Experimental Thermal and Fluid Science 72 (2016) 75–87

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Interfacial shear in adiabatic downward gas/liquid co-current annular flow in pipes

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ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form 19 October 2015
Accepted 22 October 2015
Available online 28 October 2015

Keywords:
Annular flow
Interfacial friction factor
Interfacial shear stress
Multiphase flow
Pressure gradient
Vertical downward flow

ABSTRACT

Interfacial friction is one of the key variables for predicting annular two-phase flow behaviours in vertical pipes. In order to develop an improved correlation for interfacial friction factor in downward co-current annular flow, the pressure gradient, film thickness and film velocity data were generated from experiments carried out on Cranfield University's Serpent Rig, an air/water two-phase vertical flow loop of 101.6 mm internal diameter. The air and water superficial velocity ranges used are 1.42–28.87 and 0.1–1.0 m/s respectively. These correspond to Reynolds number values of 8400–187,000 and 11,000–113,000 respectively. The correlation takes into account the effect of pipe diameter by using the interfacial shear data together with dimensionless liquid film thicknesses related to different pipe sizes ranging from 10 to 101.6 mm, including those from published sources by numerous investigators. It is shown that the predictions of this new correlation outperform those from previously reported studies.

1. Introduction

A large number of studies have been carried out on vertical air–water two-phase annular flow in pipes. This is not surprising considering the huge importance annular two-phase flow plays in the nuclear, chemical and petroleum industries where it is generally agreed to be one of the most frequently encountered flow patterns. To this end, many studies have been commissioned to investigate annular two-phase flow phenomena with the bulk of published works focussing on co-current upward annular flow. In sharp contrast there have been far fewer studies published on co-current downward annular two-phase flows. This is against the backdrop that co-current downward annular two-phase flow is also often encountered in engineering equipment such as gas absorbers as falling film flow, gas condensate pipelines, refrigeration systems, and in heat transfer equipment like boilers and heat exchangers. What little work is available is dominated by pipes of which the scales are much less than 100 mm in internal diameter. It has been noted that there is no guarantee that the use of models developed for these small pipes will predict large diameter flows well; therefore several reported studies [36,31,37,38,30,39,34,40] have addressed that there is need to expand the knowledge of multiphase flow behaviour to large diameter pipe systems. For example, Oliemans et al. [36] compared entrainment correlations with large diameter test data and concluded there is not much confidence in the predictive value of the correlations. Kataoka and Ishii [31] showed that the application of the conventional drift flux model for pool void fraction prediction to relatively large vessels was only limited to low gas fluxes, and thus had to develop a new correlation for such large systems when annular flow for instance occurs at higher gas fluxes. Disturbance waves which greatly contribute to wall shear stress and are a source of entrained droplets were observed by Azzopardi et al. [8] to be incoherent in large diameter pipes. Careful observations revealed that in large pipes, the waves were not perpendicular to the flow direction but were curved "bow waves". This is in sharp contrast to what is obtained in smaller tubes where the waves are continuous around the tube circumference. The study by Omebere-Iyari and Azzopardi [38] on disturbance wave velocity provided yet strong quantitative indication of pipe diameter effect on the gas–liquid interface behaviour. They established that Pearce's coefficient, which is proportional to wave velocity, increases with pipe diameter such that its value of 0.9 remains fairly constant at large pipe diameters.

The interfacial friction factor has been likened to surface roughness in single-phase fluid flow [9,43,28]. In addition to the wall or skin friction in two-phase flow, interfacial friction as a result of slip between the two phases contributes to the frictional pressure loss. Therefore, the contribution of interfacial friction to the two-phase frictional component increases with increasing slip velocity or as the flow pattern moves from bubbly to annular flow. Klausner

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http://dx.doi.org/10.1016/j.expthermflusci.2015.10.025
0894-1777/

Nomenclature

Roman

A	cross-sectional area [m^2]
D	pipe internal diameter [m]
e	entrained liquid fraction [–]
F	modified Martinelli flow parameter [–]
Fr	Froude number [–]
f	interfacial friction factor [–]
g	acceleration due to gravity [m/s^2]
L	pipe length [m]
P	local pressure [Pa]
ΔP	differential pressure [Pa]
$-\frac{dP}{dz}$	pressure gradient [Pa/m]
Re	Reynolds number [–]
t	film thickness [m]
t^+	dimensionless film thickness defined as a frictional distance parameter: $t_g^+ = t/v_g\sqrt{\tau_i/\rho_g}$ [–]
t^*	Nusselt's dimensionless film thickness defined as: $t^* = t(g/v_l^2)^{1/3}$ [–]
u^*	friction velocity: $u^* = \sqrt{\tau_i/\rho_g}$ [–]
u	phase superficial velocity [m/s]
W	phase mass flow rate [kg/s]
We	weber number [–]
x	gas quality [–]
X	Martinelli parameter [–]
z	axial distance along pipe [m]

Greek

δ	error in quantity indicated in bracket (unit depends on quantity in question)
ε	void fraction [–]
γ	liquid droplet hold up [–]
v	kinematic viscosity m^2/s
μ	dynamic viscosity [kg/s m]
ρ	density [kg/m^3]
σ	liquid surface tension [N/m]
τ	shear stress [Pa]

Subscripts

c	core
g	gas phase
i	interfacial
l	liquid phase
lf	liquid film
s	single phase
sg	superficial gas
sl	superficial liquid
w	wall

et al. [32] pointed out that the correlations of Henstock and Hanratty [27], Andreussi and Zanelli [5], and Asali et al. [7] are the only reported works that proposed relations for determining the downwards interfacial friction factor. Since then, Hajiloo et al. [26] and Dalkilic et al. [20] have developed downflow two-phase friction factor correlations, of which the former correlated data obtained from four different tube diameters ranging from 15.6 to 41.2 mm. The latter used data obtained for refrigerant HFC-134a in an 8.1 mm diameter vertical tube-in-tube heat exchanger and correlated the two-phase friction factor with an equivalent Reynolds number obtained as a function of gas quality and fluid density ratios. The physical correlating parameters used by Hajiloo et al. [26] using the friction length parameter and gas Reynolds number are similar to that earlier used by Asali et al. [7]. This method will further be extended in the present work using data obtained from a 101.6 mm large internal diameter pipe and it is envisaged to improve interfacial friction factor predictions for co-current downward air–water annular flow in large vertical pipelines.

2. Previous studies on downward two-phase interfacial friction factor empirical modelling

A number of empirical friction factor correlations have been put forward by prior investigators. Literature is replete with such correlations proposed for upward gas–liquid flow; however, some recommendations have been made for downward gas–liquid flow systems. The fluid combination used in most cases is air and water. Early downward co-current two-phase friction factor correlations were obtained by Chien and Ibele [13] and Fedotkin et al. [22]. Hajiloo et al. [26] noted that the results of the former study show appreciable qualitative agreement of the liquid and gas flow rates such that for a certain pipe diameter, the friction factor, f, always increases with increasing liquid flow rate but at some point, there is a decrease with increasing gas flow rate. This is also true when the friction data of Bergelin et al. [9], Chung and Mills [14], and Tishkoff et al. [41] is plotted against Re_g the superficial gas Reynolds number. The correlation of Fedotkin et al. [22] is not consistent with the others as it shows progressive decrease in the magnitude of f with increasing Re_g. Conversely, there is generally poor quantitative agreement between these studies. It might be partly due to that the different tube sizes used by each set of investigators greatly affected any agreement.

The correlations found to date factored in the effect of pipe diameter, however, as will be shown later, they do not provide satisfactory enough predictions for pipes of 100 mm and over – the so-called large diameter pipes. Table 1 summarises previous studies of f with the tube diameters given together with the fluid velocity and Reynolds number ranges.

3. Experimental data from a large diameter flow loop

3.1. Description of flow loop

The two-phase Serpent flow loop in the Oil and Gas Engineering Laboratory of Cranfield University is a specially-built test facility used in the study of flow behaviour around upward and downward pipes joined by U-bends. A schematic of this test apparatus is shown in Fig. 1. It is divided into three main parts: the fluid (air and water) supply and metering area, the test area, and the separation section. The flow rig receives measured rates of water and air from the flow metering area to the test rig and finally into the ventilation tank where the air and water are separated. The water is returned back to the storage tank while the air is vented.

The test area consists of the flow loop which is an approximately 20-m long 4-in. (101.6 mm) internal diameter pipeline which includes four ABS plastic vertical upward flowing and downward flowing sections connected by three Perspex 180 degree bends. The two middle 6 m vertical pipes are fitted with various instruments where all data is collected. While the vertical section left of the U is the upward flowing section, the right hand arm of the U is the downward flowing section which is the area of interest of this study where all data was collected. Installed instrumentation on the flow rig are conductance probes used for liquid film