Chemical Engineering Science 163 (2017) 137–144

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Profile of huge wave in gas–liquid churn flow

Ke Wang [a,b], Jing Ye [c], Bofeng Bai [b,*]

[a] Beijing Key Laboratory of Process Fluid Filtration and Separation, College of Mechanical and Transportation Engineering, China University of Petroleum, Beijing 102249, China
[b] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Shaanxi 710049, China
[c] Shanghai Marine Diesel Engine Research Institute, Shanghai 201108, China

HIGHLIGHTS

- We proposed a normal-distribution function to describe the huge wave shape.
- We analyzed the relationship between the wave amplitude and wavelength.
- The normal-distribution function reproduces the evolution of the huge wave quite well.
- The sinusoidal function comparatively has the lowest precision in prediction.
- The hemispherical function is recommended to simplify the calculation.

ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form 15 December 2016
Accepted 18 January 2017
Available online 19 January 2017

Keywords:
Churn flow
Wave profile
Huge wave
Flooding
Mathematical modeling

ABSTRACT

The knowledge of wave profile of the huge waves is crucial for the thorough study on the pressure drop in churn flow, which is of great interest in many industries where such chaotic flow occurs. The literature lacks information on the profile of a huge wave under churn flow condition. Usually, hemispherical and sinusoidal shapes are employed to feature the general characteristic of the huge wave. No doubt, errors will be inevitably result. To explore this issue, we used a high-speed camera to capture a more detailed description of the huge wave in a 19 mm i.d. tube under churn flow condition. The experimental results indicate that the ratio between wave length and wave amplitude is found to be about 5 irrespective of gas and liquid velocities. By analyzing the silhouette of the huge wave at its critical condition (stationary), we proposed a Gaussian function to describe such wave shape more accurately. Compared with the existing wave shapes, the Gaussian function qualitatively and quantitatively reproduces the evolution of the huge wave quite well whereas the sinusoidal function comparatively has the lowest precision in prediction. Though a far cry from the real wave shape, the hemispherical function is recommended to simplify the calculation on the basis of a simpler form but a sufficient accuracy.

1. Introduction

The pressure drop is of great concern for any industrial process design which in turn depends strongly on better understanding of the flow patterns. Recently, the significance of churn flow has been increasingly emphasized. This distinctive flow pattern is generally characterized by the presence of a very thick and unstable liquid film with the liquid frequently oscillating up and down (Hewitt and Hall-Taylor, 1970; Jayanti and Hewitt, 1992; Barbosa et al., 2002; Wang et al., 2013a; van Nimwegen et al., 2015; Parsi et al., 2016), leading to a violent fluctuation of the pressure gradient in the churn flow (Owen, 1986; Waltrich et al., 2013). This may cause the damage to the equipment and is of great interest in many industries where such oscillating flow occurs. Examples include applications such as gas lift in chemical engineering, emergency cooling of the reactor core in case of the loss of coolant, and potential flow pattern transition from severe slugging to churn flow in a pipeline-riser system, etc.

The existence of huge waves (or called flooding-type wave or large wave) formed on the thin falling liquid film is one of the most important features of churn flow. Previous experimental and analytical investigations on the huge wave properties have been mainly focused on the wave velocity, wave amplitude, wave frequency and its entrainment mechanism (Barbosa et al., 2002; Wang et al., 2013a; Tekavčič et al., 2016; Sharaf et al., 2016). It is noteworthy that the pressure drop in two-phase flow is largely influenced by the gas-liquid interface roughness. As in a highly-disturbed flow, huge waves with large amplitude flow up and down throughout the regime, resulting in the liquid film to act as

---

* Corresponding author.
E-mail address: bfbai@mail.xjtu.edu.cn (B. Bai).

http://dx.doi.org/10.1016/j.ces.2017.01.041

Nomenclature

A_w	wave amplitude (m)
d_T	pipe diameter (m)
F	force (kg m s^{-2})
$\sum F$	resultant force (kg m s^{-2})
g	gravitational acceleration(m s^{-2})
Q	mass flow rate (kg s^{-1})
P	pressure (Pa)
r	radial distance (m)
Re	Reynolds number
S	area (m^2)
t	time (s)
u_{gs}	superficial gas velocity (m s^{-1})
u	velocity (m s^{-1})
V_w	wave volume (m^3)
v	wave velocity (m s^{-1})
z	axial direction

Greek symbols

ρ	density (kg m^{-3})
τ	shear stress (kg m^{-1} s^{-2})
δ	film thickness (m)
μ	viscosity (kg s^{-1} m^{-1})
λ	wavelength (m)
σ	standard deviation

Subscripts

f	liquid film
g	gas phase
l	liquid phase
w	wall, wave

a very rough wall and its roughness significantly affects the frictional component of the pressure drop (Parsi et al., 2015a,b; Sharaf et al., 2016). Evidently, the huge wave has to be described with appropriate terms concerning its shape to determine the gas-liquid interface roughness. Additionally, the modeling work of huge wave behaviors and entrainment requires the description of wave shape (Wang et al, 2012; Wang et al., 2013b). No doubt, the assumption of wave shape inevitably brings errors.

Some of the experimental work available in the literature concentrates on the wave structure of disturbance wave in annular flow (Hewitt et al., 1985; Wang et al., 2004; Han et al., 2006; Omebere-Iyari and Azzopardi, 2007; Hazuku et al., 2008). Their findings indicate that the interfacial wave more likely have a log-normal distribution. However, the literature lacks information on the profile of a huge wave under churn flow condition. Usually, the hemispherical and sinusoidal shapes are employed to feature the general characteristic of the huge wave. McQuillan et al. (1985) proposed a hemispherical shape to simplify the calculation, which was also adopted by Da Riva and Del Col (2009) and Ryua and Park (2011). Definitely, this simplification makes the calculation much easier; however, the hemispherical shape is a far cry from the real wave. Shearer and Davidson (1965) estimated the standing wave as a sinusoidal shape, which was verified by Hewitt et al. (1985). Subsequently, the sinusoidal wave widely serves as a more accurate approach for interfacial wave shape (disturbance and huge waves) in modeling works (Holowach et al., 2002; Barbosa et al., 2001; Wang et al., 2012, 2013b). However, there is no comparison of these two hypothesis and investigation of their effect on modelling accuracy. As we know, the huge wave is much larger compared to the regular disturbance wave and travels at a higher velocity. To our best known, there is a dearth of data on the profile of the huge wave under churn flow condition. Part of the reason that the wave profile has not been thoroughly investigated is due to the intricate nature of churn flow, resulting in that the interfacial wave in churn flow is quite hard to measure. Thus, it is strongly desired to have correlations that can describe the accurate profile of the huge wave.

To explore this issue, one of the objectives of this work is to obtain the profile of the huge wave under churn flow condition. We used a high-speed camera to capture a more detailed description of the huge wave. According to the experimental data, we aimed to find the relationship between wave length and wave amplitude. Based on the analysis of the generation and evolution of the huge waves under various flow conditions. We proposed a Gaussian function to describe the wave shape more accurately. By comparing the proposed profile with the existing wave shapes of hemispherical and sinusoidal in wave evolution calculations, we tried to provide insight into the effect of wave shape on the modeling accuracy. It is realized that the calculations could be quite complicated with such Gaussian wave shape. With this in mind, we compared these wave shapes with the intention of finding a simpler wave shape, but features the general characteristics of the huge wave.

2. Experimental system and method

2.1. Test facility

The schematic of the test facility is presented in Fig. 1, which is mainly composed of the test section, water and air supply systems, as well as the measurement system. The vertical test section is made of a transparent acrylic resin and with the inner diameter of 19 mm. The air was fed from the compressor via the rotameter into the test section at the bottom of the pipe, whereas the water was injected into the water inlet section via the orifice flowmeter and fed through the porous wall to form a liquid film along the pipe circumference.

It should be noted that the configuration of the water inlet section (air-water mixer) is of utmost importance for the formation of the huge waves. In order to achieve the circumferential uniform distribution of the liquid phase as that in the Taylor bubble, the water inlet section (porous wall) is delicately designed. About 300 holes of 1 mm in diameter in 15 rows with the spacing distance about 2 mm is uniformly distributed in water inlet section. Additionally, an extraction sinter was also fabricated to extract the falling film out of the tube.

The Memrecam fx K3 high-speed CCD camera with the capability of up to 10,000 frame/s was employed to capture the generation and evolution of the huge waves. In the present study, the camera was placed to face the water inlet section with the sample frequency of 1000 frame/s.

2.2. Experiment procedure and conditions

The detailed experimental procedure can be referred to our previous paper (Wang et al., 2013a). When a falling film formed along the pipe circumference at a constant liquid flow rate, the gas flow rate was subsequently increased from a lower flow rate until churn flow was obtained in the tube, showing that part of the liquid flew downwards as a falling film, whereas above the injector part of the