Cryogenics 72 (2015) 161–171

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Performance analysis of no-vent fill process for liquid hydrogen tank in terrestrial and on-orbit environments

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ARTICLE INFO

Article history:
Received 11 June 2015
Received in revised form 10 September 2015
Accepted 5 October 2015
Available online 14 October 2015

Keywords:
No-vent fill
Liquid hydrogen
Launch vehicle
Orbital depot
Heat transfer

ABSTRACT

Two finite difference computer models, aiming at the process predictions of no-vent fill in normal gravity and microgravity environments respectively, are developed to investigate the filling performance in a liquid hydrogen (LH_2) tank. In the normal gravity case model, the tank/fluid system is divided into five control volume including ullage, bulk liquid, gas–liquid interface, ullage-adjacent wall, and liquid-adjacent wall. In the microgravity case model, vapor–liquid thermal equilibrium state is maintained throughout the process, and only two nodes representing fluid and wall regions are applied. To capture the liquid–wall heat transfer accurately, a series of heat transfer mechanisms are considered and modeled successively, including film boiling, transition boiling, nucleate boiling and liquid natural convection. The two models are validated by comparing their prediction with experimental data, which shows good agreement. Then the two models are used to investigate the performance of no-vent fill in different conditions and several conclusions are obtained. It shows that in the normal gravity environment the no-vent fill experiences a continuous pressure rise during the whole process and the maximum pressure occurs at the end of the operation, while the maximum pressure of the microgravity case occurs at the beginning stage of the process. Moreover, it seems that increasing inlet mass flux has an apparent influence on the pressure evolution of no-vent fill process in normal gravity but a little influence in microgravity. The larger initial wall temperature brings about more significant liquid evaporation during the filling operation, and then causes higher pressure evolution, no matter the filling process occurs under normal gravity or microgravity conditions. Reducing inlet liquid temperature can improve the filling performance in normal gravity, but cannot significantly reduce the maximum pressure in microgravity. The presented work benefits the understanding of the no-vent fill performance and may guide the design of on-orbit no-vent fill system.

1. Introduction

On-orbit fluid management of cryogenic propellants is indispensable for future space activities. One of the critical challenges is filling a propellant tank in microgravity environment. In terrestrial condition, filling a propellant tank is easily achievable since gravity can separate the liquid and gas phases thoroughly inside the tank and a continuous gas-vented method can be adopted to maintain the pressure of the tank within an acceptable range. In microgravity condition, however, the specific positions of liquid and gas phases are difficult to predict. Direct venting of gas may give rise to the discharge of liquid propellant, which may bring about liquid filling failure. In this situation, a no-vent fill concept has been proposed by NASA to successfully fill with cryogenic liquid in microgravity condition. Research on thermal and pressure performance of the on-orbit no-vent fill process is of importance to the design of the storage facilities and space transportation propellant systems.

Due to its potential applicability in space explorations, the problems associated with no-vent fill of cryogenic propellant have been paid close attention. Ground experiments and computational models have been utilized to study the performance of no-vent fill operations. Schmidt et al. [1,2] used Freon-114 as a cryogen simulant medium and conducted experiments using a 1.9 m^3 cylinder tank to reveal some basic issues of no-vent fill. It was found that liquid injection through top structure exhibited better performance than through bottom method. Moran et al. [3–6] presented results of no-vent fill tests of liquid nitrogen (LN_2) and liquid hydrogen in 34 L and 140 L stainless steel tanks, and evaluated

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http://dx.doi.org/10.1016/j.cryogenics.2015.10.001
0011-2275/

Nomenclature

c_p	specific heat, J/(kg K)
g	gravitational acceleration, m/s^2
g_0	terrestrial gravitational acceleration, m/s^2
Gr	Grashof number
h	specific enthalpy, J/kg
h_{fg}	latent heat, J/kg
L	characteristic length, m
m	mass, kg
$\dot{m}$	mass transfer rate, kg/s
P	pressure, Pa
Pr	Prandtl number
q	heat flux, W/m^2
Q_{gi}	gas-interface heat transfer rate, W
Q_{gw}	gas–wall heat transfer rate, W
Q_{li}	liquid-interface heat transfer rate, W
Q_{lw}	liquid–wall heat transfer rate, W
t	time, s
ΔT	wall superheating, K
u	specific internal energy, J/kg
V	volume, m^3
V_l	liquid volume, m^3
V_0	tank total volume, m^3

Greek symbols

α	heat transfer coefficient, W/(m^2 K)
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

CHF	Critical Heat Flux
g	gas
i	interface
in	inlet
l	liquid
L	Leidenfrost point
ONB	Onset of Nucleate Boiling
sat	saturation
w	wall

the effects of several factors on filling performance, including inlet liquid temperature, inlet mass flux, initial wall temperature, and liquid injection techniques. It showed that 90% fill level could be achieved for nitrogen and hydrogen tests with the initial wall temperature as high as 167 K and 56 K, respectively. For the tests in the 34 L tank, three liquid injection techniques were used, namely top spray, upward pipe discharge, and bottom diffuser. The test results indicated that the top spray was the most efficient method. For the tests in the 140 L tank, the top spray and spray bar were considered and these results again showed that the top spray produced a better performance under the normal gravity condition. Chato [7] reported the results of a series of no-vent fill tests in a 2.0 m^3 LH_2 tank, in which 10 of the tests with a bottom orifice inlet and 12 with a spray bar inlet. Several parameters were investigated, including inlet saturation pressure, transfer pressure, and initial wall temperature. The results concluded that the top fill method was more effective since it could enhance ullage collapse and promote condensation during the process. Moreover, Taylor and Chato [8,9] reported experiments of no-vent fill on a large hydrogen tank with a volume of 4.96 m^3, and two inlet structures consisting of top spray and bottom spray were adopted. The results showed that 94% liquid fill level could be achieved even in the case with high initial wall temperature of 126 K. By summarizing and analyzing the experimental results obtained at Lewis Research Center, Talyer et al. [10] demonstrated that the magnitude of the maximum tank pressure for the no-vent fill process dependents on the inlet liquid temperature, the inlet mass flux and the initial wall temperature. Wang et al. [11] conducted an experiment to compare the performance of vented and no-vent fills. A 180 L LN_2 tank with top spray, top nozzle and bottom nozzle inlet structures were applied. It was found that the vented fill had two regions of pressure change while the no-vent fill experienced three distinguishable stages. The effect of tank structure on the no-vent fill performance was also considered by Wang et al. [12]. The results showed that horizontal tanks performed better than vertical ones under the same operational condition. Flachbart et al. [13] performed an experimental investigation to evaluate the concept of rapid chill/fill of a LH_2 tank in an ambient environment within 5 min. In the large cylindrical tank of 18 m^3, a spray bar was used to chill down the tank wall and to fill the tank. The experimental results revealed that the residual energy remained in the tank wall was too high to allow vent valve closure within the short operation time, and severe boiling heat transfer could be observed in the region between accumulated liquid and tank wall.

Besides the ground experimental investigations, a series of computer programs have been developed to predict the thermodynamic performance of no-vent fill at different conditions. Gille and Marietta [14] used the Cryogenic Systems Analysis Model (CSAM) computer program to simulate the thermodynamics and heat transfer in a no-vent tank during the filling process. The results indicated that the fluid properties and the tank size had significant influence on the performance of no-vent transfer. Chato [15,16] developed a NVFILL computer model to predict the performance of no-vent fill process. The key assumption was that all of the incoming liquid vaporized until the wall temperature matched the temperature of the incoming liquid. This model separated the filling process into two stages. In the first stage, liquid flashing and boiling were characterized and an equilibrium energy balance between the hot wall and the incoming liquid was modeled. In the second stage, the pressure evolution was primarily affected by the condensation and compression of vapor phase, and the tank region was divided into gas, liquid, and interface nodes to better represent the thermodynamic characteristics. Successively, Taylor and Chato [17] modified the original model. In the new model, the partial vaporization of the incoming liquid and the parasitic heat leak to the accumulated bulk liquid were considered. Moreover, Chato [15] mentioned that when using NVFILL to model the on-orbit cases, only wall–liquid heat transfer was considered, and the wall–gas heat transfer could be ignored. Vaughan and Schmidt [18] developed a finite difference computer model, named FILL, to predict the no-vent fill performance in 1-g environment. This model separated the tank/fluid system into seven distinct control volumes of nodes, including ullage, bulk liquid, ullage/liquid interface layer, ullage-adjacent tank wall, liquid-adjacent tank wall, and insulation surrounding each tank wall section. Ground test data with Freon-114 were used to validate the model, and the comparisons showed the model had good predictability in 1-g environment. Fite [19] also performed a finite difference lumped analysis. In this model, the tank system was divided into four lumps: vapor, liquid, vapor-adjacent tank wall, and liquid-adjacent tank wall. The predicted results showed very good agreement with experimental data for the cases with a bottom inlet.