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Experimental investigation on pressurization performance of cryogenic tank during high-temperature helium pressurization process

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ABSTRACT

Sufficient knowledge of thermal performance and pressurization behaviors in cryogenic tanks during rocket launching period is of importance to the design and optimization of a pressurization system. In this paper, ground experiments with liquid oxygen (LO_2) as the cryogenic propellant, high-temperature helium exceeding 600 K as the pressurant gas, and radial diffuser and anti-cone diffuser respectively at the tank inlet were performed. The pressurant gas requirements, axial and radial temperature distributions, and energy distributions inside the propellant tank were obtained and analyzed to evaluate the comprehensive performance of the pressurization system. It was found that the pressurization system with high-temperature helium as the pressurant gas could work well that the tank pressure was controlled within a specified range and a stable discharging liquid rate was achieved. For the radial diffuser case, the injected gas had a direct impact on the tank inner wall. The severe gas-wall heat transfer resulted in about 59% of the total input energy absorbed by the tank wall. For the pressurization case with anti-cone diffuser, the direct impact of high-temperature gas flowing toward the liquid surface resulted in a greater deal of energy transferred to the liquid propellant, and the percentage even reached up to 38%. Moreover, both of the two cases showed that the proportion of energy left in ullage to the total input energy was quite small, and the percentage was only about 22–24%. This may indicate that a more efficient diffuser should be developed to improve the pressurization effect. Generally, the present experimental results are beneficial to the design and optimization of the pressurization system with high-temperature gas supplying the pressurization effect.

1. Introduction

Developing a new-style cryogenic liquid rocket needs sufficient knowledge of cryogenic fluid management technologies. One of the key management systems is the tank pressurization system. During the rocket launch period, cryogenic propellant is discharged from the tank bottom and simultaneously pressurant gas is introduced into the tank ullage to hold the tank pressure sufficiently high so as to prevent cavitation at the rocket pump inlet. To reduce the gas consumption requirement, a gas preheating operation is generally adopted to produce high-temperature pressurant gas. With the continuous injection of high-temperature gas, a significant stratified environment may exist in the ullage region. Complex thermodynamic phenomena may occur simultaneously within the stratified ullage including heat transfers between ullage, liquid propellant and tank wall and interfacial mass transfer. Research on the thermal performance and pressurization behaviors inside the propellant tank during liquid discharge is of importance to the design and optimization of the pressurization system.

Due to its significant effects on the pressurization system, the problems associated with pressuring a cryogenic tank have been paid close attention. Experimental and computational approaches have been utilized to investigate the thermal performance and pressurization behaviors within the cryogenic tank. Stochl et al. [1,2] performed experimental investigations on the tank pressurization and liquid hydrogen (LH_2) expulsion processes from two different spherical tanks. Influences of several parameters on pressurant gas requirement were determined including discharge rate, pressurant gas rate, initial ullage conditions, inlet gas temperature, and so forth. It was found that the inlet gas temperature had a primary influence on the gas requirement, followed by the diffuser geometry. Lacovic [3] presented the results of a series of ramp and expulsion pressurization tests conducted in a thick-wall

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liquid oxygen tank. For the expulsion tests, helium gas was injected either directly into the ullage region or beneath the liquid surface, and the helium requirement was obtained to analyze the pressurization performance. DeWitt et al. [4] conducted an experimental investigation to determine the effect of diffuser geometry on pressurant gas requirement and six diffuser geometries were concerned. The results showed that the straight pipe diffuser, which introduced pressurant gas with a concentrated stream toward the liquid surface, produced an apparent difference in gas requirement compared to the other five diffuse-type diffusers. On the basis of the existing experimental data, Van Dresar [5] modified a mathematical correlation which could predict the pressurant gas requirement for expelling LH_2 from an axisymmetric tank. Van Dresar and Stochl [6,7] presented a series of experimental results for the pressurization and discharge processes of LH_2 tanks both in low-gravity and normal gravity conditions. Ludwig and Dreyer [8,9] performed an experiment to determine the influence of inlet gas temperature on gas requirement during the active-pressurization process without liquid discharge. Fan et al. [10] conducted a ground experiment to validate the influence of high-temperature pressurant gas on the tank wall temperature. High-temperature helium exceeding 650 K was employed to provide pressurization effect to a full-scale LO_2 tank, and the experimental data were applied to assess a new 1-D pressurization model. All of the above experimental results provide important information of pressurization behaviors, making it clearer for researchers to understand the situation and process.

Several computational models, including 0-D model, 1-D model and CFD model, have been developed to predict the thermal performance and pressurization behaviors in the cryogenic tanks. Majumdar and Steadman [11] developed a finite volume procedure to model the pressurized discharge process of a propellant tank. Time-dependent mass, momentum, energy, and species conservation equations were solved to describe the pressurization performance. Karimi et al. [12] employed a 0-D model to predict the exit pressure of a pressurization system. Zilliac and Karabeyoglu [13] introduced a thermodynamic model to account for the pressurization performance of a highly volatile propellant tank. It was found that accurately modeling the propellant evaporation rate was crucial to the pressure prediction of the highly volatile propellant tank. Kim et al. [14] established a numerical model to account for the transient thermal behaviors in a cryogenic oxidizer tank, and the mass and energy conservations of oxygen/helium mixtures in both ullage and liquid regions were involved. Generally, warm pressurant gas is employed to provide a better pressurization performance, and thus the ullage temperature is actually stratified and non-uniform. Under this situation, a 1-D model, considering the physical field distribution along axial direction, was developed by Roudebush [15] to solve the stratified problem of the pressurized discharge process. This model divided the ullage space into a series of vertical nodes, and finite different approximations were obtained to represent the axial temperature profiles in ullage gas and tank wall. Masters [16] revised and extended the analysis of this 1-D model to include the energy transfer occurring at gas–liquid interface and to cover the initial pressurization (ramp) period. Kwon et al. [17] also developed a 1-D model to predict the helium mass requirement for tank pressurization during propellant discharge, and an "expanding" finite volume method was applied to divide the ullage region axially.

Besides, CFD technique has been widely used in the pressurization prediction of cryogenic tanks. Hardy and Tomisk [18] used Flow-3D computer code to determine the effects of various parameters on the inner temperature profiles during the ramp pressurization prior to liquid discharge. It seems to be the first application of CFD approach in the tank pressurization investigation. The results indicated that Flow-3D code might be an effective tool in the research of propellant management. Sasmal and Hochstein [19] developed a multi-dimensional computational model to account for the pressurization process in a LH_2 tank, and the detailed thermodynamic behaviors inside the ullage were described through mathematical relations. The results showed that heat flux at ullage boundary had a significant effect on the pressurization performance, and minimizing the ullage-wall heat exchange was beneficial to the pressurization effect. Adnani and Jennings [20] used a CFD model to analyze the pressurization behaviors of LH_2 tank, and the gas thermodynamics during helium pressurization and autogenous hydrogen pressurization were concerned. Leuva et al. [21] applied a CFD tool to simulate ullage pressure collapse experienced before the ignition of main engines, and a multiphase cryogenic model, considering the mixture ullage of hydrogen vapor and helium, was constructed. Ludwig and Dreyer [9] concerned the thermodynamic phenomena in a cryogenic propellant tank during the initial active-pressurization process and a CFD model was developed. For the simulation of helium pressurization case, a multi-component ullage model was constructed, and the partial pressure of each gas component as well as the mass fraction was solved by CFD software automatically. Wang et al. [22] constructed a CFD model to investigate the transient thermal performance and pressurization behaviors of cryogenic tanks during liquid discharge. Comparison of the numerical results with experimental data suggested that the CFD model had a good adaptability in pressurization computation. Subsequently, this CFD model was applied to investigate the effects of various parameters, such as inlet gas temperature, ramp time of inlet temperature, wall thickness, discharge rate, and so forth, on pressurization behaviors [23]. The computational results showed that an increasing gas temperature and a thin tank wall could reduce the gas requirements. In addition, the influence of outside aerodynamic heating on pressurization performance was evaluated through an improved CFD model [24]. The results showed that outside aerodynamic heating could not penetrate the foam layer to facilitate the pressurization effect. Conversely, a certain proportion of energy might be transferred from heated tank wall to foam layer, which exerted a negative effect on the pressurization performance.

In the present study, two ground experiments, conducted in a full-scale liquid oxygen tank platform, were undertaken to investigate the thermal performance and pressurization behaviors of the pressurized discharge process. High-temperature helium exceeding 600 K was introduced into the LO_2 tank to supply pressurization effect, and two diffusers with different outlet characteristics were used at the gas inlet. The pressurant gas requirement and the temperature distributions inside the tank were obtained and analyzed to evaluate the pressurization performance, and the influence of diffuser geometry on pressurization behaviors was discussed by comparing the energy distributions within the tank system. The present study may provide detailed information on thermal performance and pressurization behaviors in the cryogenic tanks during high-temperature gas injection process.

2. Experiments

2.1. Experimental apparatus

The pressurization experiment system, schematically depicted in Fig. 1, comprised five parts as following:

1) **Helium supply system**. High-pressure helium cylinder bundles were utilized as the pressurant gas source. A closed-loop pressure control circuit, which controlled inlet gas flow rate by three groups of control valve (component 2) and orifice plate (component 3), was used to maintain a relative stable tank pressure during the whole discharge period.