The 2015 World Congress on
Aeronautics, Nano, Bio, Robotics, and Energy (ANBRE15)
Incheon, Korea, August 25-28, 2015

Helium injection modeling for cryogenic propellant densification

*Youngsuk Jung[1)], Mansu Seo[2)], Youngcheol Kim[3)]
and Sangkwon Jeong[4)]

[1), 2), 3), 4)] *Department of Mechanical Engineering, KAIST,*
Daejeon 305-600, Korea
[1)] *KSLV-II System Development Team, KARI, Daejeon 305-806, Korea*
[1)] *ysjung@kari.re.kr*

ABSTRACT

Helium injection is presented for cryogenic propellant densification that can enhance the loaded mass per unit volume in the launch vehicle. The mathematical model for thermodynamic process containing heat and mass transfer between liquid oxygen and helium bubbles is presented. The key factor that determines the effectiveness of helium injection for cryogenic propellant densification is proposed. Various numerical simulations were performed in case of various tank pressure and helium temperature. As a result, the effect of helium injection is increased as the tank pressure is close to the saturation pressure of liquid oxygen and the temperature of helium injected becomes lower.

1. INTRODUCTION

Propellant densification is effective method for enhancing the loaded mass of payload or loaded propellant mass without any change of the previous design and for enhancing the performance of a launch vehicle of a new rocket generation. In the previous paper, various methods have been presented for propellant densification. Above all things, helium injection is the simplest and effective method.

In this paper, the mathematical model for analyzing the heat and mass transfer process between cryogenic propellant and helium bubbles is presented. The parametric study was performed with the model as the variation of tank pressure and the temperature of injected helium to verify the characteristic of helium injection. The specific parameter is presented as the key factor determining the cooling effect of helium injection.

1.1 Benefits of Propellants Densification

[1), 2), 3)] Graduate Student
[4)] Professor

There are many benefits to densify the cryogenic propellants on launch vehicle. The more the cryogenic propellant is densified, the less the volume of the boarded propellant is. The decrease of the propellant leads to reduce the volume of the propellant tank, which results in lower lift-off weight and larger vehicle payload. The more the cryogenic propellant is subcooled, the lower the required tank pressure is, and the required mass of the pressurization gas is reduced. Also the densified propellant lowers the turbo-pump rotation speed, which increases reliability and safety. (Mark 2002)

Several studies quantified the benefit of cryogenic propellant densification in terms of increased payload. McNelis (1997) showed a 4.9 % increase in payload to Low Earth Orbit using 14 K hydrogen and 78 K oxygen on a cryogenic upper stage. Friedlander (1991) reported that an orbital transfer vehicle can increase its payload capability from LEO to GEO by 7 % with using triple point hydrogen. Fazah (1994) examined the use of densified propellants on the Space Transportation System and found the payload to LEO could be increased by 17.5 % with the densified oxygen at 73 K and hydrogen at 16 K.

1.2 Propellants Densification Methods

Propellant densification can be provided with internal device or external device to the cryogenic propellant tank as shown in Fig. 1. (Fazah 1994) Each method has an advantage and disadvantage. Specially, helium injection method is the simplest and very effective among the internal methods and liquid nitrogen and liquid helium cooling is most useful among the external methods. In case of helium injection, cryogenic propellant is subcooled by the evaporated liquid oxygen into helium bubbles, which occurs due to the partial pressure difference of oxygen in a helium bubbles. But as the liquid oxygen cools down and its vapor pressure decreases, the cooling effect becomes less, thus large amounts of helium is required to cool the propellant.

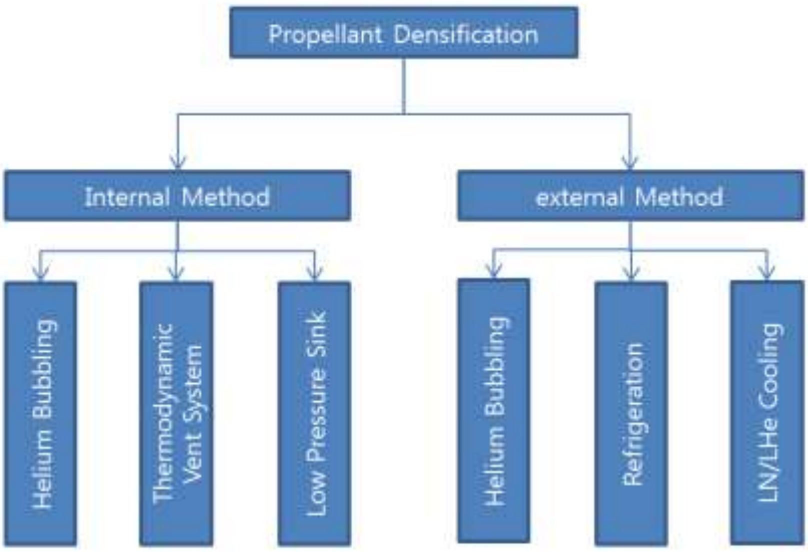

Fig. 1 Propellant densification methods

2. HELIUM INJECTION MODELING AND PARAMETER STUDIES

Helium injection is as shown in Fig. 2. Helium gas is supplied with a controlled flow rate from ground or onboard supply system and injected into the cryogenic propellant through injector installed at the bottom of the cryogenic propellant tank. During helium injection, the cryogenic propellant nearby bubbles will be evaporated into the bubbles due to the partial pressure difference of the evaporated cryogenic propellant in a bubble. The cryogenic propellant is subcooled by the effect of latent heat of the evaporation.

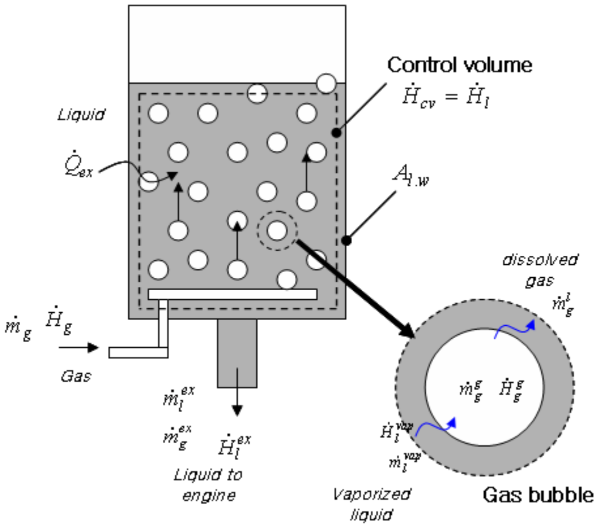

Fig. 2 The schematic of helium injection

2.1 Helium injection Modeling

Basic assumptions for thermodynamic model are as follows:

- When helium moves up through propellant in tank, an ideal mixing between the cryogenic propellant and helium is assumed;
- Thermodynamic equilibrium is maintained on the boundary between the cryogenic propellant and helium. Composition of phases corresponds to pressure of the propellant tank, injection flow rate of helium and temperature of the cryogenic propellant;
- Mass change of propellant is only due to the evaporated cryogenic propellant into helium bubbles and the cryogenic propellant fed to an engine;
- Diffusive resistance of helium into gas-vapor phase is negligible in compared with resistance into liquid phase;
- Enthalpy change of the cryogenic propellant is caused by the external heat flux through the tank wall, the heat flux from injected helium, the evaporated cryogenic propellant into helium bubble and the cryogenic propellant supplied to an engine;

- Enthalpy change by the mass change of the dissolved helium is neglected because the mass of the dissolved helium is smaller than the mass of the evaporated cryogenic propellant;
- Heat exchange between propellant and the ullage layer is neglected;

The mathematical model of thermodynamic process between injected gas and liquid propellant could be represented as:

Energy balance:

$$\frac{d(m_l\hat{H}_l)}{dt} = \hat{H}_g - \dot{H}_l^{vap} - \dot{H}_g^{g} - \dot{H}_l^{ex} + \dot{Q}_{ex} \tag{1}$$

Mass balance for propellant:

$$\dot{m}_l = -\dot{m}_l^{vap} \tag{2}$$

Mass balance for injected gas:

$$\dot{m}_g = \dot{m}_g^{l} + \dot{m}_g^{g} + \dot{m}_g^{ex} \tag{3}$$

By manipulation of Eq. (1)~(3), an ordinary differential equations for determination of temperature of propellant and density of dissolved gas into propellant could be obtained as follows:

$$\frac{dT_l}{dt} = \frac{1}{m_l C_{p.l}}\left\{\dot{q}_{ex}A_{l.w} + \dot{m}_g\left(C_{p.g}T_g - \gamma_{vap}\beta_{vap} - C_{p.g}T_l\right)\right\} \tag{4}$$

where, β_{vap} denotes the evaporation intensity of the evaporated propellant into helium bubbles. β_{vap} is the ratio of evaporation rate of propellant mass and mas flow rate of helium injection and induced from thermodynamic equilibrium condition.

$$\beta_{vap} = \frac{\dot{m}_l^g}{\dot{m}_g^g} = \frac{m_l^g}{m_g^g} = \frac{(1-y_g(t))M_{w.g}}{y_g(t)M_{w.l}},\ y_g = 1 - \frac{P_l^{sat}}{P_t} \tag{5}$$

2.2 Parametric Study

A system model for numerical analysis is shown in Fig. 3. The shape of the propellant tank is regarded as a type of cylinder which is 2 m in the diameter, 3.183 m in the height, 11.5 m^3 in the total volume of the tank and 10 m^3 in the loaded liquid oxygen.

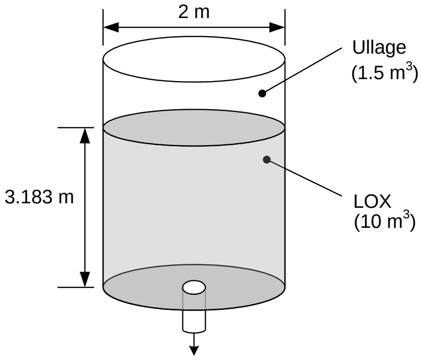

Fig. 3 system model for simulation

Two numerical simulations were executed to find an optimum condition for cooling the cryogenic propellant. The first simulation is for the temperature variation of liquid oxygen as the pressure of its tank as shown in Fig. 4. The second simulation is for the temperature variation of liquid oxygen as the injected helium temperature as shown in Fig. 5.

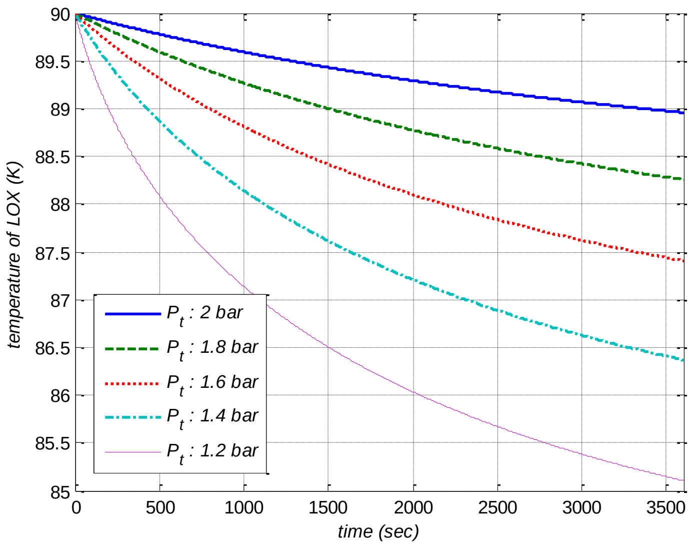

Fig. 4 The temperature variation of liquid oxygen as the pressure of the tank (at $\dot{m}_l^{ex} = 0$, $T_g = 288K$, $\dot{m}_g = 0.02kg/\sec$)

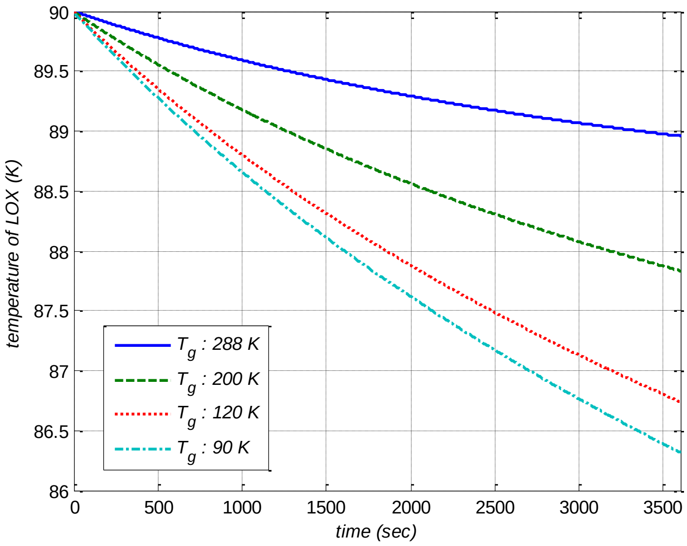

Fig. 5 The temperature variation of liquid oxygen as the Injected helium temperature (at $\dot{m}_l^{ex} = 0$, $P_t = 2bar$, $\dot{m}_g = 0.02kg/\sec$)

As shown in Fig. 4, the lower the tank pressure is, the lower the temperature of liquid oxygen is subcooled. The decrease of the tank pressure brings out the increase of β_{vap} which characterizes the evaporation intensity of liquid oxygen. The bigger the evaporation rate of liquid oxygen is, the faster the cooling rate of liquid oxygen is.

The cooling rate of liquid oxygen is influenced by the temperature of the injected helium in Fig. 5. The lower the temperature of the injected helium is, the faster the cooling rate of liquid oxygen is. It is due that the amount of heat of helium gas which is transferred to liquid oxygen decreases as the temperature of helium gas becomes lower to the temperature of liquid oxygen.

According to the results of this analysis, the pressure of the tank and the temperature of the injected helium must be kept as low as possible for cooling of liquid oxygen efficiently.

2.3 Key factor determining the characteristic of Helium injection

β_{vap} is the ratio between the evaporated mass of liquid propellant and the mass of helium injection at the thermodynamic equilibrium state and determines the characteristic of helium injection. As shown in Fig. 4, the cooling effect of helium injection increases as the pressure of tank is closer to the saturation pressure at the specific pressure. For example, β_{vap} is about 40 at which the temperature of liquid oxygen is about 95K In case that the pressure of tank is 2bar, but is lower than 8 at which the temperature of liquid oxygen is about 90K In case that the pressure of tank is 2bar. As a result, helium injection is very effective at the saturation condition around is known with β_{vap} as shown in Fig. 6.

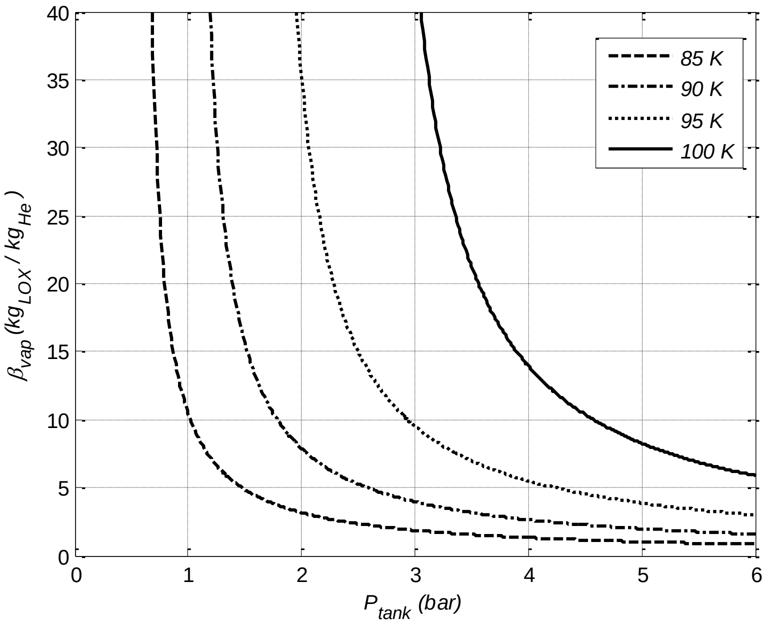

Fig. 6 Variation of evaporation intensity of liquid oxygen into helium bubbles (β_{vap}) according to the temperature of liquid oxygen and the tank pressure

3. CONCLUSIONS

Helium injection is presented as a cryogenic propellant densification method. The mathematical modeling is presented for analyzing the cooling effect of the cryogenic propellant densification with thermodynamic equilibrium condition. The simulations were performed to verify the cooling effect of helium injection with the mathematical model. As a result, Helium injection is effective at the saturation condition around, but the cooling effect of helium injection decreases rapidly at far as at the saturation condition.

REFERENCES

Mark, S.H. (2002), “Study task for determining the effects of boost-phase environments on densified propellants thermal conditions for expendable launch vehicles,” *NASA, CR-2002-210808*.

McNelis, N.H. (1997), “Hot fire ignition test with densified liquid hydrogen using a RL10B-2 cryogenic H2/O2 rocket engine”, *AIAA-97-2688*.

Friendlander, A. (1991), “Benefits of slush hydrogen for space missions”, *NASA TM-104503*.

Fazah, M. (1994), “STS propellant densification feasibility study data book”, *NASA TM-108467*.