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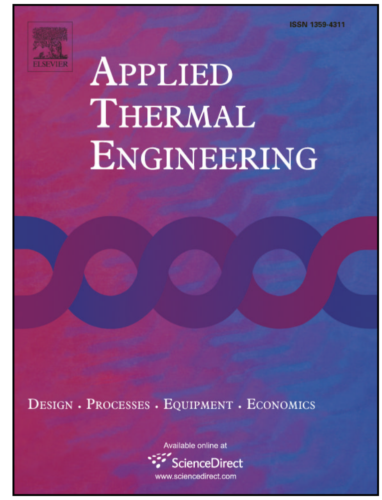

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Experimental study on film condensation characteristics at liquid nitrogen temperatures

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Abstract：

The understanding of cryogenic condensation mechanisms is insufficient mainly due to the difficulties of modeling and direct measurement, especially when the condensate film is in the wavy laminar flow regime. In this work, we designed a condensation testbed to measure the key heat transfer parameters at liquid nitrogen temperatures within a large range of flow regime. It is the first time to extend the cryogenic condensation data to the film Reynolds number (Re_δ) as high as 1151. The applicability of Kutateladze's correlation (Kutateladze, 1963) to cryogenic fluids is verified. Moreover, the condensate flow pattern is collected by a high-speed camera. The obvious large interfacial waves are found to occur after Re_δ reaches 343 and the accompanied disturbances enhance the cryogenic condensation heat transfer significantly. The large interfacial waves are gravity dominated while the small interfacial waves are determined by both surface tension and gravity. A correlation between the dimensionless interfacial wave velocity and Re_δ is further developed with the accuracy of ±20% for 82% of the data. The quantified study on the wavelength, velocity and frequency of the cryogenic interfacial wave will offer the insights of the interfacial instability enhancement mechanism on the cryogenic condensation heat transfer.

Keywords:

Cryogenic condensation; Liquid nitrogen; Heat transfer; Visualization; Interfacial wave

1 Introduction

Cryogenic condensation under the conditions of wavy laminar or turbulent flow is important in many industrial cryogenic systems. The design of the cryogenic equipment such as LNG equipment, air separation unit, helium liquefier and so forth, relies on a deep understanding of the fluid dynamic, heat transfer and mass transport processes during cryogenic condensation. For non-cryogenic fluids [1], several theoretical and empirical correlations have been developed to predict the condensing heat transfer coefficients. Compared to non-cryogenic fluids, cryogenic fluids behave differently with smaller surface tension coefficient, smaller viscosity, smaller latent heat, near zero wetting angle and larger ratio of vapor density to liquid density [2]. These differences in fluids properties lead the physical process of cryogenic condensation to be more intricate, especially in the wavy laminar and turbulent flow area. Because of the difficulties in cryogenic measurements, the experimental data for cryogenic condensation is still lacking and the mechanism of heat and mass transfer has not yet been fully understood. Thus the applicability of non-cryogenic correlations to cryogenic fluids should be carefully examined and the physical mechanisms in cryogenic condensation should be explored, which will yield far reaching benefits to cryogenic industries.

Previous research on cryogenic condensation mainly focused on condensation inside and outside the vertical tubes. The condensate film in these studies was mainly for film Reynolds number (Re_δ) smaller than 500 [1, 3-10]. It was found that the data of nitrogen and oxygen vapor condensation agreed with the predictions of the classical Nusselt theory [3-5, 7, 9] to some extent, however, large discrepancies occurred for hydrogen, deuterium and helium [1, 5, 6, 8, 9] when film subcooling was less than 2 K [1, 5]. Such discrepancies [1, 5] mainly stemmed

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