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Review

Theoretical prediction of flooding velocity in an inclined tube based on viscous Kelvin-Helmholtz instability

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HIGHLIGHTS

- Viscous Kelvin-Helmholtz theory is applied to predict flooding.
- Theoretical analysis is in satisfactory agreement with the experimental data.
- Influences of fluid properties and geometrical parameters are investigated.

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ABSTRACT

Flooding velocity is the upper limit for normal operation of industrial equipment containing countercurrent gas–liquid flow. Nevertheless, predictions for flooding gas velocity are mostly empirical or semi-empirical summarized from experiments. This paper performs the viscous Kelvin-Helmholtz instability analysis with a simplified one-dimensional model. The maximum amplification factor is deemed as the growth rate of the most dangerous waves which can trigger flooding after that the countercurrent flow in an inclined tube becomes unstable. The predicted flooding velocities for both water–air and cryogenic liquid nitrogen-nitrogen vapor are found to satisfactorily accord with both our experimental data and others' from available publications. Accordingly, the influences of fluid properties and geometrical parameters on flooding velocities are investigated. The results reveal that surface tension acts as a stabilizing force and cannot be ignored. Smaller liquid viscosity, bigger inclination and larger diameter can all delay the occurrence of flooding respectively, leading to a larger critical gas velocity at a given liquid velocity.

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1. Introduction

Flooding is a phenomenon encountered in exchange flows in pipes. A liquid normally flows down the tube and there is countercurrent gas flowing up the tube, but flooding occurs when the liquid is entrained by the gas, giving rise to flow reversal in some or all of the liquid. Flooding velocity usually means the critical gas velocity at the onset of flooding with constant liquid flow rates. Essentially, the occurrence of flooding is the upper limit of two-phase instability and often companied with the flow pattern transition. In an inclined tube, the flow pattern changes from stratified flow to slug or plug flow when flooding happens. As a result, flooding often adversely impacts the normal operation of industrial equipment that contains counter-current gas–liquid flow. For example, the Pressured Water Reactor (PWR) fails to perform because flooding affects the normal gas–liquid flow in the hot leg. Also, the heat and mass transfer processes in a structured packing column suffers from flooding, which will give rise to a sharp increase in the pressure drop. Therefore, accurate prediction for flooding velocities is significant for guaranteeing industrial equipment to work within the flooding limit.

Numerous investigations have been done to predict flooding velocities and most of them are empirical or semi-empirical correlations for the critical gas and liquid velocities summarized from experiments. The most popular used flooding correlation is Wallis type of correlations in the following form (Wallis, 1969)

$$\sqrt{U_{GS}}+t_1\sqrt{U_{LS}}=t_2 \tag{1}$$

where U_{GS} and U_{LS} are critical superficial gas and liquid velocities respectively, and t_1 and t_2 are the coefficients. Later, the correlation was improved by the work of researchers who took fluids properties and geometric parameters into consideration. For example, Zapke and Kröger (1996) replaced U_{GS} and U_{LS} with U^*_{GS} and U^*_{LS}, respectively:

$$U^*_{GS(LS)}=U_{GS(LS)}\sqrt{\frac{\rho_{\mathrm{G(L)}}}{gD(\rho_{\mathrm{L}}-\rho_{\mathrm{G}})}} \tag{2}$$

t_2 was also replaced with Ohnesorge number Z_L in the form of $Z_L=\sqrt{D\rho_L\sigma}/\mu_L$.

Nevertheless, all the aforementioned correlations were summarized from experimental data and usually only coincided with their own experimental data. A universal correlation is in urgent demand. Some other researchers attempted to theoretically derive flooding correlations that can be used generally. Taitel et al. (1982) proposed the film theory: the liquid film behaves as annular flow in the vertical tube and the turning point in the curve of gas velocity-film thickness (U_G–h) represents the onset of flooding. Trifonov (2010a, 2010b) also theoretically predicted the onset of flooding in vertical plates by the two-dimensional Navier-Stokes equations and a region of the “returning point” is found to define the onset of flooding mathematically. All the methods above are applicable to predict flooding in vertical plates with initial annular flow.

Kelvin-Helmholtz (KH) instability, considering the growth of a small-scale disturbance on the interface, has been widely used to determine the stability of a smooth stratified gas–liquid flow (Drazin and Reid, 2004). Some researchers hold the opinion that linearization methods without considering the time-varied elements can merely describe the initial stage, but fail to reflect the followed process of flow pattern transition. Other researchers, however, hold the opposite view. For example, Barnea and Taitel (1994) developed both linearization and nonlinearization approaches for KH analysis and revealed that flow pattern criteria derived from linearization procedure coincides well with that from nonlinearization procedure. Campbell et al. (2009) also confirmed the feasibility of linearization approach to study the flow pattern transition.

KH analysis was firstly used to determine the transition from stratified gas–liquid flow to small-scale wavy flow in an open system, and then it was developed to determine the flow pattern transition in tubes (Mishima and Ishii, 1980). Kordyban and Ranov (1970) regarded that in the formation of slug flow, the perturbation waves were no longer infinitesimal. In their research, the relation of wavelength and amplitude was concluded from experiment data. Wallis and Dodson (1973) further made amendments to the KH instability method with empirical coefficients in order to predict transition from stratified flow to slug flow or plug flow. Besides the aforementioned work in concurrent flow, KH instability method is also applicable to flooding prediction (Barnea and Taitel, 1985, 1989). Zhang et al. (2014) made an assumption of the proportional relation of liquid film thickness and critical wavelength at the incipient flooding in the linear inviscid KH (IKH) instability analysis. However, the relation was obtained not based on the physical derivation and the involved coefficients were obtained by comparing with the experimental data. Also, the flooding correlation failed to consider the effects of liquid viscosity. Barnea and Taitel (1993) concluded that the neutral stability lines obtained by the viscous KH (VKH) analysis were quite different from those by the IKH analysis in the case of low liquid viscosities. Therefore, liquid viscosity cannot be ignored in the analysis of cryogenic fluids that often have smaller viscosities than water. Moreover, the slip velocity in countercurrent flow is much higher than that in concurrent flow, which will exaggerate the interfacial stress force, and thus indicating that the impact of liquid viscosity is too obvious to be ignored.

The scope of this work is to propose a universal theoretical solution for flooding limit through linearization VKH analysis. Experiments are conducted to evaluate the accuracy of the correlation. Moreover, impacts of fluid properties (gas density, surface tension, liquid viscosity) and geometric parameters (inclination and tube diameter) on the flooding correlation are further investigated.

2. Viscous Kelvin-Helmholtz instability analysis of flooding

The physical process of gas–liquid countercurrent flow in an inclined tube is shown in Fig. 1. In the tube, liquid flows downward along the tube bottom by the gravitational effect, while the gas flows up above the liquid flow. When the gas velocity is sufficiently high, the suction effect imposed by the pressure difference over the two sides of the infinitesimal disturbance on the interface becomes large enough to overcome the stabilizing effect due to the gravitational force. This phenomenon can be explained by Kelvin-Helmholtz instability theory. The suction effect becomes more obvious with the increase of gas velocity according to the Bernoulli effect. After interface becomes unstable, the wave will slow down and grow up due to the shear stress of gas flow, which inversely narrows the passage of gas flow and promotes the suction effect, thus resulting in continuous growth of interfacial waves as long as