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Research Paper

Pressurization performance and temperature stratification in cryogenic final stage propellant tank

Zhan Liu [a], Yanzhong Li [a,b,*], Yonghua Jin [a]

[a] School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] State Key Laboratory of Technologies in Space Cryogenic Propellants, Beijing 100028, China

HIGHLIGHTS

- Tank pressurization performance and fluid thermal stratification are investigated.
- Both active-pressurization and pressurized discharge are researched successively.
- Aerodynamic heat has caused large change of tank pressurization time internal.
- The ullage is in condensation during the whole process.

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ABSTRACT

One CFD model is established to investigate the pressurization performance and thermal stratification in the final stage cryogenic liquid oxygen (LOX) tank, which is subjected to aerodynamic heat and space radiations during launch. Iterative calculation with variable physical properties in each time step, both aerodynamic heat and space radiation have been considered by compiling one UDF and implanting it into the CFD model. It turns out that aerodynamic heat has caused large influence on tank pressurization performance, while the effect of space radiation on tank pressurization is not obviously reflected. Influenced by the injection gas, tank pressure fluctuates between the minimum and the maximum pressure limit and the ullage mass decreases due to condensation during the active-pressurization. Meanwhile, the basic parallel advance trend of temperature distribution is roughly formed. During the pressurized discharge, tank pressure experiences a sharp decline at first, then decreases linearly, finally reduces with a larger rate. The liquid temperature increases gradually to the direction of advance as liquid height declines. Moreover, the residual liquid temperature increases obviously. With the heat continuous transferring from the ullage to the liquid, the ullage is under condensation during the whole process.

1. Introduction

Cryogens, especially liquid hydrogen (LH_2) and LOX, will inevitably play an important role, both as power supply and life support fluids in the future space explorations [1]. During the rocket launch, cryogenic propellant tanks are subjected to serious aerodynamic heat and space radiations. Due to the low boiling point, liquid propellants are quite sensitive to heat leaks from the external thermal environment [2]. Complex heat and mass transfer are involved in the pressurization and thermal stratification process. Therefore, it is essential to conduct a deep research on the pressurization and thermal stratification phenomenon in cryogenic tank, which is particularly important for the successful drainage and safety storage of cryogenic propellant for long time.

Some investigators have conducted related experimental research, theoretical analysis and numerical simulations. Aydelott [3] experimentally researched the self-pressurization of a spherical LH_2 tank in normal gravity, with variable filling percent, wall heat flux and heating location. Lin and Hassan [4] theoretically studied the thermal stratification and self-pressurization of a spherical LH_2 tank in microgravity. Panzarella et al. [5] investigated large cryogenic tank pressurization under normal and microgravity condition, by coupling a lumped thermodynamic model of the vapor region with a complete governing equations in liquid region. Zilliac and Karabeyoglu [6] proposed a quasi-phase equilibrium thermodynamic model to predict the tank pressurization. Grayson et al. [7] adopted the Flow-3D software to research the pressurization performance of cryogenic LH_2 and liquid nitrogen (LN_2) tank

* Corresponding author at: School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail address: yzli-epe@mail.xjtu.edu.cn (Y. Li).

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Nomenclature

A_t	tank cylinder surface area (m^2)
A_{tp}	projection area of tank cylinder (m^2)
c_p	specific heat at constant pressure (J/(kg K))
c_{pw}	specific heat of tank wall (J/(kg K))
D	tank diameter (mm)
d_1	gas inlet diameter (mm)
d_2	injector diameter (mm)
g_0	constant gravity, 9.81 m/s^2
GOX	gas oxygen
h	orbit altitude or flight height (km) or liquid level height (mm)
h_{fg}	latent heat (kJ/kg)
h_r	enthalpy corresponding to recovery temperature (kJ/kg)
h_w	enthalpy corresponding to wall temperature (kJ/kg)
L	cylinder height (mm)
l	dished head height (mm)
LH_2	liquid hydrogen
LN_2	liquid nitrogen
LOX	liquid oxygen
m_{in}	gas inlet mass flow rate (kg/s)
m_{out}	liquid outlet mass flow rate (kg/s)
n	empirical constant, 1/2 for laminar and 1/3 for turbulent
P_0	initial tank pressure (MPa)
Pr	Prandtl number
q_n	net radiative flux (W/m^2)
q_r	radiation heat flux (W/m^2)
q_t	total space radiative flux (W/m^2)
q_w	wall or surface heat flux (W/m^2)
q_x	aerodynamic heat flux (W/m^2)
q_1	solar incident radiation (W/m^2)
q_2	earth albedo radiation (W/m^2)
q_3	earth infrared radiation (W/m^2)
R_E	radius of the earth (m)
r	time parameters (1/s)
Re	Reynolds number
S	solar radiation intensity constant, 1414 W/m^2
S_h	energy source term (W/m^3)
S_m	mass source term (kg/(m^3 s))
t	time (s)
T_{df}	draining fluid temperature (K)
T_e	air temperature close to the boundary layer (K)
T_{l0}	initial liquid temperature (K)
T_r	recovery temperature (K)
T_{sat}	saturation temperature (K)
T_{u0}	initial ullage temperature (K)
T_w	wall temperature (K)
u_e	flight velocity (m/s)

Greek letters

α	absorptivity or void fraction
α_x	aerodynamic heat transfer coefficient (W/(m^2 K))
β	angle between tank micro surface normal and the direction of the line past the tank and the earth
β_s	angle between sunlight incident direction and surface normal (°)
κ	surface curvature (1/m)
λ	conductivity (W/(m K))
λ_w	tank wall conductivity (W/(m K))
δ	tank wall thickness (mm)
ρ	reflectivity of the earth surface or density (kg/m^3)
ρ_w	tank wall density (kg/m^3)
ε	emissivity
σ	Stefan–Boltzmann constant
σ_{lv}	interfacial surface tension (N/m)
μ	dynamic viscosity (N s/m^2)
ϕ_1	solar radiation angle coefficient
ϕ_2	earth albedo angle coefficient
ϕ_3	earth infrared radiation coefficient
ψ	phase angle

Subscripts

df	draining fluid
l	liquid
max	maximum
min	minimum
r	recovery or radiation
v	vapor
x	aerodynamic heating
w	wall
*	parameters corresponding to reference temperature

with the pressurized helium injection. Lopez et al. [8,9] developed a CFD model to study the pressure control of an ellipsoidal-shaped LH_2 tank in both normal gravity and low gravity condition. Winter and Marchetta [10] presented a complete finite volume model with an Energy of Fluid approach to control the tank pressure. To determine the tank pressure rise conveniently, Gorla [11] presented thermodynamic design charts to facilitate a rapid calculation procedure for predicting the pressurization in transport vessel containing LNG or LPG. Barsi and Kassemi [12,13] investigated the self-pressurization process and thermal stratification phenomena by conducting experiments and carrying out numerical simulation. To reduce the boil-off generation of LNG, Roh et al. [14] built a CFD model to investigate the pressurization process of LNG storage tank under the effect of transient external natural convection. Ludwig and Dreyer [15] conducted the ground experiment and performed the corresponding numerical simulations to investigate the thermodynamic phenomena in active-pressurization process of cryogenic propellant tank. Fu et al. [16] numerically studied the self-pressurization of LH_2 tank with transverse ribs. Thereafter, Fu et al. [17] also researched the self-pressurization of LH_2 tank with interface evaporation considered under microgravity. Additionally, tank pressurization process and thermal stratification were also investigated by Liu et al. [18–20].

Based on the previous studies, it is easy to find that self-pressurization and active-pressurization process have been investigated separately. The pressurized discharge process of the first stage propellant tank during the rocket ascent period is also investigated by Wang [21,22], under the effect of aerodynamic heating. Other investigators also have conducted some research on the discharge process of the first stage. As the Refs. [21,22] mainly focus on the tank discharge for the first stage tank, little attention has been paid on the final stage, which would supply the power for the rocket from the atmosphere to the designed orbit. Under the effect of aerodynamic heat and space radiation, the final stage tank would experience active-pressurization and pressurized discharge process successively. As the safety of the final stage is still greatly important for the rocket launch, the pressurization and thermal performance of the final stage LOX tank, under the influences of aerodynamic heat and space radiations during the ascent process, are specially investigated in the present study. Tank pressure