International Journal of Multiphase Flow 86 (2016) 10–20

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Two-phase slug flows in helical pipes: Slug frequency alterations and helicity fluctuations

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ARTICLE INFO

Article history:
Received 26 February 2016
Revised 4 July 2016
Accepted 10 July 2016
Available online 29 July 2016

Keywords:
Helical pipes
Slug flow
Slug frequency
Volume of fluid VOF
Helicity density
Helicity fluctuations

ABSTRACT

Air-water numerical simulations in the slug flow regime have been performed in horizontal helical pipes and the effects of geometries on the flow regime have been investigated. Depending on the length of the helix, outlet slug frequencies have been reduced with various degrees of efficiency. Correlations between mean tangential velocity and helicity density fluctuations have been identified and investigated qualitatively. These flow fields show smaller time scales than those obtained in volume fractions fluctuations. Shifts observed in the tangential velocity and mean helicity fluctuations to smaller time scales (high frequencies) are associated with regime transitions. For a slug flow undergoing a continuous transition to the annular flow regime, it is shown that the presence of slower (low frequencies) helicity fluctuations is attributed to the variations in the axial velocity. Finally, the analysis of the helicity at gas-liquid interface confirms the presence of the mixing zone at the slug front.

1. Introduction

Helical coiled pipes are commonly used in industrial applications such as power generation, process plants, refrigeration and heat recovery systems, pharmaceutical and food industries. Related published work is available, such as the one from Naphon and Wongwises (2006), where the authors reviewed investigations on various flows in curved lines.

Pressure drop and two phase friction factors in helical lines has received considerable attention to predict transition to turbulent regimes, see Xin et al. (1997) and Zhao et al. (2003). Simulations from Vashisth and Nigam (2009) and Saffari and Moosavi (2014) predicted void fraction distribution, friction factors and velocity profiles as well as shear stress in vertical coil air-water flow systems. Murai et al. (2006) conducted experiments with a vertical set up; they concluded that the transition from bubbly to plug flow is quickened and that pressure fluctuations in the slugs body present lower amplitudes with higher frequencies than in gas bubbles. Experiments on boiling flow in small diameter coils by Cioncolini et al. (2008) showed that heating effects are adequately fitted using a modified Lockhart–Martinelli correlation. A similar approach was conducted by Mandal and Das (2002) with various coil diameters and flow rates when considering isothermal conditions.

To understand the physical mechanisms involved in the inception of turbulence in coiled devices, investigations have been carried out by Germano (1982). He concluded that at low Reynolds number, curvature and torsion appear to have first and second order effects on the transition to turbulent flows. Recently, Ciofalo et al. (2014) showed that torsion has little influence on turbulence, while an increase in curvature leads to confined fluctuations near outer wall regions.

It is acknowledged by Narasimha and Sreenivasan (1979), and Sreenivasan and Strykowski (1983), that transitions to turbulent flow regimes are delayed in helical lines and occur at Reynolds numbers well above the level required for a similar straight pipe. This is largely attributed to secondary re-circulations. Furthermore, numerical studies by Hüttl and Friedrich (2000) showed that turbulence is inhibited by high curvature. The work from Di Piazza and Ciofalo (2011) confirmed the occurrence of a transitional unsteady regime between the stationary and the turbulent state; they associated this intermediate state to Dean travelling waves.

The classical theories of turbulence are dominated by the concept of the energy cascade to the small scales as postulated by Kolmogorov (1941). However, it was discovered by Moreau (1969) and (Moffatt, 1969) that helicity has also an important role in the dynamics of fluids with large structures. It was shown that the *joint cascade* of both energy and helicity to small scales takes place if the system has large helical scales, see for example

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.07.013

Brissaud et al. (1973) and Kraichnan (1973). Several scientists such as Rogers and Moin (1987), Polifke and Shtilman (1989), Levich et al. (1991), Yokoi and Yoshizawa (1993), Levich (2009), speculated that helicity fluctuations are fundamental to turbulence.

The control of flow regimes in pipelines is highly important for petrochemical industries. To that end, laboratory and field experiments are commonly carried out with various devices and tools to obtain accurate predictions. Slug flow regimes are frequently encountered at industrial scales. In the field, they are mainly due to the topology of the terrain (severe slugging) and may occur at low flow rates, (De Henau and Raithby, 1995). Slug flows are a concern for the integrity of the production facilities. Fabre and Liné (1992) explained that “the slug flow pattern results in sequences of long bubbles almost filling the pipe cross-section, successively followed by liquid slugs that may contain small bubbles”. Studies in this field of research include the mathematical modeling of slug predictions, the experimental slug characterizations and the detailed mechanisms of slug inceptions. A comprehensive investigations on gas-liquid slug flows can be found in Dukler and Hubbard (1975), Moalem Maron et al. (1991), Andreussi et al. (1993) and Kadri et al. (2010). An extended analysis is available in Hurlburt and Hanratty (2002). The intermittency and the statistical character of slug flow regimes are demonstrated and commonly recognised through various publications, see Nydal et al. (1992), Paglianti et al. (1996), Gopal and Jepson (1997) and van Hout et al. (2001).

Multiphase flow modelling and slug flow regimes (in particular in one dimensional codes) are widely approached using multi-fluid models, see Bonizzi and Issa (2003), Issa and Kempf (2003), Gourma and Jia (2015), for example. In a three dimensionnal linear pipe, a CFD approach with a level set model is adopted in Lakehal et al. (2012) while a Volume of Fluid (VOF) model described in Bartosiewicz et al. (2008), Febres and Nieckele (2010) and more recently in Lu (2015), is validated for predicting a slug flow regime.

Engineers have designed new forms of tubing that can be used as separators in multiphase flows or as slug regime controllers. Such sub-systems can be used as a compact conditioning device (Di Matteo, 2003; Vidnes and Engvik, 2014). The flow regime can be altered by damping slugs partly or totally. In industrial applications, pipelines usually have diameters greater than 50 mm with elongated coiled sub-systems and low amplitude ratio with high curvatures.

This work is not directed to perform statistical analysis on slug characteristics such as frequencies, lengths and velocities. The objective is to gain some insight into slug flow interactions with helical sub-systems through the investigation of several aspects: i.) analyse the slug frequency alterations based on the length of the helical devices, ii.) establish qualitative correlations between mean tangential velocity and helicity density fluctuations, iii.) justify the appearance of small time scales (high frequencies) and large time scales (low frequencies) in the mean helicity density histograms and their link to flow regimes, iv.) analyse the gas-liquid helicity density to predict zones of low helicity intensity (high turbulence intensity).

Simulations described here were conducted with the volume of Fluid model (VOF) and the $k-\epsilon$ turbulence model embedded in the CFD package (ANSYS, 2006).

2. Mathematical model

2.1. The volume of fluid model

The volume of fluid model originated by Nichols et al. (1981) is implemented in most commercial CFD software. This model is based on the assumption that two or more fluids are not inter-penetrating. Variables and properties in each cell are functions of the phase fractions, as detailed in the (ANSYS, 2006) user guide. Based on this definition, the continuity equations for liquid and gas volume fractions α_l and α_g can be written as:

$$\partial_t \alpha_i + \nabla \cdot (\alpha_i\ \vec{u}) = 0\ , \tag{1}$$

where the subscript i denotes either the liquid (l) or the gas (g) phase. The momentum equation uses a single velocity field $\vec{u}$ acting on the mixture with a density $\rho = \alpha_g \cdot \rho_g + \alpha_l \cdot \rho_l$ and a viscosity $\mu = \alpha_G \cdot \mu_g + \alpha_l \cdot \mu_l$.

The momentum balance in conservative form is:

$$\partial_t \rho\vec{u} + \nabla \cdot (\rho\vec{u}\vec{u}) = -\nabla p + \nabla \cdot \tau + \rho \cdot \vec{g} + \rho \cdot \vec{F} \tag{2}$$

where, τ is the deviatoric stress tensor, given by:

$$\tau = \mu \cdot (\nabla\vec{u} + \nabla\vec{u}^T) \tag{3}$$

with p the pressure. The last term on the right hand side of Eq. (2) represents the interfacial surface tension F between phases which can be expressed as:

$$F = \sigma_{ij} \cdot \frac{\kappa_i \cdot \nabla\alpha_i}{\frac{1}{2}(\rho_i + \rho_j)}\ , \tag{4}$$

and Indices i and j represent again the two phases, σ_{ij} is the surface tension coefficient, and κ_i is the curvature at the interface where the surface tension is calculated.

2.2. The $k-\epsilon$ turbulence model

The $k-\epsilon$ turbulence scheme belongs to the two-equation eddy-viscosity turbulence model family. It has been used in industry for decades due to its good compromise between numerical demands and stability. The scheme is semi-empirical. All fields are decomposed as $\vec{\psi} = \overline{\vec{\psi}} + \vec{\psi}'$, where the first term stands for the large scale (averaged) and the second term represents the fluctuating part. Hence two additional transport equations must be solved to compute the Reynolds stresses: the first one for the turbulent kinetic energy k, and the second for the rate of turbulence dissipation ϵ:

$$\partial_t \rho \cdot k + \nabla \cdot (\rho\ \bar{u}\ k) = \nabla \cdot ((\mu + \frac{\mu_t}{\sigma_k})\nabla k) + G_k - \rho \cdot \epsilon \tag{5}$$

$$\partial_t \rho \cdot \epsilon + \nabla \cdot (\rho\ \bar{u}\ \epsilon) = \nabla \cdot ((\mu + \frac{\mu_t}{\sigma_\epsilon})\nabla\epsilon) + C_1 \cdot \frac{\epsilon}{k} \cdot G_k + C_2 \cdot \rho \cdot \frac{\epsilon^2}{k} \tag{6}$$

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Quantities C_1, C_2, σ_ϵ and σ_k are empirical constants. The turbulent viscosity μ_t is derived from k and ϵ and involves an experimental constant $C_\mu \simeq 0.09$:

$$\mu_t = \rho \cdot C_\mu \cdot \frac{k^2}{\epsilon} \tag{7}$$

The source term of turbulence G_k appearing in Eqs. (5) and (6), is a function of the turbulent viscosity and velocity gradients:

$$G_k = \mu_t \cdot (\nabla\bar{u} + \nabla\bar{u}^T) \cdot \nabla\bar{u}^T - \frac{2}{3}k \cdot \nabla\bar{u} \tag{8}$$

Transport equations are solved for k and ϵ, the turbulent viscosity μ_t is computed and the Reynolds stresses are determined and substituted into the momentum equations. The new velocity components are used to update the turbulence generation term G_k, and the process is repeated.