Development of thermal stratification in a rotating cryogenic liquid hydrogen tank

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Abstract

Accurate prediction of thermal stratification in cryogenic propellant container is of significance to space missions. In the present paper, a thermal stratification model, considering phase change transmission at the liquid vapor interface, is developed and adopted to investigate the pressurization performance and stratification development in a rotating liquid hydrogen tank. Heat exchange associated with viscous flow is particularly considered to ensure that the flow and heat exchange are continuous when $Ra$ is in the range of $10^2$ to $10^{15}$. The calculated results show that the stratified layer in a rotating tank develops more slowly than in a non-rotating tank. With the rotation rate increasing from 1.0 deg/s to 4.0 deg/s, the required time of stratification developing fully has increased approximately 1.82 times. The speed of the stratification development with aspect ratio of 0.5 is approximately 2.27 times faster than that with aspect ratio of 1.0. The fluid stratification under different gravity levels express different developing speed, slower developing speed is observed at the micro-gravities. More than 10 times consumed time needs to reach fully field stratification at $10^{-3}g_0$ comparing at $1g_0$. Meanwhile the ullage pressure increases faster with the greater gravity level. It is also found that the liquid–vapor phase change has great influence on the tank pressure. The deviation of ullage pressure increased reaches by 18.27% with the consideration of phase change. It is suggested that phase change effect should be accounted for in the prediction of thermal stratification and ullage pressure of liquid hydrogen tank.

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Introduction

Thermal stratification should be taken into consideration in the design of cryogenic tank since it may exert a remarkable influence on the pressurization rate. Therefore, to maintain the successful operation of space missions, it is necessary to make fully understanding of thermal stratification phenomena.

Many investigators have conducted researches on thermal stratification, and the approaches include experimental study, theoretical derivation and numerical simulation. Experimental investigations of liquid hydrogen thermal stratification have been conducted by Tatom et al. [1], Barnett
et al. [2], and Schmidt et al. [3]. Thermal stratification developed under the effects of sidewall heating and bottom wall heating have been investigated by Joseph [4], Vliet [5], and Fan et al. [6]. A number of theoretical derivations have been carried out to predict the thermal stratification phenomena in cryogenic liquid. Bailey et al. [7] developed an analytical algorithm to predict the stratification phenomenon and compared the results with experimental data. Tellep and Happer [8] analyzed the transient stratification in a closed cryogenic container by assuming the dimensionless temperature profile in the stratified layer was not varying with time. Vliet et al. [9] developed a stratified layer flow model to numerically simulate the liquid temperature stratification, and Bourgarel et al. [10] built a theoretical model according to the stratification similitude laws and validated by experimental data of a subscale model.

With the boundary layer phenomena being considered, Robbins and Rogers [11] developed a computer program to predict thermal stratification in variable conditions, Yu et al. [12] adopted an integral method to research the transient free convective boundary layer along the concave surface, Oliveira et al. [13] developed a thermal stratification model to handle boundary layer transition and tank rotation, and Daigle et al. [14] improved one reduced dynamic model to describe the thermal stratification with considering temperature and velocity boundary layers in both ullage and liquid regions in the cryogenic tank implemented in MATLAB. Different from the smooth wall flow correlations, Khurana et al. [15], Justin et al. [16,17] and Faure et al. [18] had experimentally researched the effect of isogrid-type obstructions on thermal stratification. Despite of the experimental research on liquid hydrogen stratification, some investigators have conducted a lot of numerically simulations. Shankar and Sherif [19] developed a numerical model to study the thermal stratification in a storage dewar under both normal and reduced gravity conditions. Kumar et al. [20] numerically researched the influence of tank aspect ratio on thermal stratification with considering the surface evaporation. Walter and Ramaswamy [21] numerically investigated the thermal stratification in a rectangular tank and a hemispherical tank, considering the effect of convection. Fu et al. [22] adopted the VOF method, considering phase change in the interface, to numerically investigate the self-pressurization process and stratification under different rib spacing-to-height ratios, and different rib material and shapes. Except for liquid hydrogen, thermal stratifications of liquid nitrogen, liquid oxygen, and LNG or PLG had been investigated by Barnett [23], Yu et al. [12], Ren et al. [24], and Seo and Jeong [25].

The previous studies have mainly concentrated in the liquid region and considered a lot of influence factors, but ignored the viscous flow in laminar and change of pressure increase, thermal property change, interface transmission effect and conversion from turbulence to laminar flow in the growing process of thermal stratification. As the cryogenic tank will experience orbital transfer, slow rotation and attitude adjustment during the coast period, developments of fluid stratification in the above conditions needs to give enough attentions. So far, it is found that only Oliveira [13] and his team have done a preliminary study on thermal stratification in the rotating tank. Based on the previous research, the present paper is specially aimed at investigating thermal stratification in a rotating cryogenic liquid hydrogen tank. Heat and mass transfer mechanisms are accounted for in detail. Meanwhile the change of fluid thermal physical property and the conversion of layer flow from turbulence to laminar are given full consideration firstly. With the developed thermal stratification model, the influences of spin rate, aspect ratio and gravity level on thermal stratification are respectively investigated. The present work develops and enriches the thermal stratification model in rotation tanks, broadens and deepens the research field in cryogenic fluid thermal stratification. Moreover, some valuable conclusions are of significance to the design of propellant tank and its affiliated systems.

### Thermal stratification model

#### Formation of thermal stratification

Fig. 1 displays the development of liquid thermal stratification in a cylindrical liquid hydrogen tank. Heat transfer through the tank wall creates a free convection boundary layer along the tank interior surface. The fluid within the boundary layer is heated and consequently its density decreases due to the temperature variation. Under the effect of upward buoyancy force, warm fluid moves up and finally out of the boundary layer and then enters the central region. Simultaneously the cold fluid is supplemented by moving into the boundary layers in the bottom portion of the tank. With this process proceeding, warm liquid will be taken to the bulk central region and accumulated there, providing a warmer liquid layer along the axial direction, which is named as thermal stratification. The thickness of stratified layer increases as the input heat continuously transferred into the tank.

In the present paper, a cylinder cryogenic tank, as shown in Fig. 1, is selected as the research objective to conduct the thermal stratification analysis. The main parameters in this model are listed in Table 1.

![Fig. 1 – Schematic of thermal stratification phenomena in cryogenic tank.](image-url)