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Correlations for calculating heat transfer of hydrogen pool boiling

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ABSTRACT

Understanding the heat transfer characteristics of hydrogen pool boiling as well as constructing reliable correlations to guide the boiling heat transfer analysis is of significance to the applications of liquid hydrogen (LH_2). In the present paper, the available hydrogen experimental data in literature are summarized and analyzed. Based on these data, several existing correlations aiming at different boiling regimes are evaluated or modified in order to realize the quantitative analysis of hydrogen boiling heat transfer. After sufficient comparison studies, several improved correlations for nucleate boiling, critical heat flux (CHF) and minimum heat flux (MHF) are proposed. Moreover, a complete set of correlations for hydrogen boiling heat transfer are summarized and subsequently a predicted hydrogen boiling curve is constructed. The results show that heat flux in the nucleate boiling regime is approximately a function of $\Delta T^{2.5}$. For the calculation of hydrogen film boiling, Breen & Westwater correlation seems to be appropriate for revealing the heat transfer characteristics no matter what heater geometry is used. For the hydrogen boiling under 0.1 MPa condition, heat fluxes at onset of nucleate boiling (ONB), CHF and MHF are in the order of 10 W/m^2, 10^5 W/m^2 and 10^3 W/m^2, respectively, and the corresponding wall superheats are approximately 0.1 K, 3 K and 4 K. In addition, pressure effect on hydrogen boiling heat transfer is investigated, and it shows pressure has a significant influence on MHF while a little effect on the heat fluxes in liquid natural convection and film boiling regimes. CHF of hydrogen increases with the increase of system pressure firstly and then decreased with further pressure increase. The maximum of CHF locates at about $P/P_c = 0.35$. Generally, the present study is beneficial to understand the boiling heat transfer characteristics of hydrogen, and the summarized correlations could provide researchers with reliable mathematical tools to conduct the boiling heat transfer analysis of hydrogen systems.

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Introduction

As an excellent propellant, LH_2 has been widely used in aerospace field ever since the beginning of human space age, and will still play an important role in the future space activities. Moreover, hydrogen energy will occupy a prominent position in the future energy consumption structure. It was reported that the proportion of hydrogen to the total energy consumption in Japan will reach 20% by 2035 and then 40% by 2050 [1,2]. Besides the effect as a fuel, LH_2 can also be used as a coolant in various applications such as large-scale superconducting magnet and cold neutron moderator material for a spallation neutron source [3]. Throughout the whole hydrogen chain including its production, transportation and utilization, numerous pool boiling heat transfer phenomena could be encountered. Understanding the heat transfer characteristics of hydrogen pool boiling and constructing predictive correlations to conduct quantitative analysis are of significance to the reliable design and successful operation of LH_2 system.

In the flourishing period of aerospace activities in 1950s and 60s, a great deal of effort had been devoted to the associated fundamental and technological researches, and LH_2 boiling heat transfer was one of them. Some researchers conducted experimental investigation to obtain the boiling heat transfer data under different conditions, and also a series of correlations aiming at different boiling regimes were proposed to perform preliminary design of hydrogen heat transfer system. Class et al. [4] presented the experimental data obtained for the heat transfer of boiling hydrogen from a relatively large flat surface under a variety of conditions, and the hydrogen experimental data in previous literature were also analyzed. The results showed that these heat transfer data were not in close agreement, which might indicate that obtaining boiling curve of hydrogen faced great challenge due to lack of reliable experimental data. Graham et al. [5] investigated the influence of gravity on pool boiling heat transfer of hydrogen under subcritical and supercritical pressures. The results showed that acceleration had a certain influence on the incipience of nucleate boiling but did not remarkably affect the established nucleate boiling. Seader et al. [6] conducted an extensive survey on heat transfer to boiling cryogenic fluids including hydrogen, and the reviews of available theoretical approaches to predict boiling phenomena as well as experimental data were summarized. Brentari et al. [7] conducted a systematic study on the 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 accuracy of several famous correlations. The results suggested that in the nucleate boiling regime, the nucleate heat transfer correlation and the maximum heat flux correlation proposed by Kutateladze [8] could be applied. In the film boiling regime, Breen and Westwater correlation [9] was recommended to calculate the stable film boiling heat transfer, and Zuber correlation [10] was suggested to predict MHF. Bewilogua et al. [11] investigated the dependence of cryogenic boiling heat transfer on pressure, where experiments on a horizontal plane surface immersed in liquid helium, LH_2, and liquid nitrogen (LN_2) in the pressure range of $0.03 < P/P_c < 0.9$ were considered. The results showed that the maximum of CHF was found at about 0.35 P_c, and Kutateladze correlation could be used to predict CHF of hydrogen. Louie and Steward [12] conducted an experimental investigation to reveal the transient heat transfer characteristic of LH_2 pool boiling. The results illustrated that CHF of hydrogen was approximately 80 kW/m^2. Merte [13] presented the experimental results of incipient and steady boiling of cryogenic liquids, both LN_2 and LH_2, under reduced gravity conditions. The influence of several parameters, including fluid used, heater surface temperature, heater geometry, heater orientation, and gravity condition, on boiling heat transfer were analyzed.

In recent years, motivated by the needs of high-temperature superconductivity and aerospace explorations, the problems associated with heat transfer of hydrogen boiling had been paid attention once again, and several sets of experimental investigations had been conducted to reveal the heat transfer characteristics of hydrogen under various conditions. Shirai et al. [14] applied an experimental approach to investigate the heat transfer from a flat plate facing upward immersed in LH_2 pool. The flat plate heater was 10 mm in width, 100 mm in length and 0.1 mm in thickness, and the heat transfer was obtained for the pressures from atmospheric pressure to 1.1 MPa. The experimental data showed that the maximum CHF of hydrogen locates at about 0.3 MPa. Subsequently, Shiotsu et al. [15] studied the transient heat transfer characteristics of LH_2 pool boiling under saturated and subcooled conditions, and a flat plate heater with 5 mm in width, 60 mm in length and 0.5 mm in thickness was adopted. The results indicated that transient CHF was higher for higher subcooling conditions. Tatsumoto et al. [16] presented the experimental studies on heat transfer from a horizontal wire immersed in both liquid and supercritical hydrogen. The wire test heater was made of PtCo with a length of 101.8 mm and a diameter of 1.2 mm. The results showed that heat transfer coefficient in nucleate boiling regime was higher for higher pressure condition, and CHF was highest in the vicinity of 0.4 MPa which could be expressed by Kutateladze correlation. To obtain the character of hydrogen boiling heat transfer in low-gravity condition, Garcia [17] placed a horizontal disk heater with a diameter of 11.28 mm into a huge magnetic field, and different gravities were achieved by adjusting the magnetic field intensity. The experimental results showed that under low gravity conditions, both of nucleate boiling and film boiling heat transfer were lower than that in normal gravity. Wang et al. [18] proposed a scaling analysis to link the LH_2 boiling heat transfers under different gravities. Through this analysis, the heat flux at any gravity level could be obtained if the data in the similar condition were available at reference gravity.

A sufficient precooling operation is usually necessary for the application of cryogenic liquids including LH_2, and different heat transfer mechanisms, including film boiling, transition boiling, and nucleate boiling, dominate the temperature decrease process successively. Existing researches showed that film boiling plays a dominant role in the temperature decrease process. The ratios of temperature decrease occupied by film boiling to the total temperature decrease were approximately 95.5% and 83.3% for LH_2 and LN_2