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On the effect of liquid viscosity on interfacial structures within churn flow: Experimental study using wire mesh sensor

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HIGHLIGHTS

- Effect of liquid viscosity on mean void fraction under different flow conditions was studied.
- The changes in the flow structure due to increasing liquid viscosity were shown.
- It was shown how liquid viscosity can influence the appearance frequencies of interfacial structures within churn flow.

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ABSTRACT

In the churn flow regime, periodical interfacial structures such as liquid slugs and huge waves can coexist and undoubtedly, a phase property such as liquid viscosity can dominate the behavior of these structures. Regrettably, neither are the characteristics of churn flow widely understood nor have the effects of liquid viscosity on gas–liquid flow received enough attention.

A Wire Mesh Sensor (WMS) with a 16 × 16 spatial resolution was employed to discover the effects of liquid viscosity on the behavior of churn flow in a vertical 76.2 mm pipe. Three liquid viscosities of 1, 10, and 40 cP, and superficial liquid velocities of 0.46, 0.61, and 0.76 m/s were employed; whereas, superficial gas velocity ranged from 10 to 27 m/s. Different techniques such as Probability Density Function (PDF), and 2-D and 3-D image reconstruction methods were applied to study the flow. It was noticed that increasing liquid viscosity not only affected the flow pattern but also the appearance frequencies of interfacial structures.

1. Introduction

When gas and liquid are simultaneously introduced in a pipe, they can distribute themselves in different flow patterns/regimes. In vertical ascending gas–liquid flow, a widely accepted flow pattern classification is bubble, slug, churn and annular flow.

Amid different flow patterns observed in vertical upward gas–liquid flow, the churn flow regime has received much less consideration due to its intricate nature. This flow regime can be seen in gas condensate wells (Garber et al., 1998), hydrocarbon recovery risers, and nuclear reactors where dry out or critical heat flux can occur revealing the “technological importance” of churn flow (Hewitt, 2012).

Different factors contribute to establishing a particular flow regime. Examples are pipe inclination angle, flow direction, superficial velocities, and phase physical properties. In most of the published material related to the gas–liquid flow, water has been employed as the liquid phase, since it is safe and can be easily accessed. In industrial applications, however, other liquids, which have different physical properties from those of water, must be handled. For instance, in chemical reactors, polymer processing plants (McNeil and Stuart, 2003; Schmidt et al., 2008), and the oil and gas industry (Zhao et al., 2013), liquids with higher viscosity than the viscosity of water exist. Therefore, investigating the effects of a phase property such as liquid viscosity on gas–liquid flow is of utmost importance not only in understanding the characteristics of multiphase flow, but also designing safety

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facilities, optimizing operations, developing mechanistic models, and computational fluid dynamics (CFD) codes.

The brief introduction made here raises the question how liquid viscosity can influence the churn flow regime. Therefore, before determining the objectives of the present study, the available literature concerning churn flow and the impact of liquid viscosity on multiphase flow are reviewed in Section 2.

2. Background

2.1. Churn flow

Articles' titles such as “The myth of churn flow” and “To churn or not to churn” perhaps indicate the complexity of churn flow. In the former, Mao and Dukler (1993) suggested that churn flow is not a separate flow pattern. Instead, it is a manifestation of slug flow that can be modeled using slug flow models. In the latter, however, Hewitt and Jayanti (1993) criticized the mentioned assertion and stated that churn flow is an intermediate flow regime between slug and annular flow. They mentioned that in churn flow there are flooding-type waves that can be observed neither in slug nor annular flow.

Generally, churn flow is considered as a separate entity that is characterized by the presence of periodic large interfacial waves called flooding-type waves (Hewitt et al., 1985; Govan et al., 1991). The terms “flooding-type waves” and “huge waves” can be interchangeably used. While these waves ascend and sweep the base liquid film, between them, a reverse in the direction of the film motion is observed (Hewitt and Hall-Taylor, 1970; Jayanti and Brauner, 1994).

Churn flow is bordered by slug and annular flow. Regarding the slug to churn flow transition, different mechanisms have been postulated. Dukler and Taitel (1977) expressed that when the ratio of the Taylor bubble length to the total length of the slug unit becomes equal or greater than 0.8, the bridge of the liquid slugs is destroyed by the wake behind the Taylor bubble and consequently the transition occurs. However, the application of this criterion is limited to the churning entrance region of slug flow, where the flow is not yet fully developed. In fact, Dukler and Taitel (1977) thought of churn flow as an unstable and transitional flow regime taking place at the pipe entry region.

Another school of thought regarding liquid slug instability followed by some researchers is that the transition from slug to churn flow occurs when the liquid slug body becomes highly aerated. For example, Mishima and Ishii (1984) suggested that the transition occurs once the void fraction of the slug unit becomes higher than that of the Taylor bubble. Brauner and Barnea (1986) proposed that the transition occurs when the gas void fraction within the slug body acquires a critical value of 0.52 corresponding to the maximum volumetric packing of bubbles. Chen and Brill (1997) suggested the following criteria for the transition,

$$\beta_s \le 0.15 \quad \text{and} \quad \alpha_s \ge 0.52 \tag{1}$$

where β_s is the ratio of the liquid slug body length to the total length of the slug unit, and α_s is the gas void fraction in the liquid slug body.

However, some multiphase flow investigators have a different piece of advice with reference to the slug/churn flow transition. There are studies that attributed this transition to “flooding” (Nicklin and Davidson, 1962; McQuillan and Whalley, 1985; Jayanti and Hewitt, 1992; Spedding et al., 1998). The flooding phenomenon is explained as follows. Consider a counter-current gas–liquid flow in which gas moves upward while it is encircled by a downward moving liquid film. At lower gas flow rates, even though some small ripples exist on the film interface, the falling liquid film is stable. As the flow rate of either phase or both phases increases, the ripples grow and at a critical point become large waves. In this instance, a part of the liquid is transported upward while appearing highly disturbed. A part of the liquid, however, flows downward. This phenomenon is called “flooding” (Govan et al., 1991). In fact, flooding occurs because of formation,

Table 1
List of the flow conditions employed in different studies.

Authors	D_P (mm)	V_{SG} (m/s)	V_{SL} (m/s)	μ (cP)
Fukano and Furukawa (**1998**)	19.2, and 26.0	10–50	0.04–0.3	0.85, 3.8, 6.4, and 10
Furukawa and Fukano (**2001**)	19.2	0.05–40	0.1–1	1, 6.4, and 17.2
McNeil and Stuart **(2003)**	10	–	–	1, 50, 200, and 550
Da Hlaing et al. (**2007**)	19	0.0021–58.7	0–0.1053	0.85, and 4.5
Mori et al. (**2007**)	10	20–60	0.005–0.3	1, 3.5, 11.4, 35.9, and 85.8
Szalinski et al. (2010)	67	0.05–5.7	0.2, 0.25 and 0.7	1 and 5.25
Hewakandamby et al. (**2014**)	127	3.26–17.46	0.03–0.24	1, 12.2, and 16.2

Table 2
Effects of liquid viscosity on the characteristics of different flow patterns (Furukawa and Fukano, 2001).

Flow regime	Effects of increasing liquid viscosity
Slug flow	The liquid film becomes thicker Smaller and more bubbles appear in the liquid film Appearance frequency of liquid slugs increases Taylor bubbles and liquid slugs become shorter
Froth flow	Appearance frequency of liquid slugs increases Appearance frequency of long-life large waves decreases
Froth-annular flow	More bubbles appear in the liquid film Small waves on the liquid film become larger Velocities and sizes of liquid lumps increase Flow structure becomes more stable
Annular flow	Small waves on the liquid film become larger Liquid film thickness increases The gas–liquid interface changes from relatively smooth to extremely wavy Appearance frequency of long-life large waves decreases