Abstract

Closure models for transient cryogenic quench flow boiling heat transfer prediction are finding significant attention to realize the design of energy-efficient, cost-effective, and reliable cryogenic fluid management systems. To address this demand, improved heat transfer constitutive relations that can support accurate reduced-order thermal-hydraulic lump system models are proposed in this work. In this context, a comprehensive database is created from 115 cryogenic chill-down experiments conducted by eight different groups to consolidate the latest experimental data in this field, covering various fluids such as LH_2, LN_2, LAr, LOX, and LCH_4, several transfer line geometries, and orientations under different gravitational accelerations. Film boiling correlations from the literature are assessed using the collected database, and new flow regime-dependent heat transfer models are proposed. These new correlations demonstrate good prediction performance compared to existing ones with a mean absolute percentage error (MAPE) of less than 29%. Mutual information and conditional mutual information statistical filter algorithms and genetic algorithm-based optimization methods are employed for this purpose. Additionally, constitutive relations for predicting rewetting phenomena during cryogenic quenching in bare tubes are proposed, along with a formulation for the apparent rewetting temperature in cryogenic transfer lines with an inner wall low thermal conductive coating. These new formulations are proposed based on a careful analysis of the importance of several feed line and flow parameters on film boiling crisis and an assessment of the existing 30 formulations in the literature. Finally, the prediction performance of a non-homogeneous feed line chill-down model utilizing the proposed heat transfer constitutive relations is also presented and found to be accurate. Several practical test cases spanning different feed line geometry, wall materials, pipe orientations, cryogens, gravity levels, and inner wall low-thermal conductive coating thicknesses for a wide range of mass flux and pressure conditions are used for the assessment. These closure models are recommended for upgrading the existing thermal-hydraulic codes, developing new codes, and optimizing tasks to achieve higher chill-down efficiency for cryogenic transfer line systems.

Keywords: Cryogen, Flow boiling, Heat transfer coefficient, Heat transfer enhancement, Two-phase flow, Transfer line chill-down.