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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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In their condensation experiments, the heat transfer coefficients were higher in the U-bends than in the straight tubes and the heat transfer coefficients in the downstream straight tube with a length 48 times its diameter were larger by 33% (maximum) than that of the upstream straight tube. In their evaporation experiments, the heat transfer coefficients in the U-bends were also higher than those in the straight tubes with the maximum heat transfer in the middle of the U-bends. The local heat transfer coefficient on the outside curve of the U-bend was larger than on the inside curve. Unfortunately, they did not investigate the heat transfer enhancement mechanism in U-bends. Wen et al. [17] experimentally examined boiling heat transfer of refrigerant R-600a/R-290-oil mixtures in serpentine small-diameter U-tubes. Their experiments covered several flow patterns and showed that the average heat transfer coefficient of serpentine tubes with 2, 4 and 6 bends were 1.05, 1.08 and 1.14 times those of the straight tube, respectively.

Although there is not much evidence, U-bends are believed to enhance the local heat transfer while increasing the pressure drop. Therefore, thermal engineers need a better understanding of the heat transfer enhancement mechanism in U-bends as well as of the associated characteristics, particularly for different flow patterns. In bubbly or intermittent flows, since the U-bends alter the path of the flowing bubbles, the bubble growth process and their interactions with one another in the U-bends are very different from straight tubes. The heterogeneous effects of U-bends can also extend into the downstream straight tubes, greatly influencing the local heat transfer and pressure drop there.

The present study describes a series of visual observations of flow boiling in coiled tubes, with the local flow boiling heat transfer investigated by examining the bubble growth both in horizontal straight tubes and in U-bends. A transient simulation of the bubble growth and the resulting heat transfer using the commercial CFD software FLUENT™ is employed to reveal the heterogeneous effects of U-bends on the local flow boiling heat transfer in bubbly or intermittent flows.

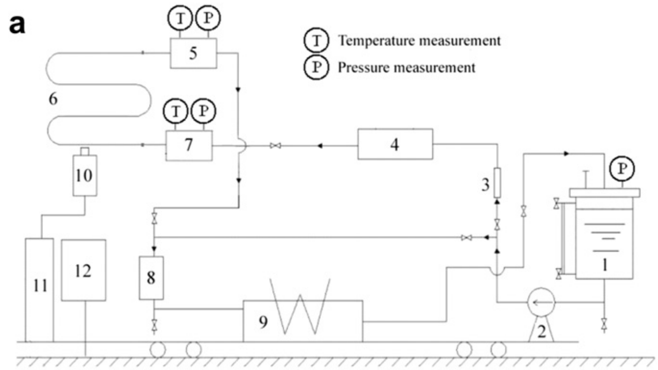
2. Experimental description

2.1. Test facility

The experimental facility is shown in Fig. 1(a) consisted of a liquid tank (1), pump (2), flow meter (3), pre-heater (4), pre-mixing chamber (5), test section (6), post-mixing chamber (7), filter (8), condenser (9), CCD camera (10), personal computer (11), and circuit controller (12). The R141b refrigerant was pumped from the tank into the closed loop, passing through the flow meter, pre-heater, pre-mixing chamber, test section, post-mixing chamber, filter and condenser, and back to the tank. The test section geometry is shown in Fig. 1(b). The test section was made of a smooth quartz glass tube, with inner diameter of 6 mm, and curvature ratio of the centerline of the U-bend to the tube diameter of 4.67 (28 mm/6 mm). The quartz hairpin tube was directly connected with the copper tube by a corrosion resistant sealant. The outer surface of the tube was coated with an optically transparent electric-conducting metal oxide film as the heater. Therefore, a constant heat flux could be obtained by applying DC voltages across each adjacent pair of contacts. The flow boiling in the transparent hairpin tube was observed with a high speed CCD and transferred to a computer for further analyses. A detailed description of the test apparatus was given previously [18].

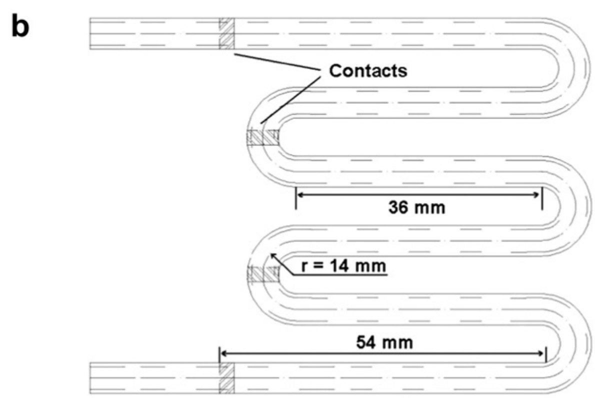
2.2. Testing and measurements

A series of experiments was conducted at different heat fluxes and mass fluxes, with the parameters listed in Table 1. The system was run at first without any heat input until it reached a stable mass flow rate. Then, the DC power was applied to each adjacent pair of contacts to give the desired heat flux. Finally, the flow rate was adjusted to give a stable flow after a period of time and the experimental images were recorded by the high speed CCD. The working liquid inlet temperature was controlled in a range of 300.85–302.35 K, with an average pressure of 0.104–0.110 MPa measured from the test section inlet and outlet. The inlet liquid sub-cooling was varied in a narrow range of 5–6 K to ensure the reliability of the experiment results and further analyses. The measurements included the flow rate using a flow meter with an estimated error of ±2.5% and the test section inlet and outlet temperatures using calibrated Pt-100 resistance temperature detectors. The temperature and pressure measurement uncertainties were estimated to be ±0.37% and ±2.5%, respectively.



Test loop

(1) tank; (2) pump; (3) flow meter; (4) pre-heater; (5) pre-mixing chamber; (6) test section; (7) post-mixing chamber; (8)filter; (9) condenser; (10) CCD; (11) computer; (12) circuit controller.



Test section

Fig. 1. Test facility. (a) Test loop, (b) Test section.

Table 1
Experimental conditions for present study.

Cases	Mass flux/kg m^{-2} s^{-1}	Heat flux/W m^{-2}	Inlet sub-cooling/K
C1-1	241.88	6191	4.9
C1-2	241.88	13 929	5.2
C2-1	181.41	6191	5.1
C2-2	181.41	13 929	6.1
C3-1	120.94	6191	5.1
C3-2	120.94	13 929	5.2