Experimental Thermal and Fluid Science 62 (2015) 85–98

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Interfacial waves in stratified viscous oil–water flow

Marcelo S. de Castro [a,*], Oscar M.H. Rodriguez [b]

[a] Department of Energy, Faculty of Mechanical Engineering, University of Campinas (UNICAMP), Av. Mendeleyev, 200, 13083-860 Campinas, SP, Brazil
[b] Department of Mechanical Engineering, Sao Carlos School of Engineering, University of Sao Paulo (USP), Av. Trabalhador São Carlense, 400, 13566-970 Sao Carlos, SP, Brazil

ARTICLE INFO

Article history:
Received 8 October 2014
Accepted 3 December 2014
Available online 12 December 2014

Keywords:
Liquid–liquid flow
Oil–water flow
Stratified flow pattern
Interfacial wave structure
Experiments
Wave geometry
Correlation

ABSTRACT

The analysis of the interfacial wave properties is an important point in understanding of many aspects of separated-flow patterns (annular and stratified). One may cite flow pattern stability, pressure drop and heat transfer as characteristics affected by the wave properties. Previous studies have shown that the phenomenon of flow pattern transition in stratified flow can be related to the interfacial wave structure (problem of hydrodynamic instability). The study of the wavy stratified flow pattern requires the characterization of the interface, *i.e.*, average wave shape, wave speed, amplitude and wavelength as a function of flow properties. Studies on waves in stratified liquid–liquid flow are scanty, even more when related to viscous oils. This article offers new experimental data on interfacial waves collected in a glass test line of 12 m and 0.026 m i.d., oil (density and viscosity of 854 kg/m^3 and 0.3 Pa s at 20 °C, respectively) and tap water as the working fluids; the stratified flow was filmed with a high speed video camera at several inclinations from horizontal (−5°, 0°, 5°, 10°). New experimental data and available literature data of interfacial waves in oil–water flow were collected, analyzed and correlated to the flow properties by dimensionless numbers of Reynolds, Froude and Weber. A second-order Fourier series is proposed to model the wave shape. The correlations can be used to predict the average wave geometry and wave speed of typical oil–water interfacial waves within a significant range of superficial velocities and pipe inclinations. Considering the simplicity of the proposed correlation, the agreement between data and predicted wave is encouraging.

1. Introduction

In industrial processes the presence of multiphase flows is very common. In multiphase flows, the way that the immiscible phases are geometrically arranged in a pipe, *i.e.* the flow pattern, is important in defining the way that each flow should be modeled. For example, dispersion should be analyzed by the homogeneous model, vertical slug flow by the drift flux model and stratified and annular flows via the separated flow model. If the longitudinal dimension of a pipe is relatively larger than the others the one-dimensional approach is usually applicable. Important characteristics of flow, as pressure drop, heat transfer, corrosion and structural vibration, are examples of topics that depend on the geometrical configuration of the immiscible phases, or flow patterns [1]. The interest in liquid–liquid flow has increased since offshore oil production is on the rise over the last years, although investigations on such flows are not as common as those on gas–liquid flow. The stratified liquid–liquid flow is present in directional oil wells and pipelines and is characterized by the heavier and lighter phases located at the bottom and top part of the pipe, respectively, divided by an interface that can be smooth, wavy or present droplets of one phase into the other. The understanding and characterization of the interfacial wavy structure allow for the correct modeling of the flow; as already pointed out by Wallis [2] and his equivalent-sand-roughness concept for annular gas–liquid flow. Recently, it was extended to stratified liquid–liquid flow by Rodriguez and Baldani [3]. According to those authors the wavy structure impacts on the interfacial friction factor and, consequently, on the pressure drop and in-situ holdup predictions.

The interfacial-wavy structure was studied in gas–liquid flow by Bontozoglou and Hanratty [4] and Bontozoglou [5]. One of the findings was that the two-phase friction factor of wavy stratified flow can be about fifty times as high as the friction factor of smooth stratified flow. Li et al. [6] also studied the gas–liquid stratified flow pattern and showed that the interfacial waves have significant influence on heat transfer and pressure drop. The interfacial wavy structure of separated flows in gas–liquid systems and its influence on the flow have been further studied by a few researches [7]. The effect of interfacial waves on the friction factor with or without gravity in annular flow, the role played by stratified-flow parameters on slug flow formation and a numerical solution for stratified

* Corresponding author. Tel.: +55 19 35213264; fax: +55 19 32893722.
E-mail address: mcastro@fem.unicamp.br (Marcelo S. de Castro).

http://dx.doi.org/10.1016/j.expthermflusci.2014.12.003
0894-1777/

Nomenclature

Uws	water superficial velocity, m/s
Uos	oil superficial velocity, m/s
V_w	water *in-situ* velocity, m/s
V_o	oil *in-situ* velocity, m/s
D	pipe's internal diameter, m
Dh	hydraulic diameter, m
g	gravitational acceleration, m/s^2
Froude (Fr^*)	modified two-phase Froude number, dimensionless
Weber (We^*)	modified two-phase Weber number, dimensionless
Reynolds (*Re*)	Reynolds number, dimensionless
c	wave's speed, m/s
y	ordinate, mm
x	abscissa, mm
QCV	quick-closing-valves technique
h_w	water height
S	standard deviation

Greek

θ	inclination of the pipeline, rad
ε	volumetric fraction, dimensionless
α	wave amplitude, mm
λ	wavelength, mm
σ	interfacial tension, N/m

Subscript

w	water-phase
o	oil-phase
m	mean
α	relative to the wave amplitude
λ	relative to the wavelength
c	relative to the wave speed

Superscript

*	normalized coordinates

flow that considers an effective roughness due to the waves have been the research subject of, respectively, Wang et al. [8,9], Dyment and Boudlal [10] and Berthelsen and Ytrehus [11]. Also, Andritsos and Hanratty [12,13] and Andritsos [14] had the interfacial wave in horizontal gas–liquid stratified (water and glycerin) flows as subject of research. Those authors measured the interfacial wave amplitude and speed via conductive probes; they found that the interfacial friction factor increases rapidly with the rise of high amplitude interfacial waves. In flows with low viscosity liquids the wave amplitude increases and the wavelength decreases with the increase of the gas flow rate; with high viscous liquids the increase in the gas flow rate make the wave crest curved.

The wavy stratified flow in liquid–liquid flows was experimentally observed by Chakrabarti et al. [15,16] using water and kerosene as working fluids. Accordingly to Charles and Lilleleht [17] the rise of waves in co-current liquid–liquid flows is related to the transition from laminar to turbulent of the less viscous phase. In the case of viscous oil–water stratified flow, Castro et al. [18] found that the wave characteristics might be related to a modified Froude number. Sotgia et al. [19] affirmed that the wavelength of the interfacial wave in viscous oil water-flow decrease as the water superficial velocity decreases. Yusuf et al. [20] studied the effect of the oil viscosity in flow pattern classification, pressure gradient and phase inversion in oil–water flows by comparing their results with other from literature. They observed that the interfacial wave amplitude increase with increasing the water superficial velocity.

Looking at the cross-sectional interface shape, Brauner et al. [21] compared the gas–liquid and liquid–liquid interfaces in stratified flow. In the former a flat interface is more likely because the flow is dominated by gravitational forces, whereas the latter tends to present a curved interface since interfacial tension also plays a role. The curvature of the interface depends on pipe geometry, physical properties of the fluids and wettability [22] and Rodriguez and Baldani [3]. The idea of a curved interface was used by Brauner et al. [23] to propose new closing equations and predict holdup and pressure drop in stratified liquid–liquid laminar flow. An experimental work was performed by Raj et al. [24] and those authors confirmed that for liquid–liquid flow the consideration of a curved interface provides better predictions, improving some correlations earlier developed based on the work of Taitel and Dukler [25] (for instance [26,27]).

An experimental work on characterization of liquid–liquid flow patterns can be seen in Trallero [26] and Trallero et al. [27], where data for horizontal flow were presented including stratified and semi-stratified flow, dispersions and emulsions. Those authors did not differentiate wavy stratified from stratified with mixing at the interface. Elseth [28] presented a more detailed horizontal oil–water flow pattern classification, observing the wavy stratified flow, and dividing Trallero's patterns into several sub-patterns. Alkaya et al. [29] continued the work of Trallero et al. [27], but now introducing the effect of pipe inclination. A wavy stratified flow pattern was reported. All the quoted authors have dealt with relatively low viscosity oils. On the other hand, Bannwart et al. [30] studied a horizontal very viscous oil–water flow and reported the stratified flow pattern among others. Interfacial waves in liquid–liquid stratified flow have been spotted, but details on the wave's geometrical properties are rarely given.

The study of wave motion is a vast scientific topic; one can cite, for instance, ocean waves in deep or shallow waters. The study of interfacial wave behavior in two-phase flow is a relatively recent research topic, but of significant importance, since key parameters as holdup and pressure drop are expected to depend on the wavy structure. In addition, an exponential increase in time or space of wave amplitude might cause instabilities and, eventually, flow pattern transition [2]. The one-dimensional two-fluid model has been suggested as a tool for analyzing separated flows [31–34] and it has been applied together with the linear hydrodynamic stability theory and the concept of an exponential increase of an interfacial perturbation wave. The study of the hydrodynamic stability of separated liquid–liquid flows, and therefore transition to dispersed flow, has been carried out by Brauner [35] and Brauner and Maron [36,37], Trallero [26], Brauner et al. [21,23], Rodriguez et al. [38] and Rodriguez and Bannwart [39]. Crowley et al. [40] studied the hydrodynamic stability of separated flows through a relation between kinematic and dynamic interfacial waves. However, those authors applied their theory for gas–liquid flow only.

There are a few studies in the literature on interfacial waves in core-annular flow. In Ooms [41], Ooms et al. [42] and Oliemans [43] it was demonstrated that the existence of waves is fundamental for the stability of the core-annular flow pattern. Feng et al. [44], working with numerical simulation, also found that waves are indispensable for the hydrodynamic stability of such liquid–liquid separated flow pattern. Soon after, several theoretical and experimental papers have been produced by the group of Joseph in which it is alleged that without the presence of waves, there is not core-annular flow [45–48]. Rodriguez and Bannwart [49] measured wave speed, amplitude and wavelength in core-annular flow