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A model for droplet entrainment in churn flow

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HIGHLIGHTS

- We established a mathematical model for droplet entrainment in churn flow.
- We analyzed the interface stability based on the Kelvin–Helmholtz instability.
- The proposed model was verified over a range of experimental data.
- The effect of parameters (e.g., pipe diameter, gas and liquid flowrate and pressure) on the entrainment was discussed.
- A new formula for entrained rate in churn flow was proposed.

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ABSTRACT

Understanding the mechanism of droplet entrainment is of great importance for the churn flow. So far, the droplet entrainment mechanism has been experimentally studied; however, no detailed model is available for this particular flow pattern. To address this, the author established an analytical model to better understand the drop entrainment in churn flow. In this model, only the entrainment mechanism named shear-off in equilibrium state is considered and detailed analysis performed for the interface stability based on the Kelvin–Helmholtz instability and force balance acting on the wave crest. The model has been verified using experimental data and different parameters (e.g., pipe diameter, gas and liquid flowrate and pressure) influencing the entrainment is presented. The author proposed a more accurate and reasonable formula for the entrained rate in churn flow based on the existing formula for annular flow. The model developed in this paper predicts the entrainment mechanism under churn flow condition to an accuracy of 30% which is essential for the development of mechanistic models to predict the dryout condition in the future.

1. Introduction

Churn flow is a highly turbulent mixed flow of gas and liquid and generally characterized by the presence of a very thick and unstable liquid film, with the liquid frequently oscillating up and down. As one of the least understood of gas–liquid flow regimes, churn flow has been enduring efforts to be defined (Zuber and Findlay, 1965; Hewitt and Hall-Taylor, 1970; Taitel et al., 1980; Mao and Dukler, 1993) and generally be considered as an intermediate flow regime between the slug flow and annular flow. This occurs after break down of slug flow as velocity increases (Hewitt and Hall-Taylor, 1970, Jayanti and Hewitt, 1992) and transits to annular flow associated with the flow reversal point in counter-current flow (Wallis, 1969). The criterion for the churn–annular transition is expressed as (Wallis, 1969; Hewitt et al., 1985)

$$U_g^* = u_{sg}\sqrt{\frac{\rho_g}{g d_T(\rho_l-\rho_g)}} \approx 1 \tag{1}$$

where U_g^*, u_{sg}, d_T, g, ρ_l and ρ_g are the dimensionless gas velocity, superficial gas velocity, pipe diameter, gravitational acceleration, liquid density and gas density, respectively.

The process of the droplet entrainment is very complex and the entrainment fraction E is defined to characterize the distribution of liquid phase flow between the liquid film and the entrained droplets. Although studies have shown that the entrained fraction is high in churn flow and reaches the minimum around the churn–annular transition (Wallis, 1962; Barbosa et al., 2002), the underlying mechanisms of droplet entrainment in churn flow is still not well explored and few studies have been reported to investigate the entrainment mechanism in churn flow. Barbosa et al. (2002) suggested that two droplet entrainment mechanisms (bag breakup and ligament breakup) were the reasons for the entrained droplets in churn flow based on the atomization theory proposed by

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Azzopardi (1983). Subsequently, Wang (2012) verified that bag breakup and ligament breakup were coexistent in churn flow based on his observation: bag breakup (under-cut) played a dominant role at low gas superficial velocity, but the ligament breakup (shear-off) came to gain greater importance with the increase of gas flowrate. However, to the best knowledge, there is no mathematical model that has been developed to understand the entrainment mechanism in churn flow. At present, theoretical studies of entrainment in annular flow are mostly based on Kelvin–Helmholtz instability and force balance on interfacial waves, including Holowach et al. (2002) and Ryua and Park (2011), and serve as good references in present study.

In this paper, the author established an analytical model to characterize the process of the droplet entrainment in churn flow based on the theory of Kelvin–Helmholtz instability. Also, analyzed in detail, the forces acting on the wave crest in order to comprehensively investigate the impact of forces including gravity, surface tension force and drag force. The present model was compared and verified carefully with the existing experimental data. On the basis of present mathematical model, the effects of parameters such as pipe diameter, gas and liquid flowrate and pressure on drop entrainment were investigated. With the aid of Ahmad et al. (2010)'s suggestion, a more accurate and reasonable formula for the entrained rate in churn flow was devised.

2. The mathematical model

2.1. Control volume

The wave distribution in the axial and circumferential directions and the control volume for the present model are shown in Fig. 1. The interfacial wave initially forms along the axisymmetric direction and its further growth leads to secondary instabilities which give rise to variations around the periphery. Therefore, the interfacial wave is three-dimensional. In addition, the droplet entrained rate m_e is defined, as Holowach et al. (2002) suggested, as a function of the number of waves in the control volume $N_{w,cv}$, the volume of liquid that entrained from the wave crest $V_{entr,w}$, the wave length λ and the wave velocity v.

$$m_e = \frac{V_{entr,w}\,\rho_l N_{w,cv}}{S_{cv}\,t_{w,cv}} \tag{2}$$

where S_{cv} and $t_{w,cv}$ are the interfacial area in the control volume and the period of the entrainment phenomena in the control volume, respectively.

Fig. 2 shows the configuration of the interfacial waves. According to Hewitt et al. (1985) and Wang et al. (2012), the sinusoidal wave shape shows a better approximation than the hemispherical shape (McQuillan et al., 1985) and provides a more simplified approach for the force balance calculation. Therefore, we employed the sinusoidal shape in this study and assumed that the wave shape was retained as the wave grows. The arbitrary thickness of liquid film δ can be described as

$$\delta = (A_w - \delta_b)\sin\frac{2\pi z}{\lambda} + \delta_b \tag{3}$$

where A_w, δ_b and z are the wave amplitude, liquid film base thickness and the axial direction, respectively. The liquid film base thickness δ_b can be calculated by Nusselt film theory (Nusselt, 1916)

$$\delta_b = \left[\frac{3\mu_l M_f}{\pi d_T \rho_l g(\rho_l - \rho_g)}\right]^{1/3} \tag{4}$$

where μ_l and M_f are liquid viscosity and liquid film mass flowrate, respectively.

Both the density of the gas core ρ_{gc} and average velocity of the gas core $\bar{u}_{gc}$ are defined in terms of the pure gas and entrained droplets

$$\rho_{gc} = \frac{M_e + M_g}{M_e/\rho_l + M_g/\rho_g} \tag{5}$$

$$\bar{u}_{gc} = \frac{M_e/\rho_l + M_g/\rho_g}{S_1(1-(2\delta_b/d_T))^2} \tag{6}$$

$$S_1 = \frac{\pi}{4}(d_T - 2\delta_b)^2 \tag{7}$$

$$M_e = M_l E \tag{8}$$

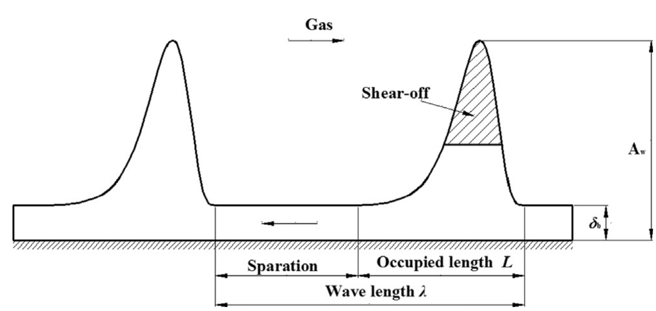

Fig. 2. Configuration of huge wave in churn flow.

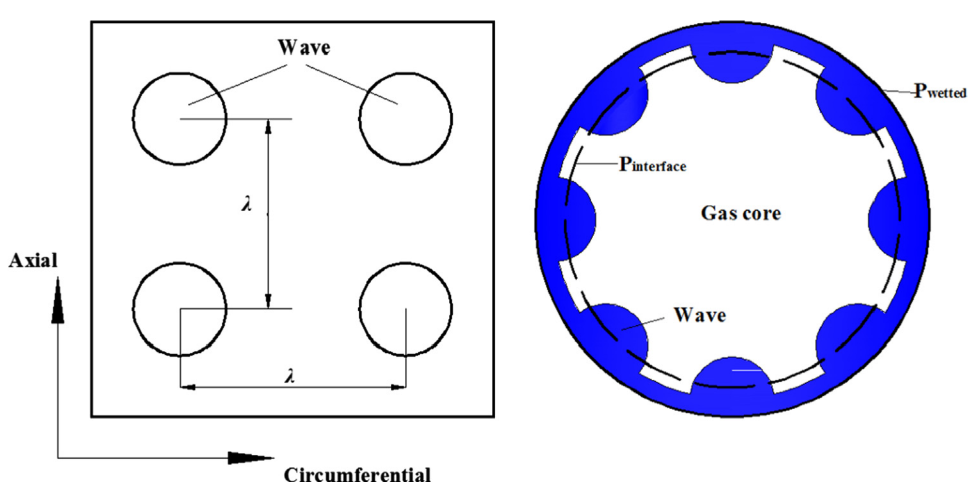

Fig. 1. Wave distribution in axial and circumferential directions and the control volume.