Investigation of Huge Wave in Gas-Liquid Two-Phase Churn Flow

S Zhang¹, Q Q Shao¹, B Hu² and K Wang*²

¹ China National Petroleum Pipeline Network Group Co., Ltd South China Branch, Guangzhou 510620, Guangdong, China;
² School of Mechanical and Storage Engineering, China University of Petroleum-Beijing, Beijing 102249, China.
E-mail: wang_ke@cup.edu.cn

Abstract. Churn flow frequently occurs in power plants, chemical engineering, petroleum, and other industrial applications. Due to its chaotic nature, churn flow has a significant influence on safety and management control. As one of the essential characteristics of churn flow, depth knowledge of the huge wave is crucial for a better understanding churn flow. However, relevant studies on these issues are still in shortage because it is difficult to capture its behaviours experimentally. In this study, we employed the high-speed camera to capture the evolution and properties of huge waves under churn flow conditions in a vertical pipe. The inner diameter of the pipe is 19 mm. Based on the observation, the flooding of the falling film in churn flow is demonstrated to be the slug/churn transition mechanism. Additionally, the liquid distribution in the cross-section of the tube is provided and discussed in detail. Compared with the existing experiment data, we carefully analyze the properties of huge waves, such as frequency and amplitude.

Keywords. Churn flow, two-phase flow, entrainment, pressure drop.

1. Introduction

The critical heat flux (CHF) is significant for system security in chemical and engineering applications, such as nuclear reactors, power plants, boilers, etc. Generally, when excessive liquid entrainment occurs in the annular flow, the so-called "dry-out" phenomenon occurs with the liquid film being utterly exhausted from the pipe wall. The deterioration of heat transfer caused by the dry-out would cause the pipe to overheat and even explode. Therefore, it is essential to predict the occurrence of dry-out to avoid such severe accidents.

Whalley et al. [1] provided a classic physical model for predicting the occurrence of dry-out under the steady-state circumstance. Note that the integration process is dependent on the initial entrained fraction E₀ at the start of the annular flow, which varies between zero and unity. Generally, E₀ is empirically assumed due to its difficulty in measurement. Table 1 illustrates the assumed value of entrained fraction E₀ at the onset of annular flow from the literature [1-9]. Although these assumed values provide good predictions on the CHF, the assumptions do not correspond with reality. It is worth mentioning that...
Ahmad et al. [10] put forward that the integration of the entrainment and deposition process from the beginning of churn flow instead of the annular flow is more logical. Thus, the characteristic of churn flow is vital for CHF prediction.

### Table 1. Assumed value of $E_0$ by different authors.

| Reference          | Assumed value          |
|--------------------|------------------------|
| Whalley et al. [1] | 0.9                    |
| Saito et al. [2]   |                        |
| Hewitt and Govan   | 0.99                   |
| Lee et al. [4]     |                        |
| Okawa et al. [5-7] |                        |
| Govan et al. [8]   | 0.99                   |
| Sugawara [9]       | 0.91                   |
|                    | 0.001                  |
|                    | 0.05                   |

Churn flow is a typical intermittent upward flow, which is normally observed in the vertical and near-vertical tubes. Due to its chaotic nature, the definition of the churn flow still has controversy. Zuber and Findley [11] considered the churn flow as a category of bubbly flow. Taitel et al. [12] argued that the churn flow is just a developing slug flow. Based on the experimental observation, Hewitt and Hall Taylor [13] believed that churn flow occurs after the crush of slug flow. They defined it as an intermediate flow regime between the slug and annular flow. Generally, there are four points of view on the formation of the churn flow, i.e., bubble coalescence mechanism, entrance effect mechanism, wake effect mechanism and flooding mechanism. Jayanti and Hewitt [14] reviewed these four models and proposed that the flooding mechanism is more proper to interpret the slug-churn transition. Additionally, Jayanti et al. [15] observed and confirmed that huge waves, also called large waves, appear on the falling film when the transition is approaching.

A typical feature of the churn flow distinguishes from the annular flow is the existence of huge waves travelling up and down periodically over a falling film throughout the regime. In the photographic study of Hewitt et al. [16] with chromium dye, it was found that there is a periodic reversal of bulk liquid. Note that the huge wave is the primary phenomenon. Ultimately, by increasing the gas velocity, the liquid downward film ceases, resulting in an upward annular flow. According to the work of Hewitt and Wallis [17] and Wallis [18], the critical condition for the flow reversal can be described by a dimensionless superficial gas velocity $U_{sg}^*$ as:

\[
U_{sg}^* = \frac{\rho_G}{u_g \sqrt{gd (\rho_L - \rho_G)}} \approx 1
\]

where $u_g$, $d$, $\rho_L$, $\rho_G$ are the superficial gas velocity, pipe diameter, densities of liquid and gas, respectively.

Owen [19] investigated the variation of the pressure gradient, including bubbly flow, slug flow, churn flow and annular flow. Based on his research, there was a sudden increase in the pressure gradient when the slug flow breaks down. After that, the pressure gradient gradually decreases during the churn flow and eventually increases when the annular flow occurs. To explore the relationship between the flooding of the falling film and the formation of churn flow, Govan et al. [20] employed the method for the flooding
measurement. They compared the pressure gradient and liquid holdup in the cases of with or without the falling liquid film below the liquid injector. According to their observation, there was no discernible difference between these two cases, demonstrating that the flooding phenomenon is closely related to the slug/churn transition. Moreover, Barbosa et al. [21] experimentally and numerically investigated the characteristics of churn flow. They employed a high-speed camera to record the process of wave formation and motion in a 31.8 mm i.d. tube under churn flow conditions. By analyzing the forces acting on the control volume, a mathematical model for wave levitation was also built. Enrico and Davide [22] used the VOF method to numerically investigate the properties of churn flow with the fluids of air-water and R134a vapour-liquid mixtures. They also proposed a simplified model to investigate the effects of liquid and gas superficial velocities and pipe diameters on the suspension process of the typical ring-type waves in churn flow.

The generation of the entrained droplets in churn flow results from undercut and sheared-off of the interfacial waves [23]. The droplet deposition in churn flow is often dominated by the radial velocities imparted at the generation of droplets. Unlike annular flow, the variation of the entrained fraction is inversely related to the superficial gas velocity [24-26]. Wallis et al. [27] used a uniaxial positioning sampling probe to measure the entrainment rate of churn and churn-annular transition. They indicated that a considerable amount of liquid is entrapped as droplets in the churn flow, and the entrained fraction reaches the lowest value at the churn-annular transition. Barbosa et al. [26] used an isokinetic probe to measure the entrained fraction both under churn and annular flow conditions. They proved that the entrained fraction has an inverse ratio to the gas velocity in the churn flow region, passing through a minimum value at the churn/annular transition, and increasing in annular flow again. Accordingly, an empirical equation for $E_o$ under adiabatic and equilibrium conditions was proposed as:

$$E_o(\%) = 0.95 + 342.55 \sqrt{\frac{\rho_L m_L}{\rho_G m_G} d_i}$$

(2)

where $m_g$, $m_L$, $d_i$, $\rho_L$, $\rho_G$ are the local gas mass flux, the local liquid mass flux, pipe diameter, liquid density, and gas density, respectively. The minimum of $E_o$ occurs at the transition to annular flow, when dimensionless superficial gas velocity $U_g^* = 1$.

Moreover, Azzopardi and Wren [28] investigated the entrained fraction with a T-junction. The results indicate that entrained fraction has a weak dependency with pipe diameter and the inlet gas flowrate but a strong relationship with liquid flowrate. Ahmad et al. [10] proposed an empirical equation for entrainment rate in churn flow. Accordingly, the CHF in both uniform and non-uniform heating tubes was predicted, and the predicted results are all less than ±20%.

$$\frac{E_{\text{churn}}}{E_{\text{annular, local}}} = -8.73 U_g^* + 9.73$$

(3)

In the present paper, the phase distributions in the axial direction and cross-section of the tube under churn flow conditions are experimentally investigated. By analyzing high-speed photography, the evolution of the huge waves and mechanism of entrainment are qualitatively studied. Since the film oscillates in the flow direction, the conventional method for measurement of entrained fraction (extracting the liquid film) is not feasible in this pattern. Therefore, the liquid distribution in the cross-section of the tube is still measured by the optical method.
2. Experiment System and Method

2.1. Experimental System

Figure 1 depicts the experimental system consisting of the test section, gas and liquid loops. The air is separated into two ways after the regulator valve, i.e., one way of developed gas is fed into the test section at the end of the tube, and the other flows into the branch gas channel. The water flows into the test section by a 0.55 kW pump through a porous wall. It can be observed that the water in the test section can also be removed in two ways: one is to discharge upward water from the upper outlet, and the other is to extract falling film from the extraction sinter.

![Diagram of the test facility.](image)

The test section is made of transparent polymethylmethacrylate with 2 m in length and 19 mm in diameter. For the convenience of extracting the liquid from the test section, there are two porous parts in the test section. The water inlet section, which is designed with 300 holes of 1 mm diameter staggered in 15 rows, is equipped with a water chamber, while the water extraction section is designed with 250 holes of 1 mm diameter. Note that the spacing of the holes is about 2 mm. The air and water are metered by a rotor flow meter and an orifice flow meter, respectively. In addition, the liquid mass flux carried upward is measured by the weighing method. For the flow visualization, a Memrecam fx K3 high-speed camera is used to obtain the movement and growth of the huge waves and the liquid distribution in the tube's cross-section. In this study, the sampling frequency is set to be 100 frame/s. A sheet beam and backlight illumination are employed to light up the test section both in the axial and the cross-section parts. To prevent the pollution of the CCD lens by entrained droplets in the gas flow, a strong lateral direction wind is introduced to avoid these injected liquids.

2.2. Experimental Procedure

The experimental method proposed by Barbosa et al. [21] is adopted in the present study. The gas first flows into the test section at a relatively smaller value, while the liquid enters the liquid chamber at an expected value. Under these circumstances, the liquid is extracted into the test section to form a falling film. Finally, the falling film would be completed extracted out of the test section from the outlet sinter. By increasing the gas flow rate to a certain value, the falling film ceases near the outlet sinter.
Accordingly, the so-called huge waves repeatedly form and eventually move upwards to the out of the pipe. During wave evolution, the huge waves break up into droplets of different sizes, causing the upper flow to oscillate wildly. Therefore, the region located above the water inlet part is the expected churn flow.

In the present study, all the experiments are carried out under atmospheric pressure and room temperature. The gas flow rates are $5.2 \sim 8.5 \text{ m}^3/\text{h}$, and the liquid flow rates are $14.9 \times 10^{-3} \sim 43.5 \times 10^{-3} \text{ kg/s}$. As illustrated in figure 2, all the experiments are performed over a churn flow condition.

![Figure 2. Distribution of the test points on the flow pattern map [29].](image)

### 3. Results and Discussions

#### 3.1. Evolution of Huge Waves

Figure 3 illustrates the evolution of a typical huge wave. It is assumed that an individual wave has already been generated in the water inlet section at $t=0 \text{ ms}$, as seen in figure 3(a). Figure 3(b) shows that the wave grows in radial and axial directions and moves slightly down the porous section. At $t=24 \text{ ms}$, the wave crest closely reaches its maximum amplitude or even forms a liquid bridge at this circumstance. In the following evolving process, the wave that picks up liquid from the film falls above and starts to move upwards, as seen in figure 3(c). Eventually, the wave is torn by the coming gas flow to form a number of entrained droplets. It is worth mentioning that the upper liquid film oscillates along the flow direction. As shown in figure 3(d), the wave almost moves out of the frame, and a newly born wave appears around the inlet section. Thus, it is demonstrated that the flooding of the falling film leads to the onset of churn flow.

![Figure 3. Evolution of huge waves in churn flow.](image)

$(u_g=6.17 \text{ m/s}, u_{sl}=74.85 \times 10^{-2} \text{ m/s}, U^*=0.49)$
Due to gravity, the huge wave would first move downwards for a distance to a “balanced” position and finally reverse upward. Figure 4 shows the positions that huge waves change to travel upward under different flow conditions. The results indicate that the lower the superficial gas velocity, the wave travels farther downward. Additionally, the critical amplitude of huge waves decreases with the increasing gas velocities, which can be attributed to the promotion of the entrainment caused by the increasing interfacial shear stress. Note that the liquid film performs quite differently after the collapse of the huge wave. As seen in figure 5, the wave becomes more distorted at the lower superficial gas velocity because of the lower shear stress.

Figure 4. The positions that huge waves reverse to travel upward at different superficial gas velocity ($G_f=16.25\times10^{-2}$ kg/s).

Figure 5. Comparison of oscillation at different flow conditions ($u_{sg}=4.99$ m/s, $u_{lu}=8.84\times10^{-2}$ m/s, $U_\nu=0.40$).
Figure 6. Axial view of churn flow. ($U_g=1.02$)
Figure 6 illustrates the liquid distribution in the cross-section of the tube from churn flow to annular flow. Unlike the uniform distribution of the liquid film along the tube’s circumference in the annular flow (figure 6(a)), which is consistent with the work of [13, 30], the circumferential distribution of the liquid film in churn flow is non-uniform. Remarkably, the oscillation of the liquid film is attributed to this irregular distribution. Therefore, 2D simplification may not work correctly in the simulation under churn flow conditions, which cannot reflect the natural characteristics of this particular flow pattern. Another essential characteristic of churn flow is the drop size, which varies in time and space. Due to the mechanism of entrainment in churn flow (undercut or bag break-up) differing from that in annular flow (ligament break-up), the drop sizes are quite different. The qualitative result inferred from figure 6 is that drop sizes are larger than annular flow, and there seem to be some liquid blocks in the gas core. Relevant research on drop size will be studied in the future.

3.2. Frequency of Huge Waves

Based on the experimental observation, part of the liquid is transported upwards during the movement of interfacial waves, while the liquid film between the waves travels downwards. Thus, the net fluid mass flow rate $G_{nl}$ (the liquid that waves carried upward) may vary from zero to total liquid mass flow rate. Parts of experimental data are listed in table 2.

| $V_g$ (m³/h) | $G_l \times 10^{-3}$ (kg/s) | $G_{nl} \times 10^{-3}$ (kg/s) | $u_g$ (m/s) | $u_{nl} \times 10^{-3}$ (m/s) | $U^*$ | $Re_g$ | $f$ (s⁻¹) |
|-------------|-----------------------------|-------------------------------|------------|-----------------------------|------|--------|------|
| 5.1         | 20.51                       | 10.15                         | 5.00       | 35.90                       | 0.40 | 6079.04 | 8.36 |
| 5.1         | 28.52                       | 17.74                         | 5.00       | 62.75                       | 0.40 | 6079.04 | 8.77 |
| 5.1         | 36.86                       | 24.98                         | 5.00       | 88.36                       | 0.40 | 6079.04 | 8.79 |
| 6.2         | 20.43                       | 14.66                         | 6.07       | 51.86                       | 0.49 | 7390.21 | 8.71 |
| 6.1         | 28.28                       | 25.78                         | 5.98       | 91.19                       | 0.48 | 7271.01 | 10.50 |
| 6.1         | 37.09                       | 29.63                         | 5.98       | 104.81                      | 0.48 | 7271.01 | 11.17 |
| 7.4         | 20.29                       | 14.61                         | 7.25       | 51.68                       | 0.58 | 8820.57 | 11.02 |
| 7.4         | 28.25                       | 25.95                         | 7.25       | 91.80                       | 0.58 | 8820.57 | 12.96 |
| 7.4         | 36.75                       | 31.80                         | 7.25       | 112.49                      | 0.58 | 8820.57 | 13.24 |
| 8.1         | 20.55                       | 16.25                         | 7.94       | 57.48                       | 0.63 | 9654.95 | 11.95 |
| 8.2         | 28.47                       | 25.26                         | 8.03       | 89.36                       | 0.64 | 9774.14 | 13.33 |
| 8.1         | 36.71                       | 31.91                         | 7.94       | 112.88                      | 0.63 | 9654.95 | 13.33 |

Figure 7 shows the variation of the net liquid mass flow rate carried by waves. As expected, the net liquid mass flux increases with the increase in gas and liquid velocities. As the gas velocity increases, more liquids are carried upwards due to the increasing interfacial shear stress.
Figure 7. Variations of the net liquid mass flow rates.
(a=16.29×10^{-3} kg/s, b=20.45×10^{-3} kg/s, c=24.36×10^{-3} kg/s, d=28.38×10^{-3} kg/s,
e=32.75×10^{-3} kg/s, f=36.85×10^{-3} kg/s, g=40.89×10^{-3} kg/s)

Figure 8 shows the variation of the wave frequency under different flow conditions. The result indicates that the wave frequency increases with increasing of gas and liquid velocities. Note that the wave frequency gradually approaches a constant value when the gas velocity increases, and the dependence on the liquid rate are fragile. It can be interpreted that when the wave amplitude reaches its maximum value, the collapse of the huge wave bursts more quickly at higher gas velocity before the liquid affects the frequency. Figure 9 compares the present study with the work of [16, 21]. Based on the current work, the wave frequency directly correlates with the Reynolds number of the gas phase, and there seems little dependency on liquid mass flow rate. Due to the limited experiment data from Barbosa et al. [21], little information can be inferred. However, the experiment data from Hewitt et al. [16] are quite different, i.e., the span of wave frequency is much larger, and the wave frequency has a strong dependency on liquid mass flow rate. The frequency increases with the increase in gas velocity at a lower net liquid mass flow rate but inverses at a higher net liquid mass flow rate. No doubt that the fluid properties and pipe diameter are suspected to be the main reason. The experiment of Hewitt et al. [16] was taken within a 10mm vertical tube, and the working fluids are trichloroethylene and air. Moreover, near the average cross-section of the same gas Reynolds number and net liquid mass flow, the smaller the diameter is, the higher the fluctuation frequency is. It is assumed that the smaller the gas circulation area is, the higher the gas velocity is and the higher the fluctuation frequency is.

Figure 8. the frequency of huge waves at different flow conditions.

Figure 9. Comparison of wave frequency with the data available in literature.
4. Conclusions
A depth understanding of the properties of huge waves in churn flow is important to accurately predict the occurrence of CHF. The characteristics of churn flow are studied qualitatively by using high-speed visualization technology. It was experimentally shown that huge waves periodically appear at the water inlet section, travel upward, and eventually entrain into the gas phase. In addition, the liquid film performs more unstable at the smaller gas velocity due to the insufficient shear stress. The liquid non-uniformly distributes in the cross-section of the pipe, and the droplet size in churn flow is intuitively larger than that in the annular flow. Moreover, the experiment data analysis indicates that the wave frequency increases with the increasing gas and liquid flow rates, but the amplitude is contrary. Comparison of data with Hewitt et al. [16] and Barbosa et al. [21] shows a sensible difference, which was suspected that physical properties and tube diameter are the reason for this difference.

References
[1] Whalley P B, Hutchinson P and Hewitt G F 1974 Calculation of critical heat flux in forced convection boiling Proceedings of the 5th International Heat Transfer Conference Tokyo, Japan p 290-294.
[2] Saito T, Hughes E D and Carbon M W 1978 Multi-fluid modelling of annular two-phase flow Nuclear Engineering and Design 50(2) 225-271.
[3] Hewitt G F and Govan A H 1990 Phenomenological modelling of non-equilibrium flows with phase change International Journal of Heat and Mass Transfer 33(2) 229-242.
[4] Lee K W, Baik S J and Ro T S 2000 An utilization of liquid sublayer dryout mechanism in predicting critical heat flux under low pressure and low velocity conditions in round tubes Nuclear Engineering and Design 200(1-2) 69-81.
[5] Okawa T, Kotani A, Kataoka I and Naito M 2003 Prediction of critical heat flux in annular flow using a film flow model Journal of Nuclear Science and Technology 40(6) 388-396.
[6] Okawa T, Kotani A and Kataoka I 2004 Experiments for equilibrium entrainment fraction in a small vertical tube Proceedings of the 5th International Conference Multiphase Flow Yokohama p 224.
[7] Okawa T, Kotani A, Kataoka I and Naitoh M 2004 Prediction of the critical heat flux in annular regime in various vertical channels Nuclear Engineering and Design 229(2-3) 223-236.
[8] Govan A H 1988 Phenomenological prediction of critical heat flux Proceeding of the 2nd UK National Heat Transfer Conference p 315-326.
[9] Sugawara S 1990 Droplet deposition and entrainment modelling based on the three-fluid model Nuclear Engineering and Design 122(1-3) 67-84.
[10] Ahmad M, et al. 2010 Drop entrainment in churn flow 7th International Conference on Multiphase Flow Tampa, FL USA.
[11] Zuber N and Findlay J A 1965 Average volumetric concentration in two-phase flow systems Journal of Heat Transfer 453-468.
[12] Taitel Y, Barnea D, Dukler A E 1980 Modelling of flow pattern transitions for steady upward gas-liquid flow in vertical tubes A.I.Ch.E.J. 26 345-354.
[13] Hewitt G F and Hall-Taylor N 1970 Annular Two-Phase Flow (Oxford: Pergamon Press).
[14] Jayanti S and Hewitt G 1992 Prediction of the slug-to-churn flow transition in vertical two-phase flow International Journal of Multiphase Flow 18(6) 847-860.
[15] Jayanti S, Hewitt G F, Low D E F and Hervieu E 1993 Observation of flooding in the Taylor bubble of co-current upwards slug flow International Journal of Multiphase Flow 19(3) 531-534.

[16] Hewitt G F, Martin C J and Wilkes N S 1985 Experimental and modelling studies of annular flow in the region between flow reversal and the pressure drop minimum Physico-Chemical Hydrodynamics 6 43-50.

[17] Hewitt G F, Martin C J and Wilkes N S 1985 Experimental and modelling studies of annular flow in the region between flow reversal and the pressure drop minimum PCH Physicochemical Hydrodynamics 6(1/2) 69-86.

[18] Wallis G B 1969 One-Dimensional Two-Phase Flow (New York: McGraw-Hill).

[19] Owen D G 1986 An Experimental and Theoretical Analysis of Equilibrium Annular Flows (UK: University of Birmingham).

[20] Govan A H, Hewitt G F, Richter H J and Scott A 1991 Flooding and churn flow in vertical pipes International Journal of Multiphase Flow 17 27-44.

[21] Barbosa J, Govan A H and Hewitt G F 2001 Visualization and modelling studies of churn flow in a vertical pipe International Journal of Multiphase Flow 27(12) 2105-27.

[22] Da Riva E and Del Col D 2009 Numerical simulation of churn flow in a vertical pipe Chemical Engineering Science 64(17) 3753-65.

[23] Azzopardi B J 1997 Drops in annular two-phase flow International Journal of Multiphase Flow 23 1-53.

[24] Verbeek P H J, Miesen R and Schellenkens C J 1992 Liquid entrainment in annular dispersed upflow 8th Annual European Conference on Liquid Atomization and Spray Systems Amsterdam, p 33-45.

[25] Azzopardi B J and Zaidi S H 2000 Determination of entrained fraction in vertical annular gas/liquid flow Journal of Fluids Engineering 122 146-150.

[26] Barbosa J R, Hewitt G F, König G and Richardson S M 2002 Liquid entrainment, droplet concentration and pressure gradient at the onset of annular flow in a vertical pipe International Journal of Multiphase Flow 28(6) 943-961.

[27] Wallis G B 1962 The onset of droplet entrainment in annular gas–liquid flows General Electric Report No. 62GL127.

[28] Azzopardi B J and Wren E 2004 What is entrainment in vertical two-phase churn flow International Journal of Multiphase Flow 30(1) 89-103.

[29] Hewitt G F and Roberts D 1969 Studies of Two-Phase Flow Patterns by Simultaneous X-Ray and Flash Photography (Harwell, England: Atomic Energy Research Establishment).

[30] Ohba K and Nagae K 1993 Characteristics and behaviour of the interfacial wave on the liquid film in a vertically upward air-water two-phase annular flow Nuclear Engineering and Design 141(1-2) 17-25.