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A study on the characteristics of upward air–water two-phase flow in a large diameter pipe

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Abstract

An adiabatic upward co-current air–water two-phase flow in a vertical large diameter pipe (inner diameter, D: 0.2 m, ratio of pipe length to diameter, L/D: 60.5) was experimentally investigated under various inlet conditions. Flow regimes were visually observed, carefully analyzed and classified into five, i.e. undisturbed bubbly, agitated bubbly, churn bubbly, churn slug and churn froth. Void fraction, bubble frequency, Sauter mean diameter, interfacial area concentration (IAC) and interfacial direction were measured with four-sensor optical probes. Both the measured void fraction and the measured IAC demonstrated radial core-peak distributions in most of the flow regimes and radial wall peak in the undisturbed bubbly flow only. The bubble frequency also showed a wall-peak radial distribution only when the bubbles were small in diameter and the flow was in the undisturbed bubbly flow. The Sauter mean diameter of bubbles did not change much in the radial direction in undisturbed bubbly, agitated bubbly and churn bubbly flows and showed a core-peak radial distribution in the churn slug flow due to the existence of certain amount of large and deformed bubbles in this flow regime. The measurements of interfacial direction showed that the main and the secondary bubbly flow could be displayed by the main flow peak and the secondary flow peak, respectively, in the probability density function (PDF) of the interfacial directional angle between the interfacial direction and the z-axis, η_{zi}. The local average η_{zi} at the bubble front or rear hemisphere (η_{zi}^{F} and η_{zi}^{R}) reflected the local bubble movement and was in direct connection with the flow regimes. Based on the analysis, the authors classified the flow regimes in the vertical large diameter pipe quantitatively by the cross-sectional area-averaged η_{zi} at bubbly front hemisphere ($\overline{\eta_{zi}^{F}}$). Bubbles in the undisturbed bubbly flow moved in a vertical way with some swerving motions and those in other flow regimes moved along the lateral secondary flow with an averaging net upward velocity.

Keywords: A large diameter pipe; Flow regime; Phase and interface distribution; Interfacial direction

1. Introduction

Large diameter pipes are extensively used in industrial equipments, such as light water reactors, chemical plants and other industrial plants. In such large diameter pipes, a gas–liquid two-phase flow is characterized by its multi-dimensional nature in bubble behavior and phase distribution. Therefore, it is important to obtain information of local flow parameters in a large diameter pipe. In view of this, the purpose of the present study is to measure local flow parameters such as void fraction, Sauter mean diameter, interfacial area concentration and so forth, and to clarify the characteristics of gas–liquid two-phase flow in a vertical large diameter pipe.

So far, some research work has been done for gas–liquid two-phase flow in a large diameter pipe. In order to simulate a once-through steam generator of a pressurized water reactor, Hashemi et al. [1] investigated flow regime and void fraction in specific geometries with D of 0.1 m ($L/D = 30$) and 0.3 m ($L/D = 9.5$). The effect of bulk liquid flow has not been investigated in two-phase system in this study.

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Nomenclature

A_0	basic determinant of the four-sensor probe
A_{01l}	directional determinant from front sensor, 0, to rear sensor, 1, for the l-th interface
A_{02l}	directional determinant from front sensor, 0, to rear sensor, 2, for the l-th interface
A_{03l}	directional determinant from front sensor, 0, to rear sensor, 3, for the l-th interface
A_p	triangle area of the three projected sensor tips in a plane perpendicular to the z-axis, mm^2
$\overline{a_i}^t$	time-averaged local interfacial area concentration, m^{-1}
D	pipe diameter, mm
$D_{\mathrm{ch}\,j}$	chord length of the j-th bubble, mm
D_{sm}	Sauter mean diameter, mm
f	local bubble frequency, s^{-1}
j	superficial velocity, m/s
L	axial distance, mm
$\mathbf{n}_{il}$	local instantaneous interfacial normal unit vector at the point of the l-th interface, at which the front sensor tip penetrates into the interface
N	Gaussian distribution
N_t	measured bubble number within the sampling time, Ω, s^{-1}
R	inner diameter of a pipe, mm
R_b	Radius of a typical bubble, mm
r	radial distance, mm
s_{12p}	projected distance between two rear sensor tips 1 and 2 in a plane perpendicular to the z-axis, mm
s_{13p}	projected distance between two rear sensor tips 1 and 3 in a plane perpendicular to the z-axis, mm
s_{23p}	projected distance between two rear sensor tips 2 and 3 in a plane perpendicular to the z-axis, mm
$\mathbf{s}_{0k}$	distance vectors from front sensor tip, 0, to rear sensor tip, k ($k = 1,2,3$), mm
t_{0l}	time at which the l-th interface touches the front sensor tip, 0, s
t_{kl}	time at which the l-th interface touches the rear sensor tip, k ($k = 1,2,3$), s
t_{kFj}	time at which the j-th bubble touches the k-th sensor tip of a probe ($k = 0,1,2,3$), s
t_{0Rj}	time at which the j-th bubble leaves the front sensor tip of a probe, s
$\bar{v}_b$	average bubble velocity, m/s
$\mathbf{V}_{il}$	the l-th interface velocity, m/s
$\mathbf{V}_{m0kl}$	measurable velocities, $k = 1,2,3$, m/s
$\mathbf{V}_{nl}$	component of the l-th interface velocity in the surface normal direction, m/s

Greek symbols

$\bar{\alpha}^t$	time-averaged void fraction, dimensionless
δ	statistical error
η_{x0k}	angle between $\mathbf{s}_{0-k}$ ($k = 1,2,3$) and x-axis, °
η_{xi}	angle between $\mathbf{n}_{il}$ and x-axis, °
η_{y0k}	angle between $\mathbf{s}_{0-k}$ ($k = 1,2,3$) and y-axis, °
η_{yi}	angle between $\mathbf{n}_{il}$ and y-axis, °
η_{z0k}	angle between $\mathbf{s}_{0-k}$ ($k = 1,2,3$) and z-axis, °
η_{zi}	angle between $\mathbf{n}_{il}$ and z-axis, °
η_{zi}^{F}	local average η_{zi} at bubble front hemisphere, °
$\overline{\eta_{zi}^{F}}$	cross-sectional area-averaged η_{zi}^{F} at bubble front hemisphere, °
η_{zi}^{R}	local average η_{zi} at bubble rear hemisphere, °
$\overline{\eta_{zi}^{R}}$	cross-sectional area-averaged η_{zi}^{R} at bubble rear hemisphere, °
Ω	sampling time, s

Subscripts

g	gas phase
l	liquid phase

Ohnuki and Akimoto [2,3] studied experimentally the flow regime transition and phase distribution in upward air–water two-phase flow along a large vertical pipe ($D = 0.2$ m, $L/D = 61.5$) to examine the dependency on the pipe scale. They distinguished five kinds of flow regimes, i.e. undisturbed bubbly, agitated bubbly, churn bubbly, churn slug and churn froth in the air–water two-phase flow in the vertical large diameter pipe. The undisturbed, agitated bubbly and churn froth flow are the fully developed flow regimes in the vertical large diameter pipe. Driven by a proposed design of a new passive cooling system in a CANDU reactor, Shoukri et al. [4] performed experiments in vertical pipes with diameter of 100 and 200 mm and height of 5.5 and 10 m, respectively, to assess the applicability of existing flow regime maps and void fraction correlations for gas–liquid two-phase flow in a vertical large diameter pipe. They found that increasing the gas flow rate, at constant liquid flow rate, resulted in transition from bubbly to churn flow and no slug flow was observed under their test conditions. Hills [5] and Cheng et al. [6] measured the transition from bubbly flow to slug flow and the radial voidage profiles in a vertical column with 0.15 m in inner diameter and 10.5 m in height. Yoneda et al. [7,8] investigated the flow structure of upward steam–water two-phase flow in a vertical pipe with an inner diameter of 0.155 m at superficial gas velocities smaller than 0.25 m/s and superficial liquid velocities smaller than 0.6 m/s by using optical dual void probes and derived a correlation of Sauter mean bubble diameter with local void fraction, pressure, surface tension and density. Summarizing previous studies, Kataoka