Experimental Thermal and Fluid Science 71 (2016) 25–41

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

The effect of the fluid properties on the wave velocity and wave frequency of gas–liquid annular two-phase flow in a horizontal pipe

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ARTICLE INFO

Article history:
Received 2 April 2015
Received in revised form 4 October 2015
Accepted 8 October 2015
Available online 20 October 2015

Keywords:
Annular flow
Wave velocity
Wave frequency
Viscosity
Surface tension

ABSTRACT

The effects of fluid properties on the wave velocity and frequency of gas–liquid annular two-phase flow were investigated in 26 and 16-mm inner pipe diameters. The liquid viscosity was varied from 1.02 to 6.57 mPa s using water and glycerol solution and the surface tension was varied from 34.0 to 71.7 mN/m using water and butanol solution. The range of superficial liquid and gas velocities were set to 0.05–0.2 m/s and 12–40 m/s, respectively.

In general, the wave frequency decreases with increasing liquid viscosity and decreasing surface tension. The wave velocity decreases with increasing liquid viscosity for all range of superficial gas and liquid velocities. The lower surface tension gives the lower wave velocity for low superficial liquid velocity. For high superficial liquid velocity, however, the wave velocity increases with decreasing surface tension. The wave frequency decreases with the increase of liquid viscosity and the decrease of surface tension, with more significant effects are found at the higher superficial gas and liquid velocities. Comparisons of experimental data with the existing correlations for wave velocity and wave frequency have been carried out and new correlations have been developed with a considerably good agreement with the experimental data.

1. Introduction

Annular flow is one of the most important flow regimes that commonly found in many industrial applications, especially ones involving phase-changes such as in geothermal, power plant, refrigeration, heat exchangers, and process industries. This flow regime is considerably complex, for both vertical and horizontal orientation, and it is characterized by liquid film flows on the inner pipe wall and a gas core containing liquid droplets flows at high velocity. For horizontal orientation, annular flow is characterized by the asymmetric distribution of liquid film, whereas the degree of asymmetry is dependent on the mass flow rates of liquid and gas. The effect of gravity-induced drainage increases the thickness of the liquid film on the bottom surface while reducing it on the top surface. Similarly, the drops concentration will be higher in the bottom part than in the top of the pipe.

In annular flow, two types of wave structures are exist in the liquid film. Those are ripple and disturbance waves. The first is located on the base film and characterized by low velocity, non-coherent, and short lifetime. With the low amplitude surface waves, they create interfacial roughness and, therefore, are responsible for the pressure drop. The second has a larger film thickness, usually forming complete rings in the pipe, travels at a higher velocity, and dominate the interfacial transfer of mass, momentum, and energy [44]. With higher amplitude and relatively long-lived structures along the pipe, disturbance waves are responsible for the entrainment of liquid droplets into the gas core when high velocity gas flows and shears the wave. To investigate the effect of disturbance waves on annular flow, the knowledge of wave velocity, frequency, and spacing are required [46].

The characteristics of the wave in two-phase flow have been studied over decades [2]. It plays an important role in the entrainment of liquid into the gas stream [25,6] which affects the heat and mass transfer in two-phase flow system and safety in nuclear reactors [1]. The roughness and the dynamic properties of the wave also influence the pressure drop and the mixing properties of the flowing liquid. The liquid entrainment in an excessive amount could cause dry-out conditions, in which the liquid film in the pipe

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http://dx.doi.org/10.1016/j.expthermflusci.2015.10.008
0894-1777/

Nomenclature

C	wave velocity (m s^{-1})
C_{fi}	friction coefficient (–)
D	pipe diameter (m)
f	wave frequency (Hz)
Fr	Froude number
g	gravitational acceleration (m s^{-2})
G	mass flux (kg m^{-2} s^{-1})
J	superficial velocity (m s^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
Re	Reynolds number (–)
St	Strouhal number (–)
We	Weber number (–)
x	flow quality (–)
X	Lockhart–Martinelli parameter
X^*	modified Lockhart–Martinelli parameter

Greek letters

ψ	coefficient used in Eq. (3)
ρ	density (kg m^{-3})
η	liquid holdup (–)
σ	surface tension (N/m)
μ	viscosity (Pa s)

Subscripts

exp	experimental
corr	correlation
G	gas
L	liquid
m	modified
SG	superficial, gas
SL	superficial, liquid
W	water

inner wall is completely removed. The pressure drop is an important factor in the investment and operation costs for the simultaneous transportation of gas and liquid in various industries [36,47,56]. Meanwhile, the mixing properties affect the heat and mass transfer [21].

Considerable researches have been carried out for horizontal annular two-phase flow. However, theoretical modeling of horizontal flow is generally less successful than those of vertical annular two-phase flow [52]. Few investigations have been carried out on the flow mechanisms during the horizontal annular two-phase flow in pipelines, and even the fundamental data is still lacking. As a result, many important questions remain unanswered. The effects of liquid properties, especially the liquid viscosity and surface tension, on two-phase flow have also been investigated over decades. Most of the works, however, were aimed for studying its effects on the flow pattern, friction factor and pressure drop, droplet properties, and inception of disturbance waves. The studies of the effects of the liquid properties on the flow pattern have been carried out by Weisman et al. [53], Hand et al. [22], Bousman et al. [8], Furukawa and Fukano [17], Hlaing et al. [23], Tzotzi et al. [51], Matsubara and Naito [31], and Xia and Chai [54]. Its effects on the interfacial friction factor and pressure drop have been studied by Fukano and Furukawa [15], English and Kandlikar [13], Xia et al. [55], Sadatomi et al. [43], and Xia and Chai [54]. The effect of viscosity on the inception of disturbance waves and droplet has been reported by Hall-Taylor and Nedderman [20] and Mori et al. [33]. The effects of surface tension on the drop properties have been reported by Jepson et al. [25], Lopez de Bertodano et al. [29], and Patruno et al. [41]. The studies of the effect of surface tension on the liquid layer characteristics have been carried out by Lioumbas et al. [27,28].

The development of correlations for the wave velocity and wave frequency has been carried out. Based on statistical analysis of waves in 25.2 and 95.3 mm inner diameter pipes using liquids of different liquid viscosity, Andritsos [4] showed that relative wave velocity trend to unity when the gas velocity is high and increases with the increase in liquid viscosity. The relative wave velocity is defined as the ratio of wave velocity to the actual liquid velocity, C/J_L, and the actual liquid velocity is the ratio of liquid superficial velocity to the liquid holdup, $U_L = J_L/\eta$. It is also shown that liquids of higher viscosity give the higher relative wave velocity than that of water.

Ousaka et al. [38] proposed correlations for wave velocity and wave frequency in terms of superficial liquid velocity and gas and liquid Reynolds numbers. In their correlations, the wave velocity and frequency were strongly depended on the superficial liquid velocity and increase with increasing liquid viscosity. The effect of surface tension was not taken into account in both correlations although it has a significant effect on it.

The ratio of film thickness and pipe diameter were also be used to develop the correlation of wave velocity. Paras et al. [40], using pipe diameters of 26 mm, 50 mm, and 95 mm, correlated the wave velocity with the gas superficial gas velocity, film thickness at the bottom, and pipe diameter. The effect of superficial gas velocity was considerably significant and the direct effect of the superficial liquid velocity was not explicitly noticed in this correlation. Its effect was, however, implicitly taken into account in term of liquid film thickness at the bottom of the pipe. The effects of liquid properties on the wave velocity were not expressed explicitly in this correlation.

To investigate the effect of liquid viscosity on the disturbance wave characteristics, Mori et al. [32] conducted experiment a series of experiments using three kinds of liquid with different kinematic viscosities in 19.2 mm vertical tube. When the liquid viscosity increase, the region where the gas–liquid interface was covered by ripple became wider. In addition, close inspection to their probability distributions of wave velocity showed that the wave velocity decrease with increasing liquid viscosity. The effect of liquid viscosity on the inception of disturbance wave and droplet has also been investigated by Mori et al. [33]. Using five different liquid kinematic viscosities, they showed that the superficial liquid velocity at the inception of disturbance waves increases as the liquid viscosity increases.

The effects of liquid viscosity on interfacial shear stress and frictional pressure drop in vertical upward gas–liquid annular flow in 26 mm inner diameter pipe have been investigated by Fukano and Furukawa [15]. The liquid viscosity was varied by using water and glycerol solutions. They reported that the passing frequency of large wave decreases significantly with increasing liquid viscosity.

Kumar et al. [26] proposed a correlation for the wave velocity in a vertical duct by equating the friction factor at gas–liquid interfacial. In their correlation, the wave velocity was expressed as a function of the superficial gas and liquid velocities, gas and liquid densities, and gas and liquid friction factor. To improve this correlation, Mantilla [30] included the effect of liquid viscosity. He also proposed correlation for wave frequency in term of Strouhal number against modified Lockhart–Martinelli parameter.

Based on experimental results by using three different pipe diameters in horizontal orientation, Schubring and Shedd [46] proposed correlation for wave velocity as a function of liquid Reynolds number. Correlation for wave frequency was also proposed as a