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Flooding prediction of counter-current flow in a vertical tube with non-axisymmetric disturbance waves

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ABSTRACT

A three-dimensional wave calculation is performed to investigate the growth of the non-axisymmetric disturbance wave for counter-current flow in a vertical pipe. The calculation is based on inviscid Kelvin-Helmholtz instability with the additional consideration of the azimuthal component of the long wavelength disturbance wave. Recognizing that the onset of flooding originates from the complicated interaction between gas flow and a wavy interface, the critical relative velocity prediction for interfacial instability is utilized to obtain an empirical formula for flooding predictions through correlations with the available experimental data. Compared with predictions based on the axisymmetric wave assumption, the present calculations reveal that the azimuthal propagation of the disturbance wave can significantly increase the interfacial stability. As a result, predictions for the onset of flooding based on the three-dimensional wave approach are found to agree better with the experimental data than that based on axisymmetric assumption. Effects of the tube diameters on interfacial instability are investigated, which becomes a crucial factor in determining the incipient flooding conditions when the diameter is small.

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1. Introduction

Counter-current two-phase flow is commonly encountered in many industrial applications such as structured packing columns and compact reflux condensers (Karimi and Kawaji, 2000). For a given liquid flux, the increase in gas velocity may eventually lead to the phenomenon of flooding, which is closely related to the stratified-slug flow regime transition (Imura et al., 1977; Schmidt et al., 2016; Suzuki and Ueda, 1977). Flooding deteriorates the normal operation of the multiphase systems, and inevitably results in an abrupt increase of pressure drop (Bankoff and Lee, 1986; Issa and Macian, 2011; Trifonov, 2010).

Plenty of experiments have provided some meaningful insights into the flooding mechanism (Mouza et al., 2002; Drosos et al., 2006); many correlations have also been proposed based on the experimental results (Issa and Macian, 2011; Zapke and Kröger, 2000a,b; Mouza et al., 2005; Ousaka et al., 2006). General reviews on these progresses are given by Bankoff and Lee (1986) and Issa and Macian (2011). Among the numerous observations, the obtained data by different authors remain significantly scattered, and contradictions in the data still persist due to the complicated nature of the flow subject to the effects of liquid viscosity, tube length, and slug position and whether the wave will reverse at incipient of flooding. In view of the multitude of factors that are involved, there is still a great need to gain more insights into the mechanism of flooding. It is therefore not surprising that reliable and robust predictive models remain absent at the present time.

In general, the phenomenon of flooding arises from the complex interaction between waves on the liquid film and gas flow (Issa and Macian, 2011; Gu and Guo, 2007; Segin et al., 2005). When the wave grows to fill the entire cross-section of the pipe, the flow transitions from stratified to slug flow and flooding occurs. A theoretical equation for predicting the onset of flooding can thus be derived by focusing on the instability of the wave which appears on the liquid film surface (Tseluiko and Kalliadasis, 2011; Vellingiri et al., 2015). Visual observation of wave growth and slug formation has revealed that slugs are formed from the propagation of long waves (Ujang et al., 2006). An accepted model for this wave growth is the Kelvin-Helmholtz instability (KHI) (Carey, 1992). By investigating the growth tendencies of original amplitude of the wave, which is primarily the function of the relative velocity, liquid viscosity and gas density (Issa and Macian, 2011), prediction of the

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Nomenclature

A	time function of liquid film wave
B	ime function of velocity or pressure wave
C_1, C_2	integral constant for Bessel function
d	tube diameter (m)
F_1, F_2	intermediate variable in Eq. (38)
g	gravity (m/s^2)
h	liquid film thickness (m)
m	Azimuthal wave number
M	ratio of $C_{1,l}$ to $C_{2,\ l}$
p	pressure (Pa)
P	intermediate variable in Eq. (29)
Q	intermediate variable in Eq. (29)
P'	intermediate variable in Eq. (1)
Q'	intermediate variable in Eq. (1)
R_0	tube radius (m)
r	radial direction
Re	Reynolds number
t	time (s)
U	superficial velocity (m/s)
u	velocity (m/s)
z	axial direction

Greek letters

α	axial wave number (m^{-1})
θ	Azimuthal direction
λ	wave length (m)
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ζ	empirical coefficient
β	angular velocity

Subscripts

g	gas
l	liquid
0	initial condition
c	critical
s	superficial

Superscripts

$'$	perturbed component
$\wedge$	amplitude of variable
$-$	base component

interface instability as well as the onset of flooding can be realized when the wave amplitude is proven to increase as time.

There are two types of KHI model: the viscous KHI model which uses the full two-fluid model and accounts for the shear stresses and the inviscid KHI model which ignores entirely the shear stresses. Lin and Hanratty (1986) compared the calculation results with the experimental data for the initiation of slug in a horizontal pipe using the viscous KHI model and inviscid KHI model. Their results revealed that the inviscid KHI in comparison to viscous KHI can well predict the stability of a stratified flow for very large liquid viscosities since it tends to ignore the destabilizing effects of liquid inertia. Barnea and Taitel (1993) also arrived at similar conclusions based on their comparative analyses. A significant aspect is that the amplification factors of the wave amplitude for both the viscous KHI and inviscid KHI are almost the same. General behaviors for the amplification factor based on the two approaches were employed to interpret the transition of flow patterns. Gu and Guo (2007) improved the viscous KHI by taking into account the normal stress in each phase and calculated the pressure based on the local momentum balance rather than invoking the hydrostatic approximation. Nevertheless, the viscid Kelvin-Helmholtz instability is formulated in terms of cross section averaged conservation equations for each phase, thus difficult to consider the three-dimensional (3D) wave effects.

The inviscid KHI contains less empiricism for the calculations of the interfacial drag coefficients, though it neglects the effects of shear stress (Crowley et al., 1992). Kusuda and Imura (1974) applied the inviscid KHI to the counter-current flow in a vertical pipe, and derived the critical relative velocity at which interfacial waves become unstable as:

$$(\vec{u}_g - \vec{u}_l)^2 = \frac{\sigma\alpha}{\rho_g Q'}\left(1 - \frac{\rho_g Q'}{\rho_l P'}\right)\left[1 - \frac{1}{\alpha^2 (R_0 - \bar{h})^2}\right] \tag{1}$$

where $\vec{u}_g$ and $\vec{u}_l$ are the velocity vector of gas and liquid, respectively. Other parameters in Eq. (1) are defined in the next section. Recognizing that the cause of flooding resides in the complicated interaction of gas flow with the wavy interface, an empirical relationship has been introduced to correlate the wave length where flooding starts with the mean film thickness, in order to obtain the flooding velocity on the basis of the above equation. The obtained correlation has been found to be in good agreement with the experimental results obtained as well as by other authors with different working fluids (Crowley et al., 1992).

The neutral stability condition for instability of interfacial wave in two-phase flow can also be derived analytically by studying hyperbolicity breaking near a singular point (No and Jeong, 1996), which turns out to be a type of onset condition of Helmholtz instability, similar to the KHI criterion. The flooding velocity was then obtained by applying the correlation to a roll or solitary wave condition, in which the wavelength is assumed to be proportional to the wavelength of the fastest-growing wave at KHI. Good agreement is obtained between the predictions by the correlations and the experimental data for entrance flooding and exit flooding.

Nevertheless, it should be stressed that the above analyses are all based on the two dimensional (2D) wave approaches, which may be appropriate for the flow in a horizontal or near horizontal pipe but not for the flow in vertical channels. Chang (1994) clearly observed 3D wavy flows characterized by spatially distributed waves when the flows evolve on free falling films. This type of 3D wavy flows were also reported by Vlachos et al. (2001). on a flat vertical surface, for film flow inside tubes of 46 and 54 mm inner diameters without gas flow by Adomeit and Renz (2000), and for film flow inside the tubes with inner diameter smaller than 10 mm with counter- current gas flow by Mouza et al. (2002). It is of particular interest that Suzuki and Ueda (1977) have found in their flooding experiments for a vertical tube of 10 mm and 18 mm inner diameters that the falling film becomes heavily disturbed and part of the liquid begins to flow into upper tube in a state of semi-annular flow at flooding. Their observations with high speed camera revealed that when the wavy height reaches a certain value, the large wave begins to extend towards the azimuthal direction before flooding. Recently, Drosos et al. (2006) observed 3D wave development in a vertical narrow channel before flooding. They argued that the large tube curvature (small inner diameter) significantly influences the wave evolution by the promotion of wave interaction. In large diameter tubes, an axisymmetric wave could not be formed, and any waves would

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