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Dimensionless oil-water stratified to non-stratified flow pattern transition

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ABSTRACT

In this paper a unified approach for the transition criterion from stratified to non-stratified oil-water flow is explained. The inviscid Kelvin-Helmholtz stability (IKH) analysis for gas-liquid flow was extended for liquid-liquid flow such that it is exactly matching the liquid-liquid stability analysis from literature. The effect of the imposed factor on the IKH is discussed in detailed in this paper. A dimensionless stratified to non-stratifed transition criterion is developed which gives more insight and clear understanding of the real parameters affecting the stratified to non-stratified flow pattern transition. The dimensionless form of the criterion enable sub-classifications of the oil-water stratified flow into the well-known sub-regimes, namely, Stratified (ST), Wavy Stratified (SW) and Stratified with mixing at the interface (ST-MI). A new prediction approach for the transition from ST to ST-MI based on Froude number is proposed and showed an excellent agreement with experimental data from literature for near-horizontal pipe configurations.

1. Introduction

Oil-water flow in pipes is commonly seen in petroleum industries. Oil and water as two immiscible liquids are transported in pipes over long distances (Pereyra et al., 2013). Oil-water flow patterns predictions are very necessary for the oil industry. Several studies revealed that a stratified flow pattern usually exists in oil-water pipelines due to the separation of oil from water along the pipe during transportation at low velocities. This may cause bottom of the pipe corrosion problems and leads to pipeline failure. Flow pattern determination is needed for optimizing the process of injecting corrosion inhibitors and other chemicals. Moreover, prediction of the flow pattern in pipes is very crucial for calculating the pressure drop along the pipe and for optimum pipeline design and maintenance. Despite of the great importance of oil-water flow pattern predictions, not many studies are available in literature. Xiao-Xuan (2007) in his review paper demonstrated that there is no generalized flow pattern map for liquid-liquid flow in pipes. In addition, it was shown that the available data in literature related to flow pattern transition for oil-water flow is very limited.

Brauner and Maron (1992a, 1992b) studied the transition from stratified liquid/liquid flow to non-stratified flow in a horizontal pipe. The stability analysis was structured based on the linear stability of stratified flow of two immiscible liquids and the equation of two-fluid model. Then, two criteria for predicting stratified to non-stratified transition were developed. The first one was called zero neutral stability (ZNS) and the second was called the zero real characteristics (ZRC). However, the same two criteria can be generated from the standard Kelvin-Helmholtz (KH) stability analysis for two-phase flow.

Trallero (1995) investigated the interfacial stability of oil-water flow with two kinds of linear stability analyses: the first is the viscous KH analysis (VKH) based on the two-fluid model which takes into account the shear stress. The second is the inviscid KH analysis (IKH) for which the viscous term is ignored. In fact ZNS and ZRC analysis are comparable to VKH and IKH analyses when the interfacial-tension terms are cancelled.

Fairuzov (2001) investigated the stability analysis of oil-water stratified flow in inclined pipes. Two criteria were developed based on the two-fluid model. The first criterion is the neutral stability condition, when the turbulent regime exists in both phases. The zero-neutral-stability line is attained by equating the wave number to zero (long wave approximation). The second criterion is basically the classical inviscid Kelvin-Helmholtz, IKH. More detailed and mathematical formulation of the IKH and VKH can be found in the dissertation of Torres (2006).

It can be concluded from the previous literature that most of the criteria are basically generated almost from the same stability concept and are equivalent at certain conditions.

In this paper, the gas-liquid IKH stability criterion with the modifying factor made by Taitel and Dukler (1976) will be extended

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Nomenclature

A cross sectional area of the pipe
A_L cross sectional area occupied by liquid
A_W cross sectional area occupied by water
C_V parameter in Eq. (4)
C_{IV} parameter in Eq. (4)
d pipe diameter
Fr_M Froude number (Eq. (10))
GDR geometry density ratio number
H_O oil holdup
H_W water holdup
H_G gas void fraction
H_L liquid holdup
h_W the water height from the bottom of the pipe
h_L the liquid height from the bottom of the pipe (liquid level)
KH Kelvin-Helmholtz
K_{TD} Taitel and Dukler factor
K any user defined factor
IKH inviscid KH
VKH viscous KH
ST smooth stratified regime
STR combined ST and SW
ST-MI stratified with mixing at the interface regime
SW wavy stratified
S_i the length of the oil-water interface
WC water cut
V velocity
$\tilde{v}_O$ dimensionless oil velocity
$\tilde{v}_W$ dimensionless water velocity

Symbols

ρ density
μ viscosity
θ angle of inclination
~ dimensionless parameter
` derivative

Subscript

O oil
W water
G gas
L liquid
s superficial
m mixture
i interface

to the liquid-liquid criterion developed by Fairuzov (2001). A novel dimensionless form of the transition criterion will be shown in the present work.

The dimensionless form of the transition criterion enables classifying the stratified flow into its main sub-regimes, namely, stratified, wavy stratified and stratified with mixing. The controlling parameters of the transition from stratified to non-stratified which are clearly demonstrated by the dimensionless parameters emerged from the transition equation are explained in detail in this paper.

2. Stability analysis

Analysis of the stability in stratified flow is of fundamental importance in fluid mechanics. It is concerned with the problem of transitions from laminar to turbulent flow. Sometimes it is very important to control the instability behavior or at least delay the transitions from laminar to turbulent flows. Occasionally, it is important to trigger the instabilities e.g. mixing layer where more turbulent flows mean better and quicker mixing. Therefore, it is very essential that one can understand the mechanism behind fluid instabilities.

2.1. Kelvin-Helmholtz (KH) stability analysis

This model is based on a wave analysis. It begins with a linearization procedure presented by Barnea and Taitel (1989). Later, Barnea (1991) perturbed the two fluid model, in linear form with a monochromatic wave, and used the marginal stability to defined relation for the transition between stratified and non-stratified flow for gas-liquid flow. The analysis of Barnea (1991) included the viscous effect in addition to the inviscid Kelvin-Helmholtz proposed previously by Taitel and Dukler (1976), who were the first to present a simplified alternative to the KH analysis neglecting the surface tension effects which is presented in Eq. (1). With the intention of including the finite waves in the analysis Taitel and Dukler (1976) added a hypothetical term, K_{TD}, shown in Eq. (2) that multiplies the right hand side of Eq. (1).

$$(\mathrm{v_G} - \mathrm{v_L}) \quad \le \quad K_{TD}\sqrt{(\rho_\mathrm{L}\, H_\mathrm{G} + \rho_\mathrm{G}\, \mathrm{H_L})\left[\frac{(\rho_\mathrm{L} - \rho_\mathrm{G})}{\rho_\mathrm{L}\,\rho_\mathrm{G}}\mathrm{g}\cos(\theta)\frac{A}{dA_L/dh_L}\right]}. \tag{1}$$

where V_G, V_L, ρ_G, ρ_L, H_G, H_L, A, A_L, h_L, θ are the gas velocity, liquid velocity, gas density, liquid density, gas void fraction, liquid holdup, pipe cross sectional area, the area of the pipe occupied by liquid, the liquid height from the bottom of the pipe and pipe angle of inclination, respectively.

$$K_{TD} = \left(1 - \frac{\mathrm{h_L}}{\mathrm{d}}\right). \tag{2}$$

Where d is the pipe diameter. Fig. 1 shows the geometrical parameters of a stratified flow.

Extending Eq. (1) to oil-water flow leads to Eq. (3), noting that K in Eq. (3) is not necessary equal to K_{TD} more discussion about K will be presented in the proceeding sections. Eq. (3) simply generated by replacing the gas for the oil (the lighter phase) and the liquid for the water (the heavier phase).

$$(\mathrm{v_O} - \mathrm{v_W}) \quad \le \quad K\sqrt{(\rho_\mathrm{W}\, \mathrm{H_O} + \rho_\mathrm{O}\, \mathrm{H_W})\left[\frac{(\rho_\mathrm{W} - \rho_\mathrm{O})}{\rho_\mathrm{W}\,\rho_\mathrm{O}}\mathrm{g}\cos(\theta)\frac{A}{dA_W/dh_W}\right]}. \tag{3}$$

where v_O, v_W, ρ_O, ρ_W, H_O, H_W, A, A_W, h_W, θ are the oil velocity, water velocity, oil density, water density, oil holdup, water holdup, pipe cross sectional area, the cross sectional area of the pipe occupied by

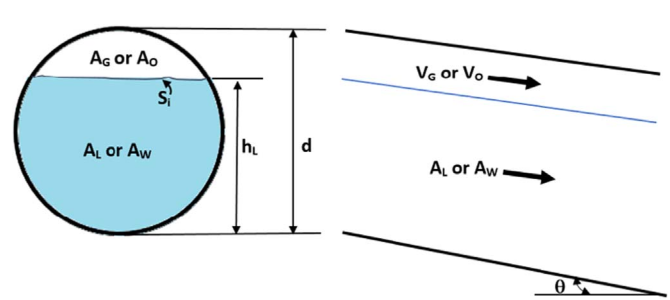

Fig. 1. The geometrical parameters in a stratified flow.