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A new flow regime map and void fraction model based on the flow characterization of condensation

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ABSTRACT

The paper presents flow characterization of condensation based on experiments with R134a in 6.1 mm inner diameter horizontal round tube. The paper presents flow visualizations and liquid film thickness measurements with mass fluxes from 50 to 200 kg m^{-2} s^{-1} and heat fluxes from 5 to 15 kW m^{-2}, showing the effect of mass flux and heat flux on the onset of condensation, flow regime, film distribution and void fraction. All the measurements are taken at constant pressure of 1.319 MPa, which corresponds to a saturation temperature of 50 °C. The result of flow visualization reveals that the condensation always starts in the bulk superheated region, which is generally defined as the beginning of condensing superheated region, as annular flow and the flow regime is strongly affected by the mass flux, instead of the heat flux. Based on the flow visualization results and underlying physics in the condensing superheated region, a new diabatic flow regime map is proposed to better represent the physics and predict flow regimes in both the two-phase and the condensing superheated region. The range of prediction of the new flow regime map extends over quality one up to the onset of condensation and the early stages of condensation are strictly in annular flow regime. A film thickness measurement technique for round tube is described as well as results of calibration. The film thickness measurement demonstrates that void fraction drops below one in superheated region, which is not taken into account for most conventional void fraction models. In addition, both the mass flux and heat flux affect the void fraction by altering the onset of condensation, a new void fraction model is proposed to include this mechanism. Moreover, having information of film distribution provides an opportunity to more realistically model the film geometry inside of the tube.

1. Introduction

Over the years, condensation has been attracting significant interest. A large number of correlations have been built to predict fluid properties, flow regime, void fraction, pressure drop and heat transfer coefficient (HTC). The improvements of those correlations are usually based on a deeper and better understanding of the process or larger data base. In recent years, more and more researchers are placing the focus of their work on describing the condensation process inside the tube before establishing the model, which makes their models more generalized and realistic. For instance, Hajal et al. [1] developed a new flow map using logarithmic mean void fraction (LMε) for calculating void fractions, and the model proposed by Thome et al. [2] was tightly based on the transition criteria of flow regime. Cavallini et al. [3] developed their model based on the difference the upper and lower part of the tube which was also observed by Sardesai et al. [4], and two-phase flow was divided into two categories: ΔT-dependent and ΔT-independent, which resembled the definitions of the annular and stratified flow regimes. Macdonald and Garimella [5,6] expressed the heat transfer process of upper part of stratified flow to be a combination of Nusselt falling film and annular film flow based on their visualization and weighed each term by gravitational and shear force, and the modeling process is closely connected to the previous visualization from Milkie [7]. Obviously, it is more and more important to first get a closer view and detailed flow characterization of condensation before the model could be established.

For in-tube condensation in a heat exchanger, the existence of condensation in the region is described by Kondou and Hrnjak [8–10] and Agarwal and Hrnjak [11] through measurement of HTC and pressure drop in the superheated region. The transition behavior of HTC and pressure drop in the condensing superheated

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Nomenclature

SH	superheated
CSH	condensing superheated
HTC	heat transfer coefficient (W m^{-2} K^{-1})
δ	thickness (m)
n	refractive index
T	temperature (°C)
P	pressure (Pa)
G	mass flux (kg m^{-2})
Q	heat flux (kW m^{-2})
S	slip ratio
h	specific enthalpy (kJ kg^{-1})
ρ	density (kg m^{-3})
x	quality

Subscripts

r	refrigerant
sat	saturated
w	wall
f	film
superheat	superheat of the bulk flow
sup	superficial
l	liquid
v	vapor

(CSH) region is considered as an indirect indication of condensation in superheated region which deviates the experimental results from existing correlations. Meyer and Hrnjak [12] further proved the existence of liquid film in superheated region from flow visualization and film thickness measurement of R134a in one working condition. These studies confirmed that condensation can happen in superheated region, yet the physics behind the heat transfer and pressure drop mechanism need to be better explained. Moreover, there is still no prediction regarding the flow regimes in the CSH region, and little discussion about the film distribution in early stages of condensation. Additionally, the existing correlation [8–10] takes a very empirical and asymptotic approach. Hence even though the predictions from the correlation is very close to the experimental data, the correlation relies on an independent two-phase correlation, which technically should include predictions in the CSH region. In order to address these issues and better understand the reasons behind them, flow visualization and film thickness were performed simultaneously at different working conditions for the purpose of comparison. The visualization of flow studies the effect of working conditions on the flow characters, including the onset of condensation and flow regime with emphasis in the CSH region. The film thickness measurement quantitatively supports the visualization by giving void fractions and film distribution along the tube circumference. The characteristics of the flow can be linked with other measurements such as HTC and pressure drop, especially in the CSH region, for the development of a more generalized and realistic model.

2. Description of experiment

2.1. Facility and balances

The facility is made out three loops: refrigerant, water and chilled water. In the refrigerant loop, the heater and pre-cooler are used to adjust the condition at the inlet to the test section as in Eq. (1). The outlet condition of the refrigerant can be determined through the energy balance from the water side in the second loop as in Eq. (2). In the film thickness measurement section, film thickness is measured using a non-intrusive method named as the critical angle method. In the visualization section, the condensation process is recorded with a high speed camera under diabatic conditions. The distance between the film thickness section and test section is around 30 cm and in adiabatic condition. The distance between the visualization section and the film thickness section is around 3 cm and in adiabatic condition. Therefore, the condition of the refrigerant for the film thickness sections is assumed to be the same as the outlet of test section. The condition of the refrigerant for the visualization section can be calculated by the average of the inlet and outlet enthalpies. Eventually the refrigerant is subcooled again in the after-cooler. In water loop, thermocouples are inserted into different locations of the loop and mass flow rate of water is determined by Coriolis mass flow meter. The heat transfer in this loop is balanced from the heat transfer in the refrigerant loop. The chilled water loop, uses chilled water from the building to maintain the total energy balance for the entire facility. The measurement uncertainties are included in Table 1.

$$\mathrm{h}_{\mathrm{rb,TSi}} = \mathrm{h}_{\mathrm{rb,MC}} - [(T_{water,PCo} - T_{water,PCi})\dot{m}_{PC}Cp_{water} - H_{gain,PC}]/\dot{m}_r \quad (1)$$

$$h_{rb,TSo} = h_{rb,TSi} - [(T_{water,TSo} - T_{water,TSi})\dot{m}_{TS}Cp_{water} - H_{gain,TS}]/\dot{m}_r \quad (2)$$

2.2. Visualization section

As is shown in Fig. 1, the visualization section is a transparent coaxial heat exchanger made out of glass. The heat exchanger is around 20 cm long. The refrigerant flows through a tube with 6 mm inner diameter and 12 mm outer diameter. The secondary fluid is water taken directly out of the outlet of test section to better simulate the conditions in test section. The inner diameter of the outer tube is 17 mm and the outer diameter is 20 mm. High-speed video is recorded under diabetic condition at 1000 frames per second and the resolution was 512 by 512 pixels. The bulk enthalpy of refrigerant is taken as the inlet enthalpy of the visualization section because the change of quality in visualization section is generally less than 0.1.

2.3. Film thickness measurement principle and calibration

The film thickness measurement is based on the principle proposed by Hurlburt and Newell [13] and refined by Shedd and Newell [14]. Wujek and Hrnjak [15] developed an optical model for the application of this method in round tube using minor diameter, whose advantage over using major diameter as is introduced in this paper is that the brightness of light is higher for minor diameter, whereas the model is complex and the change of minor

Table 1
Measurement uncertainties.

Variable	Instrument	Uncertainty
$T_{rb,MC}$, $T_{water,}$	Sheathed T-type thermocouple	±0.05 K
P_{MC}	Diaphragm absolute pressure transducer	±4 kPa
$\dot{m}_{water,TS}$, $\dot{m}_r$	Coriolis mass flow meter	±0.1 g s^{-1}
$\dot{m}_{water,PC}$	Coriolis mass flow meter	±0.5 g s^{-1}