버블링을 이용한 추진기관 가압 시스템에서 극저온 추진제 변수의 결정

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Determination of The Cryogenic Propellant Parameters at Pressurization of The Propulsion System Tank by Bubbling

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ABSTRACT

In this paper, a calculation method of the thermodynamic parameters of cryogenic propellant is proposed when a cryogenic propellant tank is pressurized by gaseous helium(GHe) bubbling. Temperature of cryogenic propellant and mass of dissolved GHe into propellant were analyzed at the various operation of pressurization of the liquid oxygen(LOX) and hydrogen(LH_2) tank using helium bubbling. It was evaluated how the GHe bubbling influences to the thermodynamic parameters of LOX and LH_2 with results of the analysis. With the proposed calculation method, It will be able to confirm the feasibility of GHe bubbling as a pressurization system of cryogenic propellant tank and to optimize the pressurization system using GHe bubbling.

초 록

본 논문에서는 극저온 추진제 탱크가 가스 헬륨(GHe) 버블링에 의해 가압될 때 극저온 추진제의 열역학 변수들에 대한 계산 방법을 제시하였다. 헬륨 분사를 이용한 액체 산소(LOX)와 액체 수소(LH_2) 탱크의 가압 과정에서의 극저온 추진제 온도와 추진제로 용해되는 가스 헬륨의 질량을 분석하였다. 해석 결과를 통해 헬륨 버블링이 LOX와 LH_2의 열역학적 변수들에 어떻게 영향을 주는지 확인하였다. 제시된 계산 방법을 통해 가압 시스템으로써 헬륨 버블링의 실현 가능성과 헬륨 버블링을 이용한 가압 시스템의 최적화가 가능할 것이다.

Key Words: Propulsion System(추진기관), Pressurization System(가압시스템), Bubbling(버블링), LOX(액체산소), LH_2(액체수소), GHe(헬륨가스)

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Nomenclatures

m_l	Mass of propellant in control volume (kg)
$\hat{H}_l$	Specific enthalpy of propellant (kJ/kg)
$\dot{H}_g$	Enthalpy from injected GHe to propellant in control volume (kJ/kg)
$\dot{H}_l^{vap}$	Enthalpy caused by vaporization from propellant in control volume to gas phase (kJ/kg)
$\dot{H}_g^g$	Enthalpy from injected GHe to gas phase (kJ/kg)
$\dot{H}_l^{ex}$	Enthalpy caused by propellant fed to engine (kJ/kg)
$\dot{Q}_{ex}$	Heat flux from external to propellant in control volume though wall (kJ/sec)
$\dot{q}_{ex}$	Heat flux into propellant per a unit contact area between propellant and tank (kW/m^2)
m_l^{vap}	Vaporization mass of propellant in control volume (kg)
m_l^{ex}	Mass of propellant fed to engine (kg)
m_g	Mass of injected gas to propellant in control volume (kg)
m_g^l	Mass of dissolved GHe in propellant in control volume (kg)
m_g^g	Mass of transferred GHe to gas phase (kg)
m_g^{ex}	Mass of expelled GHe with propellant fed to egine (kg)
T_l	Temperature of propellant in control volume (K)
$C_{p.l}$	Heat capacity of propellant in control volume (kJ/kgK)
$A_{l.w}$	Contact area between propellant and wall of tank (m^2)
$C_{p.g}$	Heat capacity of injected GHe (kJ/kgK)
T_g	Temperature of injected GHe (K)
γ_{vap}	Heat of vaporization of propellant in control volume (kJ)
β_{vap}	Vaporization factor between mass of injected GHe and vaporization mass of propellant
ρ_g^l	Density of GHe in propellant in control volume (kg/m^3)
$\rho_{g.sat}^l$	Saturation density of GHe in propellant in control volume (kg/m^3)
$\beta_{g.l}$	Dissolution factor of GHe in propellant in control volume
P_t	Pressure of tank (bar)
y_g	Mole fraction of GHe in gas phase
$M_{w.g}$	Molecular weight of GHe (kg/kmol)
$M_{w.l}$	Molecular weight of propellant (kg/kmol)
ρ_l	Density of propellant (kg/m^3)
Re_M	Modified Reynolds number
Pr	Diffusion Prandtl number
Bo	Bond number
D_g	Molecular diffusion coefficient (m^2/sec)
h_l	Height of propellant in control volume (m)
V_t	Volume of propellant (m^3)
$\dot{v}_t$	Discharged volume flowrate of propellant to engine (m^3/sec)
A, B	Empirical constants for dissolution coefficient
t	Time (sec)

1. Introduction

In the pre-launch process of Saturn booster, the bubbling of non-condensible gas has been done to prevent geysering phenomenon. The cryogenic propellant was subcooled by injected non-condensible gas [1,2]. Larsen, et al.[2] and Kozlov, et al. [3] have performed theoretical analyses for the process of injection cooling, including the effects of liquid vaporization, ambient heating, and gas enthalpy flux and experimental investigation of liquid hydrogen cooling by helium gas injection[1,2,3].

Also, some papers present several advantages as cooling effects of liquid propellant, preventing of temperature stratification of propellant during standby before lift-off, lighter weight than other pressurization system and preventing ullage pressure collapse caused by liquid sloshing during flight in case that bubbling is used as a prepressurization and pressurization system during flight of launch vehicle[4-7].

In this manner, the non-condensing bubbling method is very useful for thermal management of cryogenic propellant for launch vehicle. But the dissolution of non-condensing gas into cryogenic propellant or the mixing of non-condensing gas with propellant can decrease performance of engine, because dissolved non-condensing gas can be vaporized in supplying pipeline, which could result in failure of pumps.

Therefore, the estimation of thermodynamic parameters of cryogenic propellant during the bubbling of non-condensible gas is important[8].

In this paper, the physical and mathematical models have been presented for transient analysis of pressurization process and it was evaluated how the GHe bubbling influences to the thermodynamic parameters of LOX and LH_2 with results of the analysis.

2. Description of pressurization system using the bubbling of non-condensing gas into propellant

Basic schematics of pressurization system is given in Fig. 1. Non-condensing gas is supplied at a controlled flow rate from ground or onboard supply system and injected into propellant through injector installed at the bottom of propellant tank.

During injected gas with ambient temperature moves up through cryogenic liquid, the liquid nearby non-condensing gas will be vaporized into bubbles of gas due to the temperature difference. And liquid is cooled by effect of latent heat of the vaporization. Eventually, the injected non-condensing gas is emitted to ullage volume of tank and pressurize the propellant tank.

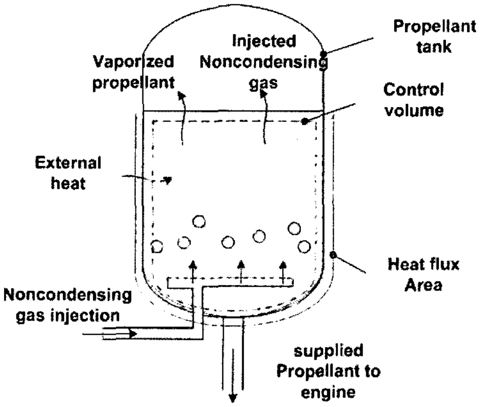


Fig. 1 Description of Bubbling of Noncondensing Gas As Pressurization System

3. Modeling of thermodynamic processes in a liquid phase

In previous studies [2,4,5], physical and mathematical thermodynamic models of heat-mass transfer between injected gas and cryogenic propellant (see Fig. 2) have been studied.

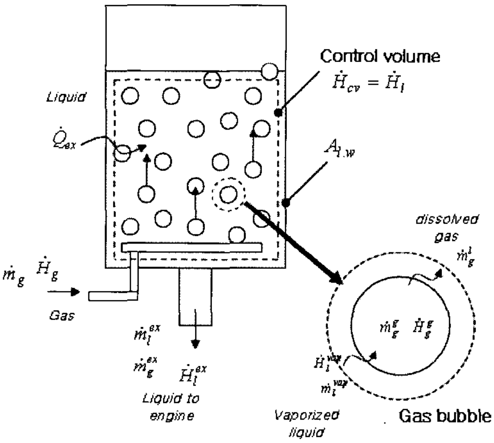


Fig. 2 Schematic for Pressurization System of Propellant Tank Using GHe Bubbling Method

Basic assumptions for thermodynamic models are as follows:

- When gas moves up through propellant in tank, an ideal mixing between liquid and gas is assumed;
- Thermodynamic equilibrium is maintained on the boundary between liquid and gas. Composition of phases corresponds to pressure of the propellant tank, injection flow rate of non-condensing gas and temperature of propellant;
- Mass change of propellant is only due to vaporized propellant into bubbles and propellant fed to engine;
- Diffusive resistance of gas into gas-vapor phase is negligible in compared with resistance into liquid phase;
- Enthalpy change of propellant is caused by external heat flux through tank wall, heat flux from injected gas, vaporization of propellant into injected gas bubble and propellant supplying to engine;
- Enthalpy change by mass change of dissolved gas is neglected, because mass of dissolved gas is very small;
- Geometrical characteristics of tank and gas injection device, pressurization gas diffuser and consumption regime of cryogenic propellant from tank are given;
- Heat exchange between propellant and ullage layer is negligible;

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

Energy balance:

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

Mass balance for propellant:

$$\frac{dm_l}{dt}=-\frac{dm_l^{vap}}{dt}-\frac{dm_l^{ex}}{dt} \tag{2}$$

Mass balance for pressurization gas:

$$\frac{dm_g}{dt}=\frac{dm_g^l}{dt}+\frac{dm_g^g}{dt}+\frac{dm_g^{ex}}{dt} \tag{3}$$

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

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

$$\frac{d\rho_g^l}{dt}=\beta_{g.l}(\rho_{g.sat}^l-\rho_g^l) \tag{5}$$

where, β_{vap}, $\beta_{g.l}$ denote the vaporization intensity of vaporized propellant into non-condensing gas and the dissolution intensity of injected gas into propellant, respectively.

An empirical relations for ρ_g^l, $\beta_{g.l}$, β_{vap}, are necessary, because of complexity of gas-vapor-liquid structure in a propellant tank and absence of reliable information for elementary process. Bershadskiy, et al.[5] and Bershadskiy[8] have formulated empirical relationship based on experimental results:

$$\rho_{g.sat}^l=\frac{P_ty_g}{Aexp(B/T_l)}\rho_l\frac{M_{w.g}}{M_{w.l}} \tag{6}$$

$$\beta_{vap}=\frac{(1-y_g(t))M_{w.g}}{y_g(t)M_{w.l}} \tag{7}$$

$$\beta_{g.l}=\frac{3.78Re_M^{0.8}\,\mathrm{Pr}^{0.53}\,Bo^{0.28}\,D_g}{h_l^2} \tag{8}$$

4. Feature of numerical determination of parameters of cryogenic propellant

Numerical algorithms for determination of thermodynamic parameters of cryogenic propellant were developed on the basis of the above mentioned mathematical model. In this paper, we have considered GHe as non-condensing gas and LOX, LH_2 as cryogenic propellant.

Calculation algorithm provides concentration of dissolved He in LOX, LH_2 and temperature of solution during pressurizing the propellant tank by bubbling of non-condensing gas. The fourth order Runge-Kutta method was used for integration of Eqs. (4), (5) with consideration of thermo-physical characteristics of liquid, gas and change of phase compositions as well.

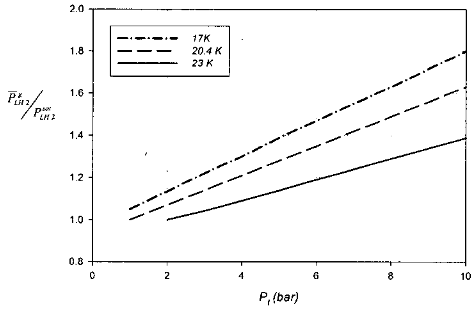


Fig. 3 Variation of The Ratio of Partial Pressure of GH_2 in Gas Phase($\bar{P}^g_{LH_2}$) to Vapor Pressure of LH_2($P^{sat}_{LH_2}$) According to Condition of Tank Pressure(P_t) and Temperature of LH_2, When GHe Is Saturated in LH_2. ($P_t=\bar{P}^g_{LH_2}+\bar{P}_{He}$)

In case of LOX as propellant, the balanced mixture of injected GHe and vapor of LOX could be considered as ideal. But, in case of LH_2, the balanced mixture of injected GHe and vapor of LH_2 is not ideal. No ideal phenomenon of the balanced mixture of injected GHe and vapor of LH_2 is represented by excessive increasing of vapor pressure of LH_2 in comparison with saturation pressure of pure LH_2 according as partial pressure of GHe in LH_2 increases. Such phenomenon is shown in Fig. 3 and was considered in calculation algorithm by using empirical relations.

Calculation flow chart of transient analysis program for analysis of thermodynamic parameters of propellant is shown in Fig. 4.

As an initial data of program, the following parameters are needed: A) geometric characteristics of tank and gas injection equipment, B) ullage pressure of propellant tank, C) mass flowrate of propellant fed to engine, D) temperature of loaded propellant, E) external heat flux rate , F) operation time of system.

Pressurization process of propellant tank are divided to three steps: pre-pressurization, standby and main pressurization steps.

At the pre-pressurization step, thermodynamic parameters are integrated until the tank pressure reaches a given value. At the step of standby, thermodynamic parameters are integrated on the condition of absence of gas injection. At the main step of pressurization, thermodynamic parameters are integrated during a given system operating time with the consideration of propellant feed to engine and controlled tank pressure on the condition of established pressure.

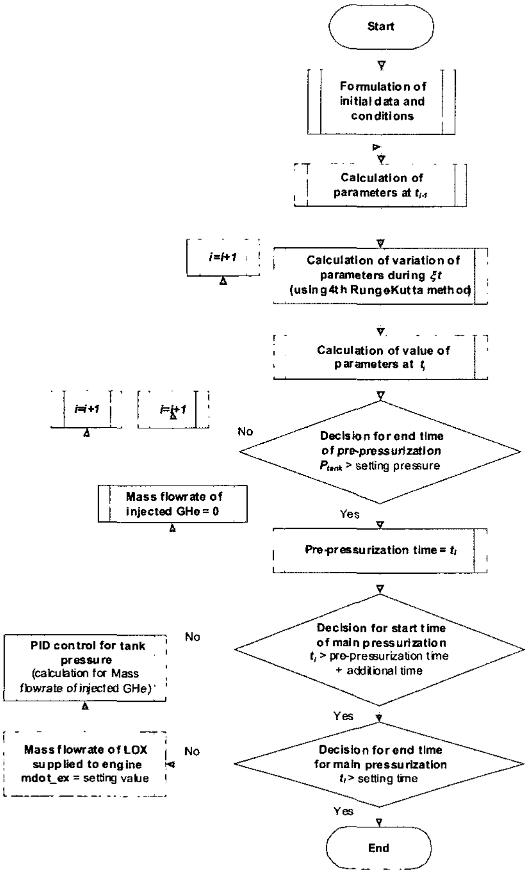


Fig. 4 Calculation Flowchart of Tansient Analysis Program for Pressurization System of Propellant Tank Using GHe Bubbling Method

4. Results of researches

The parametric variant of $\beta_{g.l}$ and β_{vap} for LOX-He and LH_2-He system is depicted in Fig. 5 and Fig. 6, respectively. Physically, the changes of $\beta_{g.l}$ and β_{vap} depend on gas-phase volume and moving velocity of ascending bubbles through the liquid.

P_t and V_l mainly influence on the change of $\beta_{g.l}$. The decrease of V_l corresponds to the increase of $\beta_{g.l}$, and the increase of partial pressure of pressurization gas in the tank makes $\beta_{g.l}$ decrease.

P_t and T_l mainly influence on change of β_{vap}. A rise of T_l corresponds to the increase of β_{vap}, and a rise of the tank pressure makes β_{vap} decrease.

Temporal variations of T_l and ρ_g^l are shown in the Fig. 7 and Fig. 8 during the pre-pressurization (including standby step) and main pressurization step. The change of thermodynamic parameters were evaluated for the cryogenic propellants LOX and LH_2 under same set of initial values: initial volume of liquid in a tank $V_l = 10\ m^3$, volumetric flow rate of propellant discharged from a tank $\dot{v}_l = 0.01\ m^3/\mathrm{sec}$, operation pressure in the tank $P_t = 4\ bar$ and external heat influx $\dot{q}_{ex} = 0.15\ kW/m^2$.

At the first moment of prepressurization, a significant temperature drop was found due to the partial vaporization of liquid at the temperature $T_g = 288\ K$. After the tank pressure comes to the established value, T_l began to increasing. The increase of P_t reduces the cooling effect by the vaporization of liquid into bubbles. To make no change of propellant temperature, the pressurization gas flow rate should be increased several times more over the needed one, which is necessary to get the given value of P_t. The minimum increase of T_l was observed when the value of T_g is similar to T_l

The changes of ρ_g^l depend on not only the changes of $\beta_{g.l}$, but the concentration difference $(\rho_{g.sat}^l - \rho_g^l)$ at the boundary of phase separation, too. Concentration difference decreases with the increase of the partial pressure of gas in the tank. So we could find

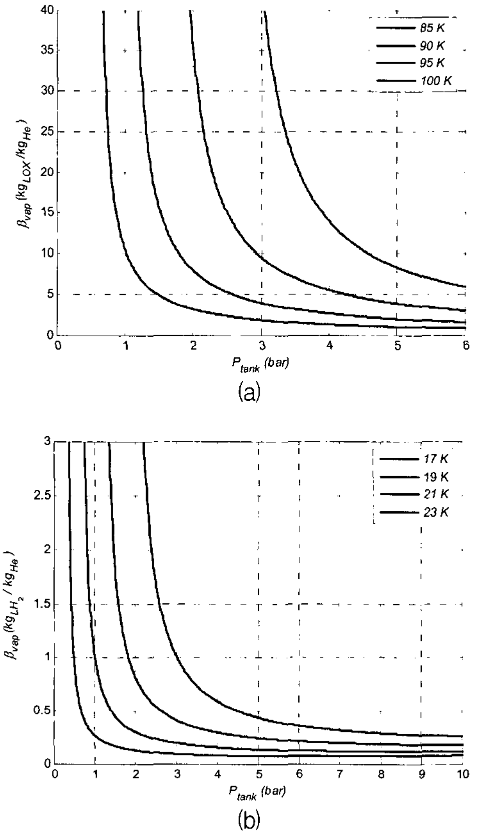


Fig. 5 Effect of Temperature of Cryogenic Propellant and Pressure of Propellant Tank about Vaporization Factor(β_{vap}) (at $\dot{m}_g$, $T_g = const.$) (a) Variation of β_{vap} in Case that Cryogenic Propellant is LOX, (b) Variation of β_{vap} in Case that Cryogenic Propellant is LH_2

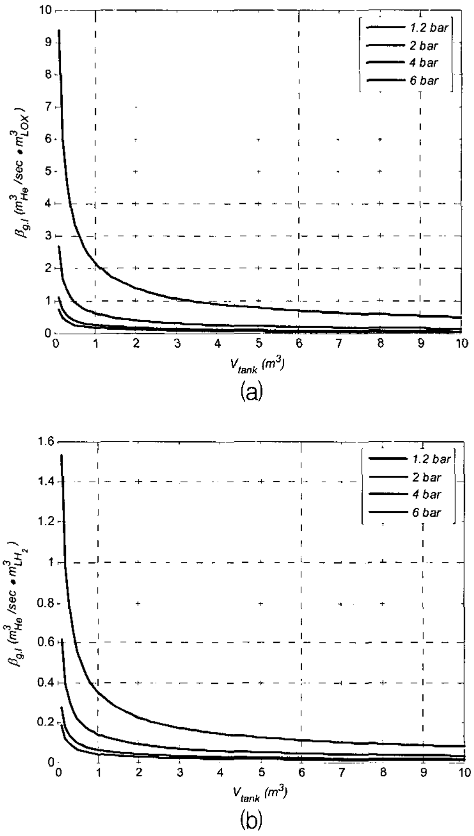


Fig. 6 Effect of Volume of Cryogenic Propellant and Pressure of Ppropellant Tank about Dissolution Factor of GHe in Propellant ($\beta_{g.l}$) (at $\dot{m}_g$, $T_g = const.$) (a) Variation of $\beta_{g.l}$ in Case that Cryogenic Propellant is LOX, (b) Variation of $\beta_{g.l}$ in Case that Cryogenic Propellant is LH_2

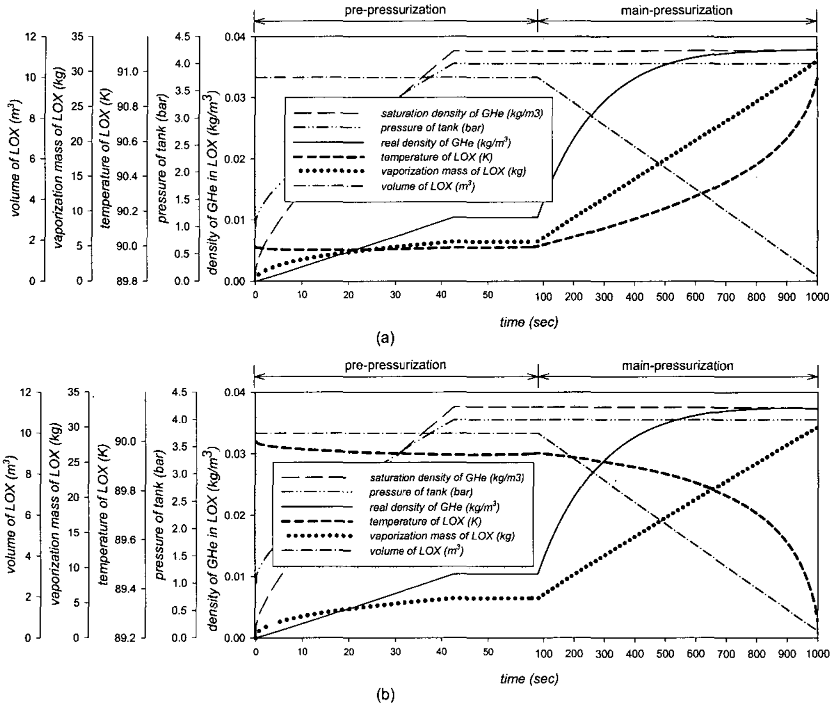
in Fig. 7, 8 the ρ^l_g increases abruptly during main pressurization step.

During the pre-pressurization step, it is also found that ρ^l_g is not saturated since the increasing rate of tank pressure is more faster than the dissolution rate of gas into liquid propellant.

During main pressurization, saturation density of gas in the liquid has constant values but ρ^l_g increases up to saturation density of gas in the liquid and reaches at the saturation state.

In consideration of allowable density of gas in propellant, the saturation of gas into liquid during main step of pressurization restricts operation time of pressurization system using non-condensing gas bubbling method.

5. Conclusions



(a)

(b)

Fig. 7 Variation of Parameters($\rho^l_{g.sat}$, ρ^l_g, T_l, P_t, m^g_l, V_l) during Pre-Pressurization and Main Pressurization Stage in Case of Using GHe Bubbling Method As Pressurization system of LOX propellant tank (at $\dot{m}_g = 0.02kg/\sec$, $\dot{m}^{ex}_l = 0.01m^3/\sec$) (a) Variation of Parameters in Case of $T_g = 288K$, (b) Variation of Parameters in Case of $T_g = 92K$

Mathematical model and algorithms have been developed for analyzing the thermodynamic parameters of cryogenic propellants on the propulsion system with pressurization system using bubbling of noncondensing gas. The empirical relations are used for the description of intensity of heat-mass transfer and the change of composition of gas and liquid phase in propellant tank.

As the results of analysis, it was validated that the bubbling of non-condensing gas can be applied as pressurization system of liquid propulsion system including pre-pressurization and. But the allowable operation time of pressurization system might depends on the characteristics of density saturation of dissolved gas into cryogenic propellant. Therefore, for the realization of the bubbling method as main pressurization system, the additional analyses are required for estimation of thermodynamic parameters of mixed gas at ullage and for study of cavitation which can be made at the pump inlet.

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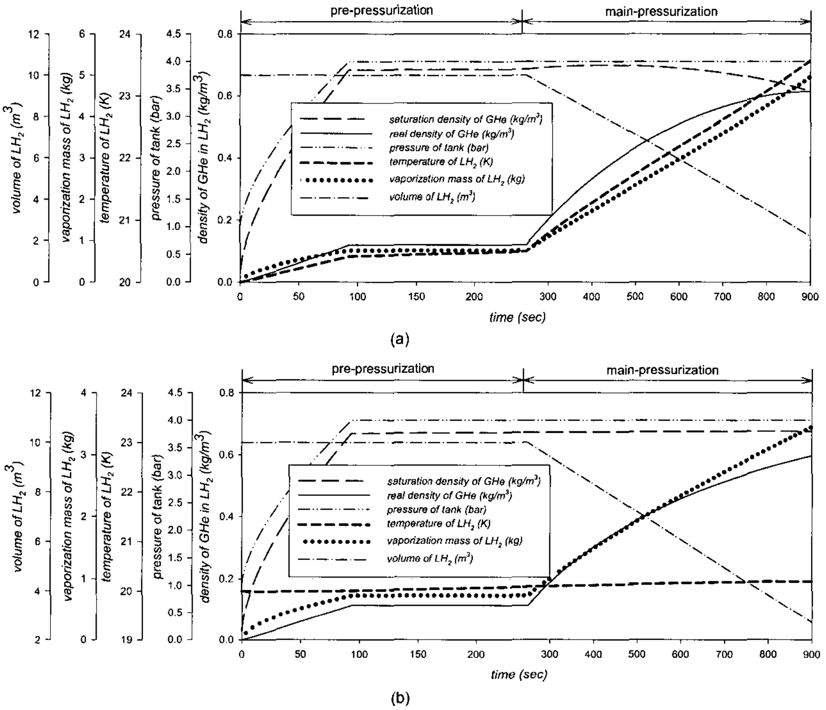

Fig. 8 Variation of Parameters($\rho^l_{g.sat}$, ρ^l_g, T_l, P_t, m^g_l, V_l) during Pre-Pressurization and Main Pressurization Stage in Case of Using GHe Bubbling Method As Pressurization System of LH_2 Propellant Tank (at $\dot{m}_g = 0.02kg/\sec$, $\dot{m}^{ex}_l = 0.01m^3/\sec$) (a) Variation of Parameters in Case of $T_g = 288K$, (b) Variation of Parameters in Case of $T_g = 20K$

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