액체로켓 추진기관의 추진제탱크 가압시스템 최적변수 설계 방법

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The Way of Determinating the Optimal Parameters of the Propellant Tank Pressurization Gas in the Feeding System for Liquid Rocket Engine

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ABSTRACT

The design method to calculate the main features of propellant tank pressurization system during the development procedure of propellant feed system of the liquid rocket engine was suggested. We have considered the influences of parameters of pressurization gas on the efficiency of the thermodynamic processes in the tank. The optimum value of temperature and velocity of pressurization gas at the entrance of tank are obtained by the suggested way.

초 록

액체로켓 추진기관의 추진제 공급계 개발을 위한 추진제 탱크 가압시스템의 주요 변수들을 계산하는 설계방법이 본 논문에서 제시되었다. 가압 유체의 공급 조건들이 추진제 탱크 내부에서 발생하는 열역학적 프로세스의 효율성에 미치는 영향을 분석하였고 이를 바탕으로 하여 추진제 탱크 입구에서의 가압 유체의 최적 공급온도, 공급 속도를 계산하였다.

Key Words: Liquid Propulsion(액체 추진기관), Propellant Feed System(추진제공급시스템), Tank Pressurization System(탱크가압시스템), Optimization Design(최적설계), Supply Temperature(공급온도), Injection Velocity(분사속도)

1. Introduction

The propellant feed system on the liquid rocket propulsion system consists of the propellant tanks, tank fill/drain system,

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propellant supply system from tanks to engine(s) and tank pressurization system. The present paper is concerned with the development of tank pressurization system which should work effectively in the structure of propellant feeding system. From the development procedure of propulsion system[1,2], it is shown that the pressurization system development procedure can be divided into three steps : Determination of main specification at the stage of conceptual design of propellant feeding system; Design, manufacturing of components and its optimization by tests; Acknowledgement of system function as a part of propulsion system at the integrated system tests.

One of most important parameters for design of tank pressurization system is the required mass flow rate of pressurization gas ($\dot{m}_g$). The energy-mass characteristics of tank pressurization system which minimize $\dot{m}_g$ can be obtained by the rational selection of pressurization gas supplying parameters to the propellant tank. At the conceptual design stage, therefore, it is necessary to determine the optimal parameters for pressurization gas at the entrance of propellant tanks. However, an analytical correlations between $\dot{m}_g$ and the parameters describing the supplying conditions of pressurization gas to the propellant tanks are not yet obtained. It is caused by the complicated transient heat and mass transfer phenomena at the tank ullage volume. The methods to determine $\dot{m}_g$ given at the references [3, 4] do not take into consideration the effects of specific parameters of pressurization gas on the distribution patterns of energy contained in the supplied pressurization gas. In principle, the heat and mass transfer between the pressurization gas, the propellant and the tank wall characterizes the pressurization gas energy distribution mode.

The methodology for determination of optimal pressurization gas parameters based on the exergy, ϕ (the thermodynamic property representing the maximum work extracted from the thermodynamic system) and the empirical data from the literatures is suggested in this paper. This method could include the effects of the specific parameters of pressurization gas on the characteristics of heat and mass transfer in the tank.

2. Methodology Description

Typically, the propellant tank pressurization system is mainly composed of pressurization gas storage tank (He tank), pressurization gas heating device (Heat exchanger) and pressurization gas injection device(diffuser) as shown in Fig. 1.

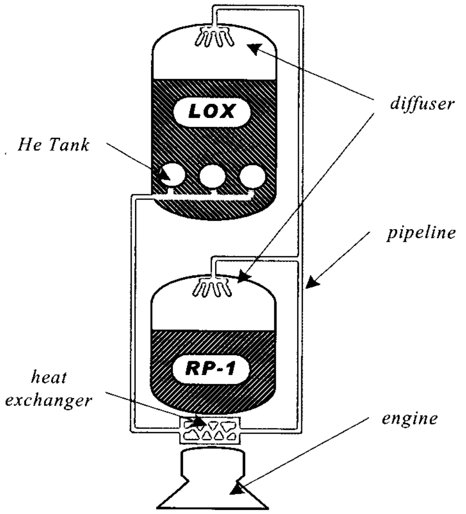

Fig. 1 Schematic of typical tank pressurization system for propellant feed system of liquid rocket engine

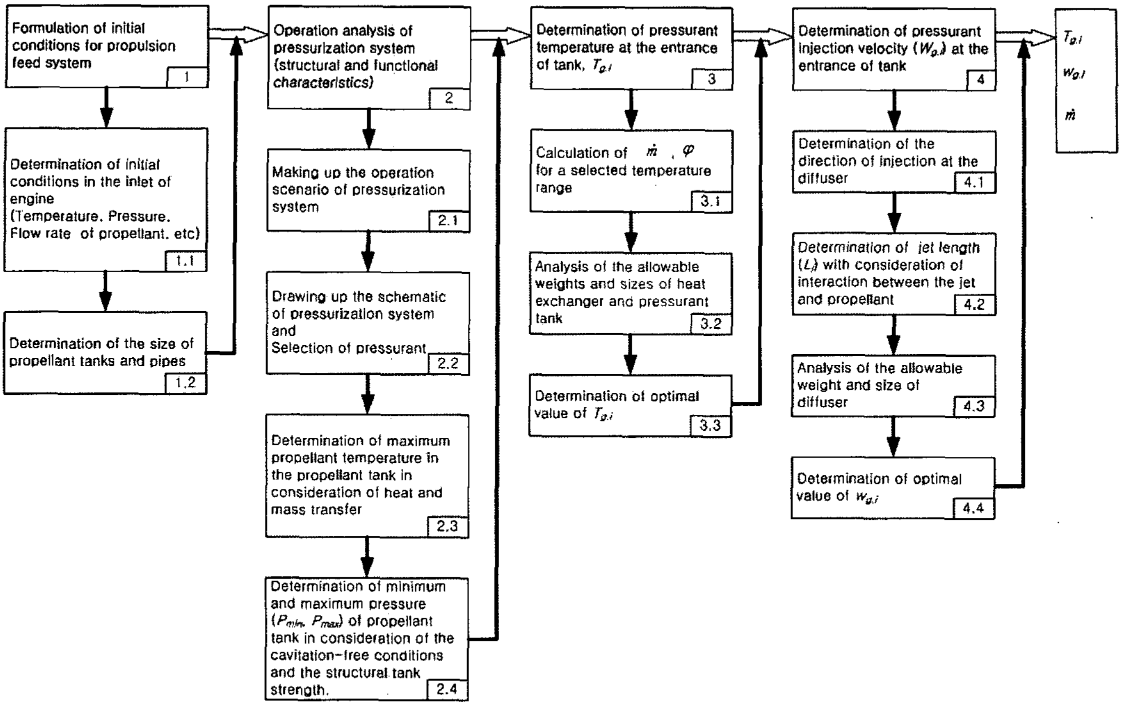

Fig. 2 Block diagram for the determination of optimal parameters of propellant at the entrance of tank

It is necessary to consider the optimal parameters of pressurization gas such as the sort of gas, supplying temperature, supplying velocity and direction which ensure the effective thermodynamic process in the tank. These optimally selected parameters will contribute to reduce the required weight of pressurization gas and thus the total weight of pressurization system including the pressurization gas storage tank, pressurization gas injection device in the propellant tank and pressurization gas heating device could not exceed the limit weight allocated to the pressurization system.

In general, when the propulsion system works normally, the energy contained in the pressurization gas at the entrance of tank is converted to the useful work for discharging the propellant from tank and is also consumed to increase the energy of ullage gas and to warm up the tank wall and the upper layer of propellant stored in the tank.

To estimate the efficiency of thermodynamic system, we have introduced the exergy factor, ϕ which usually applied to study the transformation of energy to work [5]. In our case, the exergy could be defined as;

$$\phi = W_t/Q_{g,i} \qquad (1)$$

where, $Q_{g,i}$ represents the energy contained in the pressurization gas at the entrance of tank and W_t means the work done by pressurization gas on discharging the propellant from the tank.

If we consider that the pressure in the tank during the discharging process of propellant is constant (isobaric process) and that the change of pressurization gas energy is equal to the change of enthalpy (neglect the kinetic energy of pressurization gas), then the Eq. (1) becomes

$$\phi = (P_t V_l \tau_d) / (\dot{m} i_{g,i} \tau_p) \qquad (2)$$

where, P_t, V_l represent the time-averaged ullage pressure of tank and the propellant (liquid) volume flow rate, respectively. $\dot{m}$ denotes the pressurization gas mass flow rate and $i_{g,i}$, its specific enthalpy. τ_d and τ_p mean the duration time of propellant discharge and that of tank pressurization, respectively

Equation (2) allows to calculate the pressurization gas mass flow rate $\dot{m}$, as a first approximation, at a given values of P_t, V_l, τ_d, $i_{g,i}$, τ_p and ϕ. The conceptual design process for obtaining the pressurization gas mass flow rate, its supplying temperature and velocity is summarized at Fig. 2. The determination of ultimate $\dot{m}$ requires the physical and mathematical models for each design and its experimental acknowledgement [2].

3. Optimal temperature of pressurization gas at the entrance of tank

The analysis of pressurization gas temperature at the tank inlet could be executed after the formation of input data (step 1 on Fig. 2) and the structural/functional operation analysis of pressurization system (step 2 on Fig. 2). The determination of optimal pressurization gas temperature includes the calculation of ϕ, $\dot{m}$, the weight and size analyses of heat exchanger and pressurization gas storage tank. It should be noted that the optimal temperature is selected on the basis of the weight of specified devices.

The empirical relation for calculation of exergyϕ which takes into account the effect of pressurization gas type, its temperature at the entrance of tank and the size of tank on the efficiency of process in the tank is given as [6]:

$$\phi = 1/\Theta^{\beta} \qquad (3)$$

where, $\Theta = T_{g,i}/T_l$ is the ratio of gas temperature at the tank inlet $(T_{g,i})$ and propellant temperature (T_l), $\beta = 0.2575 + 0.3467(F_t/V_t)(R/C_p)$ is the empirical parameter which contains the geometrical factor of tank (F_t and V_t denote the inner surface and volume of tank, respectively) and the thermodynamic properties of pressurization gas (R and C_p denote the gas constant and constant pressure specific heats of pressurization gas, respectively). This relation is obtained from the experimental works for cylindrical and spherical tanks with the range of $1.25 \leq \Theta \leq 20$ and $1.45 \leq F_t/V_t \leq 5.87$. Both condensible and non-condensible pressurization gases are utilized on this experimental study. The relation (3) shows that the pressurization gas mass flow rate $\dot{m}$ decreases exponentially with an increase of Θ (as depicted in Fig. 3). It is also found that the tank volume V_t has a significant effect on the variation of mass flow rate. Fig. 3 shows that the decrease of mass flow with pressurization gas temperature becomes more faster as the tank volume increases.

For the non-condensible pressurization gas, the temperature, $T_{g,i}$ obtained by the *above-mentioned procedure could be counted* as an optimal temperature. However, for the condensible one, it is necessary to estimate the supply temperature, $T_{g,i}$ which prevents the condensation of pressurization gas in the tank ullage volume. The condensation of gas reduces the efficiency of the pressurization process due to the partial loss of pressurization gas and the increase of upper layer temperature of propellant.

The temperature of gas in the tank, T_g at which the mass transfer between the gas and the propellant does not occur could be obtained by [8]:

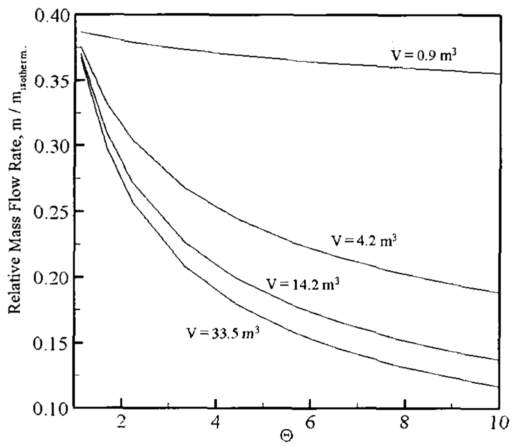

Fig. 3 Variations of pressurization gas mass flow rate with the temperature ratio, Θ and the tank volume, V for spherical tank of ullage pressure P_t= 0.5 MPa, propellant temperature T_l= 90 K and propellant discharge rate V_l= 0.088 m³/s. $m_{isotheraml.}$ denotes the required mass flow rate of pressurization gas for isothermal process ($T_g = T_l$)

$$T_g = (T_s - T_l)\{1 + [(\rho c_p \lambda_\epsilon)_g / (\rho c_p \lambda_\epsilon)_l]^{0.5}\} + T_l \quad (4)$$

where T_s denotes the saturation temperature of propellant at the tank pressure, P_t and ρ, c_p, λ_ϵ represent the density, the constant-pressure specific heats and the effective thermal conductivity of fluids, respectively. The subscripts, g and l mean the pressurization gas (gas) and propellant (liquid).

It is noticeable that the value of λ_ϵ exceeds considerably λ (the molecular thermal conductivity of fluid). For example, λ_ϵ/λ can have values of 10~20 depending on the heat flux to the propellant from the environments. And its values could be increased up to 20~50 or 102~105 by the contact interaction of pressurization gas with the surface of *propellant or by the oscillation of liquid* surface occurring when the direction of forces on the rocket is changed during the flight [2].

The temperature of pressurization gas at the entrance of tank, $T^1_{g,i}$ which gives the value of T_g as defined in the Eq. (4) is calculated from the relation:

$$T_g/T_l = (T^1_{g,i}/T_l)^{1-\beta} \quad (5)$$

In practice, the temperature of pressurization gas at the tank inlet, $T_{g,i}$ is recommended as about 15% higher than $T^1_{g,i}$ in consideration of modeling accuracy for the pressurization system design with condensible pressurization gas.

4. Optimal velocity of pressurization gas at the entrance of tank

To select the injection velocity of pressurization gas at the tank inlet, it is necessary to consider the direction of propellant supply. The propellant could be injected in the vertical direction to the surface of propellant, or along the surface of tank inner wall (radial injection), or also their combination. The vertical injection, on the basis of experimental data [6,7], has the minimal energy loss of pressurization gas caused by warming up the tank wall. This injection scheme provides the good mixing of gases in the tank ullage volume and thus results in the increasement of the gas mean temperature and the decrease of tank wall temperature which reduces the thermal stress of propellant tank. Fig. 4 shows the experimentally obtained values of exergy for the vertical injection of pressurization gas. K_w means $(w_{g,i}/w_l)$ where w_l is the velocity of liquid surface. As we can see on the Fig. 4, the exergy ϕ for the vertical injection has values about 0.3~0.65 typically. However, for radial injection, its values are about 0.2~0.42 [7].

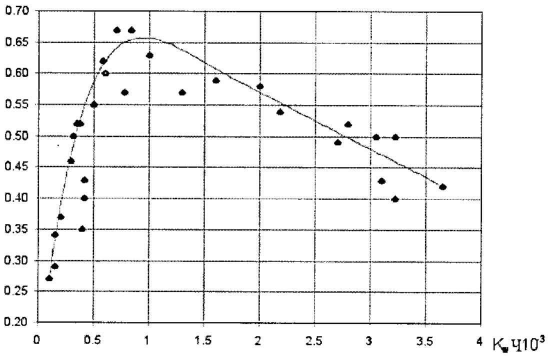

Fig. 4 Variation of exergy with relative velocity of pressurization gas injection for vertical injection of pressurization gas

There is a value of pressurization gas injection velocity at which the exergy at eqn. (1) becomes maximum. The mixing of gas in the ullage would depends on the pressurization gas injection velocity. As the parameter representing the mixing of gas, it is found experimentally that the non-dimensional variables defined as L_j/D_e is appropriate, where the L_j is the length of zone of uniform temperature and D_e is the equivalent injection diameter of diffuser. For the vertical injection, this penetration length is empirically given as:

$$L_j/D_e = 5 \cdot \mathrm{Ar}^{-0.3} \qquad (6)$$

where $\mathrm{Ar} = (1-\rho_{g,i}/\rho_g)\cdot(2gD_e/w_{g,i}^2)$ is the Archimedes' criterion and $\rho_{g,i}$, ρ_g denote the density of pressurization gas at the temperature of $T_{g,i}$, T_g respectively. $w_{g,i}$ is the gas injection velocity at the diffuser. The relation (6) is applicable for $6.5\times10^{-5} < \mathrm{Ar} < 9.8$ and $L_j/D_e < 100$. It is found experimentally that the maximum value of time-averaged ϕ during the propellant discharge process is obtained when

$$L_j = (0.5 \sim 0.7)H_g. \qquad (7)$$

The distance from the injection device (diffuser) to the surface of propellant at the end of propellant discharge process is represented as H_g. The relation between equivalent diameter of diffuser and pressurization gas injection velocity is simply expressed as

$$w_{g,i} = (4\dot{m})/(\rho_{g,i}\pi D_e) \qquad (8)$$

It is not difficult to find the optimal size of diffuser from the Eq. (6) - (8). This value, however, should be revised in view of the

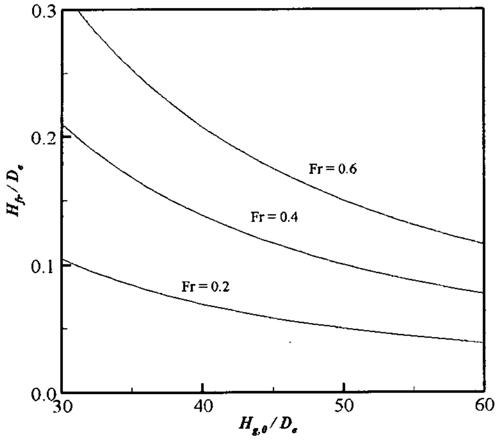

Fig. 5 Variation of surface deflection depth with the initial ullage volume lengths and Froud numbers

interaction between the jet of pressurization gas and the surface of propellant. The momentum energy of pressurization gas jet could deflect the surface of propellant. It makes the local turbulent flow and splashing of the propellant. These phenomena promote the pressurization gas energy loss due to the cooling and condensation of pressurization gas. The depth of liquid surface deflection, H_{fr} can be estimated as follows [1]:

$$H_{fr}/D_e = 61.32\mathrm{Fr}\,n\,(H_{g,0}/D_e)^{-1.453} \tag{9}$$

where, $\mathrm{Fr} = (\rho_{g,l} w_{g,l}^2)/(D_e \rho_l g)$ is the Froud number, $\rho_{g,l}$ and $w_{g,l}$ represent the density and velocity of pressurization gas at the interface with propellant, respectively. ρ_l denotes the density of propellant and n, g-loads. $H_{g,0}$ means the distance from the injection device to the surface of propellant at the beginning of propellant discharge process. This correlation is applicable for $0.1 < \mathrm{Fr} < 0.52$ and $23 < H_{g,0}/D_e < 65$.

It is permissible to allow the value of H_{fr} less than 10% of D_e (See Fig. 5). It is necessary, otherwise, to reduce the injection velocity. The size of diffuser obtained with the consideration of the interaction between jet and surface could be taken as optimal value if it meets the weight limitation.

And the computational program of calculation for determination of optimum values $T_{g,i}$ and $w_{g,i}$ has been developed. This program contains several algorithms which can calculate the minimum/maximum tank pressures, the weight of pressurization gas heat exchanger, the weight of pressurization gas storage tank and the optimum temperature of pressurization gas at the inlet of a tank and optimum velocity of pressurization gas from a diffuser and its effective diameter.

4. Conclusion

The methodology of determining the optimal parameters of pressurization gas at the entrance of propellant tank for liquid propulsion system and the conceptual design process of pressurization system was suggested.

It is based on the concept of exergy and the empirical correlations given from references which take into account the complicate heat and mass transfer occurring in the tank ullage volume. The pressurization system design process consists of the determination of pressurization gas supply parameters by using the suggested calculation methodology and the allowable weight analysis. We have developed the calculation program for determination of optimum values of $T_{g,i}$ and $w_{g,i}$.

The interaction between pressurization gas and the surface of propellant due to the oscillation of surface during the flight does not be included in the suggested methodology. It would be the further research works to complete the methodology.

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