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Influence of U-bend heterogeneous effects on bubble dynamics and local flow boiling heat transfer in hairpin tubes

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A B S T R A C T

The present study describes a series of flow boiling experiments with R141b in coiled tubes conducted to investigate the local heat transfer enhancement mechanism of U-bends compared with bubbles growing in horizontal straight tubes. The study focuses on two-phase flows with boiling in U-bends of a vertical upward coiled tube of inner diameter 6 mm at mass fluxes of 120.94, 181.41 and 241.88 kg m^{-2} s^{-1} and heat fluxes between 6191 and 13 929 W m^{-2}. The experimental results show that the bubble growth rates in U-bends are 2–4 times faster than those in the downstream horizontal straight tube. The local heat transfer mechanism was analyzed using a transient CFD model with faster bubble growth rates predicted in a U-bend than in a horizontal straight tube. The heterogeneous effects of reheating and thermal non-equilibrium at the tube walls caused by the U-bend structure were found to play critical roles in the two-phase flow and heat transfer, as the main reason for local heat transfer enhancement in bubbly or intermittent flows.

1. Introduction

Typical industrial heat exchangers including boilers, condensers, evaporators or reactors always contain U-bends or similar tube structures to make the system more compact. Unlike single phase flows [1,2], which have been extensively investigated in recent decades, two-phase flows in U-bends are much more complicated and still far from being well understood. Unlike a straight tube, a U-bend has a non-uniform velocity distribution and secondary flows caused by the centrifugal force [3], leading to significant interactions between the liquid and vapor phases, and consequently, altered flow and heat transfer characteristics.

The many applications of two-phase flows with boiling in U-bends require a more comprehensive understanding, which is in fact rather limited in the literature, of the unique heat and mass transfer mechanisms. Although two-phase flows in tubes/channels of various types have been frequently studied by numerous researchers, with flow pattern maps as the most popular tool for predicting the pressure drop and heat transfer of two-phase flows, research on flow boiling mechanisms is relatively rare, especially for U-bends. A large quantity of investigations have been conducted for adiabatic gas-liquid two-phase flows in straight tubes, with the well-known flow pattern map proposed by Taitel and Dukler [4]. Traditional definitions of flow regimes for a horizontal round tube include bubbly flow, plug flow, slug flow, wavy flow and annular flow [5], with some other flow regimes also widely adopted, such as stratified flow, intermittent flow, and so on. Recently, researchers have begun to extend flow pattern investigations into other specific areas. Thome et al. [6–9] conducted a series of studies to develop flow pattern maps for diabatic two-phase flows in small tubes, and found that the flow pattern transitions for two-phase flows with boiling differed significantly from those in adiabatic two-phase flows. Wang et al. [10–14] conducted a series of visual observations to investigate the flow patterns in U-bends of horizontal and vertical tubes. They proposed a flow pattern map for different test section layouts and reported that the 180°-return bend could cause temporal annular flow in its downstream straight tubes.

Although the previous studies as well as others provided important information related to the physical nature of two-phase flows with boiling in U-bends, flow patterns alone are unable to give a full picture of the underlying mechanisms. The heat transfer in U-bends resulting from the flow patterns can in turn influence the flows, so this feedback needs to be carefully considered. Among the few available studies concerning heat transfer during flow boiling in U-bends, Cho and Tae [15,16] reported that tube bends enhanced the heat transfer while increasing the frictional pressure drop. They conducted a series of evaporation and condensation experiments with R-22 and R-407C refrigerant-oil mixtures in a micro-fin tube with U-bends and found that the flows had an annular flow pattern.

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