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Comparison of three computational models for predicting pressurization characteristics of cryogenic tank during discharge

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ABSTRACT

In order to select an effective approach to predict the pressurization characteristics of cryogenic tank during rocket launching, three computational models, defined as 0-D, 1-D and CFD models, are used to obtain the pressure evolution and thermal performance of a cryogenic tank during pressurized discharge period. Several pressurization cases are computed by all of the three models to evaluate their predictive abilities and effects, respectively. The comparative study shows that for the case with a diffuser-type injector at the tank inlet, the consistent results by the three models are obtained in the most of period, except that 1-D model has a peak departure prediction of pressure value at the beginning of process. All of the three models can be used to predict the pressurization performance, and their predictive abilities could be validated with one another. The CFD model is the unique suitable model to display the pressurization performance including physical distribution in radial direction especially for the system with no-diffuser-type injector. Based on the analysis, the application selection of three models for different cases is accomplished. The 0-D model is the priority selection for a simple pressure prediction of tank ullage, even for the situation that severe temperature distribution exists in the ullage range. The 1-D model is the optimal selection as considering both the convenience and the time consumption for the constant-pressure cases. But it is not recommended in a constant-inlet flux cases for its distinct predicting deviation at the beginning of the process. When the detailed distributions within the tank are concerned, the CFD model is the unique selection. The results of this paper may be beneficial to the model selection and optimization analysis of a pressurization system.

1. Introduction

The pressurization system of a cryogenic propellant tank is to ensure that the ullage pressure and temperature inside the tank remain within acceptable limits and the pressure of the propellant leaving the tank satisfies the net positive suction pressure (NPSP) requirement of the feeding pump. The pressurized discharge process is a complex thermodynamic process with heat and mass transfer in a stratified environment. Selecting an appropriate computational model to predict the ullage pressure evolution and temperature distribution is of importance for the design and optimization of a pressurization system.

Owing to its apparent effects on pressurization system, the problems associated with pressurizing a cryogenic tank have been paid close attention. Dewitt et al. [1], Stochl et al. [2,3] and Lacovic [4] conducted experimental studies to determine the effects of various parameters on pressurant gas requirements, including liquid discharge rate, pressurant inlet flux, pressurant temperature, initial ullage conditions, and so forth. On the basis of experimental data, Van Dresar [5] modified an existing correlation which could predict the pressurant gas requirement for expelling liquid hydrogen from an axisymmetric tank. Van Dresar and Stochl [6,7] introduced a series of experimental results for the pressurization and discharge processes of liquid hydrogen tanks both in low-gravity and normal gravity. Ludwig and Dreyer [8,9] performed an experiment to determine the influence of inlet gas temperature on pressurant gas requirement during the active-pressurization process. All of the above experimental results provide important information of pressurization behaviors, making it easier for researchers to understand the situation and process.

Besides the experimental approaches, several computational models, including thermodynamic equilibrium model (0-D model), one-dimensional stratified model (1-D model) and computational

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Nomenclatures

A	heat transfer area (m^2)
c_p	specific heat (J/(kg K))
Gr	Grashof number
h_{uw}	heat transfer coefficient between ullage and tank wall (W/(m^2 K))
h_{ui}	heat transfer coefficient between ullage and liquid interface (W/(m^2 K))
i_{in}	input enthalpy (J/kg)
l	height of dished-heat ends (m)
l_{u0}	initial ullage height (m)
l_w	tank wall thickness (mm)
m	gas mass within ullage space, kg
m_c	calculated pressurant gas requirement (kg)
m_e	experimental pressurant gas requirement (kg)
m_{in}	mass flux of inlet gas (kg/s)
M	molar mass of ullage gas (kg/mol)
Nu	Nusselt number
P	ullage pressure (MPa)
P_0	initial ullage pressure (MPa)
P_{c0}	calculated ullage pressure by 0-D model
P_{c1}	calculated ullage pressure by 1-D model
P_{c2}	calculated ullage pressure by CFD-based model
Pr	Prandtl number
Q_{uw}	heat transfer rate between ullage and tank wall, W
Q_{ui}	heat transfer rate between ullage and liquid interface (W)
q_o	heat leak rate per unit area from outside the tank (W/m^2)
r_i	tank radius (m)
R	molar gas constant, $R = 8.314$ (J/(mol K))
t	time (s)
t_{total}	total discharge time (s)
T	temperature (K)
T_0	initial ullage temperature (K)
T_{sat}	saturation temperature (K)
T_{in}	inlet gas temperature (K)
T_{c0}	calculated temperature by 0-D model
T_{c1}	calculated temperature by 1-D model
T_{c2}	calculated temperature by CFD-based model
T_{w0}	initial ullage-adjacent wall temperature (K)
u	internal energy (J/kg)
v_x	axial velocity (m/s)
V	ullage volume (m^3)
V_0	initial ullage volume (m^3)
V_{out}	volume flux of expulsion (m^3/s)
x_c	characteristic length (m)
x	distance from the tank top (m)

Greek symbols

λ	thermal conductivity (W/(m K))
ρ	density (kg/m^3)
γ	specific heat ratio

Subscripts

u	ullage
w	wall
i	liquid interface

fluid dynamics model (CFD model), have been developed to predict the pressurization behaviors. In the 0-D model, ullage space is treated as a temporally-varying, spatially-uniform region, and relevant calculations including time-dependent mass, momentum, energy, and fluid species conservation equations are solved only in the ullage region. Majumdar and Steadman [10] developed a thermodynamic equilibrium procedure to predict the ullage pressure and temperature evolutions during the liquid discharge process. The heat transfers from ullage gas to tank wall and to liquid propellant were assumed to be controlled by natural convection. Similar analysis has also been utilized by Karimi et al. [11] and Estey et al. [12]. Zilliac and Karabeyoglu [13] employed a thermodynamic model to describe the self-pressurization behaviors of highly volatile nitrous oxide propellant tank. It was found that accurately modeling the propellant evaporation rate was crucial to the pressure prediction of the nitrous oxide tank. Kim et al. [14] established a 0-D model to account for the transient thermal behaviors in a cryogenic oxidizer tank, and mass and energy conservation of oxygen/helium mixtures in both ullage and liquid regions were involved.

Experimental studies show that ullage temperature is actually stratified and non-uniform [2,3]. Hence adopting the ullage averaged temperature may overestimate the ullage-liquid heat transfer. Under this circumstance, a simple one-dimensional model, considering the formation of thermal stratification in the ullage region, was developed by Roudebush [15] for the problem of pressurizing a cylindrical tank. This model divided the ullage space into a series of vertical nodes and finite different approximations were obtained for the dynamic and heat transfer equations to calculate the axial temperature distributions in ullage gas and tank wall. Masters [16] revised and extended the analysis of the 1-D model to include the energy transfer occurring at gas–liquid interface in tanks of arbitrary symmetric shape and to cover the initial pressurization (ramp) period. The comparison of 1-D model results with experimental data suggested that the 1-D model could accurately predict the pressurant gas requirements and axial temperature distributions when a diffuser-type injector was applied at the inlet [2,3,15]. However, when using a straight pipe injector, this 1-D model seemed to be invalid since a clear radial temperature distribution existed in the ullage region. Moreover, Roudebush and Mandell [17] transformed the equations of 1-D model and associated initial and boundary conditions in terms of dimensionless variables to investigate the various factors affecting the pressurization performance, and only two parameters, which had the form of modified Stanton numbers, were of principal importance. Kwon et al. [18] also developed a 1-D model to predict the helium mass requirements for tank pressurization during propellant discharge, and an "expanding" finite volume method was applied to divide the ullage region axially.

CFD technique, since its convenience, efficiency and quickness, has become a popular tool in the prediction and analysis of field parameters, and great emphasis has been placed on the CFD approach of tank pressurization prediction. Hardy and Tomsik [19] and Sasmal and Hochstein [20] selected Flow-3D code to model the pre-pressurization process without liquid surface decline. In their approaches, the phase change effect at liquid surface was ignored and a solid boundary was used to model the free surface. Adnani and Jennings [21] used the commercial CFD software Fluent to predict the ullage pressure behaviors and pressurant gas requirements during pre-pressurization stage. An adequate turbulence model combined with an appropriate wall function was used to determine the tank wall temperature. Mattick et al. [22] developed a comprehensive suite of analysis tools to carry out the simulations of pressurization in propellant tank.