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Interfacial area transport of vertical upward steam–water two-phase flow in an annular channel at elevated pressures

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ABSTRACT

The interfacial area transport of vertical, upward, steam-water two-phase flows in a vertical annular channel has been investigated. The inner and outer diameters of the annular channel were 19.1 and 38.1 mm, respectively. The test section had a 2845 mm heated section followed by a 1632 mm unheated section. Fifty seven experimental conditions were selected, which cover bubbly, cap-slug, and churn-turbulent flows. Each one of flow conditions was obtained by achieving different inlet sub-cooling temperatures, liquid velocities, wall heat flux or system pressures. The local flow parameters, such as void fraction, interfacial area concentration, and bubble interface velocity, were measured at different radial positions for the five axial locations. The radial and axial evolutions of local flow structure were interpreted based on presence of wall superheat, wall nucleation, bulk condensation and evaporation, bubble sizes, coalescence and break-up mechanisms. The measured data can be used for both the assessment of the bubble coalescence/breakup models and the development of closure models for computational fluid dynamics.

1. Introduction

Two-phase flows in annular channels are frequently encountered in industrial applications. In addition, the study of the flow in the annular channel provides a basis for investigations of the flow through more complicated geometries like the shell side of a shell and tube heat exchanger and the rod bundle of a nuclear reactor. This has motivated extensive research on the two-phase flow in annular channels for flow regime [1–3], pressure drop, interfacial drag, critical heat flux, etc. However, there are very few experimental data for interfacial area research.

In the two-fluid model, the liquid and gas phases are separately described by using two sets of conservation equations for mass, momentum and energy. The equations are linked by interfacial transfer terms, which represent the mass, momentum, and energy transfer at the liquid–vapor interface. These terms are generally given by the product of the interfacial area concentration (IAC) and the local transfer rate per interfacial area. The IAC is defined by interfacial area per unit volume of two-phase mixture.

Interfacial area transport is a term related to the behavior of the interfacial structure between the two-phases and its evolution along the flow channel. The formulation of interfacial area transport equations is based on statistical mechanics and its concept has been fully established [4]. Particularly, the source and sink terms of interfacial area due to bubble coalescence and breakup have been investigated widely. These are strongly dependent on flow conditions and geometries. So far, most of the experiments for interfacial area research have been performed in round tubes [5–14] mostly under adiabatic air-water flow conditions. It was also recognized early on that the transport mechanisms of large and small bubbles need to be modeled separately, resulting in the two-group interfacial area transport equation. By separating the gas phase into two bubble groups, the mechanisms effecting the interfacial area concentration of small, spherical and distorted bubbles (Group-1), and larger cap, slug, and churn bubbles (Group-2) can be properly identified and modeled [15]. The database containing two-group information is limited to only adiabatic flow [16–19].

A detailed literature review of studies for two-phase flow with phase change is provided by Bartel et al. [20] and Hibiki and Ishii [21]. A summary of the studies in boiling flow is presented in this paper.

There have been various studies, particularly for axial void fraction measurement in boiling conditions, which were performed near atmospheric pressures. Whittle and Forgan [22] measured the pressure drop for sub-cooled boiling flow in a rectangular channel.

Evangelisti and Lupoli [23] obtained void fraction data using a single-shot gamma-ray densitometer system. The geometry was an annulus with 13 mm inner diameter of the outer tube and

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Nomenclature

a_i	interfacial area concentration [m^{-1}]
D	channel diameter [m]
$D_{d,\max}$	maximum distorted bubble size [m]
D_h	channel hydraulic diameter [m]
D_{Sm}	sauter mean diameter [m]
g	gravitational acceleration [m s^2]
i	enthalpy [j kg^{-1}]
L_H	heated length [m]
N_{sub}	subcooling number [–]
N_{Zu}	Zuber number [–]
n_i	normal vector [–]
P	pressure [Pa]
q''_w	wall heat flux [W m^{-2}]
R_o	channel outer radius [m]
R_i	channel inner radius [m]
Re	Reynolds number [–]
r	radial coordinate [m]
T	temperature [°C]
t	time [s]
v	velocity [m s^{-1}]
v_i	interface velocity [m s^{-1}]
v_r	relative velocity [m s^{-1}]
We	particle Weber number [–]
z	axial position [m]

Greek symbols	
α	void fraction [–]
Δ_ρ	density difference between the liquid and gas phases [kg m^{-3}]
Δi_{sub}	subcooling enthalpy [J kg^{-1}]
ΔT_{sub}	sub-cooling temperature [°C]
Δt	incremental time [s]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
μ	viscosity [Pa s]
Subscripts$_{\text{in}}$	
	inlet
$_1$	group-1 property or x axis
$_2$	group-2 property or y axis
$_3$	z axis
d	particle property
$_f$	liquid phase
$_g$	gas phase
$_j$	index for the jth bubble or interface
$_{\text{sat}}$	saturation
$_{\text{w}}$	wall

7 mm outer diameter of the inner tube. They measured the local steam quality by means of heat balance.

Sekoguchi et al. [24] performed experiments and obtained local measurements. They measured the void fraction and temperature distribution in a sub-cooled boiling flow within a circular test section. They also developed a correlation to predict the sub-cooling at PNVG. They are the first to make such local measurements in a sub-cooled boiling flow via a single point electrical conductivity probe with a nominal thickness of 0.2 mm.

Edelman and Elias [25] measured the void fraction using a gamma-ray densitometer and an X-ray radiography system.

Rogers et al. [26] performed experiments in sub-cooled boiling in an annulus. They measured the PNVG and the axial void fraction profile in low-pressure, low-velocity vertical, upward flow systems. The test section was an annulus with the center rod being heated and the outer tube of glass. The void fraction was measured by axially traversing a gamma-ray densitometer system. Thermocouples were used to measure the inlet and outlet temperatures.

Zeitoun and Shoukri [27] performed experiments to measure the axial vapor void profile in sub-cooled boiling. Their test section was an annular geometry and oriented vertically. The inlet and exit temperatures were measured. The wall temperature in the heated section was measured with a *J* type thermocouple mounted on the inside of the heated section. The void fraction was measured with a gamma-ray densitometer system. For most cases the inlet sub-cooling is between 15 and 20 °C.

Also, high pressure tests ranging from 1 MPa to 15 MPa were of considerable interest. Martin [28] conducted experiments to simulate a plate-type reactor. The test section was rectangular and made of stainless steel. The channel was aligned vertically with the water flowing up-ward through the test section.

Bartolemei et al. [29] collected data on sub-cooled boiling to help fill in the lack of available experimental data. Their experiment was conducted on sub-cooled boiling in vertical up-flow in a circular tube. The experimental facility was made entirely of stainless steel. The test section was heated using Joule heating. The void fraction is determined using a gamma-ray densitometer system. They used a vertical and horizontal traversing System

St. Pierre and Bankoff [30] measured the transverse and axial void fraction in a rectangular test section. The tests were made in the sub-cooled boiling region for vertical up-flow.

Labuntsov et al. [31] also measured the axial void fraction distribution for vertical up and down-flow. They used a gamma-ray densitometer system to measure the void fraction. The author discussed the effects of flow velocity, test section geometry, heating method for an annulus, inlet sub-cooling, and pressure on the void fraction in the sub-cooled boiling regime.

Bartel et al. [20] investigated the axial development of boiling flow structure at atmospheric pressure. The conditions were limited to subcooled boiling allowing for bubbly flow. Similar tests were performed by Situ et al. [32]. A two-sensor conductivity probe was used to measure the radial distribution of void fraction, bubble interface velocity and interfacial area concentration for bubbly flow conditions. The conditions of Situ et al. [32] were extended in Lee et al. [33] using the same test facility. Due to the limitations of the two-sensor conductivity probe, only conditions in bubbly flows were measured.

The brief literature review shows that local measurements of two-phase flow parameters such as void fraction, bubble interface velocity and interfacial area concentration are sorely lacking. Most of the database is limited to area or line averaged void fraction. The only detailed local data was produced by Situ et al. [32], Bartel et al. [20], and Lee et al. [33]. These datasets are limited to atmospheric pressure and bubbly flow. Currently there are no datasets which present the local flow structure of both bubble groups at elevated pressures in boiling flows.

In this paper, the interfacial area transport of vertical, upward, steam–water two-phase flows in an annular channel has been investigated. The geometry of the cross section is the same compared to these previous studies. Fifty seven inlet flow conditions were selected so that a wide range of flow conditions can be covered, including bubbly, cap-slug, and churn-turbulent flows at