Chemical Engineering Science 104 (2013) 638–646

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

# Huge wave and drop entrainment mechanism in gas–liquid churn flow

Ke Wang [a], Bofeng Bai [a,*], Weimin Ma [b]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Shaanxi 710049, China
[b] Royal Institute of Technology (KTH), Stockholm, Sweden

## HIGHLIGHTS

- Huge wave and liquid distribution in churn flow were investigated.
- Conditions for transition from churn flow to annular flow or slug flow were discussed.
- Flooding of the film is a characteristic of churn flow throughout the regime.
- Drops are generated due to both bag breakup mechanism and ligament breakup mechanism in churn flow.

## ARTICLE INFO

*Article history:*
Received 21 April 2013
Received in revised form
30 August 2013
Accepted 5 September 2013
Available online 23 September 2013

*Keywords:*
Churn flow
Multiphase flow
Flooding
Huge wave
Entrainment
Interface

## ABSTRACT

A profound knowledge of huge wave and droplet entrainment mechanism is crucial for the thorough study on the gas–liquid churn flow. Although studies have shown that the entrained fraction is high in churn flow and reaches the minimum around the churn–annular transition, the underlying mechanism of the drop entrainment in churn flow is still not well explored. To address this, we investigated the properties of the huge waves and the droplet entrainment in two vertical pipes with the inner diameter of 19 mm and 34 mm under churn flow conditions. We found that the flooding of the film was a characteristic of the churn flow throughout the regime. In addition, increasing the gas or liquid flow rate could lead to the transition from churn flow to annular flow or reverse to slug flow, providing the insight into the differences among slug, churn and annular flow. We also discussed the film instability under different flow conditions and tried to reveal the physical mechanism based on the instability analysis. In our study, the bag breakup and the ligament breakup were observed to coexist. The analysis of the liquid distribution in the cross-section of the pipes not only revealed the variations of the entrained fraction of churn flow from that of annular flow, but also indirectly illustrated the differences between their breakup mechanisms. Moreover, the wave properties (amplitude and frequency) were also analyzed in detail.


## 1. Introduction

Churn flow appears a highly disturbed flow of gas and liquid and is generally characterized by the presence of a very thick and unstable liquid film with the liquid frequently oscillating up and down. It normally occurs in vertical or nearly vertical pipes and features interfacial waves, termed as huge waves (Sekoguchi and Takeishi, 1989; Sekoguchi and Mori, 1997; Kaji et al., 2009), over a liquid film which are larger in amplitude, wavelength and velocity than disturbance waves. Churn flow is one of the least understood gas–liquid flow regimes due to its complexity and there have been enduring efforts to define it (Zuber and Findlay, 1965; Hewitt and Hall-Taylor, 1970; Taitel et al., 1980; Mao and Dukler, 1993; Hewitt, 2012). Generally, churn flow is considered as an intermediate flow regime between slug flow and annular flow and occurs after the break-down of slug flow as its velocity increases (Hewitt and Hall-Taylor, 1970; Jayanti and Hewitt, 1992). The churn–annular transition is often related to the flow reversal boundary in the counter-current flow and the criterion 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 $U_g^*$, $u_{sg}$, $d_T$, $g$, $\rho_l$ and $\rho_g$ are dimensionless gas velocity, gas superficial velocity, hydraulic diameter, gravitational acceleration, liquid density and gas density, respectively. However, there appear to be four major schools of thought on the criteria of the transition from slug flow to churn flow, including the entrance effect mechanism (Dukler and Taitel, 1986), the flooding mechanism (McQuillan et al., 1985; Jayanti and Hewitt, 1992), the wake effect mechanism (Mishima and Ishii, 1984; Chen and Brill, 1997) and the bubble coalescence mechanism (Brauner and Barnea, 1986). Various experiments have been conducted to demonstrate that the flooding of the liquid film

* Corresponding author. Tel.: +86 29 82665316; fax: +86 29 82669033.
*E-mail address:* bfbai@mail.xjtu.edu.cn (B. Bai).

0009-2509/$ - see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ces.2013.09.022

surrounding the Taylor bubble is attributed to the transition from slug flow to churn flow (Wallis, 1969; McQuillan et al., 1985; Govan et al., 1991; Jayanti and Hewitt, 1992; Jayanti et al., 1993, 1996). The continuity of the liquid phase in slug flow between successive Taylor bubbles is frequently distorted by the gas phase, and meanwhile the liquid slug falls. The falling liquid accumulates, forms a bridge, and is again lifted by the gas. During this process, huge waves, also referred to as large waves or flooding-type waves, are observed to travel upwards with the falling film regions between the waves (Hewitt et al., 1985; Barbosa et al., 2001). Although the experimental data of pressure gradient and entrained fraction are available for the study of churn flow and its corresponding transition regions (Hewitt et al., 1965; Wallis, 1962; McQuillan et al., 1985; Owen, 1986; Zabaras et al., 1986; Govan et al., 1991; Barbosa et al., 2002; Azzopardi and Wren, 2004; Ahmad et al., 2010), relevant studies on the huge wave and droplet entrainment mechanism in churn flow are still scarce due to its chaotic nature.

Few studies have been reported to investigate the huge wave and the entrainment mechanism in churn flow. Barbosa et al. (2001) provided a detailed visualization of the huge wave and verified the postulated mechanisms of churn flow proposed by Hewitt et al. (1985). The comparison of their experimental data with those from Hewitt et al. (1985) showed that the pipe diameter and fluid properties had influences on the huge wave. Also, Hernandez Perez et al. (2010) used a conductance wire mesh sensor system to identify the wave under different conditions. They observed the existence of wisps (huge waves) and proposed a new structure in churn flow with a form of thick ligaments of liquid. In addition, Wang et al. (2012) proposed a physical model to investigate the huge wave under the churn flow condition, and theoretically demonstrated that the flooding of the film was the overall characteristic of the regime. In addition, fluid properties were also found to affect the interfacial conversion during the wave levitation process (Da Riva and Del Col, 2009). Moreover, Barbosa et al. (2002) tried to analyze the drop entrainment mechanism based on the atomization theory proposed by Azzopardi (1983) and suggested that bag breakup and ligament breakup were the reasons for the droplets generated from the liquid film. It should be noted that previous studies serve as good references in this research field; however, some underlying mechanisms are still to be discovered due to the limited experimental data.

In this study, we focused on the behavior of the huge wave and the drop entrainment mechanism under the churn flow condition. The high-speed camera was employed to capture a more detailed description of the huge wave and the liquid distribution in churn flow and annular flow in the cross-section of the pipes with the inner diameters of 19 mm and 34 mm. It should be noted that churn flow appears to be a highly disturbed flow of gas and liquid and it is very difficult to be measured. As mentioned above, the flooding of the film is a characteristic of the overall regime. Accordingly, we employed the method widely used in the study on the flooding to investigate the characteristics of churn flow, the method which was also adopted by Hewitt et al. (1985) and Barbosa et al. (2002). Using this experimental approach, we analyzed the effects of the gas and liquid flow on the wave behavior and film instability. The analysis of entrainment mechanisms in churn flow concluded the features of the phase distribution over the pipe cross-section, providing insights into the differences between churn flow and annular flow. We also analyzed the wave properties (amplitude and frequency) and aimed to provide a better understanding of churn flow.

## 2. Experimental system and method

### 2.1. Experimental system

Fig. 1 shows the schematic of the test facilities. The vertical pipe is made of a transparent acrylic resin and has sections of porous

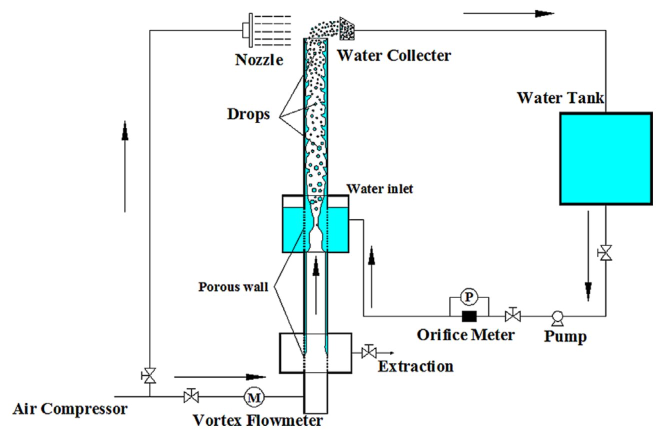


**Fig. 1.** Schematic of the test facilities.

wall at its mid part and lower part. Our experiments were carried out on two test sections with the inner diameter of 19 mm and 34 mm, respectively. Air was fed from the compressors via the rotameter into the test section at the bottom of the pipe under the atmospheric condition; after fully development it was released into the atmosphere from the upper end of the pipe. Water was injected into the water-inlet section via the orifice flowmeter and fed through the porous wall to form a film along the pipe circumference. It was removed from the test section in two ways: the upward liquid was removed from the upper outlet and the falling film was extracted from the extraction sinter. Obviously, the configuration of the air–water mixer was critical for the formation of the huge wave. In order to achieve the distribution of the liquid phase as circumferentially uniform as in the Taylor bubble, the water flowing into the test section has to be smooth and well-distributed. This was realized by making the holes small enough and uniformly-distributed. The water inlet section featured 15 rows of 300 holes of 1 mm in diameter and the space between the holes is about 2 mm. The water extraction section consisted of 250 holes of 1 mm in diameter.

Two Memrecam fx K3 high-speed CCD cameras which were capable of up to 10,000 frame/s were used for the flow visualization. In the present work, the sample frequency was set to be 1000 frame/s. The cameras were placed to face the porous section to capture the behavior of the huge wave and the outlet of the pipe to obtain the liquid distribution in the cross-section, respectively. The pipe length between the liquid inlet and the measurement position in the cross-section was about 1 m, assuming that the flow was in equilibrium. In addition, backlight illuminations were employed to illuminate the cross-section of the pipe and the water inlet section, respectively. At the end of the pipe, a strong laterally-directed wind was introduced to blow the upward liquid into the water collector and prevent the gas–droplet mixture from interfering the camera positioned at the outlet of the test section. The upward liquid carried by the waves was measured with the weighing method.

### 2.2. Uncertainty analysis

The water flow is measured by an orifice mass flux meter with the uncertainty of 0.5%, and the pressure drop by a Rosemount 3051 transmitter with the uncertainty of $\pm 0.5\%$. Inevitably, small amount of gas may be extracted with a falling liquid film from the water extraction sinter. A valve is used to control the amount of the gas escaping from the extraction sinter. Therefore, the amount of the extracted gas is negligible. In addition, under the condition of greater liquid mass flow rate, the pressure accumulation in the gas core near the water inlet may also cause small amount of gas