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# Experimental investigation of interfacial structures within churn flow using a dual wire-mesh sensor

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ABSTRACT

A challenging area in the field of multiphase flow is the study of churn flow. According to the multiphase flow community, churn flow has not been widely investigated in intermediate and large diameter pipes at high gas and liquid flow rates. The present work deals with an experimental study of upward vertical air–water flow in a 76.2 mm I.D. pipe. Superficial gas velocities ranging from 10 to 38 m/s and four superficial liquid velocities (0.30, 0.46, 0.61 and 0.76 m/s) were employed. The experimental data points are mostly located in churn flow and at the transition between churn and annular flow. A dual 16 × 16 Wire Mesh Sensor (WMS) was used to obtain the temporal/spatial variations of phase distributions over the pipe cross-section at one specific axial location ($L/D = 236$).

Sequences of phase distributions, axially sliced images, virtual 3-D images as well as void fraction time-series were used to distinguish between different interfacial structures such as slugs and huge waves. Results showed that huge waves occur with either a continuous gas core with a distinct boundary between two phases or a core with a gas–liquid mixture. Furthermore, velocities and frequencies of interfacial structures were obtained. Results are qualitatively and quantitatively consistent with the previous findings available in literature.



## Introduction

Churn flow is one of the least investigated multiphase flow regimes. Not because the study of the churn flow regime is not important but rather due to the complicated nature of this flow pattern. Hewitt (2012), for example, showed that critical heat flux or dry out can occur in the churn flow regime, which reveals the "technological" importance of churn flow.

There has been confusion about the definition of churn flow. The term "churn", for instance, has been used to refer to different flow types such as bubbly flow (Zuber and Findlay, 1965) or developing slug flow (Taitel et al., 1980). Furthermore, Mao and Dukler (1993) suggested that churn flow is a "continuous extension of the condition of slug flow" and there is no transition between slug and churn flow. This leads to the conclusion that churn flow should not be considered as a separate flow regime. However, different hypotheses have been suggested regarding the slug to churn flow transition (Brauner and Barnea, 1986; Nicklin and Davidson, 1962; Mishima and Ishii, 1984; McQuillan et al., 1985; Jayanti and Hewitt, 1992; Chen and Brill, 1997).

Generally, multiphase flow investigators now believe that churn flow is a separate flow regime between slug flow and annular flow (Hewitt et al., 1985; Govan et al., 1991; Hewitt and Jayanti, 1993) and has been referred to by different names in the past such as "frothy slug" and "pulsating annular" (Brauner and Barnea, 1986). Churn flow typically appears in near-vertical and vertical pipes and is characterized by the presence of large interfacial waves called flooding-type or huge waves. These waves, hereafter referred to as huge waves, are periodic structures. They move upward and sweep the liquid film, and as a result a portion of the liquid is entrained into the gas core. Between these waves, there exists a falling liquid film.

Azzopardi and Wren (2004) reported that 71% of the liquid was in the form of huge waves, indicating that they are the major source of droplet entrainment. Understandably, the frictional pressure gradient is primarily caused by the presence of these waves. Sawai et al. (2004) used time-series void fraction to determine the frictional component of pressure drop. They showed that at lower liquid velocities the frictional component has a negative

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slope against superficial gas velocity. Wang et al. (2012) recently developed a model for huge wave movement. They showed that when the superficial gas velocity increases the wave amplitude decreases.

Different interfacial structures exist in churn flow. Therefore, time/space information of the phase distributions would give insight into the behavior of these structures. Using many needle probes in a 25.6 mm vertical pipe, Sekoguchi and Mori (1997) differentiated various "liquid lumps" in churn flow. They observed three groups of liquid lumps namely: slugs, huge waves, and disturbance waves. Slugs bridge the pipe cross-section and move with an almost constant velocity. Huge waves are those liquid lumps in which a gas core is formed. Disturbance waves appear at higher gas and lower liquid flow rates, and they have velocities lower than the velocity of huge waves (Sekoguchi and Takeishi, 1989).

Recently, Parsi et al. (2014) and Hewakandamby et al. (2014) have studied the effect of viscosity on churn flow. They have shown that void fraction increases when liquid viscosity increases up to a certain value.

In the current study, periodic structures were also observed during experiments. They appeared as dark zones (Fig. 1a and b), when they were viewed through a transparent observation section. They swept the base liquid film on the pipe wall, and a falling liquid film was observed between them (Fig. 1c). However, the falling film was not observed at higher superficial gas velocities. What is the distribution of the phases within these dark zones? Are they the huge waves observed by other researchers (Sekoguchi and Mori, 1997; Sekoguchi and Takeishi, 1989)? How does the velocity of these structures change with the change in liquid or gas flow rates? Regrettably, an extensive literature survey showed that churn flow has not been dealt with in depth at high gas and liquid flow rates. This study seeks to address the mentioned questions and experimentally study various aspects of churn flow at high liquid and gas flow rates in an intermediate diameter pipe.

This paper is organized as follows. Section 'Experimental apparatus' explains the experimental facilities and the operational principles of the WMS. In section 'Results and discussion', results are demonstrated and discussed in detail. Finally, conclusions drawn from the study are presented.

## Experimental apparatus

Void fraction data were obtained at different points of a pipe cross-section with respect to time in order to study churn flow. To obtain void fraction data, a dual Wire Mesh Sensor (WMS) was used. WMS delivers void fraction data at each point of the WMS grid. The WMS was mounted within a flow loop at the Erosion/Corrosion Research Center (E/CRC) at the University of Tulsa.

### *Flow loop*

Fig. 2 displays the flow loop and the location of the WMS. This apparatus has been previously used in the work of Parsi et al. (2014), Hewakandamby et al. (2014), Vieira et al. (2014a, 2014b) for multiphase flow and erosion studies. The primary components of the loop are four pumps, three compressors, a 250 gallon liquid tank, a separator tank, two gas flow-meters and an inclinable boom that houses the test section.

There are two sets of pumps (totaling 4 pumps). The first set consists of pumps P2a and P2b (see Fig. 2) which are Ingersoll Rand ARO 3-in. outlet metallic double diaphragm pumps. These are the bigger pumps which provide higher liquid flow rates. A Caterpillar Sullair 375H air compressor is used to drive this set of pumps. This compressor (compressor 3 in Fig. 2) has a capacity of 375 standard cubic feet per minute (scfm).

The other set of pumps consisted of pumps P1a and P1b which are Ingersoll Rand ARO 2-in. outlet non-metallic diaphragm pumps. These two pumps are powered by a 100 scfm electric air compressor. Pumps P1b and P2b are used to transfer liquid from the separator to the liquid tank.

The flow loop includes two Ingersoll Rand diesel compressors (compressors 1 and 2 in Fig. 2), each with a maximum gas flow rate of 400 scfm. One of these compressors was used to supply the gas flow inside the pipe. The gas flow rate is measured using a TRIO-WIRL V gas vortex flow meter. The flow meter was calibrated by means of a rotameter. The gas flow rate measurement uncertainty was ±2.5%. The gas used in the experiments was air.

The liquid rate was measured by timing the volume loss inside the water tank. This measurement was performed several times to quantify the measurement uncertainty. The liquid flow rate measurement uncertainty was ±5%. The liquid used in the experiments was tap water. Liquid was re-circulated in the loop.

The inclinable boom loop has a 76.2 mm diameter pipe 18 m in length that was used in the present study. The test section pipe was 316 stainless steel, but there were three clear PVC observation sections used for observing the flow pattern.

All the experiments were carried out in the vertical configuration. The inclinable loop in the vertical configuration is shown in Fig. 2. The superficial gas (air) velocity ($V_{SG}$) ranged from 10 to 38 m/s. Liquid (water) superficial velocities ($V_{SL}$) of 0.30, 0.46, 0.61 and 0.76 m/s were employed.

### *Wire mesh sensor*

Different measurement techniques have been used by researchers to study multiphase flow. Among them are X-ray tomography (Reinecke et al., 1998), gamma-ray tomography (Johansen, 2005), Electrical Capacitance Tomography (ECT) Abdulkadir et al., 2014, Electrical Resistance Tomography (ERT) Wang et al., 2012, and WMS (Prasser et al., 1998). Techniques such as conventional X-ray and gamma-ray tomography cannot be used for rapid transient multi-phase flow, since they have low imaging speed. Ultrafast X-ray tomography (Fischer and Hampel, 2010; Barthel et al., 2013) is suitable for fast flow imaging with the advantage of nonintrusive imaging; however, the method is very complicated and not applicable for an outdoor loop. ECT and ERT techniques provide coarse spatial resolution. The key advantages of WMS are its higher temporal and spatial resolutions in comparison to other measurement techniques. Regarding WMS intrusiveness, it has been found that at higher velocities WMS has no impact on flow structure (Szalinski et al., 2010). In the recent years, there has been a rapid rise in the use of WMS for scrutinizing multiphase flow (Prasser et al., 2005; Omebere-Iyari et al., 2008; Kaji et al., 2009; Hernandez-Perez et al., 2010; Da Silva and Hampel, 2013).

The WMS used in this study consisted of 2 layers of evenly distributed wires. The distance between the two layers was 1.5 mm. Each layer had 16 wires which were made of 316L stainless steel. The diameter of the wires was 0.3 mm. The distance between wires of a layer was 4.76 mm. The two layers formed 256 pairs of perpendicular crossing wires. Each pair of crossing wires was formed by a transmitter wire ($i$) and a receiver wire ($j$) (i.e. one layer consists of transmitter wires and the other layer consists of receiver wires). The WMS and its data acquisition were constructed and supplied by HZDR Dresden, Germany.

The WMS operation principle is based on the significant difference in the electrical conductivities of the utilized fluids with the electrical conductivity of water being much higher than the electrical conductivity of air. An electrical voltage is passed through the transmitter wires in successive order. Consequently, the corresponding receiver wires experience current pulses successively. At a receiver wire, a current pulse is a measure of the