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Improved Heat Transfer Prediction Methods in Channels for Natural Gas Liquefaction

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Liquefied natural gas (LNG), as a widely available and renewable fuel, can address the growing energy demand and significantly reduce greenhouse gas emissions. In the liquefaction of natural gas, pivotal components such as heat exchangers require reliable methods for predicting heat transfer coefficients. Existing prediction methods are mostly focused on conventional channels with hydraulic diameters larger than 3 mm. However, the condensation and flow pattern transition within the mini channels of compact heat exchangers remain obscure, attributable to the complexity of multi-component condensation in the natural gas liquefaction process. For example, the diffusion coefficient of methane-nitrogen at low temperatures is an order of magnitude lower than that of water-air. Hence it is necessary to further clarify the inhibitory effect of non-condensable gas on heat transfer of LNG. This research simulates the flow condensation of methane with and without nitrogen by adjusting the diffusion terms in the component transport model in horizontal mini channel with a hydraulic diameter of 1 mm. Comparative analyses are conducted with conventional channels with a hydraulic diameter of 3mm.Experimental data validate the proposed model, encompassing mass flow rates ranging from 200 to 600 kg/m2s, pressure conditions from 1 to 3 MPa, and non-condensable gas fractions from 0 to 20%. The findings reveal distinctive characteristics between flow condensation in conventional and mini channels. In annular flow, the distribution of the liquid film in the vertical direction of mini channels is more uniform, with the influence of gravity reduced and the influence of surface tension increased, preventing the condensate from accumulating towards the bottom. The thickness of the liquid film in the horizontal direction is reduced due to increased shear stress, leading to a decrease in thermal resistance. Furthermore, the criteria for transition from laminar to turbulent flow in conventional channels do not apply to mini channels. For flow condensation with non-condensable gas in mini channels, heat transfer coefficients decrease by over 20% at high vapor quality conditions ($x > 0.8$). A diffusion boundary layer exists at the gas-liquid interface, and the local concentration of nitrogen increases due to methane condensation, leading to increased vapor diffusion resistance and reduced mass transfer rate. Additionally, the decrease in methane partial pressure leads to a lower saturation temperature, resulting in a decrease in the driving force for condensation, further inhibiting methane condensation heat transfer. This comprehensive analysis holds significant value for designing compact heat exchangers in natural gas liquefaction processes.

Submitters Country

China

Authors: WANG, Jinglei (Zhejiang University); Mr WANG, Kai (Zhejiang University); Mr QIU, Limin (Zhejiang University); Mr ZHU, Shaolong (Zhejiang University); BAO, Shiran (Zhejiang University); Ms ZHI, Xiaoqing (Zhejiang University)

Presenter: WANG, Jinglei (Zhejiang University)

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