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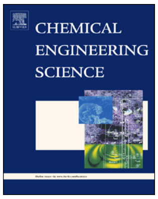

Experimental study on flow patterns for water boiling in horizontal heated tubes

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HIGHLIGHTS

- Six boiling flow patterns are observed in the experiments.
- Influence of variables on evolution and transition of flow patterns are discussed.
- Experimental data are compared with the adiabatic flow pattern maps.
- A new flow pattern map for water boiling is proposed.

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ABSTRACT

An experimental study on flow patterns for water boiling in horizontal heated tubes was conducted to observe the evolution and transition of flow patterns while controlling various parameters, such as heat flux, mass velocity, and tube diameter. Six boiling flow patterns are observed in the test tubes, namely, bubble, plug, slug, wave, stratified, and annular flows, which can be further classified into three types based on their various characteristics: intermittent, stratified-wave, and annular flows. The evolution of flow patterns for water boiling in horizontal heated tubes was significantly affected by heat flux, mass velocity, and tube diameter. The increment of heat flux pushed the starting point of each flow pattern toward the inlet of the tube. Intermittent and stratified-wave flows occurred at lower mass velocity, and annular flow occurred with an increase in mass velocity. Moreover, annular flow easily appeared in tubes with smaller diameters. Since the heat per unit of mass for the full tube length increases with either an increase in heat flux or a decrease in mass velocity and tube diameter, the transition always occurs at smaller vapor qualities with the increase of the heat per unit of mass during the transition of the three flow patterns. The experimental data in this study were compared with the adiabatic flow pattern maps proposed by Baker, Mandhane, Taitel, and Weisman. Based on the experimental data, a new flow pattern map for water boiling was proposed for predicting flow patterns in horizontal heated tubes.

1. Introduction

Two-phase flow boiling is extensively used in different applications because of its higher heat flux capacity compared to single-phase flow. The transfer of boiling heat inside horizontal tubes plays a significant role as a chemical process in nuclear and conventional power plants. At present, tubes with a smaller diameter are extensively used in designing heat exchangers because such tubes can significantly increase heat transfer performance and reduce the charge of the working medium. From this, a considerable reduction in the size of the heat exchanger can be achieved. Unlike with two-phase flow in adiabatic tubes, heat flux affects flow pattern in heated tubes, thus leading to variations in heat transfer and pressure characteristics (Collier, 1982).

Various techniques can be used to study two-phase flow patterns in diabatic and adiabatic channels. Wang et al. (1998) experimentally performed an evaporative two-phase flow pattern for R22 inside a 6.5 mm smooth horizontal tube, and analyzed pressure and heat transfer characteristics for various flow patterns. They concluded that intermittent and stratified-wave flows occur successively when mass velocity is less than 100 $kg/(m^2 s)$. Annular flow occurs when mass velocity is higher than 200 $kg/(m^2 s)$. Two-phase multipliers strongly depend on mass velocity for

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stratified-wave flow patterns, and the heat transfer coefficient increases with an increase in vapor quality for annular flow patterns. Zurcher et al. (2002) improved an evaporative two-phase flow pattern map in horizontal tubes to accurately predict the flow patterns of hydro fluorocarbon refrigerants HFC-134a, HFC-407C, and ammonia. Nayak et al. (2003) developed a mathematical model for studying flow-pattern transition instability and pressure drop in vertical and horizontal pipes. They found that the instability features were the same as those of the Ledinegg-type instability. Wojtan et al. (2005) proposed a new adiabatic two-phase flow pattern map for refrigerants in horizontal tubes. Their flow pattern map had annular-to-dryout and dryout-to-mist flow transition curves. Ghajar (2005) studied the heat transfer characteristics of non-boiling, two-phase air–water flow in vertical, horizontal, and inclined pipes for a variety of flow patterns. They observed six different flow patterns, such as plug, stratified, wavy, slug, dispersed bubble, and annular flows. Cheng et al. (2006) proposed a new boiling flow pattern in horizontal tubes for carbon dioxide and developed a flow boiling heat transfer model in response to nucleate boiling heat transfer in heat exchangers. Fabio and Gherhardt (2012) conducted an experimental study on the two-phase flow patterns and pressure drop of R134a in a tube with an inner diameter of 15.9 mm, with twisted tape inserts. Wang et al. (2012) conducted experimental investigations on gas–liquid two-phase flow regimes in microchannels. They captured four distinctive flow patterns, namely, slug, slug-annular, annular, and parallel-stratified flows, through a digital video recording system. Galvis and Culham (2012) investigated flow patterns, boiling curves, and heat transfer coefficients in single-channel microevaporators, and observed six different flow patterns, namely, bubbly, slug, churn, annular, wavy-annular, and inverted annular flows. Kashid et al. (2012) performed liquid–liquid flow experiments in glass microcapillary equipped with a high-speed camera under various operating conditions. They applied an analytical model based on flow stability analysis to study flow patterns in microcapillaries or microstructured reactors. These studies on flow patterns in horizontal tubes mainly focused on evaporative flow patterns for refrigerants or in microchannels.

However, different thermo-physical properties exist between refrigerants and water. The evolution and transition of flow patterns for water boiling are important in establishing a theoretical model. Therefore, an experimental study on the flow patterns for water boiling in horizontal heated tubes was conducted to observe the evolution and transition of flow patterns at various parameters, such as heat flux, mass velocity, and tube diameter. The experimental data from this study were compared with the adiabatic flow pattern maps proposed by Baker (1954), Mandhane et al. (1954), Taitel and Dukler (1976), and Weisman et al. (1979). Based on the experimental data, a new flow pattern map for water boiling was proposed for predicting flow patterns in horizontal heated tubes. The results of this study can provide significant guidelines for enhancing heat transfer and designing heat exchangers.

2. Experimental apparatus and methods

The schematic diagram of the experimental apparatus used to investigate two-phase flow patterns for water boiling in horizontal heated tubes is depicted in Fig. 1. The test rig consists of a storage water tank, a circulating pump, a preheater, test tubes, a gas–liquid separator, valves, and measurement instruments.

When the circulating pump is in service, the water in the storage tank passes through the preheater and is heated electrically. The water enters the test tubes and displays boiling flow patterns after being heated by an electric heating film coating the outer surface of the test tubes. Regulating the heating powers of the preheater and test tubes can result in various vapor qualities of the fluid in the test tubes. A gas–liquid separator measures the vapor quality of the fluid by weighing residual liquid after vapor is removed.

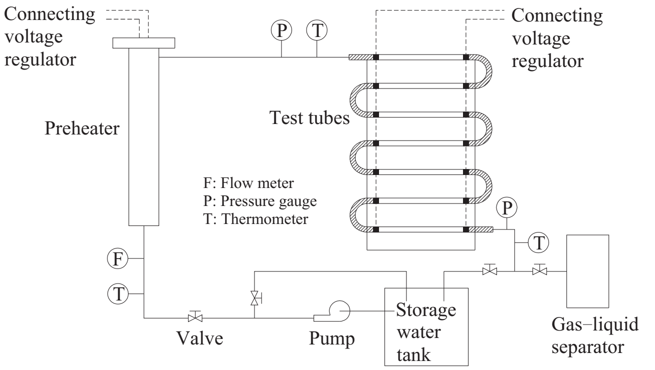

Fig. 1. Schematic diagram of the experimental apparatus.

Fourteen transparent quartz glass tubes with a transparent tin-oxide film coated on the outer surface are used as test tubes to observe two-phase flow patterns for water boiling in horizontal heated tubes. The lengths of the test tube and coating are 25 cm and 23 cm, respectively. Copper electrodes with a length of 1 cm are coated on two sides of the test tubes to connect with the voltage regulator. U-bents made of silicone hose are used to connect the quartz tubes. To reduce the influence of U-bents on flow patterns, the bending radius of U-bents is three times the tube diameter, and straight pipe with a length of 1 cm are placed at the two ends of the U-bents. Heat flux of the test tubes can be regulated by changing the voltage. The test tubes are evenly divided into two groups, and their internal diameters are 8 mm and 10 mm, respectively. The mass flow of the fluid was measured using an LZB-6 type vortex flow meter. Two-phase flow patterns for water boiling are recorded by visual observations and by taking photographs.

Vapor quality of the fluid entering a test tube is determined by the mass flow and enthalpy of the fluid at the inlet and outlet of the preheater. The water temperature at the inlet and outlet of the preheater are measured using Φ0.3 mm E-type contacting thermocouples. Assuming the vapor is in equilibrium with the boiling water, vapor quality of the fluid at the inlet of the test tube can be calculated using the following equation:

$$x_{in} = \frac{[(Q_p/\dot{m}) - (h' - h_{in})]}{h'' - h'} \tag{1}$$

where the gross heat flux of the preheater Q_p can be calculated as

$$Q_p = U_p^2/R_p \tag{2}$$

Total heat flux absorbed by the water in the preheater and test tubes is related to their heating power, which can be varied by adjusting the voltage. Gross heat flux of the test tube Q_t can be calculated as

$$Q_t = U_t^2/R_t \tag{3}$$

Assuming the vapor is in equilibrium with the boiling water, the increase in vapor quality of the fluid from the inlet to position i in the test tubes can be calculated as

$$\Delta x_i = \frac{Q_t \times (1-\eta)}{\dot{m} \times (h'' - h')} \tag{4}$$

Heat loss ratio of the test tube η is related to the wall temperature of the test tube and ambient temperature. The wall temperature is determined by the heat flux of the test tube and