

# Churn flow in high viscosity oils and large diameter columns

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## Abstract

Churn flow is an important intermediate flow regime occurring in between slug and annular flow patterns in two-phase flow, with profound implications in chemical and petroleum industry. The majority of studies to date in churn flow have been carried out mainly using water or liquids of low viscosities and limited information exists regarding the behaviour of high viscosity liquids which resemble realistic process conditions. In this paper, a study that investigated churn flow and its characteristics in high viscosity oils (360 and 330 Pa.s) and large diameter columns (240 and 290mm) is presented for a first time. Transition to churn flow regime starts when the structure velocity, length and frequency of the liquid bridges, which appear at the end of slug flow, increase. In churn flow, gas flows at the core of the oil column with a wavy passage, leaving the top surface open to atmosphere with a possibility of creating a very long bubble. The average length of the bubbles seen to decrease with increasing the gas flow rate. While, no considerable change is observed in void fraction, structure velocity and film thickness at this flow pattern.

## Keywords:

High viscosity liquids, transition to churn, churn flow, large diameter, Electrical Capacitance Tomography, volcanic conduits.

## 23        **1. Introduction**

24            Churn flow, which is an intermediate flow regime that appears between slug and annular flow  
25 regimes, is an important flow pattern in gas-liquid two-phase flow. Churn flow occurs during operations in  
26 many hydrocarbons industries and chemical processes such as pipelines in oil and gas industry. It can also  
27 be found in some natural phenomena such as volcanos. The pressure drop, mass and heat transfer are design  
28 parameters which have a significant role in the safety and the stability of gas-liquid systems and can be  
29 affected during churn flow. In churn flow, the gas-liquid travels upward and downward in a churning or  
30 oscillating movement with a resultant of upward flow. This oscillating motion is a result of two forces,  
31 gravity and shear forces, acting in opposing directions on the falling film around Taylor bubbles. Churn  
32 flow was first defined by Zuber and Findlay (1965) as "churn-turbulent" bubbly flow. Then, it was  
33 considered as an intermediate region that occurs between slug and churn flow regimes by Hewitt and Hall-  
34 Taylor (1970). Finally, it was defined as churn flow regime by Taitel et al. (1980). Furthermore, Hewitt et  
35 al. (1985) reported similarities between these two flow regimes by employing a visual technique. In  
36 addition, a modified form of slug flow model was applied by De Cachard and Delhaye (1996) for churn  
37 flow. However, the pressure that drops in the pipe in churn flow is seen to be better predicted by annular  
38 flow model, Holt et al. (1999). Churn flow was correlated to be a developing form of slug flow regime. On  
39 the other hand, Barbosa Jr et al. (2001) defined this flow regime as it appears after the breakdown of slug  
40 flow when the velocity increases. Since churn flow is similar to annular flow regime in features, a number  
41 of studies considered it as annular flow. For instance, Nicklin (1962) used the name "semi-annular" flow to  
42 recognise the annular properties churn flow is distinguished from the annular flow regime based on 3  
43 criteria. First, the change of the pressure gradient inside the pipe with an increasing gas flow rate. The  
44 friction and the intensive wave activity which result from the sudden breakdown of slug flow increase the  
45 pressure gradient significantly inside the pipe. Owen (1986) presented the change of the pressure gradient  
46 data against the dimensionless gas velocity for air-water flow in a 32 mm diameter vertical pipe. According  
47 to his results, the pressure gradient values showed a sudden drop at the transition to churn flow due to the  
48 high-frequency wave activity and friction. However, in Owen's work, the values of the pressure gradients  
49 decreased with an increasing gas flow rate at a constant liquid flow rate. The decrease in the amount of the  
50 interaction between the gas and the liquid is a reason of the decrease of the pressure gradient at the selected  
51 gas flow rate. Then by increasing the gas flow rate, the values of the pressure gradients increased again.

52           Second, the mechanism of the two-phase flow. Churn flow establishes when the falling liquid film  
53 accumulates and starts to flow upward in a form of large waves. This flow mechanism, which was proposed  
54 by Hewitt et al. (1985), is similar to the flooding phenomenon due to the flow of large waves. The third  
55 criterion, for starting churn flow, is the entrainment of the droplets from the large liquid fractions which  
56 travel as large flooding waves along the column. Wallis (1962) found that increasing the gas velocity  
57 decreases the entrained fraction to a minimum value (churn flow). Then a further increase in the upward  
58 gas flow rate increases the liquid entrained fraction in the annular flow. Churn flow in low viscosity liquids  
59 was also studied by Brauner and Barnea (1986), Sekoguchi and Mori (1997), Kaya et al. (2000), de  
60 Carvalho and Ferreira (2000), Furukawa and Fukano (2001), Sawai and Kaji (2001) and Azzopardi and  
61 Wren (2004).

62           Knowledge regarding churn flow in high viscosity liquids and large diameter columns is still limited  
63 despite its importance. Such high viscosity liquids can be found for example in crude oil and bitumen  
64 production (with a viscosity up to 2000 Pa.s, Shu, 1984) and in polymer manufacturing (100-1000 Pa.s). It  
65 is also important to predict the volcanic degassing process where gas-Silicatic magmas rise in volcanic  
66 conduits as multiphase flow mixtures. The viscosity of the common type of magma is ranged from 100 to  
67 1000 Pa.s. No experimental studies to date have so far introduced churn flow in liquids of 360 Pa.s viscosity.  
68 In addition, all existent empirical correlations in slug-churn flow transition are based on low viscosity  
69 liquids (commonly, water). Therefore, the characteristics of the dynamic of two phase flow using realistic  
70 liquids need more attention and investigation. The aim of this work is to investigate the characteristics of  
71 churn flow in very high viscosity liquids and large diameter columns for the first time. Two columns of  
72 240 and 290 mm diameters and 360 and 330 Pa.s Silicone oil respectively were employed in this work.  
73 Electrical Capacitance Tomography (ECT) was used to collect information about the characteristics of the  
74 flow in both columns. Mean void fraction, Probability Density Function (PDF), structure velocity, film  
75 thickness, pressure gradient, large bubbles lengths and frequency were all determined and compared with  
76 analytical approaches from literature.

## 77           **2. Experimental setup**

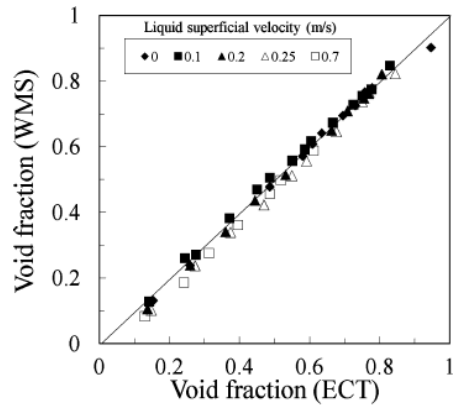
78           In the present work, two experimental rigs of similar design are used to study churn flow in high  
79 viscosity liquids and large diameter columns. Each rig consists of a large vertical column open to the  
80 atmosphere with internal diameters of 240 and 290 mm contained Silicone oils with viscosity of 360 and

81 330 Pa.s respectively. An Electrical Capacitance Tomography, ECT sensor is placed at 2.56 m from the gas  
82 inlet section in both columns in order to allow full development of the flow structure. The ECT sensor (with  
83 twin, 8 electrodes) is connected to a TFLR 5000 electronic box and a PC for data acquisition and processing.  
84 This non-intrusive sensor measures the cross-section distribution of capacitance in the column, which can  
85 be then correlated to the cross-section phase distribution for the non-conductive fluids. The sensor is  
86 capable of measuring up 5000 frames per seconds with excitation frequency range of 1 –10 MHz.

87 Measured capacitances are converted into permittivity and concentration distribution as follows. The  
88 properties of the capacitance sensor are initially calculated or measured to generate a sensitivity matrix for  
89 the empty column. This matrix consists of a set of sub-matrices which elements are related to the individual-  
90 pixels in a rectangular  $32 \times 32$  grid that can be used to define the cross-section of the sensor/pipe. Normally,  
91 for a circular pipe, 812 pixels are used. An ECT sensor is calibrated using two different permittivity  
92 materials by first filling the sensor with low permittivity material and measuring all possible individual  
93 inter-electrode capacitances values. The same procedure is repeated for the sensor filled with high  
94 permittivity material. The calibration data obtained is then stored in a calibration-file which helps to set up  
95 the measurement-parameters for each measuring channel. Once the calibration has been completed,  
96 capacitances between all unique pairs of sensor-electrodes can be measured continuously. The possible  
97 unique capacitance values are  $N(N-1)/2$  per image frame or measurement, where N is the number of  
98 electrodes. Therefore 28 unique capacitance values per plane were obtained for the experimental work  
99 described in this paper. The measured capacitances were then normalised to the measured values during  
100 the calibration of the system. The overall volume ratio (VR), which is simply the ratio of the two materials  
101 (phases) presented in the pipe can then be easily obtained. For more details on ECT, see for example, Byars  
102 (2001) and Abdulkareem (2011).

103 Azzopardi et al. (2010) validated the ECT using the Wire Mesh Sensor (WMS) for air/Silicone oil  
104 flow in a vertical pipe at different flow regimes (i.e. bubbly, slug and churn flow). Although WMS is an  
105 intrusive technique, placing a WMS sensor downstream the ECT (to prevent flow disturbances across the  
106 ECT) allows the ECT to be validated. Figure 1 shows the comparison of the overall cross-sectional averaged  
107 void fraction between ECT and WMS. The standard deviation between two measurement techniques is  
108 displayed in Fig. 2.

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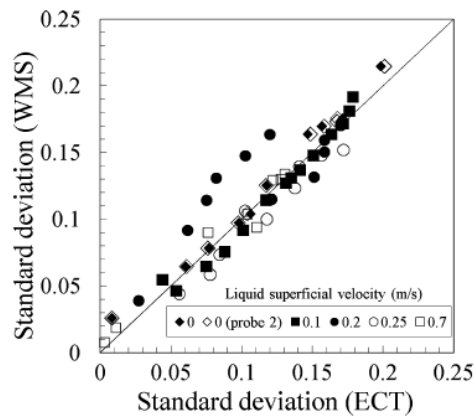


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Figure 1: Averaged void fraction measured using ECT and WMS.

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Figure 2: Standard deviation of measurements between ECT and WMS, Azzopardi et al. (2010).

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In addition, ECT technique was compared and validated using other measurement techniques as well as CFD simulations. Chaminda Pradeep et.al (2014), investigated the validation of an ECT using gamma-ray meter. They reported that ECT showed most of the features and characteristics seen in the gamma-ray meter. CFD simulations were also conducted and the results were in good agreement with their experimental work. Marashdeh (2009) carried out a series of experiments to validate (quantitatively and qualitatively) an ECT using Magnetic Resonance Imaging and fibre optics probes in two phase fluidized bed. He showed that the shape of the bubbles obtained and the voidage distribution from MRI and ECT are almost the same. He reported that, the time averaged cross sectional of solids concentrations calculated from the fibre optic probes and ECT exhibited very good agreement.

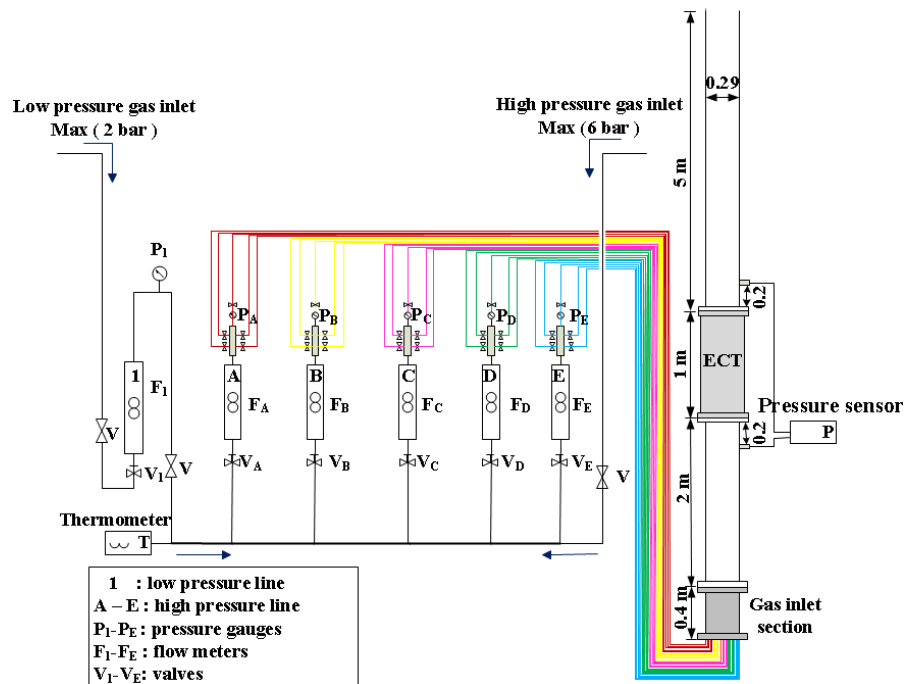
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Figure 3 displays the experimental setup which is used in the present work showing the gas injection arrangements, instrumentation, and the dimensions. The rig is also incorporated a temperature measurement sensor (thermocouple) to indicate the temperature of the air at the gas lines besides the air-oil mixture in

127 the column. Both columns contain stagnant Silicone oil with initial heights of 3.30 m, the properties of the  
 128 fluids are listed in Table 1. The gas injection system consists of two main gas lines to obtain a wide range  
 129 of gas flow rates, high pressure of 6 bar and low pressure of 2 bar. The high-pressure line is connected to 5  
 130 flow meters and pressure gauges. Then each line is divided into 5 more lines. Thus, the total number of the  
 131 gas injection lines is 25 lines distributed equally at the bottom of the column. Sealed pressure transmitters  
 132 were mounted along the 290 mm diameter column to indicate a continuous pressure outputs. The 2 Keller,  
 133 PR-25/8797.1-5 transmitters are installed at 2.2 and 3.6 m from the gas inlet section. The pressure  
 134 measurements were collected at a sampling rate of 50 Hz for 300 s at flow rate range of 10–3000 L/min.



135  
 136 Figure 3: The experimental setup employed to study the flow structure of gas-high viscosity liquids.

137  
 138 Through the gas inlets, air of superficial velocities 0.127–0.314 and 0.108–0.566 m/s was injected  
 139 into the 240 and 290 mm diameter columns respectively. Data acquisition time for each run was 600 s with  
 140 a sampling rate of 50 Hz.

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 142  
 143

Table 1: Properties of the fluids

<b>Fluid (1)</b>	<b>Silicone oil</b>			
Column diameter (m)	Viscosity (Pa.s)	Density (Kg/m <sup>3</sup> )	Surface tension (N/m)	Eötvös number $G\rho_l D^2/\delta$
0.24	360	950	0.02	26812
0.29	330	950	0.02	39148
<b>Fluid (2)</b>	<b>Air</b>			
Column diameter (m)	Gas injections diameters (mm)	Density (Kg/m <sup>3</sup> )	Gas-line pressure bar	Temperature (°C)
0.24	3	1.225	6	20–23
0.29	4	1.225	6	19–22.5

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146 The overall average void fraction,  $\varepsilon_g$  was also calculated from the level swell (i.e. by monitoring the  
147 oscillation level at the top section of the column and determining the initial height of the liquid,  $H_{liquid}$  before  
148 gas injection and the height of the gas-liquid mixture,  $H_{mix}$  after gas injection). This can be calculated based  
149 on the assumption that the volume of the liquid in the column remains constant (Hills, 1976, Al-Oufi et al.,  
150 2010). Therefore;  $\varepsilon_g = \{(H_{mix} - H_{liquid})/H_{mix}\}$ . Table 2 shows the relative error between measured (from  
151 ECT) and calculated void fraction. It should be mentioned that, as the gas superficial velocity increases,  
152 determination of  $H_{liquid}$  becomes more difficult as the liquid becomes milky and the considerable sheared  
153 bubbles stick into the wall of the Perspex pipe which affect the visual appearance of the silicone oil level.

154

155 Table 2: Comparison of measured and calculated void fraction for 240 mm diameter column

Flow regime	Gas superficial velocity (m/s)	Void fraction		
		Level swell	ECT	Relative error
Slug flow	0.016	0.198	0.373	0.468
	0.028	0.321	0.432	0.258
	0.114	0.491	0.487	- 0.008
Transition to churn flow	0.127	0.506	0.496	- 0.020
	0.148	0.509	0.491	- 0.036
	0.175	0.519	0.507	- 0.024
	0.201	0.528	0.501	- 0.053
	0.232	0.546	0.505	- 0.081
	0.260	0.565	0.451	- 0.252
	0.284	0.587	0.435	- 0.348
0.314	0.605	0.505	- 0.196	

### 156 3. Results

#### 157 3.1. Visual observation and time series of void fraction

158 Videos and photos were obtained and compared with the data of the time series of void fraction.  
159 Images were also reconstructed from the recorded data using Tikhonov iterated regularization technique.  
160 Transition to churn flow was observed at gas superficial velocities of 0.127–0.314 and 0.108–0.243 m/s in  
161 the 240 and 290 mm diameter columns respectively. Churn flow appeared at 0.276–0.566 m/s in the larger  
162 diameter column.

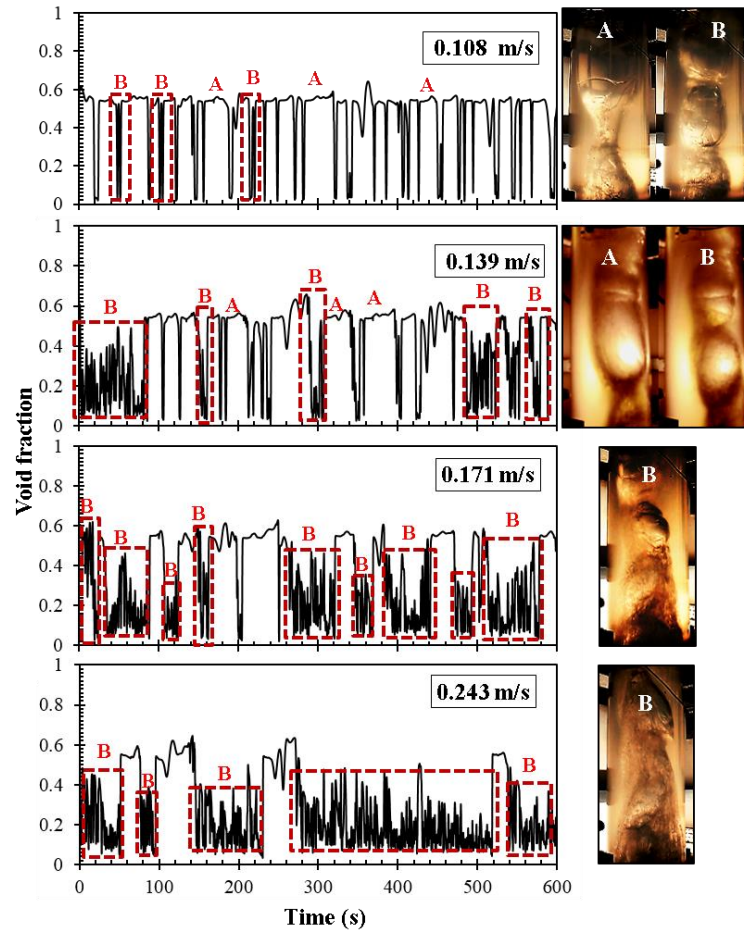
163 At a gas superficial velocity of 0.108 m/s, regions of high frequency activity started to appear. This  
164 extends systematically as the gas flow rate is further increased. These regions are shown as (B) on the time  
165 series of void fraction in the figures below and also depicted on the photos of the column. Figure 4 displays  
166 the time series of void fraction and the equivalent photos which show the flow structure at the selected gas  
167 flow rates. The transition to churn flow regime starts when the length and the frequency of the regions of  
168 the high frequency activity, which appeared at the end of slug flow, increases. These regions of high  
169 frequency activities were observed as the liquid bridges flow up and down. The void fraction of these  
170 regions is lower than that in Taylor bubbles. The source of liquid bridging is believed to be from the drained  
171 falling film from the Taylor bubbles. With increasing gas flow rate, the length of Taylor (A) bubbles  
172 increases until it reaches the total height of the column, producing larger volumes of falling film which lead  
173 to increase the length of the high frequency liquid bridges region and their frequency decreases. The high  
174 frequency liquid bridges region is considered to be churn flow. The maximum amount of the coalescence  
175 between Taylor bubbles occurs in this flow regime (transition to churn). The length of Taylor bubbles  
176 increases dramatically with increasing gas input till it reaches the total height of the column.

177 According to the visual observations, Taylor bubbles become deformed when the gas flow rate is  
178 increased. This is due to increasing the rate of the coalescence and therefore increasing the length of the  
179 bubbles. The Top and/or the bottom of the bubbles lose the round shape. The liquid slugs between the  
180 bubbles eventually disappear and get replaced by the churn areas (B). The churn areas are connected to the  
181 deformed Taylor bubble by a small neck (See (A) in Figure 4). The deformed long Taylor bubbles are  
182 referred to as long bubbles at this flow regime. Coalescence between bubbles appears from about 100–150s  
183 and 230–280s for 0.243 m/s gas superficial velocity in the time series data. The photos of the column in



184 (B) show the developing of the churn areas which become more complicated and deformed with increasing  
185 gas flowrate. By the end of this flow regime, only a small number of long bubbles appear.

186 The Silicone oil which used in this work showed the behaviour of Newtonian liquids during the  
187 viscosity bench test. The viscosity of the oils was measured by applying a certain shear rates using a rotating  
188 spindle. The viscosity of the oil was found to change with changing temperature, not with the amounts of  
189 applied shear force, (Papanastasiou et al., 1999).

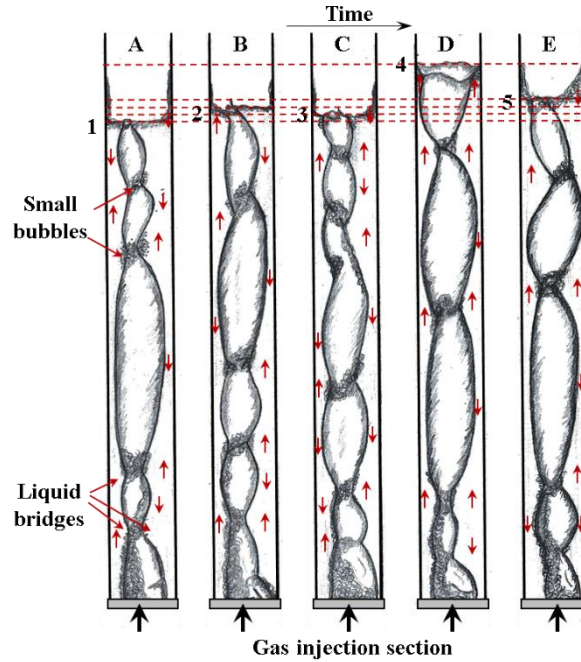


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191 Figure 4: Time series of void fraction and photos of transition to churn flow in 330 Pa.s Silicone oil and  
192 290 mm diameter column at different gas superficial velocities. A is the large bubbles, B is the churn  
193 areas in both photos and the time series

194 The time series data from the ECT besides the videos obtained from the top section at different  
195 positions of the column provide local information about the flow behaviour in the column. Therefore, an  
196 overall picture of the gas-high viscosity liquid behaviour in the column is presented in a schematic drawing  
197 in Figure 5. This schematic drawing shows the overall flow structure in the column at the transition to churn

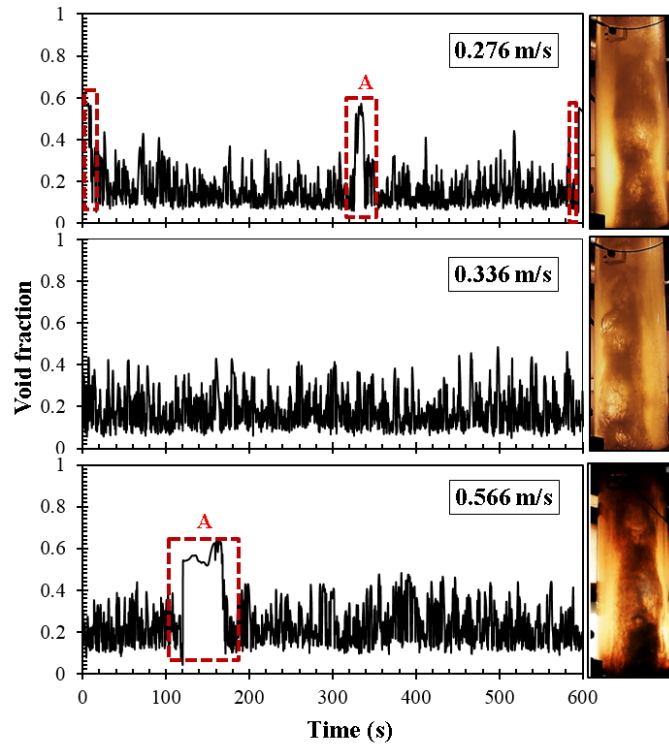
198 flow regime. The letters A–E correspond to the behaviour of the flow structure at different times for  
 199 constant gas superficial velocity (0.205 m/s).



200

201 Figure 5: Schematic drawing showing the transition to churn flow pattern in high viscosity liquids and  
 202 large diameter columns. The arrows in the figure correspond to the direction of the liquid flow, the  
 203 numbers at the top section of the column corresponding to the liquid levels in the column. The gas  
 204 superficial velocity is 0.205 m/s.

205 At a gas superficial velocity of 0.276 m/s, the flow structure changed significantly. The long bubbles  
 206 disappeared and the churn areas dominated the flow structure. According to the time series data and the  
 207 photos shown in Figure 6, and the schematic drawing in Figure 7, churn flow consists of two regions. First  
 208 an open gas core with a thick liquid film with the possibility of liquid bridging the cross-section creating  
 209 series of short bubbles (columns D and E in Figure 7 and the photos in Figure 6). This gas core might not  
 210 exist at the centre of the column. Subsequently, with increasing gas flow rate, the gas builds up and push  
 211 the liquid (column A in Figure 7) creating a very long bubble with a falling thin film. This long bubble  
 212 bursts at the top section of the column and remain open to the atmosphere. This open large core is shown  
 213 in Figure 6 at 120–180 s (A) in 0.566m/s gas superficial velocity and (B) in Figure 7. Then the falling film,  
 214 which drains along the pipe wall, accumulates at the bottom of the column (column C in Figure 7) and  
 215 creates the next churn unit. The schematic drawing in Figure 7 shows the overall behaviour churn flow  
 216 regime along the column, as it described earlier, at a constant gas flow rate and at different times.

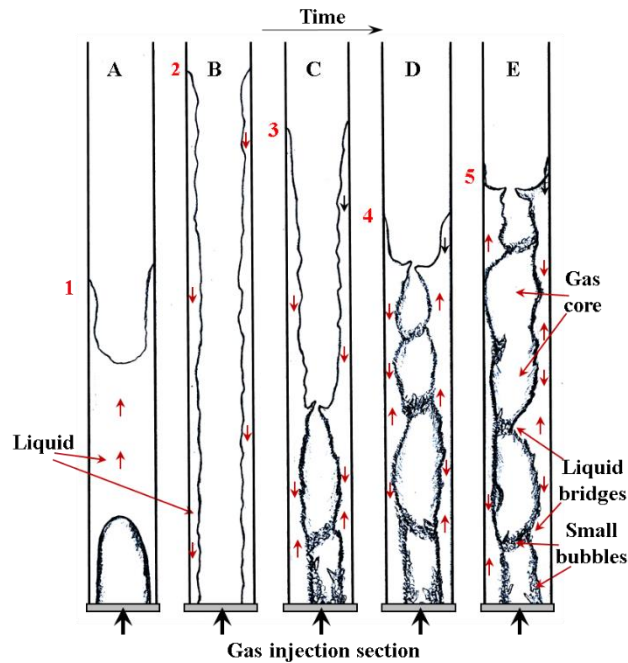


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218 Figure 6: Time series of void fraction and photos showing churn flow in 330 Pa.s Silicone oil and 290  
 219 mm diameter column. The marked areas correspond to the large bubble and the photos show the churn  
 220 regions.

221 Churn flow can also be distinguished from the transition to churn flow regime by the sound of the  
 222 gas flowing inside the column. At the end of slug flow and the transition to churn flow regime the sound of  
 223 the bubble eruption at the top surface could be heard with every single bubble and is totally different from  
 224 the, the sound generated by the flowing fluids in the churn flow regime. The open gas core sounds like the  
 225 volcanic conduit during volcanic activity. This continuous sound of the air passage through the viscous oil  
 226 stops when the fraction of the drained liquid increases at the bottom of the column. At this stage, the gas  
 227 builds up and pushes the drained liquid until the liquid fraction becomes very thin and bursts at the top  
 228 section. Then the sound from the open core starts again. The sounds of the air passing through the high  
 229 viscosity liquid which used in this work were approximately similar to the Arenal Volcano in Costa Rica.  
 230 The volcano sounds are studied by Woulff and McGetchin (1958), Richards (1963), Garcés and McNutt  
 231 (1997), and Dubosclard et al. (2004).

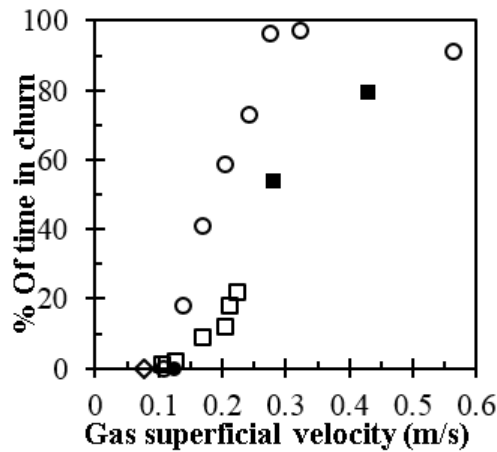
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234 Figure 7: Schematic drawing showing churn flow pattern in high viscosity liquids and large diameter  
 235 columns. The arrows in the figure correspond to the direction of the liquid flow, the numbers at the top  
 236 section of the column corresponding to the liquid levels in the column. D and E are the more common  
 237 structure for this flow regime. A-C occur when the liquid accumulates at the bottom of the column and the  
 238 gas build up and rise as one long bubble and carry the whole liquid up to drain again as a falling film. The  
 239 gas superficial velocity is 0.566 m/s.

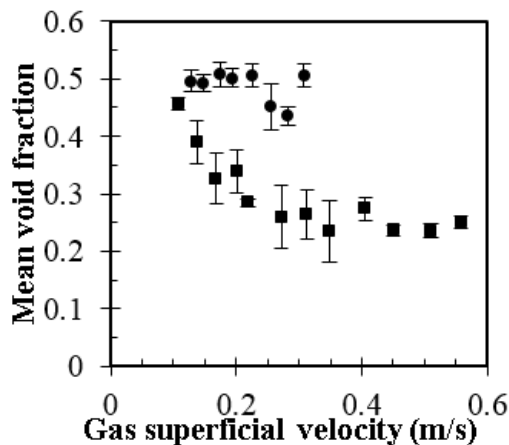
240 The percentage of churn is calculated from the time of churn and the overall flow of each gas flow  
 241 rate. The time of churn can be defined as the time when the areas of the high frequency activity (churn  
 242 areas) pass through the ECT planes. Figure 8 displays the effect of gas flow rate on the time of churn in  
 243 high viscosity liquids and large diameter pipes. It should be noted that data in Fig. 8 was read and extracted  
 244 qualitatively from void fraction data measured from the ECT whose uncertainty was already reported in  
 245 Fig. 9. In the 290 mm diameter column, the time of churn increased significantly with increasing the gas  
 246 flow rate at the transition to churn regime (from 0 to 80%). While it decreased slightly from 96% to 91%  
 247 in churn flow regime. This slight decrease in time of churn can be attributed to the single long bubbles that  
 248 appear at the end of this flow regime. The time of churn increased by approximately 22% over the range of  
 249 gas superficial velocities at which ECT measurements were taken (0.127–0.314 m/s). According to data  
 250 obtained using the pressure transducers for a wider range of gas flow rates, it continued increasing to about  
 251 79%.



252

253 Figure 8: Time of churn calculated from the time series of void fraction of 240 and 290 mm diameter  
 254 columns using the ECT, the pressure transducers in the smaller diameter column and the transition points  
 255 are calculated from two straight lines on drift flux ( $U_{gs}/\alpha_g$  vs  $U_{gs}$ ). □ 240 mm ECT, ■ 240 mm pressure  
 256 transmitters, ◇ 240 mm transition point, ○ 290 mm ECT, ● 290 mm transition point.

257 Figure 9 compares the average void fraction in two different flow regimes and two different column  
 258 diameters. In general, mean void fraction decreases with increasing gas flow rate in both columns. In the  
 259 290 mm diameter column, the mean void fraction continues to decrease in the transition to churn flow until  
 260 it stabilises when churn flow is achieved. It decreases from 0.455 to 0.284 when gas superficial velocity  
 261 was varied from, 0.108 to 0.243 m/s. This is due to the rise in the time of churn with increasing gas flow,  
 262 as void fraction is lower at the churn sections. Then it varies between 0.259 to 0.250 from 0.276 m/s and  
 263 higher gas superficial velocities (churn flow).



264

265 Figure 9: The effect of gas superficial velocity on the mean void fraction in high viscosity liquids and  
 266 large diameter columns. ● D=240 mm, ■ D=290 mm.

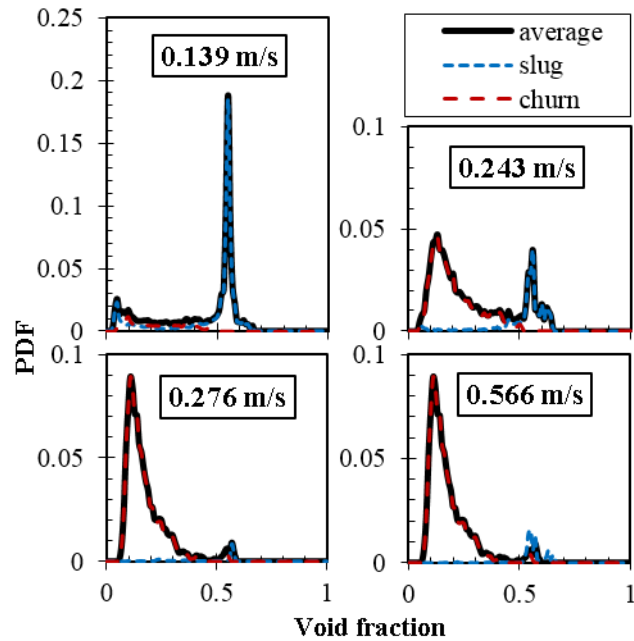
267 In this flow regime, the structure is dominated by the low void fraction churn, and this explains the  
 268 stability of void fraction values. Therefore, increasing gas flow rate at this flow regime does not limit the

269 volume fraction of the gas which can pass through the viscous liquid column. This behaviour could be  
270 important for the volcanic degassing process. In this process, the rate of degassing from volcanic conduits  
271 might be controlled by the availability of the gas from the magmatic system. As a result, the rate of  
272 degassing might not be limited by the volcanic plumbing system.

273 On the other hand, the average void fraction showed a different behaviour in the 240 mm diameter  
274 column. Void fraction decreased slightly by 0.06 then it increased again by 0.07 at the last gas flow rate in  
275 this range. The difference in the void fraction between both columns at the transition to churn regime can  
276 be explained by comparing the data of the time series of void fraction in Figure 4 and 4. First, the transition  
277 to churn flow region in the smaller diameter column consists of longer bubbles of higher frequency, higher  
278 coalescence rate, and lower frequency of churn regions compared to the case in the larger diameter column.  
279 This explains the higher values of void fraction which are due to the difference in the column diameter and  
280 the small variation of viscosity in two columns. The gas volume fraction is larger in the smaller diameter  
281 column for the same gas flow rate due to the geometry. In addition, the void fraction increases with  
282 increasing liquid viscosity, Philip et al. (1990). Although the study conducted by Philip et al. was performed  
283 for bubbly and slug flows, they covered fairly wide range of highly viscous fluids (i.e. 115–300 mPa.s).  
284 Further investigation is required to study the effect of the viscosity on the void fraction of highly viscous  
285 oil (i.e. up to 300 Pa.s) in churn flow. The percentage of churn time increases gradually with increasing gas  
286 flow rate in the smaller diameter column while it increases significantly in the larger diameter column.  
287 However, void fraction exhibits an increase at the highest gas flow rate in the smaller diameter column.  
288 This might be a beginning of fluctuation due to the significant increase in the coalescence between the  
289 bubbles before starting churn flow regime.

## 290 **3.2. Probability Density Function**

291 The Probability Density Function (PDF) signature is commonly used to identify the flow structure  
292 of two phase flow Costigan and Whalley (1997). PDF in combination with the time series of void fraction  
293 data extracted from the ECT was used to identify the flow structure of churn flow in high viscosity oils.  
294 Data from the void fraction time series, where long bubbles occur, was extracted from the overall time  
295 series of void fraction and separated from that in the churn regime. The PDF was calculated for each  
296 segment separately. Figure 10 compares the overall PDF (which represents the whole flow structure) with  
297 the PDFs of the churn and slug flow separately.



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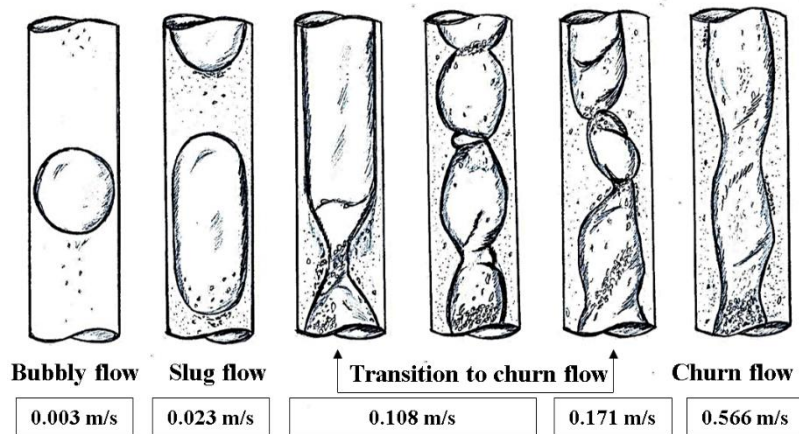
299 Figure 10: PDF for air flow in 330 Pa.s viscosity Silicone oil and 290 mm diameter column at different  
 300 gas superficial velocities. The dashed lines in blue and red correspond to the slug and churn areas which  
 301 were extracted from time series of void fraction of the 290 mm diameter column. The first two graphs at  
 302 0.139 and 0.243 m/s gas superficial velocities which show the transition to churn flow. While the last two  
 303 PDFs at gas superficial velocities of 0.276 and 0.566 m/s show churn flow regime.

304 This figure can be divided into 4 parts. First, the beginning of the transition to churn flow (the lowest  
 305 gas superficial velocity in the figure), when the structure contains long bubbles separated by regions of  
 306 churning. At this gas flow rate, the long bubbles with high void fractions (PDF in blue) dominate the  
 307 structure of the flow, while the probability of "churn" regions is still low (PDF in red). Then, with  
 308 increasing gas flow rate, at the transition to churn flow, the frequency of churning regions increases. For  
 309 example at a gas superficial velocity of 0.243 m/s the PDF of the higher void fraction in blue (the long  
 310 bubbles) peaks at an approximately equal value to the PDF of the lower void fraction which is the churning  
 311 regions (in red). Furthermore, at the beginning of churn flow, at a gas superficial velocity of 0.276 m/s the  
 312 frequency of churning regions (PDF in red) increases dramatically with a probability of appearing in a  
 313 number of long bubbles. Finally, at the higher gas flow rate, the probability of presence of churning regions  
 314 is almost similar to the lower gas flow rate with the existence of one long bubble. However, at gas  
 315 superficial velocities of 0.336 and 0.518 m/s (in the churn flow range) churn regions appear to dominate  
 316 the whole flow structure with no evidence of any large bubbles, see Figure 6.

317

318 **3.3. Pressure gradient**

319 A wide range of gas superficial velocities of 0.003–0.517 m/s was applied to study the pressure drop  
 320 in the 290 mm diameter column at different flow patterns. Figure 11 shows a schematic drawing for the  
 321 flow patterns observed in high viscosity liquids and large diameter columns. It displays the structure of gas  
 322 flow in 330 Pa.s Silicone oil and 290 mm diameter column. Measurements of the pressure gradient were  
 323 collected for each flow regime shown in this figure.



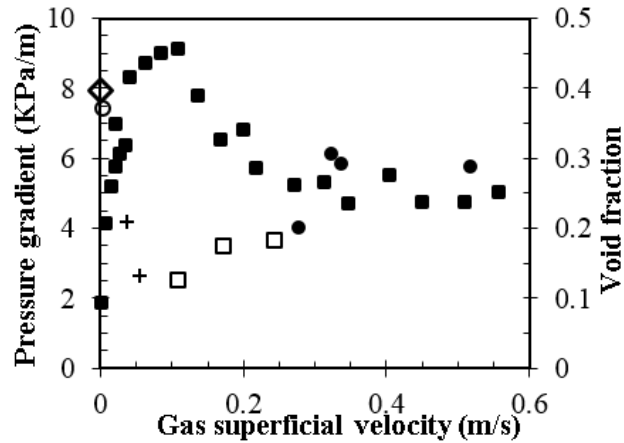
324

325 Figure 11: Schematic drawing showing the flow patterns in 330 Pa.s Silicone oil and 290 mm diameter  
 326 vertical pipe. The arrows in the figure correspond to the direction of the liquid flow.

327 The results of the pressure gradient measurements are shown in Figure 12 came in agreement in  
 328 trend with the work done by Owen (1986) who used air-water in a 32 mm diameter vertical pipe and  
 329 presented the change of pressure gradient data against dimensionless gas velocity for a number of liquid  
 330 flows in vertical pipes. According to his results, the pressure gradient values at slug region showed a sudden  
 331 drop and then a sharp increase again at the slug/churn transition region due to the high frequency wave  
 332 activity and friction. A similar trend in the pressure gradient values was observed in this work. As shown in  
 333 Figure 12, the pressure gradient at the onset of churn region increased gradually by 2 KPa/m from 0.276 to  
 334 0.322 m/s due to increase in frequency of the churn areas where the interaction is very intense between the  
 335 oil and the air. Pressure gradient then remained almost constant until a gas superficial velocity of 0.517 m/s  
 336 was reached. The flow structure in churn flow regime was found more stable in terms of structure velocity,  
 337 mean void fraction, and mean film thickness. The deviation in the pressure gradient behaviour can be  
 338 attributed to the substantial difference in the liquid viscosities, surface tension, and the pipe diameters.  
 339 Wallis (1962) found that during the start of churn flow, entrainment of the droplets occurs from the large



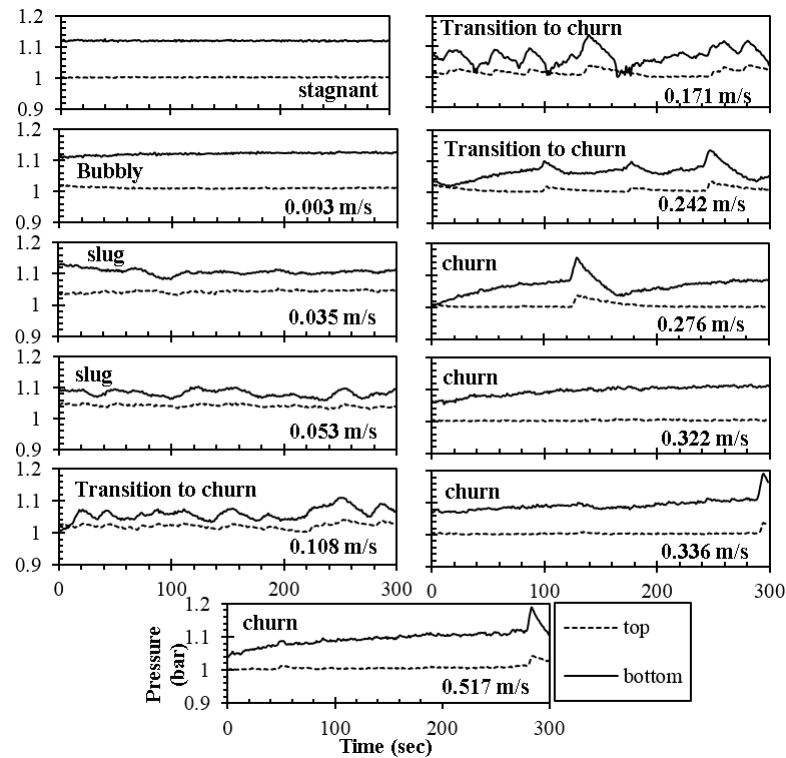
340 liquid fractions which travel as large flooding waves along the column. This mechanism of churn flow  
 341 formation is not applicable for high viscosity liquids such as the oils used in the present work. No droplets  
 342 were observed in the 330 and 360 Pa.s Silicon oils due to the very high viscosity.



343

344 Figure 12: Mean pressure gradient and mean void fraction with changing the flow patterns of air flow in  
 345 330 Pa. Silicone oil and 290mm diameter column.  $\circ$  dP in bubbly,  $+$  dP in slug,  $\bullet$  dP in churn,  $\diamond$  stagnant,  
 346  $\square$  dP in transition to churn,  $\blacksquare$  void fraction.

347 Figure 13 illustrates the changing in pressure with time in air-viscous oil mixture in 290 mm  
 348 diameter column for different gas flow rates. Pressure starts to fluctuate steadily during slug flow at slug  
 349 flow regime. This is due to the high frequency of the long Taylor bubbles which occupy a significant portion  
 350 of the cross-sectional area of the column. The fluctuation of the pressure outputs reaches the maximum due  
 351 to the increase in the frequency of the liquid bridges (churn regions) during transition to churn flow. The  
 352 pressure gradient in churn flow can be seen in the last four flow rates. The oscillation in pressure decreases  
 353 gradually for increasing gas flow rates; this potentially is due to the thick film around the air conduit in the  
 354 column. The uniform pressure drop downstream the ECT (see Fig. 13, for gas superficial velocities  $U_{gs} =$   
 355 0.276, 0.332, 0.336 and 0.517 m/s) indicates that the fully developed flow is achieved. Such uniformity can  
 356 also be seen from the void fraction data (at  $U_{gs} > 0.276$  m/s) obtained from the ECT and already displayed  
 357 in Figure 12. In addition, a series of high quality videos reveal that the characteristics of the churn flow are  
 358 exist.

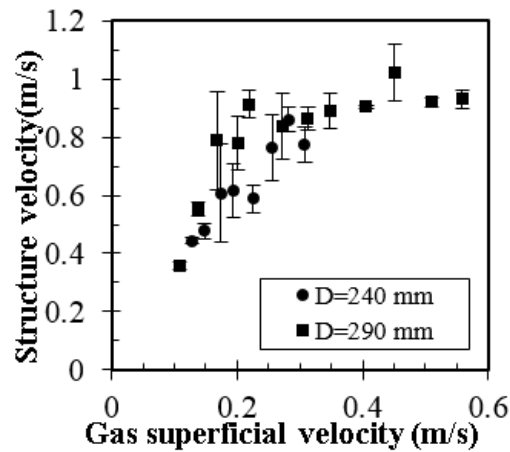


359

360 Figure 13: Effect of gas-viscous oil flow on the pressure inside the 290 mm diameter column for different  
 361 gas flow rates. The distance between the two sensors is 1.4 m, the bottom sensor is located at 2.2 m from  
 362 the gas inlet section.

363 **3.4. Motion, Dimensions and Structure of the Flow**

364 Structure velocity, length of long bubbles and frequency have been determined in the transition to  
 365 churn and in the churn flow regimes in high viscosity oils and large diameter columns. They have been  
 366 calculated from the time series data of void fraction obtained from the ECT. Structure velocity was  
 367 calculated by cross-correlating the void fraction signal from both ECT planes. Figure 14 illustrates the  
 368 effect of increased gas flow rate on the structure velocity. In general, structure velocity increases with  
 369 increasing gas flow rate in both columns at the transition to churn flow regime. It increased by 0.56 m/s in  
 370 the larger diameter column and 0.33 m/s in the smaller diameter column. While no considerable increase  
 371 was seen in churn flow regime in the larger diameter column, structure velocity is lower in the smaller  
 372 diameter column because the large bubbles are longer and the rate of coalescence is higher. On the other  
 373 hand, structure velocity in churn flow regime showed an increase of 0.02 m/s in the 290 mm diameter  
 374 column, potentially due to the oscillating movement of the liquid bridges in this flow regime. The slight  
 375 fluctuation in the values of the void fraction at this flow regime is caused by the single bubble that appears  
 376 at some gas flow rates.



377

378 Figure 14: The structure velocity of gas flow in 360 and 330 Pa.s Silicone oil and 240 and 290 mm  
 379 diameter respectively at the transition to churn flow and churn flow regimes. The maximum standard  
 380 errors calculated for the structure velocity are 16% and 9% for the 240 and 290 mm diameter columns  
 381 respectively.

382 The experimental structure velocity was compared with a theoretical approach by Viana et al. (2003)  
 383 and Guet et al. (2004) in Figure 15. The rise velocity of Taylor bubble  $U_{TB}$ , which bridges the pipe cross  
 384 section area in stagnant liquid, was determined both theoretically and experimentally by Davies and Taylor  
 385 (1950) and Nicklin (1962).  $U_{TB} = F_r \sqrt{g D_B}$ , where:  $D$  is the pipe diameter,  $g$  is the gravitational  
 386 acceleration and  $F_r$  is Froude number, a dimensionless velocity represents the ratio of the gravitational and  
 387 inertial forces which are equal to 0.351 and 0.328. These values are constants proposed by Dumitrescu  
 388 (1943) and Davies and Taylor (1950) to represent  $F_r$ . Dumitrescu (1943) proposed  $F_r$  equal to 0.351 for the  
 389 first time analytically. Then, Davies and Taylor (1950) presented a value of 0.328 analytically and  
 390 experimentally. Viana et al. (2003) presented an equation to determine the value  $F_r$  basing on the  
 391 dimensionless inverse velocity Buoyancy Reynolds number,  $R$ .  $R = \sqrt{D_B^3} g (\rho_l - \rho_g) \rho_l / \mu$ , and Eötvös  
 392 number,  $E_o$  which is the ratio of the interfacial tension and viscous forces;  $E_o = g \rho_l D_B^2 / \sigma$ . Where  $\mu$  is  
 393 liquid viscosity,  $\sigma$  is surface tension and  $\rho_l$  and  $\rho_g$  are densities of the liquid and the gas respectively. They  
 394 also presented a universal correlation for the flat region of high Buoyancy Reynolds number and inclined  
 395 region of low Buoyancy Reynolds number. These two regions are separated by a transition region ( $10 < R <$   
 396  $200$ ), which was described by fitting the data to a "logistic dose curve", the equation has 13 empirical  
 397 constants. The accurate values of  $F_r$  were shown by Viana et al. (2003) and Azzopardi et al. (2014) for  
 398 liquids up to 300 Pa.s viscosity.

399 The rise velocity of the isolated Taylor bubble,  $U_{TB}$  in a flowing turbulent liquid can be determined  
 400 by the following relationship, Nicklin (1962);

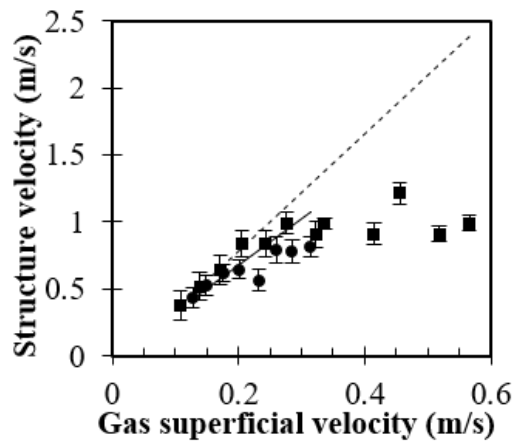
$$401 \quad U_{TB} = C_o(U_{gs} + U_{ls}) + K F_r \sqrt{g D_B}. \quad (1)$$

402  $U_{gs}$  and  $U_{ls}$  are gas and liquid superficial velocities respectively,  $K = 0.905/(1 - \varepsilon_{gs})^{3.95}$ . The  
 403 coefficient  $C_o$  represents the ratio of the maximum centreline velocity of the bubble to the mean upward  
 404 liquid velocity. Nicklin (1962) suggested a value of 1.2 for the coefficient  $C_o$ . Collins et al. (1978) suggested  
 405 a slight modification of Nicklin (1962) relationship, basing on a strong theoretical support. He suggested  
 406 a value of 1.29 for  $C_o$ . In Equation 1 2.25 the difference between the two  $C_o$  values is due to the difference  
 407 of pipe diameters. However, according to Nicklin (1962) the higher values of  $C_o$  are more suitable when  
 408 the flow rates decrease. Another study by Dukler and Fabre (1994) and Guet et al. (2004) proposed more  
 409 complicated equation for  $C_o$  value. It can be written as:

$$410 \quad C_o = \frac{C_{Bc}}{\left[1 + \left(\frac{R_{em}}{R_{ec}}\right)^2\right]} + \frac{C_{0,Re=\infty}}{\left[1 + \left(\frac{R_{ec}}{R_{em}}\right)^2\right]} \quad (2)$$

411 where:  $C_{Bc} = 5$  or  $2.27$ ,  $R_{ec} = 4000$ ,  $C_{0,Re=\infty} = 1.2$ , and  $R_{em} = D_B \rho_l (U_{gs} + U_{ls})/\mu$ .

412 Experimental and analytical data in Figure 15 showed relative errors of 0.01 and 0.04 in the 240 and  
 413 290 mm diameter columns respectively at the transition to churn flow regime.

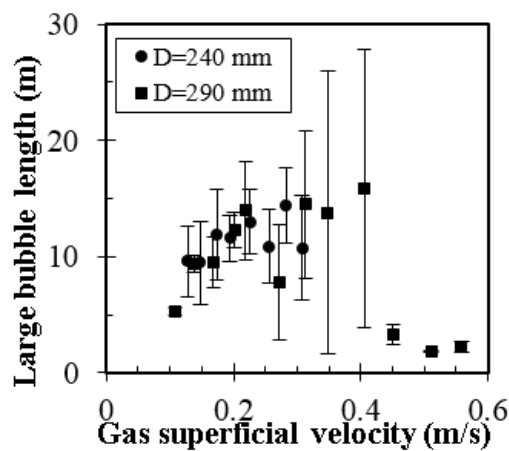


414  
 415 Figure 15: Theoretical and experimental large bubbles velocities in viscous Silicone oil for both columns.  
 416 ●:240mm, ■: 290mm (experimental) and — 240mm, ---290mm (from Viana et al. (2003), and Guet et al.  
 417 (2004), using  $C_{Bc}=2.27$ ).

418 However, in the smaller diameter column, the ECT measurement fluctuation is due to the increasing  
 419 coalescence rate between the bubbles. The calculated and experimental structure velocities show a big

420 divergence in the churn flow regime (relative error of 1.3). The models used in these predictions are not  
421 applicable for churn flow regime, as slip velocity is calculated based on the velocity of large bubbles.

422 The length of the large bubbles was calculated from the structure velocity and the time of the bubble  
423 passing through the ECT electrodes. The length of large bubbles flow in high viscosity liquids and two  
424 large diameter columns are displayed in Figure 16. In general, large bubble length increased significantly  
425 with increasing gas flow rate in the transition to churn flow region. Whereas, it decreased in the churn flow  
426 regime in the 290 mm column. Also, bubble length is higher in the smaller diameter column for the most  
427 of the gas flow rates.



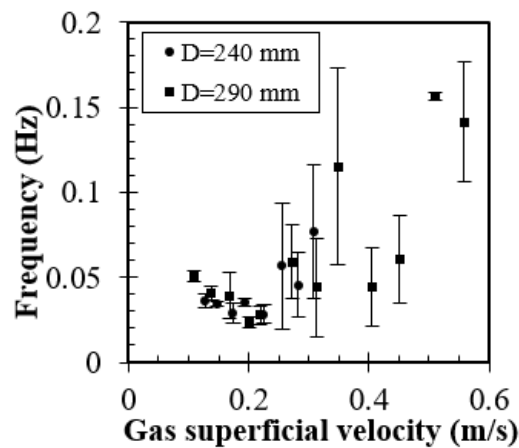
428

429 Figure 16: Lengths of the large bubbles in viscous oil and large diameter columns at the transition to  
430 churn flow and churn flow regimes.

431 In the 290 mm diameter column, the bubbles length increases significantly from 5.2 to 13.9 m when  
432 the gas superficial velocity is increased from 0.108 to 0.243 m/s (transition to churn flow regime). While it  
433 increases gradually from 9.5 to 14.4 m for gas superficial velocity increase from 0.127 to 0.314 m/s (churn  
434 flow). These high values of the bubble lengths are due to the high rate of coalescence between the bubbles  
435 which produces a very long bubble. At the same time, the frequency of bubbles decreases due to the  
436 increasing frequency and length of the churn regions. It in turns increases due to the increasing fraction of  
437 liquid draining from the very long bubbles. The bubbles' length which appears in the figure is higher than  
438 the length of the column at certain gas flow rates. Some large bubbles that burst at the top section of the  
439 column in this flow regime remain as an open core for some time. The length of the bubble is calculated  
440 from the time of the bubble passing through the ECT sensor, therefore open core can be considered a very  
441 long bubble. This long bubble is not a Taylor bubble as it contains large waves on the falling film and does  
442 not have a rounded top and/or bottom as the Taylor bubbles that appear in slug flow.

443 At churn flow, the length of the bubbles fluctuates between 15.8 to 2 m for the whole range of gas  
 444 flows. This is due to the complicated structure in this flow regime which consists of an open gas core with  
 445 liquid bridging of varying film thicknesses and a possibility of creating a very long bubble and leads to an  
 446 error of 122% for the 290mm diameter column. The maximum standard error for the bubble length  
 447 calculated for the smaller diameter column is 14%.

448 The large bubble frequency was also calculated from the time series of void fraction data by counting  
 449 the number of bubbles over the gas injection time. Unlike bubble length, the frequency of the bubbles  
 450 appears to decrease with increasing gas flow rate in the transition to churn flow region. In the larger  
 451 diameter column, the frequency decreases approximately by 0.023 Hz in the transition to churn flow region.  
 452 This can be attributed to the increasing length of bubbles due to bubble coalescence. In the churn flow  
 453 regime, frequency increases by 0.113 Hz. See Figure 17.



454  
 455 Figure 17: Frequency of the large bubbles at the transition to churn flow and churn flow regimes in high  
 456 viscosity liquids and large diameter columns. The maximum errors are 3.9% and 5.7% for 240 and 290  
 457 mm diameter column.

458 . When the time series of void fraction are used to determine the bubble frequency it appears that  
 459 bubble frequency increases when there is only one long bubble appearing in the void fraction signal at the  
 460 same flow rate range. This is potentially due to the increase in the frequency of liquid bridges that behave  
 461 like a series of bubbles connected to each other. Therefore, in the transition to churn flow region, the  
 462 dominant frequency represents the frequency of long bubbles which decrease with increasing gas input.  
 463 While in churn flow the dominant frequency represents that of short bubbles produced by liquid bridging  
 464 which increases with increasing gas flow rate.

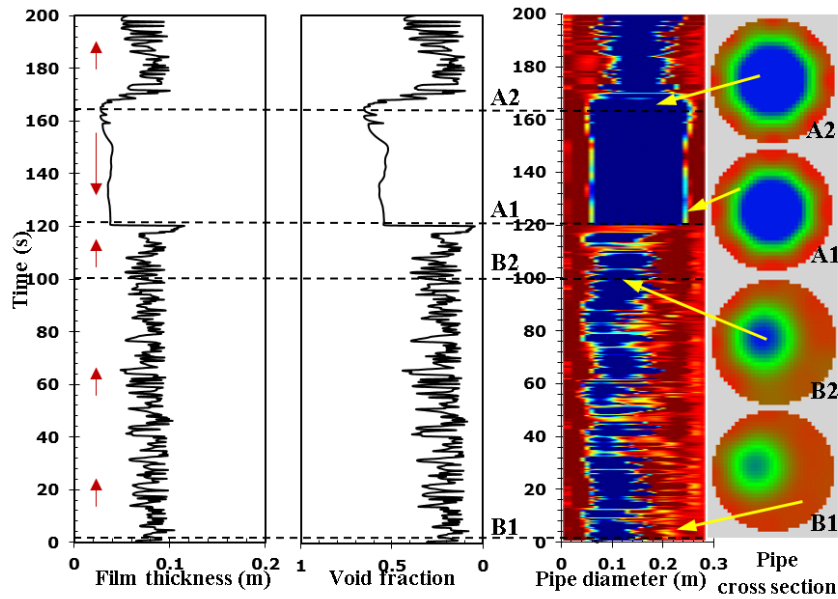
465

### 466 3.5. Film Thickness and Wave Velocity

467 Phase distribution images for the cross-sectional of the column of air and 330 Pa.s Silicone oil in  
468 290 mm diameter were reconstructed using the ECT32 and Recon commercial software that incorporate  
469 the iterated Tikhonov regularisation technique. The structure of flow in such viscous oils was studied by  
470 comparing the time series of void fraction, film thickness, and the reconstructed images of the phase  
471 distribution inside the column. The average film thickness in the transition to churn and in churn flow  
472 regions was determined in the 240 and 290 mm diameter columns. It was calculated by the geometric  
473 relationship  $\delta = (D / 2) (1 - \sqrt{\varepsilon_g})$ , where  $\delta$  is the film thickness,  $\varepsilon_g$  is the void fraction from the ECT. The  
474 film thickness was estimated in both flow regimes using the void fraction data collected from the two ECT  
475 planes.

476 Figure 18 compares the reconstructed time-resolved images of the gas-liquid flow with the void  
477 fraction and the calculated film thickness for churn flow in the 290 mm diameter column. The Tikhonov  
478 regularisation technique with 100 iterations (using a commercial ECT32 and Recon software) was used to  
479 generate the reconstructed images. The three plots are at the same flow rate and the same time period. In  
480 Figure 18, the phases' distribution in the cross section from the upper plane of the ECT is displayed at  
481 different time instances. They have been generated using the ECT32 software at 0.566 m/s gas superficial  
482 velocity. The red colour corresponds to the high permittivity fluid which is the 330 Pa.s Silicone oil and  
483 the blue colour corresponds to the low permittivity fluid, the air. The green and the yellow colours represent  
484 the interface between the two fluids. B1, B2, A1, and A2 in the figure refer to a time or sections. For  
485 example, A1 presents the phase distribution of the large bubble at 120 s. It also refers to the corresponding  
486 void fraction, film thickness, and the reconstructed image. The churning regions exist between 3 and 100  
487 s, corresponding to B1 and B2 in these two figures. Also, (B) at 350 and 500 s for the time series in Figure  
488 4, at the same flow rate. The gas core in churn flow regions seems to change its location from the centre to  
489 near the wall of the column unlike the case for low viscosity liquids where it always exists in the centre of  
490 the pipe. For example, the gas core in B1 is next to the column's wall while in B2 is almost at the centre of  
491 the column. This also can be seen clearly from the photos of the column in Figure 6. This might be due to  
492 the effect of the very high viscosity and the low surface tension (0.02 N/m) which can be negligible in very  
493 high gas flow rates (Snabre and Magnifotcham, 1998).

494



495

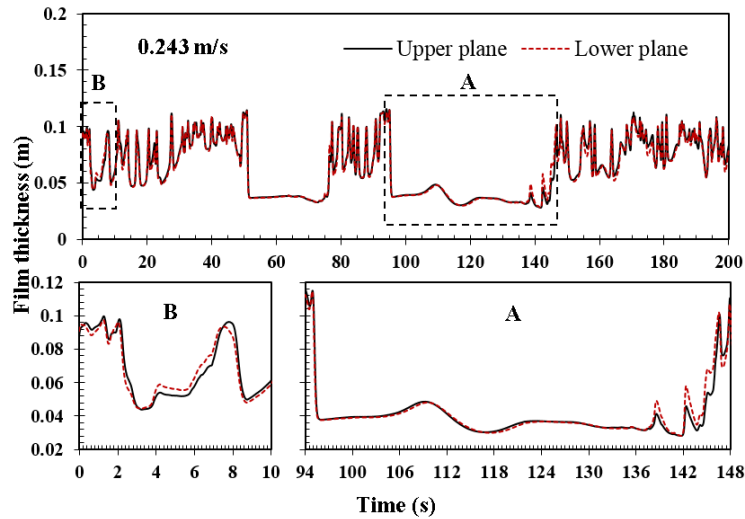
496 Figure 18: Film thickness, void fraction, the reconstructed image using Tikhonov regularisation technique  
 497 with 100 iterations and the pipe cross section for gas flow in 330 Pa.s Silicone oil and 290 mm diameter  
 498 column. The 4 plots represent the flow structure for 200 s (10000 frames) at 0.566 m/a gas superficial  
 499 velocity obtained from the upper plane of the ECT. B1 and B2 represent the churn areas. A1 and A2  
 500 represent the large bubble in the column.

501 At about 120 and 166 s (A1 and A2) in both figures, the flow appears as a large bubble. The  
 502 difference between this large bubble and the Taylor bubbles in classical slug flow regime is the top and the  
 503 bottom shape of the bubbles. Large bubbles have almost a flat top and end and separated from the churn  
 504 regions by a thin film. The length of these large bubbles in churn flow regime seem to be dependent on the  
 505 gas flow rate. This very long bubble represents the open core with the falling liquid film, B in Figure 7.

506 The liquid film in churn flow varies in direction and thickness in both sections A and B. The liquid  
 507 film surrounding the large bubbles flows downward to merge with the liquid travelling upwards in the  
 508 following churn region. While the film in the churn region flows in different directions and rests at some  
 509 points. The average film thickness seems to decrease slightly at the same gas flow rate, this will be discussed  
 510 in the next section.

511 Figure 19 and Figure 20 show the film thickness of gas flowing in 330 Pa.s Silicone oil and 290 mm  
 512 diameter column at two different flow regimes. The first figure is the transition to churn flow at a gas  
 513 superficial velocity of 0.243 m/s.



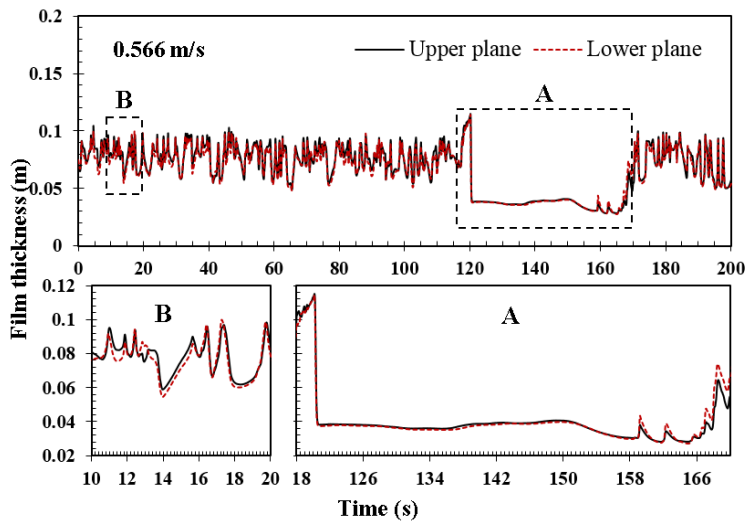


514

515 Figure 19: Film thickness at the transition to churn flow in 330 Pa.s and 290 diameter column at a gas  
 516 superficial velocity of 0.243 m/s.

517 The second figure (Figure 20) is at a gas superficial velocity of 0.566 m/s which represents the film  
 518 thickness in churn flow regime. In both figures, 200 s length of data is presented at acquisition frequency  
 519 of 50 Hz. Both figures focus on the direction of the film in the large bubble and the churn sections. In the  
 520 ECT sensor, the electrodes in plane 1 are located above the ones in plane 2. This makes the value of wave's  
 521 velocity positive when they pass from plane 2 (lower plane) first.

522



523

524 Figure 20: Film thickness at churn flow in 330 Pa.s and 290mm diameter column at a gas superficial  
 525 velocity of 0.566 m/s.

526 The values of the wave velocities were calculated from the time delay of each wave and the distance  
 527 between the two planes. Velocity is equal to the distance between the planes (0.036 m in this sensor) divided

528 by the difference in time. Similarly, if the values of the calculated wave velocity are negative, this indicates  
529 downward film flow. Since the wave passes through the upper plane P1 first then to the lower plane P2.

530 In general, the liquid film flow shows an average of downward movement in the large bubbles area  
531 (A in both figures) and upward flow in churn flow region (B) with some difference. Starting with the  
532 direction of liquid flow in the large bubbles (A) in both flow regimes (both figures). The waves' velocity  
533 showed negative values (downward flow) for all the waves in churn flow while it showed some upward  
534 flow in the transition to churn flow regime. For example, the calculated velocities for the wave on the film  
535 around the large bubble at the transition to churn flow were -0.078, -0.052, 0, 0.3, and 0.3 m/s at about 107,  
536 120, 138, 142, and 146 s respectively. The velocity and the direction of the flow are not constant in this  
537 flow regime. The film flows downward between about 94 and 130 s. Then there is a time when the liquid  
538 holds/stagnates (between about 137–140 s) before it changes direction flowing upward from about 142 to  
539 146 s. This area is followed by churn section. This upward direction for the film around the large bubble  
540 might be due to the development of this fraction to churn.

541 Different behaviour is exhibited by the liquid film around the large bubble (A) in the churn flow is  
542 shown in Figure 20. In this flow regime, the calculated velocities of the waves were -0.045, -0.075, -0.22,  
543 0, -0.225 m/s and hold at about 136, 152, 159, 162, 166, and 168 s respectively. This provides an evidence  
544 of the downward direction of movement of the film around the large bubble.

545 The following churn section in churn flow regime did not show a significant effect on the direction  
546 and velocity of the film around the large bubble at the bottom. This might be due to the structure of flow in  
547 churn flow regime which seems to be more stable in terms of structure velocity, mean void fraction and  
548 mean film thickness. The wave velocities in the transition to churn flow and churn flow regimes were less  
549 than the values reported by Benjamin (1957). This can be referred to the very high viscosity of the liquid  
550 employed in this study. Benjamin studied the characteristics of the stability of laminar stream of viscous  
551 falling film on an inclined plane. According to his analysis, the velocity of the wave was equal to  $-3 U_f$  for  
552 liquid film Reynolds number equal to 0.  $U_f$  is the velocity of the falling film.

553 The film thickness in churn sections -(B) in both flow regimes- shows different values in film  
554 thickness and directions compared to that in large bubbles. In general, the direction of flow fluctuates  
555 between upward and liquid stagnation in churn flow regime, and upward flow in the transition to churn  
556 flow regime. The waves' velocity in the transition to churn flow is higher than the ones registered in churn  
557 flow. They vary from 0.22, 1.8, 4, and 0.1 m/s at about 0.2, 1.2, 2, and 8 s respectively, Figure 19. While in

558 churn flow regime in Figure 20. The wave velocities were 0.6, 0, 0, 0, 0.3, and 0.9 at about 11, 12.4, 15.6,  
559 17 and 19.7 s respectively. These times of liquid holding agree with the visual observation as the gas seems  
560 to move as pulses during experiments.

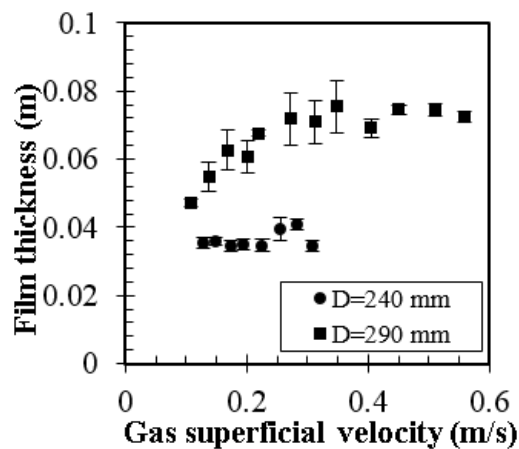
561 Comparing these results of the film thickness, reconstructed images and the photographs of these  
562 two flow regimes show two different flow characteristics. Both consists of two sections, one contains large  
563 bubbles which differ from Taylor bubbles but has a thin falling film. And second, sections of high-  
564 frequency activity of liquid bridges with a thick film travelling in different directions. These two flow  
565 regimes can be distinguished by the frequency of the high activity sections (churn) which increases with  
566 increasing the gas flow rate. Also by the decrease of frequency of large bubbles with increasing gas input.  
567 Then, at a specific gas flow rate, the flow structure changes significantly (at 0.276 m/s gas superficial  
568 velocity). The flow at this gas flow rate is dominated almost completely by high-frequency liquid bridging.  
569 A single large bubble might appear in a number of gas flow rates. Therefore, the flow regime from the gas  
570 superficial velocity of 0.108 – 0.243 m/s can be characterised as a transition to churn flow. While the flow  
571 regime from the gas superficial velocity of 0.276 – 0.566 m/s is churn flow, refer back to the time series of  
572 void fraction plots in Fig. 6. The liquid film motion directions in churn areas are upwards and stagnation as  
573 indicated by the holdup which in turn refer to flooding. However, the waves in the flooding regions are not  
574 always showing the holdup effectively.

575 Seemingly, one of the known mechanisms for the transition to churn flow regime is flooding of the  
576 liquid film which occurs in slug flow inside the Taylor bubbles (Jayanti and Hewitt (1992) and Jayanti et  
577 al. (1993)). Govan et al. (1991) proposed that the transition to churn flow regime occurs due to the  
578 generation of "flooding-type wav". They also assumed the existing of the strong relation between churn  
579 flow and flooding phenomenon. The difference between the present work and the previous works from  
580 literature is the much larger pipe diameter and the much higher viscosity. For example, the droplets which  
581 from the breaking up of the flooding waves that occur in low viscosity liquids were not observed in the  
582 present study. In such high viscosity, no entrained fractions of liquid were found due to the very high  
583 viscosity of the oil.

584 Figure 21 displays the effect of increasing the gas flow rate on average film thickness in the transition  
585 to churn and churn flow regimes. In general, gas flow rate shows more effect on film thickness in the larger  
586 diameter column and also a change in the trend of the liquid film between the two flow regimes appears  
587 clearly in the larger diameter column. However, the film thickness in the smaller diameter column

588 represents only one flow regime (the transition to churn flow). In addition, in the larger diameter column,  
 589 the film thickness increased gradually by 0.2 m in the transition to churn flow regime while it increases  
 590 slightly by only 0.005 m in the 240 mm diameter column. This increase in the film thickness values might  
 591 be caused by the increasing frequency of the liquid bridges (churn) which have higher film thickness  
 592 compared to the large bubbles region. Then when comparing the time series data in Fig. 5 and 6, the  
 593 frequency of the churn regions is higher in the larger diameter column. This explains the difference between  
 594 the trends in both columns. Also, in the larger diameter column, the frequency of the churning regions  
 595 increases significantly in the transition to churn flow regime while it exhibits a slight increase in the smaller  
 596 diameter column. This corresponds to the film thickness values in Figure 21.

597 In the churn flow regime, starting from 0.276 m/s gas superficial velocity in the 290 mm diameter  
 598 column, the film thickness appears to be more stable. It increases by only 0.003 m over a wide range of gas  
 599 flow rates. This can be related to the time series data in Figure 6 and 6. The mean film thickness can also  
 600 be linked to with Figure 9 the averaged void fraction. The maximum errors are 0.76% and 0.35% for the  
 601 290 and 240 mm diameter columns respectively.

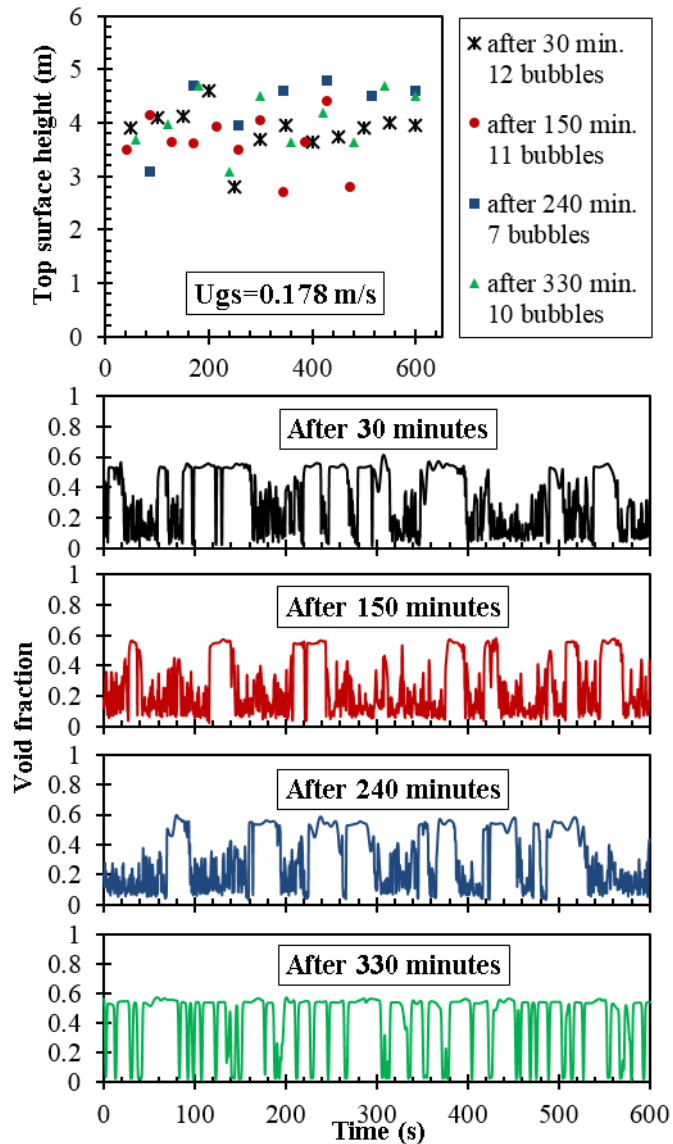


602  
 603 Figure 21: Averaged film thickness around the gas passing through 360 and 330 Pa.s Silicone oil in 240  
 604 and 290 mm diameter columns respectively at the transition to churn flow and churn flow regimes. The  
 605 error bars represent the standard error for the film thickness values.

### 606 3.6. Oscillations at the Top Section

607 The height of the liquid in the column was recorded at a gas superficial velocity of 0.178 m/s for 10  
 608 min at four different times over 5.5 h of the gas injection. In this experiment, the gas was injected for 5.5 h  
 609 at a constant flow rate to study the effect of the gas injection time on the flow structure in 330 Pa.s Silicone  
 610 oil. Figure 22 shows the top surface height obtained at four different times during 5.5 hours of constant gas

611 injection in 290 mm diameter column and the corresponding time series of void fraction. In general, the top  
 612 surface oscillation corresponds to the eruption of long bubbles shown in the time series of void fraction.



613

614 Figure 22: The change of the position of the top surface (liquid height per single bubble) during the time  
 615 for constant gas superficial velocity in four different times during the day in 290 mm diameter column.  
 616 The colours of the time series of void fraction correspond to the height of the top surface for each time.

617 The liquid height oscillates periodically in the data collected at 150 and 330 min from the start of  
 618 the injection, while a different trend was obtained in the data collected at 30 and 240 min. This is due to the  
 619 unstable structures in the transition to churn flow. It also might belong to the uncertainty of locating the  
 620 liquid height due to the presence of liquid film on the pipe wall from the previous bubble's eruption.

621 The difference in the average heights of the top surface of the 5.5 h is 140 mm. This is due to the  
 622 increase in the concentration of the trapped small bubbles (centimetres-millimetres bubbles) in the column

623 which also contribute to increasing the average void fraction as it shown earlier. The fluctuation of the top  
624 surface decreases slightly from 1.8 to 1.6 m from 30 to 330 min. The reason behind that can be stemmed  
625 from the time series of the 330 minutes where the structure of the flow seems more organised. It reflects a  
626 lower rate of bubble coalescence.

#### 627 **4. Conclusion**

628 The churn flow regime in high viscosity liquids has been studied in two large diameter columns over  
629 a wide range of gas flow rates. ECT was employed to reconstruct the image of phase distribution of air-  
630 Silicone oil of 330 and 360 Pa.s viscosities. Results from the present work can be concluded as:

- 631 • The transition to churn flow regime appeared in the range of gas superficial velocities between 0.127-  
632 0.314 m/s and 0.108–0.243 m/s in the 240 and 290 mm diameter columns respectively. Churn flow  
633 regime was observed in the larger diameter column at a gas superficial velocity range of 0.276–0.566  
634 m/s.
- 635 • The transition to churn flow regime starts when the length and frequency of the regions of the high  
636 frequency activity, which appears at the end of slug flow regime, increases. These regions can be  
637 described as liquid bridges flowing upwards and then stagnates.
- 638 • The liquid flow shows an average downward flow movement as a film in the large bubbles areas and  
639 upward flow as large waves/bridges in the churn regions. The direction of the flow fluctuates between  
640 upwards and liquid stagnation in churn flow regime, and upwards in transition to churn flow regime.
- 641 • With increasing the gas flow rate, the length of Taylor bubbles increases producing a larger fraction  
642 of liquid film falling downwards which leads to increase in the length of churn areas.
- 643 • With increasing the gas flow rate, where the transition to churn starts to appear, pressure gradient  
644 starts to increase and void fraction to decrease due to the increase of the liquid film thickness around  
645 the air conduit in the column.
- 646 • From the results of pressure drop presented in this paper, the pressure gradient behaviour is mainly  
647 due to the void fraction effects on the total pressure drop.
- 648 • The averaged void fraction seems to decrease with increasing gas flow rate in both columns due to  
649 the increase of the frequency of churn units that have a low void fraction. In the 290 mm diameter  
650 column, the mean void fraction continues to decrease at the transition to churn flow until it stabilises  
651 in churn flow.

- 652 • The structure velocity increases with increasing gas flow rate in both columns in the transition to churn  
653 flow regime.
- 654 • Bubble velocity increases with increasing gas flow rate at the transition to churn flow regime. Then  
655 no considerable increase was seen at churn flow regime. No fine bubbles were observed flowing in  
656 this flow regime.
- 657 • The length of large bubbles increases significantly with increasing gas flow rate in the transition to  
658 churn flow region. Whereas, it decreases in the churn flow regime in the 290 mm diameter column.  
659 Also, the length of the bubbles appears to be higher in the smaller diameter column for most of the  
660 gas flow rates.
- 661 • The droplets caused by the breaking up of the flooding waves which occur in low viscosity liquids  
662 were not observed in the current study. In addition, no entrained fractions of liquid were found due to  
663 the very high viscosity of the oil.
- 664 • Unlike the case for low viscosity liquids, the gas core in churn flow regions, in the current study,  
665 seems to change its location from the centre to near the wall of the column.
- 666 • In the transition to churn flow region, the dominant frequency represents the frequency of long bubbles  
667 which decrease with increasing gas input. While in churn flow the dominant frequency is due to the  
668 short bubbles produced by liquid bridging which increases with increasing gas flow rate
- 669 • The top surface oscillation of the column in the transition to churn flow seems to fluctuate according to  
670 the eruptions of long bubbles where the liquid height oscillates periodically.

## 671 **Dedication**

672 This paper is dedicated to the memory of my supervisor Prof Barry J Azzopardi who passed away  
673 recently. This new finding in viscous fluids flow could not have been achieved without his knowledge,  
674 guidance and support.

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