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CFD Analysis on Heat Leakage, Self-Pressurization in Liquid Hydrogen Storage Tank

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Extended Abstract

The world is currently undergoing a transition from fossil fuels to reduce greenhouse gas emissions and combat climate change. As part of this transition, alternative fuels are being explored, and one promising option is liquid hydrogen (LH_2)[1]. Hydrogen gas can be liquified by cooling it to about 20 K (-253 °C) under atmospheric pressure. However, the hydrogen will inevitably evaporate due to the temperature differential between the ambient air and the liquid hydrogen that is being stored. The resultant vapor from the evaporation process is frequently referred to as boil-off gas (BOG). Self-pressurization is a process whereby the storage tank's pressure rises as a result of the production of BOG. The outcome is the loss of valuable hydrogen because the tank must be vented to release the excess pressure into the atmosphere via a relief valve. The rate of BOG formation is influenced by factors such as the tank's insulation quality and its surface-to-volume ratio. Moreover, the heat leakage causes a rapid temperature increase in the vapor than in the liquid, primarily due to the; vapor's higher thermal diffusivity. As a result, there is a temperature difference inside the top layer of the liquid phase due to heat conduction that occurs at the interface between the vapor and liquid phases. The result is thermal stratification, in which the interface temperature is greater than that of the bulk liquid. The current study investigates upon two major important aspects that are crucial for industrial application of LH_2 tank i.e., heat leakage to the tank from the environment and self-pressure estimation of the tank. In first part, the heat leakage to a 2.5-ton LH_2 tank is computed using a computational fluid dynamics (CFD) model, which is solved using a commercial software i.e., ANSYS-CFX. In the computational model inner/outer vessel, vacuum and insulation domains are modelled for the accurate predication of heat leakage to the LH_2. The heat transfer simulations for the tank were performed with different values of thermal conductivity for insulation ranging from 0.02 mW/mK to 0.05 mW/mK. Furthermore, the heat transfer data is utilized in self-pressurization estimation of LH_2 tank. Self-pressurization of LH_2 tank is computed using a time-dependent thermodynamic model. The results of the developed thermodynamic model were validated with NASA's experimental data [2]. The analysis of the data reveals an interesting trend: as the thermal conductivity of the multilayer insulation (MLI) increases from 0.02 mW/mK to 0.5 mW/mK, there is a noticeable increase in the heat leakage to the tank. Specifically, the heat leakage increases by approximately 29.4% at the corresponding thermal conductivity values. Furthermore, the results showed that the self-pressurization of the LH_2 tank could take anywhere from 7 to 10.5 days, depending on the best and worst-case scenarios. Moreover, the study of boil-off gas formation revealed the importance of insulation quality and surface-to-volume ratio. Even with the worst insulation quality (0.05 mW/mK), the daily boil-off mass formation for a 2.5-ton LH_2 tank was only 0.03%. These findings can provide important information regarding the safe transportation of liquid hydrogen (LH_2) via cryogenic storage tanks.

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[2] M. E. M. Stewart and J. P. Moder, "Self-Pressurization of a Flightweight, Liquid Hydrogen Tank: Simulation and Comparison with Experiments Figure 1: Cryogenic hydrogen tank without MLI insulation. From NASA TN D-8320".