Progress in Nuclear Energy 85 (2015) 164–177

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Slug flow in a vertical narrow rectangular channel – Laminar and turbulent regimes in the main flow and turbulent regime in the wake region of the Taylor bubble

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ARTICLE INFO

Article history:
Received 24 September 2014
Received in revised form
1 June 2015
Accepted 9 June 2015
Available online 26 June 2015

Keywords:
Narrow rectangular channel
Slug flow
Taylor bubble length
Taylor bubble velocity
Liquid slug length
Distribution

ABSTRACT

Using a high-speed video-camera system, the hydrodynamics of gas–liquid two-phase slug flow in a vertical narrow rectangular channel with the cross section of 2.2 mm × 43 mm is investigated for laminar and turbulent regimes in the main flow and turbulent regime in the wake region of the Taylor bubble. The Taylor bubble velocity is the function of the liquid slug length ahead of it, and the interaction of Taylor bubbles for turbulent flow in main flow is weaker than that for laminar flow. Thus, two correlations are proposed for laminar and turbulent flows, respectively. The distributions of Taylor bubble velocity, lengths of liquid slug and Taylor bubble are all positively skewed. The lengths of Taylor bubble and the liquid slug decrease with the liquid flow rate. The Taylor bubble length increases with the gas flow rate, whereas the influence of the gas flow rate on the liquid slug length is insignificant.

1. Introduction

Two-phase slug flow can be described as a series of slug units, each of which consists of a Taylor bubble with a liquid film around it and a portion of liquid slug behind the Taylor bubble. Slug flow in a narrow rectangular channel is encountered in many important applications, such as high performance micro-electronics, supercomputers, high-powered lasers, medical devices, high heat-flux compact heat exchangers and research nuclear reactors with plate type fuels (Satitchaicharoen and Wongwises, 2004). It has been the subject of increased research interest in the past few decades (Griffith, 1963; Maneri and Zuber, 1974; Sadatomi et al., 1982; Mishima et al., 1993; Clanet et al., 2004; Ide et al., 2007; Sowinski et al., 2009; Bhusan et al., 2009; Wang et al., 2014a,b,c). However, the majority of the studies are confined to slug flow in circular tubes, a few works deal with the slug flow in narrow rectangular channels.

For a vertical circular tube, Nicklin et al. (1962) proposed Eq. (1) to predict the velocity of a single Taylor bubble (V_T) in a moving liquid.

$$V_T = C_0 V_m + V_0 \tag{1}$$

where V_0 is the drift velocity of a single Taylor bubble in a stagnant liquid, V_m is the mean liquid velocity. The value of C_0 is based upon the assumption that the velocity of the Taylor bubble follows the maximum local velocity (V_{max}) in the front of its nose tip, and thus, $C_0 = V_{max}/V_m$ (Nicklin et al., 1962; Bendiksen et al., 1984; Shemer and Barnea, 1987). Therefore, C_0 equals approximately 1.2 for fully developed turbulent flow and 2.0 for fully developed laminar flow. For inertia-controlled region when viscosity and surface tension can be neglected (Eotvos number $Eo = g(\rho_L - \rho_G)D^2/\sigma > 70$ and $\rho_L^2 g D^3/\mu_L^2 > 3 \times 10^5$), White and Beardmore (1962) recommended

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http://dx.doi.org/10.1016/j.pnucene.2015.06.010
0149-1970/

Nomenclature

C_0	distribution parameter
D	diameter (m)
D_h	hydraulic diameter (m)
Eo	Eotvos number
F_{scale}	scale factor
f_S	slug frequency (Hz)
G_{TP}	two-phase mixture mass velocity (kg/(m^2 s))
P	wetted perimeter (m)
g	gravitational acceleration (m/s^2)
h_1, h_2	distances relative to images bottom edge (pixel)
j_G	gas superficial velocity (m/s)
j_L	liquid superficial velocity (m/s)
j_{TP}	two-phase superficial velocity (m/s)
L_S	liquid slug length (m)
L_T	Taylor bubble length (m)
L_U	length of a slug unit (m)
N_1	frame of Taylor bubble nose arriving at h_1
N_2	frame of Taylor bubble nose arriving at h_2
N_3	frame of Taylor bubble bottom arriving at h_1
N_4	frame of trailing Taylor bubble nose arriving at h_1
Re_{TP}	Reynolds numbers based on two-phase superficial velocity
Re_{V_s}	Reynolds numbers based on liquid slug velocity relative to Taylor bubble
St	Strouhal number
s	gap of rectangular channel (m)
V_0	drift velocity (m/s)
V_{max}	maximum local velocity (m/s)
V_m	mean liquid velocity (m/s)
V_T	Taylor bubble velocity (m/s)
$V_{T\infty}$	Taylor bubble velocity in undisturbed condition (m/s)
X_L	liquid volume fraction
w	width of rectangular channel (m)
w_{image}	width of channel in the image (pixel)
z	axial distance from the inlet (m)

Greek letters

β	occurrence rate of Taylor bubble
ζ	parameter defined in Eq. (14)
μ_L	liquid phase viscosity (Pa s)
μ_{TP}	two-phase viscosity proposed by McAdams et al. (1942) (Pa s)
σ	surface tension (N/s)
π	circumference ratio
ρ_L	liquid density (kg/m^3)
ρ_G	gas density (kg/m^3)
$\Delta\rho$	density difference between liquid and gas phases (kg/m^3)
τ	time interval between two frames
ω	parameter defined in Eq. (14)

Subscripts

G	gas phase
L	liquid phase
TP	two-phase

that the drift velocity V_0 for the vertical tube can be expressed by following equation proposed by Dumitrescu (1943).

$$V_0 = 0.35\sqrt{\Delta\rho g D/\rho_L} \tag{2}$$

where the tube diameter D is taken as the characteristic length, g is the gravitational acceleration, μ_L is the liquid phase viscosity, σ is the surface tension, $\Delta\rho$ is the density difference between the two phases, ρ_G and ρ_L are the gas and liquid density, respectively.

Most researchers also predict the Taylor bubble velocity in continuous slug flow using Eq. (1), whereas substituting the mean liquid velocity (V_m) by the two-phase superficial velocity (j_{TP}).

$$V_T = C_0 j_{TP} + V_0 \tag{3}$$

For a vertical narrow rectangular channel, researchers also have attempted to correlate the Taylor bubble velocity with the same relationship of Eq. (3) (Sadatomi et al., 1982; Ide et al., 2007; Sowinski et al., 2009; Wang et al., 2014a). Ishii (1977) proposed the following empirical formula for C_0 for rectangular channels.

$$C_0 = 1.35 - 0.35(\rho_G/\rho_L)^{0.5} \tag{4}$$

Since there is not an extensively accepted characteristic length for a rectangular channel, several characteristic lengths and correlations for the drift velocity were put forward (Griffith, 1963; Ishii, 1977; Sadatomi et al., 1982; Clanet et al., 2004). Clanet et al. (2004) recommended the wetted perimeter (P) as the characteristic length for a vertical tube of the arbitrary cross-section,

$$P = 2(s + w) \tag{5}$$

where w is the channel width, and s is the gap width, and proposed a correlation for calculating V_0.

$$V_0 = 0.2\sqrt{gP} \tag{6}$$

The knowledge of the mean values of the characteristic lengths and the velocities of Taylor bubble and liquid slug is, however, insufficient for accurate modeling, and the statistical parameters are also required. For circular tubes, experimental investigations on the length distributions of liquid slug and Taylor bubble have been carried out for horizontal, inclined and vertical flows (Bernicot and Drouffe, 1989; Barnea and Taitel, 1993; Cook and Behnia, 2000; van Hout et al., 2001, 2003; Mayor et al., 2007a, 2008a,b). The liquid slug length distribution can be described by positively skewed distributions, such as the log-normal, the gamma, or the inverse Gaussian (Dhulesia et al., 1991; Nydal et al., 1992; van Hout et al., 2001, 2003).

Modeling of the evolution of slug flow was undertaken by several researchers (Bernicot and Drouffe, 1989; Barnea and Taitel, 1993; Cook and Behnia, 2000; van Hout et al., 2001, 2003; Mayor et al., 2007b, 2008b). Predictions by these models compared reasonably well with the experimental data. As the dependence of the Taylor bubble velocity on the liquid slug length ahead of it, $V_T = f(L_S)$, should be provided as an input relation to these model. Several researchers proposed the relationship of $V_T = f(L_S)$ based on experimental data. Correlations of $V_T = f(L_S)$ for the circular tube existing in literature are listed in Table 1. $V_{T\infty}$ is the velocity of the Taylor bubble in undisturbed condition in which the trailing Taylor bubble is undisturbed by the leading one.

Up to now, there is few information about the relationship of $V_T = f(L_S)$ for the narrow rectangular channel.