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Influence of slosh baffles on thermodynamic performance in liquid hydrogen tank

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HIGHLIGHTS

- A calibrated CFD model is bulit to investigate the thermal dynamic performance of LH_2 tank.
- The slosh baffles have a great influence on the pressurization process in cryogenic LH_2 tank.
- Caused by baffles, the stratification thickness increases with the distance from tank axis to tank wall.
- The fluid temperature change should be considered in the calculation of heat transfer coefficient.

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ABSTRACT

A calibrated CFD model is built to investigate the influence of slosh baffles on the pressurization performance in liquid hydrogen (LH_2) tank. The calibrated CFD model is proven to have great predictive ability by compared against the flight experimental results. The pressure increase, thermal stratification and wall heat transfer coefficient of LH_2 tank have been detailedly studied. The results indicate that slosh baffles have a great influence on tank pressure increase, fluid temperature distribution and wall heat transfer. Owning to the existence of baffles, the stratification thickness increases gradually with the distance from tank axis to tank wall. While for the tank without baffles, the stratification thickness decreases firstly and then increases with the increase of the distance from the axis. The "M" type stratified thickness distribution presents in tank without baffles. One modified heat transfer coefficient correlation has been proposed with the change of fluid temperature considered by multiplying a temperature correction factor. It has been proven that the average relative prediction errors of heat transfer coefficient reduced from 19.08% to 4.98% for the wet tank wall of the tank, from 8.93% to 4.27% for the dry tank wall, respectively, calculated by the modified correlation.

1. Introduction

Future space explorations mostly rely on the ability to efficiently store, transfer and refill the propellant, which are mainly involved a variety of multi-phase fluids in reduced gravity environment. In these situations pertaining to future missions to deep space, cryogens, especially LH_2 and liquid oxygen, will inevitably play an important role, both as propellant and life support fluids [1]. Cryogenic propellant tanks in space are exposed to incident solar radiation, space radiation, or heat conduction by the support structure. With the low boiling point, liquid propellants are sensitive to heat leaks from space environment. Once these heat leaks penetrate into the tank, it will cause the intensive evaporation of cryogens, which leads the tank pressure increase and brings serious security issues, such as overpressure explosions [2–5].

Boil-off losses control of cryogenic propellant is of significance to deep space explorations. Accurate assessment of tank pressurization and boil-off rate are, therefore, critically important for defining design requirements for tank's maximum operating pressure and reducing cryogen loss. So far, reliable management of cryogenic propellants is continuously investigated to effectively reduce the propellant loss. Due to prohibitive costs, most of the future cryogenic storage tank designs are developed without the benefit of in-space testing, reliance on predictive computational

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Nomenclature

c_p	Special heat at constant pressure (J/kg K)
E	Internal energy(J/kg)
g	Gravity acceleration(m/s^2)
h	Height from the of the tank bottom (m)
HTC	Heat transfer coefficient
h_{fg}	Latent heat (J/kg)
l	Characteristic length (m)
P	Pressure (kPa)
Pr	Prandtl number
Q	Heat transfer(W/m^2)
$\dot{q}_w$	Wall heat flux(W/m^2)
R	Tank radius or distance from the tank axis (m)
Ra^*	Modified Rayleigh number
S_m	Mass source term (kg/(m^3 s))
S_h	Energy source term (W/m^3)
t	Time (s)
T	Temperature (K)
T_{WU}	Temperature of the wall contact with ullage (K)
ΔT	Temperature difference (K)

Greek letters

α	Volume fraction, convection heat transfer coefficient (W/(m^2 K))
β	Thermal expansion coefficient (1/K)
λ	Thermal conductivity (W/(m K))
ρ	Density (kg/m^3)
μ	Dynamic viscosity (N s/m^2)
σ	Surface tension (N/m)
φ	Correction factor

Subscripts

ave	Average
i	Interface
l	Liquid
v	Vapor
sat	Saturation
U	Ullage

models for storage tank pressurization and pressure control are ever-increasing.

Pressurization performance of cryogenic tank is still the present research hotspot. Several models [6,7] with varying levels of sophistication have been developed to predict the pressurization performance in partially filled cryogenic tanks. Homogeneous thermodynamic analyses were the earliest developed, which assumed that the average energy of the liquid and vapor phases change at the same rate. As this assumption was typically not met the initial phases conditions, the agreement between the thermodynamics and experiments were generally poor. In order to make up for defaults of the homogeneous model, investigators chose CFD technique to simulate the cryogenic tank pressurization process with liquid-vapor interface transport effects considered. Although some approximate models [8,9] have been developed to account for transportation effects, the results were not satisfied against the actual situation. To obtain more accurate predictions, Hochstein et al. [10] developed a conductivity model to account for transport process in liquid region. The results indicated that the comparisons with experiments yielded reasonable agreement for the given case. Thereafter, Panzarella et al. [11,12] introduced a two-phase CFD model, with coupled a lumped energy and mass model of the ullage to the transport equations in the liquid, to study the self-pressurization of cryogenic tank. Barsi and Kassemi [13] assessed the fidelity of two-phase lumped vapor model by comparing the prediction results against the experimental data. By solving the solutions of the N–S equations and energy equation in liquid and vapor phases [14], the two-phase lumped vapor model was expanded to consider effects of heat transfer and fluid flow in the vapor phase. Barsi and Kassemi [15] also modeled the tank pressure control by solving the incompressible equation with Boussinesq approximation to consider the buoyancy effect. Lopez et al. [16,17] selected the commercially Flow-3D software to study the pressure control of an ellipsoidal-shaped LH_2 tank under the external heat leaks both in normal gravity and low-gravity. Whitmore and Chandler [18] developed a simple engineering model to investigate self-pressurized propellant feed systems. Sim et al. [19] adopted a 3-D adaptive Eulerian-Lagrangian method implemented with a phase change model to research the self-pressurization process of a cryogenic fuel tank. Wang et al. [20] investigated the transient thermal and pressurization performance of cryogenic liquid oxygen tank during the ascent process. By establishing a 2D axial symmetry VOF model, Chen and Liang [21] studied the vaporization and pressure variation of a cryogenic LH_2 tank. Ludwig and Dreyer [22] experimentally investigated the thermodynamic phenomena of the active-pressurization process in a cryogenic propellant tank. The related results have given some valuable guidance for engineering design and application. Fu et al. [23] numerically studied the influence of transverse ribs on self-pressurization process in a LH_2 tank. Thereafter, Fu et al. [24] researched the self-pressurization of a LH_2 tank in microgravity. Moreover, the corresponding tank pressurization and fluid temperature stratification were also investigated by Liu et al. [25–27].

In brief, most of investigators have conducted lots of researches on cryogenic tank pressurization and fluid temperature distributions, some valuable conclusions were arrived as well. However, the previous research is mainly focus on pressurization in smooth tank, there are few documents considering the baffles' effects on tank thermodynamic performance. In the present paper, CFD technique is used to research the pressurization process of cryogenic LH_2 tanks. Validated by the flight experimental data [28], a calibrated CFD model is adopted to investigate the thermal physical process in LH_2 tank with baffles. The influences of baffles on pressure increase, thermal stratification and wall heat transfer coefficient are estimated respectively. The present work is of significance for optimization design of cryogenic storage tanks.

2. CFD model

2.1. Physical object

The Saturn IB AS-203 LH_2 tank [1,28] is selected to be the research object. As Fig. 1 shows, the cavity of the present LH_2 tank is defined by a cylindrical shell with a concave ellipsoidal forward dome and a convex aft bulkhead. The slosh baffles are conical in shape and are attached at sidewall. The baffles in the model are seals against the wall with no flow through area. In the present simulation, the tank is filled with a level of 32% by volume with the liquid level just below slosh baffle 1. The initial conditions and tank parameters are listed in Table 1. Note that the present flight experiment was conducted in 1966, less information has been given about the structure and materials of the slosh baffles. The thermal boundary of slosh baffles could not be obtained as well. As many investigators [1,28,29] adopted this flight AS-203 experiment to validate the numerical calculation model and treated the boundary of slosh baffles as adiabatic, the same adiabatic treatment is also adopted on the slosh baffles in the present study.

Differing from the previous analysis [29], the assumption of constant wall heating is not reasonable. Heat transfer character-