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Interfacial area transport of subcooled water–steam condensing bubbly flow in vertical pipe

Keshuai Ma, Liejin Guo *, Yubo Wang

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, 710049 Xi'an, China

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ABSTRACT

The interfacial area transport of a subcooled water–steam condensing bubbly flow in a vertical pipe with inner diameter of 29 mm was investigated. Three fundamental parameters, the void fraction, interfacial area concentration (IAC) and bubble Sauter mean diameter, were experimentally obtained using a double-sensor conductivity probe technique. The radial and axial developments of local flow structure were interpreted based on the phase change and bubble interaction mechanisms, such as the bubble condensation, coalescence and break-up. Based on the experimental data sets, a critical Weber number range to identify the core peak was developed for one-component steam–water systems. Furthermore, the theoretical modeling of the one-dimensional interfacial area transport equation (IATE), including the condensation sink term, was discussed and compared with the experimental data. The axial distributions of area-averaged IAC profiles were best computed via the use of the IATE. The evaluation results showed that the interfacial area transport was dominated by the heat-mass transfer mechanism causing bubbles condensation in the flow.

1. Introduction

Heat and mass transfer phenomena in one-component two phase flows are encountered in many applications, such as the chemical industry, nuclear reactors and liquid propellant rocket engines (LPRE). In the LPRE system, gas-oxygen condenses in sub-cooled liquid oxygen [1,2]. Steam–water flows are common in the field of nuclear reactor design, where large heat fluxes within fluids are found. The geometric distribution within the flow may strongly effect the interfacial area available for mass, momentum and energy exchange between the phases [3]. Under such thermal non-equilibrium conditions, accurate knowledge of the void fraction and IAC is required to help researchers or engineers to gain a better understanding of this complex phenomenon.

The void fraction is an important parameter for thermal and hydrodynamic design. Furthermore, the IAC, a geometric parameter characterizing the interfacial transfer "capability", plays a significant role in evaluating the momentum exchange as well as the heat and mass transfer between the phases. The Sauter mean diameter is also an important parameter to identify the bubble shape and size. The bubbles are assumed to migrate either near walls (wall peak characterized by a peak of high void fraction near the wall) or around the center (core peak, for which a peak of the void fraction is observed around the center of the channel). The phase distribution correlates with the bubble force balance. However, most studies about phase distribution have addressed air–water systems while a few have been executed in steam–water systems. Although Lucas et al. [4] used wire-mesh sensors to study the structure of steam–water flow and got the evolution of radial gas fraction profiles along the pipe, they did not have the IAC in their results. In addition, most of the experiments for the IAC measurement have been performed under adiabatic air–water flow conditions [5–8]. Although, under thermal non-equilibrium conditions, subcooled boiling flow in an annulus have been studied [9–12], a few works have examined subcooled water–steam condensing flow in a circular pipe. Moreover, the data on the axial development of flow parameters remains scarce. The study of subcooled water–steam condensing flow in circular pipes has high academic value.

In widely used analysis codes, such as RELAP5 [13], TRAC [14], and WAHA3 [15,16], in which a two-fluid model is employed, the void fraction is solved for while the IAC should be given as a constitutive relation. It is worth mentioning that WAHA3 has a quick condensation model, which is capable to describe quick steam condensation induced water hammer (CIWH), in physically existing pipe systems [17]. The model employed to describe the IAC evidently plays an important role in predicting the void fraction

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* Corresponding author. Tel.: +86 29 8266 8767; fax: +86 29 8266 9033.
E-mail address: lj-guo@mail.xjtu.edu.cn (L. Guo).

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Nomenclature

a_i	interfacial area concentration (IAC)
A_b	interfacial area of a bubble
d_b	bubble diameter at region boundary
d_{sm}	Sauter mean bubble diameter
f_B	bubble eddy random collision frequency
f_C	frequency of bubble collision
h_{fg}	latent heat
K_B	coefficient
K_C	coefficient
n_b	bubble number density
n_e	number of eddies per mixture volume
N_b	number of bubbles
Nu_c	condensation Nusselt number
P	pressure
P_c	fraction of bubbles in the inertia controlled region
Pr	Prandtl number
Re	Reynolds number
T	temperature
t_c	bubble collapsing time
v_g	bubble velocity
v_i	interfacial velocity
v_{iz}	z-component of interfacial velocity
V_{sg}	superficial gas velocity
V_{sl}	superficial liquid velocity
We	Weber number
z	axial coordinate

Greek symbols

α	average void fraction
α_0	maximum angle
$\alpha_{\max}$	maximum allowable void fraction
Γ_B	adjustable valuable
Γ_C	adjustable valuable
ε	energy dissipation
η_{ph}	volume change rate due to phase change per mixture volume
λ	thermal conductivity
λ_B	breakup efficiency
λ_C	coalescence efficiency
ρ	density
σ	surface tension
σ_z	root mean square of the interface velocity fluctuation
ϕ	the change rate of the interfacial area concentration

Subscripts

CO	condensation in the inertia controlled region
in	inlet
l	liquid
ph	phase change
PC	condensation in the heat transfer controlled region
PV	volume change due to the pressure change
RC	random collision
s	steam
sat	saturation
TI	turbulent impact

Mathematical symbols

$< >$	area averaged quantity
$<< >>$	void fraction weighted area averaged quantity

distribution. Many correlations of the IAC have been developed based on the adiabatic gas–liquid flow databases [18,19] as well as boiling bubbly flows. However, these correlations may lead to inaccurate predictions due to its assumptions and dependence on the flow regime. Thus, the IATE is required to mechanistically predict the IAC.

Experiments on subcooled water–steam condensing bubbly flows in vertical pipe were conducted in this study. The axial developments of the local void fraction and IAC were obtained using the double-sensor conductivity probe method. Experimental data covering different inlet subcooling values and inlet velocities were presented. The IATE model with phase change was reviewed and evaluated using the experimental data.

2. Experimental facility

The experimental facility was designed to measure the local and global two-phase flow parameters under condensing conditions. Fig. 1 schematically shows the experimental loop, which mainly consists of a test section, a steam generator, two water tank, a temperature controlled heating tank, a heat exchanger and two pump.

The working fluids in the operation were distilled water and steam. Distilled water was heated with an electrical heater submerged in the stainless steel tank to remove the-non-condensable gases before each experiment. Downstream of the tank, water was circulated by a centrifugal pump. After the pump, the water flowed through a temperature-controlled heating tank. Fig. 2a shows the schematic of the temperature-controlled heating tank. The internal flow was designed multi-channel, so that the water was uniformly heated. The temperature of water at inlet and outlet of the temperature-controlled heating tank were measured using T-type thermocouple with a maximum relative deviation of 0.2%, and the outlet temperature was controlled using a temperature controller (SR-3, shimaden, Japan) and electrically heated rod. So, the water temperature was strictly controlled to the desired temperature before it entered the test section. Then the flow rate of the water was measured by a CMF050M Micro Motion mass flow meter with a maximum relative deviation of 0.1%. The steam generator supplied continuously saturated steam at a maximum pressure of 0.7 MPa (absolute) and a maximum flow rate of 100 kg/h. To maintain the supplied steam saturated during testing, the steam supply line is insulated with fiberglass covering. The flow rate of the steam was measured by a vortex type steam flow meter with a maximum relative deviation of 0.5%. Valves in the system and pass lines were used to control the flow rate. Finally, before the mixtures flowed through the test section, the steam was injected circularly into sub-cooled water through a mixing chamber, which supplied the steam via a ring of orifices in the pipe wall. The injection diameter of the orifice, which affects the primary bubble size, was 3 mm. The schematic diagram of the mixing chamber is shown in Fig. 2b.

The test section was a vertical round transparent tube that consisted of polycarbonate. Its inner diameter and length were 29 and 2000 mm, respectively. The temperature of each fluid before mixing and at outlet of the test section was measured using T-type thermocouple with a maximum relative deviation of 0.2%. A Keller pressure transmitter was used to monitor the pressures before mixing and outlet of the test section with a maximum relative deviation of 0.4%. The local void fraction, IAC and bubble Sauter mean diameter were measured using a double-sensor conductivity probe. It was attached to traversing mechanism, and can be moved back and forth. Four measurement ports were taken at