Experimental Thermal and Fluid Science 94 (2018) 9–22

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental study and modelling of average void fraction of gas-liquid two-phase flow in a helically coiled rectangular channel

Guodong Xia[a,*], Bo Cai[a], Lixin Cheng[a,b,*], Zhipeng Wang[a], Yuting Jia[a]

[a] College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China
[b] Department of Engineering and Mathematics, Faculty of Arts, Computing, Engineering and Sciences, Sheffield Hallam University, UK

ARTICLE INFO

Keywords:
Air-water two-phase flow
Helically coiled rectangular channel
Flow regime
Void fraction
Experiment
Model

ABSTRACT

Void fraction is an important parameter in designing and simulating the relevant gas-liquid two-phase flow equipment and systems. Although numerous experimental research and modelling of void fraction in straight circular channels have been conducted over the past decades, the experimental data and prediction methods for the average void fraction in helically coiled channels are limited and needed. Especially, there is no such information in helically coiled channels with rectangular cross section. Therefore, it is essential to advance the relevant knowledge through experiments and to develop the corresponding prediction methods in helically coiled rectangular channels. This paper presents experimental results of the average void fraction and new models for the void fraction in a horizontal helically coiled rectangular channel. First, experiments were conducted with air-water two-phase flow in the horizontal helically coiled rectangular channel at a wide range of test conditions: the liquid superficial velocity ranges from 0.11 to 2 m/s and the gas superficial velocity ranges from 0.18 to 16 m/s. The average void fractions were measured with a quick-closing valve (QCV) method. The measured void fraction ranges from 0.012 to 0.927 which cover four flow regimes including unsteady pulsating, bubbly, intermittent and annular flow observed with a high speed camera. Second, comparisons of the entire measured average void fraction data to 32 void fraction models and correlations were made. It shows a low accuracy of these models and correlations in predicting the experimental data for the void fraction smaller than 0.5 while the drift flux model of Dix (Woldesemayat and Ghajar, 2007) predicts 98.3% of the entire experimental data within ± 10% for the void fraction larger than 0.5. Therefore, the Dix model is recommended for the void fraction larger than 0.5. Furthermore, the observed flow regimes in the coiled channels were compared to two mechanistic flow regime maps developed for horizontal straight circular tubes. The flow regime maps do not capture all flow regimes in the present study. Finally, the effects of the limiting affecting parameters on the void fraction models are analyzed according to the physical phenomena and mechanisms. Incorporating the main affecting parameters, new void fraction models have been proposed for the void fractions in the ranges of $0 < \alpha \leq 0.2$ and $0.2 < \alpha \leq 0.5$ respectively according to the slip flow model. Both models predict the experimental data reasonably well. Overall, the new proposed models and the recommended model predict 92.8% of the entire void fraction data within ± 30%.

1. Introduction

Gas-liquid two-phase flow in helically coiled channels is frequently encountered in various industrial units such as various heat exchangers, power generations, nuclear reactors, oil-gas process systems, gas-liquid mixing units and so on [1,2]. Understanding the channel average void fraction of two-phase flow is significant and necessary for modelling the flow regimes and their transitions, the two-phase pressure drop and phase change heat transfer in various gas-liquid two-phase flow systems [3–5]. Accurate knowledge of the average void fractions of gas-liquid two-phase flow is significant in modelling the numerical computation and beneficial to the design and application for various industrial processes.

A number of researchers have conducted experimental investigations on the void fraction in straight circular tubes under various conditions such as flow boiling, condensation and adiabatic two-phase flow. Srisomba and Mahian [6] conducted the experiments to measure the void fraction of R-134a in a horizontal circular tube using a quick-closing valve (QCV) method and optical observation techniques. Based on their measured void fraction, they have proposed new correlations

* Corresponding authors at: College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China.
E-mail addresses: xgd@bjut.edu.cn (G. Xia), l.cheng@shu.ac.uk (L. Cheng).

https://doi.org/10.1016/j.expthermflusci.2018.01.027
Received 11 October 2017; Received in revised form 21 December 2017; Accepted 21 January 2018
0894-1777/

Nomenclature

A_R	rectangular cross-section area, m^2
C_0	the distribution parameter
D	coil diameter, m
d_E	equivalent diameter, m
G	mass flux, $kg/(m^2s)$
g	gravity acceleration, m/s^2
h	channel height, m
M	the mass of water filled in the test section, kg
M_i	the water mass of two-phase flow remained in the test section, kg
P	pitch, m
U_{gm}	drift velocity, m/s
U_M	mixture velocity, m/s
U_{SG}	superficial gas velocity, m/s
U_{SL}	superficial liquid velocity, m/s
V	the volume of liquid phase filled in the test section, m^3
V_i	liquid volume of two-phase flow remaining in the test section, m^3

Greek letters

α	channel average void fraction
α_H	homogeneous volume fraction
β	gas volumetric flow fraction
φ	helix angle, °
ρ	density, kg/m^3
μ	dynamic viscosity, Pa·s

Subscript

E	equivalent
R	rectangular cross-section
SG	gas superficial
SL	liquid superficial

Dimensionless number

Fr	Froude number

Abbreviation

QCV	quick-closing valve method

for predicting the void fraction for different flow regimes. Oliviera [7] investigated the effects of the inclination angles on the void fraction, which closely related with flow regimes during condensation with R134a inside smooth tubes. Jagan and Satheesh [8] investigated the flow regimes and the void fraction of air-water two-phase flow in a circular tube at different inclination angles ranging from 0° to 90°. The void fractions were measured using the QCV method in their study. Milkie [9] investigated the flow regimes and void fractions for condensation of propane flowing through horizontal tubes with a diameter of 7 mm and 15 mm. Detailed analyses of the video frames were used to develop a new multi-regime void fraction model based on the drift flux model. The model provides improved agreement with the experimental results when compared to correlations in the literature. Lockanathan and Hibiki [10] presented a comprehensive review and analysis of the flow regime, void fraction and pressured drop for downward two-phase flow and pointed out the future research needs in their review. Just to name a few studies of void fraction in straight tubes here. Furthermore, the available prediction models and correlations for the void fraction in the two-phase flow have been extensively developed for straight circular channels [11].

However, studies of the void fraction of gas-liquid two-phase flow in helically coiled channels are very limited. Due to the centrifugal acceleration effect which generating the secondary flow in the main two-phase flow, the flow structure and the relative motion between phases in a helically coiled channel are much more complicated than those in a straight tube. In particular, studies of the void fraction and flow structure for gas-liquid two-phase flow in a helically coiled rectangular channel are very limited in the literature so far. Recently, Liu et al. [15] investigated the characteristics of air-water two-phase flow in a vertical helically coiled rectangular channel and observed the phase distribution and fluid structure using a high speed video system. They indicated that the presence of the secondary flow leading to a complex asymmetry phase distribution for two-phase flow in the helically coiled rectangular channels. They illustrated the flow pattern evolutions in different position of the helically coiled rectangular channels. However, their study does not concern the void fraction in the helically coiled rectangular channels, which is important in understanding the fundamentals of gas-liquid two-phase flow and worth being investigated in such a coiled channel with non-circular shape.

Furthermore, there are many void fraction correlations/models available in the literature. Based on the major three typical models, i.e. homogeneous model, slip flow model and drift flux model, many models and correlations for predicting the void fraction were developed based on these models. Woldesemayat and Ghajar [11] investigated the predictive performance of 68 void fraction models and correlations for straight tube with different orientations. Xue [12] did a comparative work to evaluate the accuracy of 39 models and correlations for calculating void fraction in downward two-phase flow system. Jagan and Satheesh [8] measured void fraction in straight tubes under different inclined angles and compared with five existing correlations. Mandal and Das [13] and Biswas and Das [14] investigated the two-phase pressure drop and the liquid holdup with three varying gas-non-Newtonian two-phase flow for both horizontal and vertical helical coils with circular cross section. They presented the void fraction correlations for helically coiled channel by dimensionless analysis. Furthermore, Xia and Liu [15–17] investigated the effect of liquid holdup on the phase distribution and pressure drop of two-phase flow in helically coiled rectangular channel only by the numerical simulation method. However, nearly all the available void fraction models and correlations of air-water two-phase flow were developed for straight circular tubes. It is unclear if these correlations are applicable to helically coiled rectangular channels. Furthermore, flow regimes are intrinsically related to the corresponding void fractions. It is essential to predict the flow regimes properly using the relevant flow regime map when developing the relevant prediction methods for the void fractions. Several mechanistic flow regime models and maps have been developed for flow regime pattern prediction, i.e. the mechanistic maps and models of Taitel and Dukler [52], Taitel [53] and Zhang et al. [54-56]. These maps and models are generally applicable to straight circular channels. For the flow regimes in the coiled rectangular channels in the present study, it is essential to evaluate the mechanistic flow regime maps and models with the experimental data in such channels. Due to the secondary flow generated in the coiled channels, possible different flow regimes may occur in such channels.

To the authors' knowledge based on the literature review, the experimental data and prediction methods for the average void fraction of two-phase flow in helically coiled channels are limited. Especially, there is no such information in helically coiled channels with