International Journal of Multiphase Flow 84 (2016) 279–291

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

A unified model to predict flow pattern transitions in horizontal and slightly inclined two-phase gas/shear-thinning fluid pipe flows

Davide Picchi, Pietro Poesio*

Università degli Studi di Brescia, Dipartimento di Ingegneria Meccanica e Industriale, Via Branze 38, 25123 Brescia, Italy

ARTICLE INFO

Article history:
Received 13 February 2016
Revised 13 April 2016
Accepted 16 April 2016
Available online 20 April 2016

Keywords:
Shear-thinning fluid
Flow pattern transition
Non-linear stability
Stratified flow
Annular flow
Dispersed flow

ABSTRACT

Flow pattern transitions in two-phase gas/shear-thinning fluid pipe flows represent a key aspect during oil transportation and in chemical industry. In this paper a unified model to build a complete flow pattern map is proposed and models to predict flow patterns are provided. The transitions from stratified flow regime are investigates performing a linear stability and well-posedness analyses, and a non-linear stability analysis. The steady and fully developed two-fluid model for the annular flow is proposed and validated; the flow pattern transition from the annular flow is discussed considering, also, the structural stability. The transition to dispersed flow, the slug stability approach, and criteria to obtain the slug/plug and the bubbly/plug boundaries are considered. A sensitivity analysis on the effect of the rheology of the shear-thinning fluid on flow pattern boundaries is carried out and, then, the complete flow pattern maps are validated with data taken from the literature showing a good agreement.

1. Introduction

Gas/liquid mixtures in pipes, where the liquid exhibits a non-Newtonian shear-thinning behaviour, are frequently encountered in the design of industrial processes, but these flows have not been extensively studied. The flow pattern influences the transport rates, so, an analysis of flow pattern transitions is necessary for a complete description these flows. Depending on the flow conditions, different flow patterns can be identified, see Chhabra and Richardson (2008).

The first experimental investigations on gas/non-Newtonian liquid fluid flows were reviewed by Chhabra and Richardson (1984), references are therein, where data taken from the literature were reported and a modified version of the Mandhane et al. (1974) correlation for flow pattern transitions was proposed. More recently, Xu et al. (2007) studied air/shear-thinning fluid flows in inclined pipes for different pipe diameters and inclination angles: the different flow patterns were identified and flow pattern transitions were compared to the criteria for gas/Newtonian fluid flows given by Barnea (1987).

The transition boundaries for gas/shear-thinning fluid stratified flow were obtained for the first time by Picchi et al. (2014), where a linear stability and a well-posedness analyses on the set of governing equations were developed. These criteria were validated with a new set of experimental data (air and CMC-water solutions were chosen as test fluids) by Picchi et al. (2015) and were used to investigate the stability of multiple hold-up solutions by Picchi and Poesio (2016).

Considering the transition to slug and to dispersed flow regimes, only models valid for gas/Newtonian fluids systems are present in the literature, such as the stability of the slug unit given by Hurlburt and Hanratty (2002) and the criteria for transition to dispersed flow by Brauner (2001). The annular flow regime is always unstable for the interfacial stability analysis, and therefore, the transition is due to the blockage of the gas core, see Barnea (1987), and to the instability of the structure, see Barnea and Taitel (1989,1990,1994b).

In the present study, a unified model to predict flow pattern transition boundaries is presented for the case of gas/shear-thinning fluid flows for the first time. The linear and well-posedness stability analyses (Section 2.1) was previously derived by Picchi et al. (2014), and, here, a sensitivity analysis on the effect of the rheology of the shear-thinning liquid on stratified flow stability boundaries and the trends of the variation of the amplification as a function of the wave number are provided to complete the previous study. The non-linear stability analysis is carried out for gas/non-Newtonian fluid stratified flow for the first time in Section 2.2, while the results are commented in Section 3.2. In Sections 2.4 and 2.5 the transition boundary to dispersed flow and the slug stability analysis are extended to gas/shear-thinning fluids systems. In addition, a new version of the steady fully

* Corresponding author Tel.: +39 030 3715646.
E-mail addresses: davide.picchi@gmail.com (D. Picchi), pietro.poesio@unibs.it (P. Poesio).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.04.010
0301-9322/

developed two-fluid model for the annular flow regime is derived and the flow pattern transition from annular to slug flow regime is discussed in Section 2.3. Finally, the proposed criteria are validated with data taken from the literature in Section 3.4, while in Section 4 the conclusions are presented.

2. Theoretical considerations: flow pattern transition criteria

2.1. Linear interfacial stability and well-posedness analyses of the stratified flow regime

The stability of the stratified flow regime is checked carrying out an interfacial linear stability and a well-posedness analyses on the two-fluid model governing equations. Under long wave hypothesis, Picchi et al. (2014) obtained transition boundaries for gas/power-law fluid stratified flow: the 'zero neutral stability' boundary (ZNS) and the 'zero characteristics' boundary (ZRC). The question of what flow pattern regime results from these instability analyses (slug or annular) for gas/power-law fluid mixtures will be the focus of this Section.

Brauner and Moalem Maron (1991) and Barnea and Taitel (1994b) proposed a complete description of the behaviour of the interface due to the linear instability analysis for gas–Newtonian fluid pipe flows. Here, this approach is extended to gas/shear-thinning fluid stratified flows. The ZNS line bounds the region of existence of stable smooth stratified flow (SS); the buffer region between the ZRC and the ZNS boundaries gives a region where finite interfacial disturbances exist (wavy stratified flow, SW), but these disturbances can produce a transition if the liquid level is high enough for waves to bridge the pipe. Taitel and Dukler (1976) consider $h/D = 0.5$ as the liquid level sufficient to the bridging of the pipe: if $h/D > 0.5$ (high liquid level), the ZNS boundary gives a transition from smooth stratified to slug flow (SL), and, if $h/D < 0.5$ (low liquid level), the ZNS boundary gives a transition from SS to SW and the ZRC boundary the transition from SW to A (annular flow).

In Section 3.1 a sensitivity analysis on the effect of the rheology of the shear-thinning liquid on these boundaries is presented and in Appendix A the full expressions for the calculation of the ZNS boundary, extending the work by Picchi et al. (2014), are provided.

2.2. Non-linear interfacial stability of the stratified flow regime

The linear stability analysis considers modal infinitesimal disturbances of the interface and gives a necessary (but not sufficient) condition for the existence of the smooth stratified flow regime; however, it gives no information on the evolution of the interface due to finite disturbances. A non-linear stability analysis of gas/Newtonian fluid systems was performed by Crowley et al. (1992), Barnea and Taitel (1994a,1994b,1994c), Guo et al. (2002), and Salhi et al. (2010), where most of the results of the linear stability analysis were confirmed. In this section, the non-linear stability analysis is extended to study the response to finite disturbances for gas/shear-thinning fluid stratified flow.

The non-linear stability analysis is carried out performing numerical simulations with the method of characteristics, which can accurately simulate the wave propagation without distortion. Following the approach by Barnea and Taitel (1994c), instead of the rigorous set of governing equations, a simplified formulation, assuming the gas in a quasi-equilibrium condition (the gas velocity is much larger than the liquid one and the dynamic response of the gas is very quick), is considered

$$\frac{\partial h}{\partial t} + U_l\frac{\partial h}{\partial x} + \frac{A_l}{A_l'}\frac{\partial U_l}{\partial x} = 0, \tag{1a}$$

$$\frac{\partial U_l}{\partial t} + U_l\frac{\partial U_l}{\partial x} + G\frac{\partial h}{\partial x} - \frac{\sigma}{\rho_l}\frac{\partial^3 h}{\partial x^3} + E = 0, \tag{1b}$$

where

$$G = \frac{(\rho_l-\rho_g)g\cos\beta}{\rho_l} - \frac{\rho_g A^2 U_{gs}^2 A_l'}{\rho_l A_g^3}, \quad E = -\frac{\Delta f_{gl}}{\rho_l}, \tag{2}$$

$h(t, x)$, $U_l(t, x)$, σ, ρ_l, ρ_g, β, g, A, A_l, and A_g are the liquid height, the liquid phase velocity, the surface tension, the liquid density, the gas density, the pipe inclination angle (positive for downward inclined flow), the gravity acceleration, the pipe cross section, the liquid flow cross section, and the gas flow cross section, respectively. $A_l' = dA_l/dh$ and Δf_{gl} is the RHS of the combined momentum equation for the stratified flow and includes the modelling of the wall and interfacial shear stresses, see Picchi et al. (2014) for details.

The simulations start from a steady fully developed equilibrium configuration upon which a solitary wave is added. The surface tension is neglected ($\sigma = 0$): σ does not affect the linear stability analysis under the long wave hypothesis. The results of the numerical simulations are described in Section 3.2, while the details about the numerical scheme and the boundary conditions used are reported in Appendix B.

2.3. Annular flow regime

2.3.1. Two-fluid model for gas/shear-thinning fluid annular flow

The steady fully developed two-fluid model for concentric annular flows has not been presented in the literature for the case of gas/shear-thinning fluid systems. The combined momentum equation for this case yields

$$\Delta f_{annular} = \frac{\tau_i S_i}{A}\left(\frac{1}{\epsilon_l} + \frac{1}{\epsilon_g}\right) + (\rho_l - \rho_g)g\sin\beta - \frac{\tau_l S_l}{A\epsilon_l} = 0, \tag{3}$$

where $\epsilon_{l,\,g}$ is the liquid or gas hold-up, β is the inclination angle (positive for downward inclined flow). The liquid wall shear stress τ_l and the interfacial shear stress τ_i are expressed as,

$$\tau_l = \frac{1}{2}\rho_l f_l U_l^2, \qquad \tau_i = \frac{1}{2}\rho_g f_g U_g^2. \tag{4}$$

The friction factor for the liquid is the one calculated for a power-law fluid in analogy to the single phase flow

$$f_l = C_l Re_l^{-m_l}, \qquad Re_l = \frac{D_l^n U_l^{2-n}\rho_l}{m8^{n-1}\left(\frac{1+3n}{4n}\right)^n} \tag{5}$$

where the constants are chosen as $C_g = C_l = 16$, $m_g = m_l = 1$ for the laminar flow regime and as $C_g = C_l = 0.046$, $m_g = m_l = 0.2$ for the turbulent flow regime; we consider the laminar-turbulent transition criteria for a power-law fluid given by Chhabra and Richardson (2008).

In this work, it is chosen to use the Blausius correlation for the friction factor also for shear-thinning fluid, as previous done by Heywood and Charles (1979), Xu et al. (2007), Picchi et al. (2014, 2015), and Picchi and Poesio (2016). Dodge and Metzner (1959) proposed a correlation based on experimental results and theoretical considerations to estimate the friction factor of a fully developed turbulent power-law fluid single phase flow, but this correlation fails to predict the friction factor when CMC-water solutions are considered as test fluids. Dodge and Metzner (1959) put in evidence that for the case of CMC-water solutions Dodge and Metzner's correlation does not give satisfactory results and an evident effect of the diameter is present. Therefore, Dodge and Metzner (1959) claimed that their correlation should be used only for the case of non-Newtonian slurries and it may not be a suitable model for the case of CMC-water solutions. Thus, since most of the