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Prediction of pool boiling heat transfer for hydrogen in microgravity

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ABSTRACT

Pool boiling heat transfer of hydrogen frequently occurs in microgravity. Understanding the heat transfer characteristics of liquid hydrogen (LH_2) in low gravity condition is of importance to its space application. In this paper, an existing gravity scaling analysis, proposed based on the experimental data of non-cryogenic fluids, is assessed using the boiling heat transfer data of hydrogen under different gravities. Validation study shows that this scaling analysis is also acceptable in predicting the nucleate boiling heat transfer of hydrogen in low gravity condition. Through this analysis, the heat flux at any gravity level can be obtained if the data in the similar condition are available at a reference gravity. Moreover, another scaling analysis aiming at the film boiling regime is proposed, and its predictive accuracy is validated by comparing with the hydrogen experimental data. The comparison study shows that an excellent agreement is obtained and the deviation is within 15%. Furthermore, the hydrogen boiling curves under normal gravity and microgravity conditions are constructed. It exhibits that microgravity yields lower heat flux throughout the overall boiling range, and the influence of gravity on heat flux is most significant in the film boiling regime. Generally, the validated and the proposed scaling analysis can provide researchers with reliable mathematical tools to perform a preliminary investigation of hydrogen heat transfer system in microgravity.

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1. Introduction

Liquid hydrogen, due to its excellent specific impulse when reacting with oxidant, has been widely used in aerospace field for over fifty years, and will still play a significant role in the future space activities. To implement the deep-space exploration to moon and Mars, some basic on-orbit fluid management technologies need to be developed, including long-term on-orbital storage of LH_2, on-orbital pressure control, propellant depot and refuel in microgravity, and so forth. Throughout the whole on-orbital process of LH_2, numerous pool boiling heat transfer could be encountered. An understanding of hydrogen boiling heat transfer in microgravity is of importance to the reliable design of these systems and their successful operation.

As a popular research concern, the problems associated with pool boiling heat transfer have been paid close attention for over a century, and a large number of data have been accumulated from many boiling experiments which were usually conducted under normal gravity condition. Relatively, the body of literature on low-gravity pool boiling phenomena is small due to the challenges of high cost, hardware complexity and short-duration of the experimental system, especially for cryogenic liquids. Some studies had been performed to reveal the relationship between microgravity heat transfer and normal gravity heat transfer. Straub [1] and Marco [2] pointed out that the heat transfer coefficients under different gravities satisfied a power law relation of $\alpha_a/\alpha_g = (a/g)^n$. Chung [3] conducted boiling experiments using FC-72 as the working fluid and using a 2.1 s falling tower to create microgravity environment. The results revealed that the microgravity heat transfer was lower than the corresponding heat transfer in normal gravity. Based on the platforms of Chinese recoverable satellites RS-22 and SJ-8, Zhao et al. [4] conducted temperature-controlled pool boiling experiments under microgravity condition and the level of residual gravity was estimated in the order of $10^{-3}g$–$10^{-5}g$. Comparing with the situations in normal gravity it was found that the nucleate boiling heat transfer in microgravity was slightly enhanced, while about 20–40% decrease of heat flux was observed in the transition boiling regime. The CHF in microgravity was only one third of the value in terrestrial condition. Lee et al. [5] presented the results of the microgravity pool boiling experiments which using R-113 as the working fluid. Comparison study showed that both of CHF and minimum heat flux (MHF) reduced considerably in microgravity, while the onset-boiling temperature was found

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Nomenclatures

a	acceleration, m/s^2
c_p	specific heat, J/(kg K)
g	normal gravity, g = 9.81 m/s^2
Gr	Grashof number
h_{fg}	latent heat of vaporization, J/kg
L_c	capillary length, m
L_h	characteristic length of heater size, m
m_{BDB}	power exponent of buoyancy dominated boiling
m_{SDB}	power exponent of surface tension dominated boiling
Nu	Nusselt number
P	pressure, Pa
P_c	critical pressure, P_c = 1.2858 MPa for hydrogen
Pr	Prandtl number
q	heat flux, W/m^2
q_{nb}	heat flux in nucleate boiling regime, W/m^2
T	temperature, K
T^*	dimensionless temperature
ΔT	wall superheat, K
ΔT_l	difference between wall temperature and liquid temperature, K

Greek symbols

α	heat transfer coefficient, W/(m^2 K)
β	volume expansion ratio, K^{-1}
λ	thermal conductivity, W/(m K)
μ	dynamic coefficient of viscosity, Pa s
ν	kinematic coefficient of viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

a	acceleration condition
BDB	buoyancy dominated boiling
CHF	critical heat flux
g	normal gravity condition
l	liquid phase
L	Leidenfrost
ONB	onset of nucleate boiling
ref	reference
sat	saturation
sub	subcooling
SDB	surface tension dominated boiling
tran	transition between BDB and SDB regimes
v	vapor phase

independent, or at least, dependent much weakly on gravity. Kannengieser et al. [6] and Henry and Kim [7] presented the microgravity boiling experiments based on a parabolic flight, and the experiments showed that gravity had a relatively weak influence on the nucleate boiling heat transfer but strongly affected the value of CHF. Konishi and Mudawar [8] reviewed the current research on heat transfer in reduced gravity, and 24 literatures on microgravity pool boiling experiments were summarized. On the basis of a large number of experimental boiling heat transfer data covering different gravity levels, Raj et al. [9–10] constructed a mathematical relation to link the heat fluxes under different gravity conditions by which heat flux in any gravity condition could be solved if the data at a reference gravity had been known.

Some researchers concerned the bubble dynamic behavior as well as its departure diameter in microgravity by which the heat transfer characteristics of microgravity boiling could be interpreted. Xue et al. [11] indicated that the value of heat flux had a significant influence on the microgravity bubble behavior. At low heat flux, vapor bubble increased in size but little coalescence occurred among bubbles. At high heat flux, a coalesced large bubble was produced quickly and almost covered the heater surface. Lee [12] applied force balance to analyze bubble departure process in microgravity. The results showed that different forces dominated the bubble behavior at different geometry heater surfaces. Dhir et al. [13] analyzed the experimental bubble behavior data under different gravity conditions and indicated that the bubble departure diameter and bubble growth period were the functions of $a^{-1/2}$ and a^{-1}, respectively. Zhao et al. [14] found that there were three critical bubble regimes in microgravity, including tiny bubble with a diameter of about 0.1 mm, bigger bubble and biggest bubble with a diameter of the order of 10 mm, while only the tiny bubble could be observed in normal gravity. Kim et al. [15] found that a large primary bubble almost covered the whole heater surface in low-g environment, which had the dominated effect on the boiling heat transfer.

Motivated by the aerospace exploration requirement, the pool boiling heat transfer of hydrogen had also been investigated continuously in the past sixty years. Several ground boiling experiments were performed and heat transfer correlations aiming at different boiling regimes were proposed. Class et al. [16] presented the hydrogen boiling experimental data obtained from a relatively large flat surface under a variety of conditions. Brentari et al. [17] conducted a study to provide an orderly examination of information relative to boiling heat transfer for four cryogenic fluids including nitrogen, oxygen, hydrogen, and helium. For the hydrogen pool boiling, experimental data for eight sets of nucleate boiling and three sets of film boiling were used to assess the predictive accuracy of several famous correlations. Bewilogua et al. [18] investigated the dependence of heat transfer of LH_2 on pressure experimentally. The results showed that the maximum of CHF was found at about 0.35 P_c. Shirai et al. [19] performed an experiment to investigate the heat transfer from a flat plate facing upward immersed in LH_2 pool. The experimental data showed that CHF of hydrogen increased with the increase of pressure up to about 0.3 MPa and then decreased with further pressure increase. Tatsumoto et al. [20] presented the experimental studies on heat transfer from a horizontal wire immersed in liquid hydrogen, and the results showed that the CHF was highest in the vicinity of 0.4 MPa. Owing to the requirement of cryogenic propellant application in microgravity, the boiling heat transfer of cryogenic fluid under low-g environment had also been investigated, and experimental platforms based on short-time falling tower or high-intensity magnetic field were applied to provide the low-g condition in ground environment. Graham et al. [21] found that for pool boiling hydrogen, the gravity level influenced the incipience of nucleate boiling but did not affect the established nucleate boiling. Also, the film boiling heat transfer was affected by the gravity level. Lewi et al. [22] presented the experimental investigation on pool boiling of nitrogen under low-g environment. Using a falling tower, the gravity level of 0.002g was realized. Merte [23] performed the boiling heat transfer of LH_2 under different gravity conditions. In this study, falling tower was used to supply low-g environment and temperature-controlled heater was designed specially to obtain the complete boiling curve of hydrogen. To

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