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Thermal performance of liquid hydrogen tank in reduced gravity

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Abstract

Fluid temperature stratification is significant to the safe operation of space storage tanks. A calculation model, accounting for the liquid–vapor phase change, is developed to investigate the thermal physical process in a liquid hydrogen (LH_2) tank in reduced gravity. Viscous flow is considered in calculation model with Ra ranging from 0.1 to 10^5 to ensure the continuity of natural convection. The stratified layer parameters, the tank pressure rise, and the interface phase change are studied respectively. Influences of the initial liquid height, the initial ullage temperature and the tank wall heat flux on the development of thermal stratification are estimated. The results show that the stratified layer thickness rises with the initial liquid height. While the initial liquid height is large, it costs more time for the wholly development of fluid thermal stratification. Largely influenced by the temperature of the stratified layer, both tank pressure and phase change capacity increase with the initial liquid height. It seems that the initial ullage temperature has a weak effect on the development of fluid thermal stratification. Both the tank pressure and the phase change quality increase with the initial ullage temperature. The external tank wall heat flux promotes the development of thermal stratification. The stratified layer has a larger thickness and develops faster for the larger heat flux. Both tank pressure and phase change capacity increase with the external heat flux. Meanwhile, the intersection point exists between any two profiles.

Keywords: Thermal performance; Liquid hydrogen; Reduced gravity; Constant wall heat flux

1. Introduction

With the inevitable space radiation, fluid temperature stratification forms in cryogenic storage tank with the penetration of external heat leaks. As the fluid thermal stratification promotes the tank pressure increase and the boil-off loss, and causes serious influences on the safe on-orbit operation of cryogenic storage tanks, it is necessary to give enough attention on the thermal physical process on cryogenic tanks, including the fluid thermal stratification and tank pressurization performance.

During the past several decades, a lot of investigations have been done to investigate the fluid temperature stratification in cryogenic storage tanks. The related investigations are consisted of the experimental study, theoretical derivation and numerical simulation. In the earlier stage, cryogenic fluids, such as liquid hydrogen, liquid nitrogen and liquid oxygen, are used to be the experimental working fluid. During 1960–1965, thermal stratification in liquid hydrogen storage tank have been experimentally studied. Considering the external heat leakage, the temperature stratification was measured by Bailey and Fearn (1964) in a liquid hydrogen storage tank. The results showed that the tank pressure increase was not uniform, i.e. the upper propellant layers experienced a larger increase than the lower layer. To effectively prevent the pump cavitation

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Nomenclature

c_p	specific heat at constant pressure, J/(kg K)
g	gravity acceleration, m/s^2
g_0	constant gravity acceleration, 9.81 m/s^2
Gr	Grashof number
$H,\ h$	liquid height, m
L	tank height, m
l	characteristic height, m
$\dot{m}$	mass flow, kg/s
Nu	Nusselt number
p	tank pressure, kPa
Pr	Prandtl number
q	heat flux, W/m^2
R	radius of tank, m
Ra	Rayleigh number
Ra^*	modified Rayleigh number
T	temperature, K
t	time, s
u	boundary layer vertical velocity, m/s
y	vertical coordinate

Greek letters

α	convection heat transfer coefficient, $\text{W/(m}^2\text{ K)}$
β	thermal expansion coefficient, 1/K
δ	boundary layer thickness, m
λ	thermal conductivity, W/(m K)
v	kinematic viscosity, $\text{m}^2\text{/s}$
θ	excess temperature difference, K
ρ	fluid density, kg/m^3
σ	surface tension, N/m
Δ	the stratified layer thickness, m

Subscripts

B	bulk fluid
b	boundary layer
l	liquid
pch	phase change
s	the stratified layer
u	the ullage
w	tank wall

when the high-temperature propellant was injected into the propellant feed system, Tatom et al. (1964) has conducted theoretical analysis for the inner mechanism of cryogenic fluid thermal stratification. Based on the test data in a cylindrical tank of Saturn configuration, Barnett et al. (1965) analyzed the liquid hydrogen thermal stratification by using hyperbolic profile with the boundary layer considered. Aiming at the temperature stratification phenomenon in cryogenic liquid hydrogen tank, Schmidt et al. (1960) conducted an experimental study on tank pressurization and fluid stratification. Afterwards, the influence factors of sidewall heating (Ruder, 1964), bottom heating (Vliet, 1966), and both of sidewall and bottom heating (Fan et al., 1969) on fluid temperature stratification were experimentally investigated. The related investigations showed that the different heat types have caused different thermal dynamic processes in cryogenic propellant tank, which has a great influence on tank pressurization and fluid thermal stratification. Meanwhile, the theoretical derivations on fluid thermal stratification were developed as well. Schmidt et al. (1960), have adopted a one-dimensional semi-infinite solid heat conduction correlation to predict the liquid hydrogen temperature distribution. Bailey et al. (1963), wrote an analytical procedure and made the quantitative analysis for fluid stratification. Harper and Tellep (1963) analyzed theoretically the transient stratification in a closed cryogenic container. Brogan et al. (1964) developed one stratified layer flow model to simulate the liquid temperature stratification, with assuming the dimensionless temperature profile in stratified layer being constant. Bourgarel et al. (1967) conducted the theoretical determination of stratification similitude law. Meanwhile, the validation was made between the theoretical model and the subscale experiment results. Robbins and Rogers (1988) developed a computer program to predict thermal stratification with the fluid boundary layer considered. The transient free convective boundary layer along the concave surface was investigated with an integral method by Yu et al. (1992). The thermal stratification in rotating tank was investigated by Oliveira et al. (2009). Moreover, a dynamic model to describe thermal stratification has been improved by Daigle et al. (2012). Except for the smooth tank wall, the fluid thermal stratification in tank with transverse wall ribs or isogrid roughness, were studied by Khurana et al. (2006), Justin et al. (2007a, 2007b), and Faure et al. (2007). From their investigations, it shows that the structure of the wall ribs or isogrid roughness has a great effect on the thermal stratification and pressurization performance. Shankar and Sherif (2004) numerically studied the thermal stratification in a cryogenic storage tank under the normal and reduced gravity. With the surface evaporation considered, Kumar et al. (2007) numerically researched the influence of tank aspect ratio on fluid stratification. Fu et al. (2014) adopted the VOF method to numerically investigate the development of fluid thermal stratification under different rib spacing-to-height ratios, and different rib material and shapes. Liu et al. (2017, 2016) numerically studied the fluid thermal stratification in a liquid oxygen tank during the ground static and the ascent period. The influences of slosh baffles (Liu and Li, 2018) and gravity levels (Liu et al., 2018) on the thermal physical process in cryogenics storage tank were also studied in detail. It was found that slosh baffles have caused large disturbances in fluid thermal stratification, while the

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