

# Performance Studies on Sub-cooling of Cryogenic Liquids Used for Rocket Propulsion Using Helium Bubbling

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**Abstract**—The sub-cooling of cryogenic propellants contained in tanks is an important and effective method for bringing down the lift-off mass of launch vehicle and thus the performance of the rocket engine is greatly improved. This paper presents the technical and experimental studies conducted on cryogenic liquids such as Liquid Oxygen, Liquid Nitrogen, and Liquid Hydrogen using helium bubbling method. The influence of cooled Helium on the degree of sub-cooling and the variation in flow rate of Helium gas admitted are discussed. The experimental and theoretical studies indicate that the sub-cooling technique using helium injection is a very simple method and can be very well adopted in propellant tanks used for ground and launch vehicle applications.

**Keyword**-Sub-cooling, Diffusion, Liquid Nitrogen, Liquid Oxygen, Liquid Hydrogen.

## I. INTRODUCTION

The cryogenic propellants namely Liquid Hydrogen and Liquid Oxygen are filled in the propellant tanks. The mass of tank shall be as less as possible in order to limit the total lift-off mass of launch vehicle to a minimum value. This keeps the specific impulse of the cryogenic Engine to a higher value. The helium gas injected inside the propellants contained in the tank, reduces the temperature of the propellant. The density of the propellants is increased which ultimately reduces the volume of tank. Yesteryears, several experiments are conducted on the helium injection cooling. Larsen and Clarke have achieved best results of the experiments by injecting helium gas inside the oxygen tanks[1]. Schmidt has achieved sub cooling of Liquid Hydrogen by similar technique of helium injection[2]. Cleary et al have sub cooled liquid oxygen by injected helium with various injection flow rates[3].

The basic principle behind sub cooling of cryogenic propellants is diffusional mass transfer. When a helium bubble passes through Liquid Nitrogen, the liquid Nitrogen surrounding the bubble will spontaneously evaporate and diffuses into the bubble due to diffusional mass transfer. This mass diffusion occurs due to pressure differential across the helium bubble. The evaporation of liquid takes away the latent heat from the bulk liquid, there by the temperature of bulk liquid Nitrogen is reduced.

In the launch vehicle, the sub cooling of propellants can be done either prior to pre-pressurisation or after pre-pressurisation of tanks. If it is done before pre-pressurisation, the warm up of liquid takes place during pre-pressurisation period. Hence it is preferred to carry out sub-cooling after pre-pressurisation.

The experimental studies have been carried out on Liquid Nitrogen (LN<sub>2</sub>), Liquid oxygen (LOX) and Liquid Hydrogen (LH<sub>2</sub>) to predict the influence of different factors like helium injection temperature, helium injection flow rate. The numerical and experimental studies conducted to analyse the rate of sub cooling and the behavior of sub cooling shows that the rate of sub cooling increases with decrease in injection helium temperature and increase in helium flow rate. Also the helium injection pattern play a major role in achieving higher sub-cooling rate. Circumferential injection yields better results than axial injection.

In the paper, analytical and experimental methods have been used to study the sub cooling behavior of Liquid Oxygen, Liquid Nitrogen and Liquid Hydrogen which are normally being used as cryogenic liquids in ground and launch vehicle applications.

## II. MATHEMATICAL MODEL

The schematic diagram of helium injection cooling system is shown in fig 1. The very basic principle of sub cooling of cryogenic liquids by helium injection is diffusional mass transfer. Since the injected helium gas is pure, the difference in the partial pressure of Nitrogen in helium bubble and the vapour pressure of liquid Nitrogen causes diffusional mass transfer of Nitrogen vapour into the helium bubble. The diffusion of Nitrogen into the helium bubbles continues until thermodynamic phase equilibrium is reached. The diffusion process brings the cooling of bulk liquid caused by the vaporization of surrounding liquid. The phenomenon of diffusion taking place during helium injection is explained in fig 2.

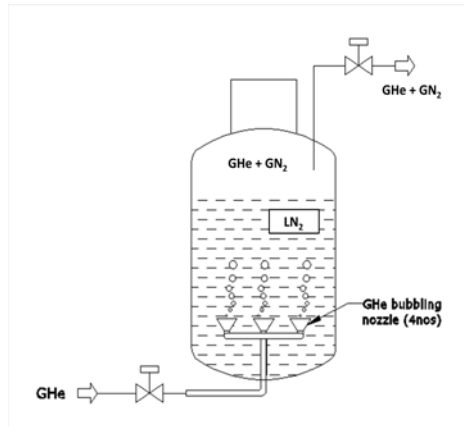


Fig. 1. Schematic diagram of helium injection cooling system

In order to clearly define the partial pressure at the interface surface, imaginary surfaces ‘a’ and ‘b’ are defined. As helium bubble raises just above the injection point and when it travels liquid Nitrogen gets evaporated into helium gas stream. At ‘a’ surface mole fraction of Nitrogen  $X_{N_2,a}$  while at ‘b’ surface, gas phase quantity of Nitrogen is present. When helium gas is injected into liquid Nitrogen, the partial pressure of Nitrogen vapour at the ‘b’ surface would differ significantly from that of bulk gas which causes diffusional mass transfer according to Fick’s law of diffusion.

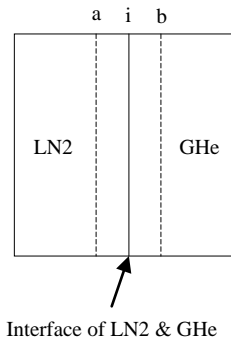


Fig. 2. Schematic diagram of principle on helium injection cooling

The total vaporization rate of liquid Nitrogen  $\dot{m}_{LN_2}$  is expressed as the addition of two forms of vaporization taking place. One due to heat transfer between gas bubble and liquid Nitrogen  $\dot{m}_{LN_2,h}$  and the other due to pure diffusion  $\dot{m}_{LN_2,diff}$  as given in Eqn(1). The amount of vaporization due to the heat transfer from the helium bubble to Liquid Nitrogen is normally negligible. The rate at which the bulk liquid Nitrogen energy change is given in Eqn(2) where  $\dot{Q}_{gi}$  is the heat transfer rate from the gas bubble to the liquid Nitrogen interface,  $\dot{m}_{LN_2}h_{fg}$  is the latent heat transfer rate by phase change of liquid Nitrogen and  $\dot{Q}_{amb}$  is the heat transfer rate into liquid Nitrogen from ambient. The liquid Nitrogen vaporization due to heat transfer  $\dot{m}_{LOX,h}$  can be related to  $\dot{Q}_{gi}$  is shown in Eqn(3). Substituting Eqn(1) & (3) into the energy balance equation, Eqn(2) the vaporization due to heat transfer  $\dot{m}_{LOX,h}$  is now cancelled. Therefore the vaporization due to diffusion  $\dot{m}_{LOX,diff}$  is the main drive for cooling. Liquid Nitrogen sub cooling by helium injection can be characterised by diffusion driven evaporative cooling.

$$\dot{m}_{LN_2} = \dot{m}_{LN_2,h} + \dot{m}_{LN_2,diff} \tag{1}$$

Where  $\dot{m}_{LN_2}$  is the mass flow rate of  $LN_2$ ,  $\dot{m}_{LN_2,h}$  is the evaporation rate of  $LN_2$  due to heat flux and  $\dot{m}_{LN_2,diff}$  is the evaporation rate of  $LN_2$  due to diffusion.

$$\dot{m}_{LN_2}c_{pLN_2} \frac{dT_{LN_2}}{dt} = \dot{Q}_{gi} - \dot{m}_{LN_2}h_{fg} + \dot{Q}_{amb} \tag{2}$$

Where  $c_{pLN_2}$  is the specific heat of  $LN_2$ ,  $T_{LN_2}$  is the temperature of  $LN_2$ ,  $t$  is the time,  $h_{fg}$  is the latent heat of evaporation,  $\dot{Q}_{gi}$  is the heat transfer rate from the gas bubble to the  $LN_2$  and  $\dot{Q}_{amb}$  is the heat transfer rate into liquid Nitrogen from ambient.

$$\dot{Q}_{gi} = \dot{m}_{LN_2}h_{fg} \tag{3}$$

Where  $\dot{m}_{LN_2}h_{fg}$  is the latent heat transfer rate by phase change of  $LN_2$ .

In the theoretical studies conducted three limiting cases can be arrived in terms of heat and mass transfer aspects. First case is instantaneous heat and mass transfer in which the bulk liquid and gas are always in thermodynamic phase equilibrium state. This approach gives maximum sub cooling rate and the second case is finite heat transfer and instantaneous mass transfer. In this case the temperature of bulk liquid and gas are different due to finite heat transfer. However due to the assumption of infinite mass transfer rate, the partial pressure of the Nitrogen vapour at the 'b' surface remains equal to that of the bulk gas. The third case is finite heat and mass transfer. Though the finite heat and mass transfer is the most realistic description of the phenomenon, the finite heat transfer and instantaneous diffusional mass transfer model gives satisfactory agreement with experimental data for small bubbles and gas with high diffusion coefficient such as helium.

In the case of finite heat transfer and instantaneous diffusional mass transfer model, liquid Nitrogen evaporation rate  $\dot{m}_{LN2}$  is calculated with the prescribed heat transfer coefficients (gas to interface  $h_{gi}$ , liquid to interface  $h_{li}$ , net bubble surface Area ( $A_s$ ) and interface temperature ( $T_i$ ) for a given system as given in eqn(4).

$$\dot{m}_{LN2} = \frac{A_s [h_{gi}(T_g - T_i) - h_{li}(T_i - T_{LN2})]}{h_{fg}} \quad (4)$$

Liquid Nitrogen has finite vaporization rate depending on the net bubble surface area and the relevant heat transfer coefficients. Since thermodynamic phase equilibrium in bubble requires the partial pressure of Nitrogen in the bubble to be equal to the saturated vapour pressure of liquid Nitrogen at particular temperature of liquid the difference between the partial pressure of the Nitrogen in the bubble and the vapour pressure of the liquid nitrogen propels the generated vapour into the bubble without degradation. The transferred Nitrogen vapour mixes with helium gas instantaneously.

### III. EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is given in fig 3. It consists of a Super Insulated Dewar of 1000 liters capacity in which the test liquid to be sub cooled is filled.

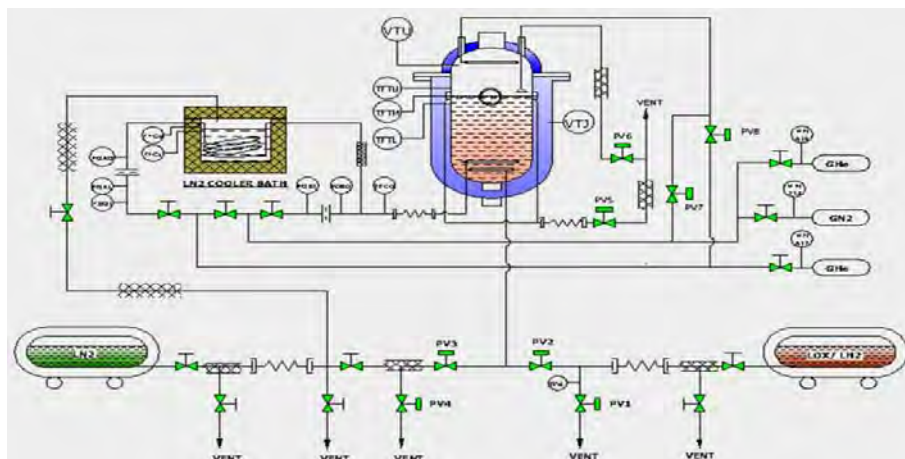


Fig. 3. Schematic diagram of the experimental setup for sub cooling with ambient/cold helium supply

The Dewar has an inner vessel of diameter 900 mm and shell height 1030 mm welded with semi-elliptical dishes at its top and bottom. The vacuum level of Super Insulated Dewar is maintained at  $1 \times 10^{-4}$  mbar. Axial temperature distribution is measured with 4 numbers of RTD type temperature sensors. The Dewar has provision for filling the cryogenic liquids inside the tank, a vent circuit with electro pneumatic valve for remotely venting the vapours, pressurization circuit with GN2/GHe for pressurization of Dewar and helium injection circuit for injecting helium inside the Dewar.

Helium gas at constant volume flow rate was injected through submerged nozzles (4 nos). Each nozzle has 10 holes of 2mm diameter each. For varying the helium gas flow rate the upstream helium supply pressure was varied. The volume flow rate of helium supply gas is measured by differential pressure transmitter. The heat-in-leak of Dewar was calculated from the measured Liquid Nitrogen temperature for ambient condition where Liquid Nitrogen exists at saturated condition (77.36 K at 1.0 bar,a) and the heat in leak value was 220W.



Fig. 4. Photograph of Super Insulated Dewar with fluid circuits

A. Experimental Procedure

Liquid Nitrogen is filled inside the Dewar by operating the Electro pneumatic valve. During filling process, the vent valve is kept open until the filling is completed upto 90% level of tank. Measurement of pressure is done by a pressure transducer. Before starting the experiments, the heat in leak of the tank is calculated from the increase in LN2 temperature and the resulting pressure increment over time.

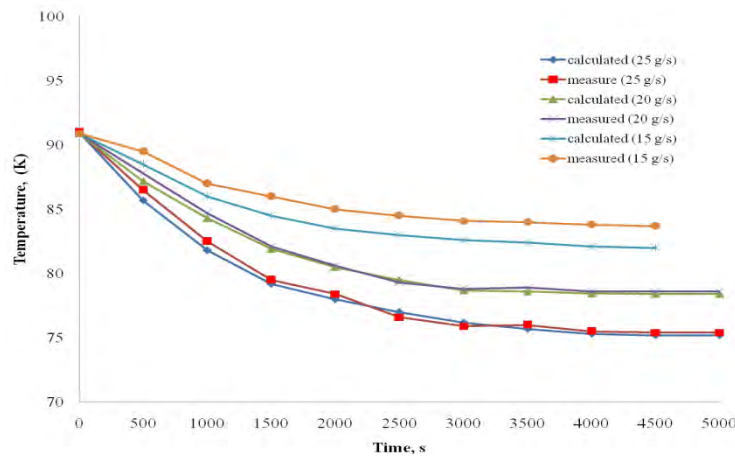


Fig. 5. Temperature of sub-cooling of LOX with variation in helium injection flow rates (atmospheric condition)

As seen from fig.5, larger helium injection rate brings out more amount of cooling. The reason is larger helium injection increases the helium gas fraction in the bubbles and accordingly lowers the GO2 fraction which increases the Liquid side heat transfer and net cooling. In the case 25 g/s injection rate the measured LOX temperature reaches as low as 75K at 4000 sec. The theoretical results and experimental results almost matches well.

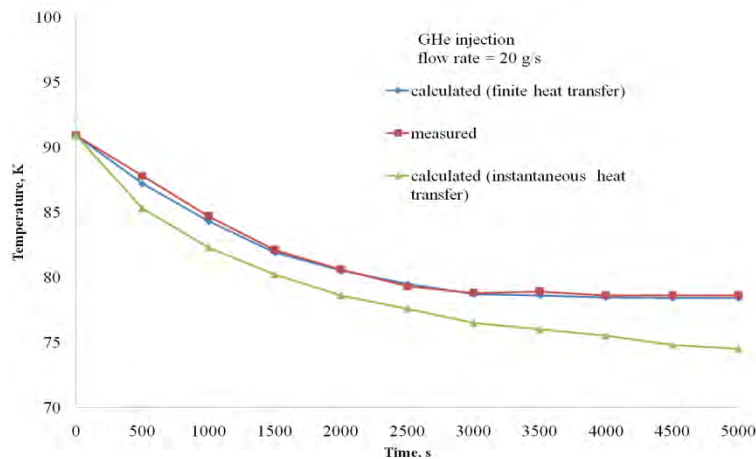


Fig. 6. Comparison of analytical and experiment results with instantaneous and finite heat transfer.

The curve with diamond marks in fig 6 is the case of finite heat transfer and instantaneous mass transfer. The curve with triangle marks is the case of instantaneous heat and mass transfer for comparison. This curve indicates the maximum sub cooling of Liquid Oxygen. The case of finite heat transfer and instantaneous mass transfer shows much better agreement with experimental data. The finite heat transfer model looks very useful for helium injection application.

#### B. Parameters for analysis and experiments

The difference in the Nitrogen partial pressure in helium bubble  $P_{GN_2,b}$  and the vapour pressure of Liquid Nitrogen  $P_{sat}(T_{LN_2})$  is the main source of diffusion driven evaporative cooling. Two methods are conceived to increase the difference and the net diffusion-driven evaporation.

First method is to increase the vapour pressure. The maximum vapour pressure that Liquid Nitrogen can attain is the saturation vapour pressure corresponding to the saturation temperature of Liquid Nitrogen. Since the vapour increases with Liquid Nitrogen temperature, saturated Liquid nitrogen is more susceptible to helium injection cooling than sub-cooled one.

Second method is to decrease the partial pressure of nitrogen in helium bubble. To decrease the partial pressure of nitrogen, high volume rate of helium is preferred. However, if the injected helium temperature is higher than Liquid Nitrogen, the high mass flow accompanies high energy influx which vaporizes Liquid Nitrogen by heat transfer between the warm helium and Liquid Nitrogen. This heat induced vaporization subsequently increases gaseous nitrogen partial pressure in helium bubbles. We have to consider, therefore the net effect of helium flow rate. To effectively lower the partial pressure of nitrogen in helium bubble at high helium flow rate, low temperature helium can be utilized. Theoretically if the injected helium has the same temperature with the liquid nitrogen, the vaporization due to heat transfer is zero and all the injected helium is used to lower the gaseous nitrogen partial pressure in bubbles. The variation range of main parameters for experiments and analysis is given in Table-1, 2 & 3.

TABLE 1  
Medium of Liquid: Liquid Nitrogen

No	Parameter	Parameter variation	Reference
1	Pressure of Dewar, Psys in bar,a	1.0	
2	Helium injection flow rate (g/s)	15, 20, 25	
3	Injection helium temperature $T_{He}$ , (K)	85, 150, 295	To obtain 85K, 150K helium is cooled in LN2 bath

TABLE 2  
Medium of Liquid: Liquid Oxygen

No	Parameter	Parameter variation	Reference
1	Pressure of Dewar, Psys in bar,a	1.0	
2	Helium injection flow rate (g/s)	15, 20, 25	
3	Injection helium temperature $T_{He}$ , (K)	85, 150, 295	To obtain 85K, 150K helium is cooled in LN2 bath

TABLE 2  
Medium of Liquid: Liquid Hydrogen

No	Parameter	Parameter variation	Reference
1	Pressure of Dewar, Psys in bar,a	1.0	
2	Helium injection flow rate (g/s)	30, 35, 40	
3	Injection helium temperature $T_{He}$ (K)	85, 150, 295	To obtain 85K, 150K helium is cooled in LN2 bath

## IV. RESULTS AND DISCUSSION

#### A. Results for helium supply temperature variation in case of Liquid Nitrogen

To examine the effect of injected helium temperature, tests were conducted under atmospheric condition with helium temperature variation. Fig.7 shows the experimental results for Liquid Nitrogen under atmospheric condition. Three cases were studied, helium at 295 K, 150 K and 85K.

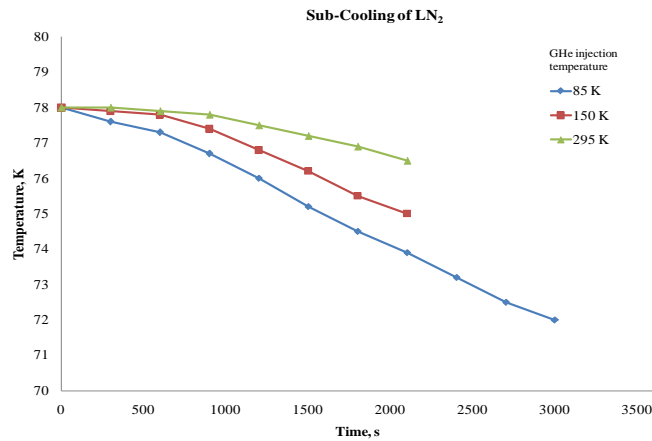


Fig. 7. Temperature of sub-cooling of LN<sub>2</sub> with variation in helium injection temperature (atmospheric condition)

The sub cooling effect is more when we go for cooled helium gas injection although the flow rate of cold helium is less than the flow rate at ambient temperature.

*B. Results for helium supply temperature variation in case of Liquid Oxygen and Liquid Hydrogen*

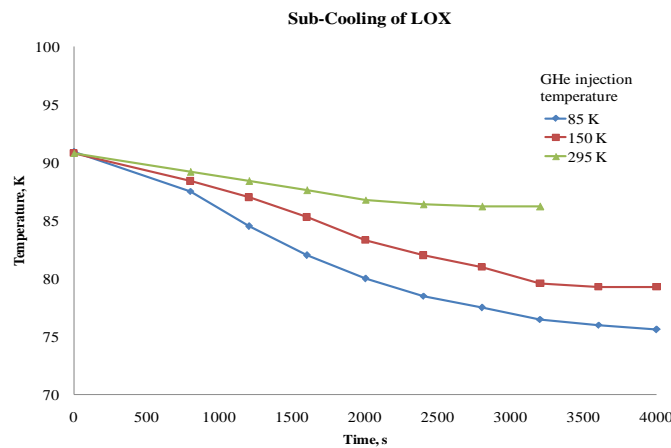


Fig. 8. Temperature of sub-cooling of LOX with variation in helium injection temperature (atmospheric condition)

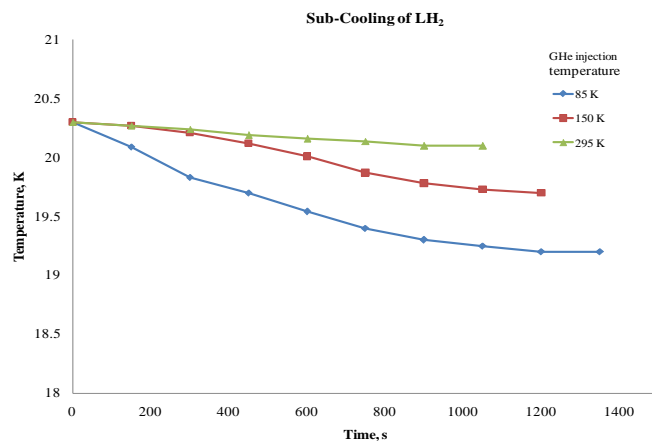


Fig. 9. Temperature of sub-cooling of LH<sub>2</sub> with variation in helium injection temperature (atmospheric condition)

The results obtained by sub cooling Liquid Oxygen and Liquid Hydrogen with injection of atmospheric helium and cold helium is given in fig 8 and fig 9.

### C. Results for variation in helium injection flow rate in case of Liquid Oxygen and Liquid Hydrogen

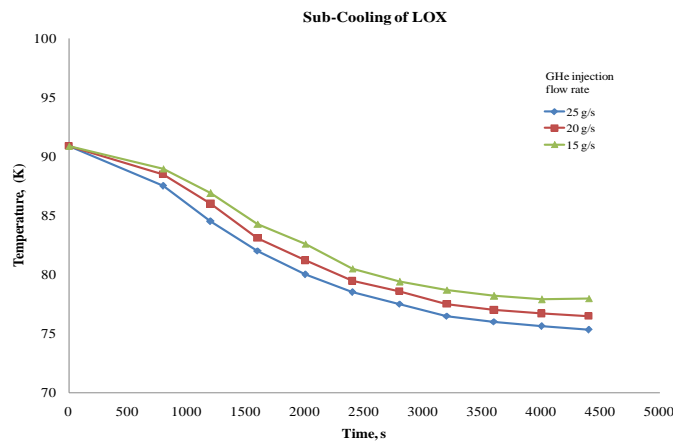


Fig. 10. Temperature of sub-cooling of LOX with variation in helium injection flow rate (atmospheric condition)

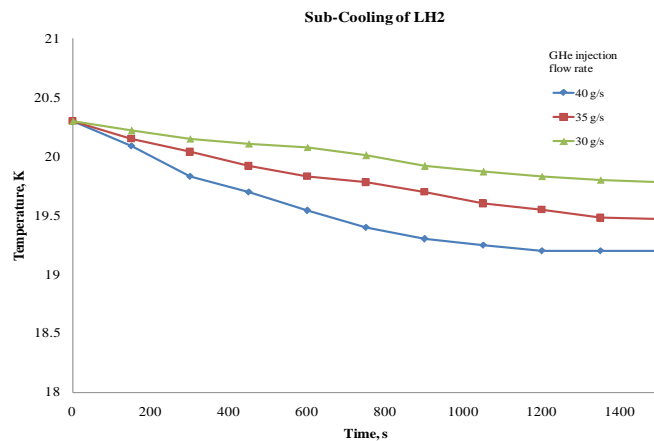


Fig. 11. Temperature of sub-cooling of LH2 with variation in helium injection flow rate (atmospheric condition)

The results obtained by sub cooling Liquid Oxygen and Liquid Hydrogen with different injection flow rates of Helium gas is given in Figs. 10 & 11. From the results it is very clear that the injection of helium at higher flow rate increases the cooling rate in the case of Liquid Oxygen and Liquid Nitrogen, whereas it is unaffected for Liquid hydrogen.

## V. CONCLUSION

A very detailed Study has been carried out analytically and experimentally to find the effect of cooling Liquid Nitrogen, Liquid Oxygen and Liquid Hydrogen at atmospheric condition by varying the inlet temperature and injection flow rate of helium gas. In the case of Liquid Nitrogen and Liquid Oxygen as the helium supply temperature is lowered the sub cooling rate increases, where as in the case of Liquid Hydrogen it is unaffected. It is noticeable that the vaporization due to the vapour side heat transfer and Liquid side heat transfer is more or less same. Therefore for Liquid Hydrogen the cooling is unaffected. Initially saturated Liquid Nitrogen sub cooling is easily achieved regardless of injected helium temperature. The finite heat transfer and instantaneous diffusion mass transfer model is applied for the analysis. The experimental results and theoretical model results are closely matching. Thus lowering injected helium temperature is an effective means for lowering gaseous nitrogen partial pressure in helium bubble. Also the nozzle Patten plays a major role in cooling rate. It is noticeable that instead of having the nozzles along the axis if it is placed radially it gives a stirring effect to the bulk liquid and more surface area contact takes places. This increases the cooling rate.

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