \right)} \right]^{1/4} \] (13)

To compute the temperature gradient in the stratified layer, solution of transient 1-D conduction heat transfer in partial differential form is used as given below:

\[ \frac{\partial T_s}{\partial t} = \alpha \frac{\partial^2 T_s}{\partial z^2} \] (14)

Solution for the above equation is

\[ T_s(z,t) = T_b + (T_s - T_b) \text{erfc} \left[ \frac{H - z}{2\sqrt{\alpha t}} \right] \] (15)

8. Experimental data and computed values

Figure 4 shows the temperature rise of liquid and ullage gas as measured by temperature sensors mounted at different height of LH2 Tank. This indicates liquid level fall due to outflow at 38 lps during engine operation and the stratified layer increase with time.

![Figure 4 Stratified layer temperature measured at different heights during test](image_url)
Table 1. Stratified layer thickness (measured and computed)

| Time (s) | $T_{sat}$, K | $\Delta(t)$ Measured, m | $\Delta(t)$ Computed, m |
|----------|--------------|--------------------------|--------------------------|
| $T_0+56$ | 23           | 0.074                    | 0.064                    |
| $T_0+117$| 22.8         | 0.181                    | 0.127                    |
| $T_0+420$| 22.6         | 0.413                    | 0.352                    |

The above computed values indicate the stratified layer thickness $\Delta(t)$ without considering heat transfer from ullage gas. Since the measured $\Delta(t)$ is higher than the computed, it is concluded that the additional thickness of stratified layer is caused by the admission of warm gas into the tank ullage for pressurization. Also, it may be noted that LH2 tank pressure was not constant during the hot test which resulted in reduction in stratified layer temperature with time as shown in table-1.

![Figure 5: Thickness of stratified layer](image1)
![Figure 6: Liquid temperature gradient in stratified layer](image2)

9. Conclusion
A mathematical model describing thermal stratification driven by natural convection in a liquid hydrogen tank of cryogenic propulsion system has been developed. It accounts for effect of tank wall heat flux and heat transfer from warm pressurant gas (supplied for tank pressure maintenance) to stratified layer. Temperature and velocity boundary layers at the tank inner surface are taken into account to predict the temperature of stratified layer, $T_s$ and its thickness, $\Delta(t)$. Thermal stratification effect is investigated considering liquid outflow of 38 lps during engine operation. The model simulated the thermal stratification in foam insulated LH2 tank of 30 m$^3$ employed in ground test hardware of indigenously developed cryogenic upper stage (CUS) and the results of the model have a close match with experimental data.

10. Acknowledgement
Authors owe a deep sense of gratitude to Shri. Somanath S, Director, Liquid Propulsion Systems Centre for encouraging and guiding us to prepare this technical paper for presentation in ICEC26-ICMC 2016.
12. Appendix Symbols

LH2  Liquid Hydrogen
LOX  Liquid Oxygen
µ  Dynamic viscosity of LH2, Pa-s
ν  Kinematic viscosity of LH2,
Cp  Specific heat of LH2, kJ/kg.K
ρ  Density of LH2, kg/m³
k  Thermal conductivity of LH2, W/mK
β  Volumetric Thermal expansion coefficient of LH2,K⁻¹
h₁₀  Heat transfer coefficient of LH2, W/m²K
q  Local acceleration, m/s²
qₗ  Heat flux to tank wall from ambient, W/m²
θₗ  Temperature difference (Tₗ - Tₜ), K
Tₗ  Tank wall temperature, K
Tₜ  Liquid bulk temperature, K
Tₛ  Temperature of stratified layer, K
R  Radius of LH2 tank, m
D  Diameter of LH2 tank, m
H  Cylindrical height of LH2 tank, m
Pₖ  Tank pressure, MPa
Pₚ₉  Saturation pressure corresponding to LH2 temperature, MPa
ΔP  Pressure drop from tank to pump inlet, MPa
NPSP  Net positive suction pressure, MPa
Pₘ₉  Static pressure due to vehicle acceleration, MPa
Aₙ₉  Area of liquid free surface, m²
µ₉  Dynamic viscosity of ullage gas, Pa-s
Cₚ₉  Specific heat of ullage gas, kJ/kg.K
k₉  Thermal conductivity of ullage gas, W/mK
h₉  Heat transfer coefficient of ullage gas, W/m²K
T₉  Temperature of ullage gas, K
Q₉  Heat flow from ullage gas to liquid free surface, W
ρ₉  Density of ullage gas, kg/m³
β₉  Volumetric thermal expansion coefficient of ullage gas, K⁻¹

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