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Characteristics of slug flow in a vertical riser

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Abstract

This paper presents the results of a series of experiments conducted on a vertical 67 mm internal diameter riser to study the characteristics of slug flow generated within a multiphase air-silicone oil mixture, for a range of injected superficial gas and liquid flow rates. Air/ silicone oil flows in a riser have been investigated using advanced instrumentation called Electrical Capacitance Tomography (ECT), described in Hammer (1983), Huang (1995) and Zhu et al. (2003). The ECT was used to determine: the velocities of the Taylor bubbles and liquid slugs, the slug frequencies, lengths of Taylor bubbles and liquid slugs, the void fractions within the Taylor bubbles and the liquid slugs over a range of superficial liquid ($0.047 \leq U_{SL} \leq 0.38$ *m/ s) and gas* ($0.344 \leq U_{SG} \leq 0.745$ *m/ s) velocities. An examination of the experimental data concluded that the rise velocity of the observed Taylor bubbles (structure velocity) were strongly dependent on the mixture superficial velocity. The void fraction within the liquid slug and the Taylor bubbles were observed to increase with gas superficial velocity. The lengths of liquid slug and Taylor bubbles were also observed to increase with an increase in the gas superficial velocity. The liquid slug frequency was observed to increase as the liquid superficial velocity increases, but was observed to be weakly dependant on the superficial gas velocity.*

Introduction

Slug flow occurs in horizontal, inclined, and vertical pipes over a wide range of two-phase gas-liquid flow rates. It is the dominant flow pattern observed in upward inclined pipe flow. Slug flow is typically characterised by an alternating flow of gas pockets and liquid slugs. Most of the gas-phase is concentrated in large bullet-shaped gas pockets, named Taylor bubbles. The Taylor bubbles are separated by liquid slugs, which contain small entrained gas bubbles. For vertical flow, the liquid film flows downward between the Taylor bubble and the pipe wall. A major characteristic of slug flows is their inherent unsteadiness. It is interesting to note that these two states follow in a random-like manner, inducing pressure, velocity and phase distribution fluctuations. As this kind of flow occurs over a wide range of intermediate flow rates of gas and liquid, it is of significance for many industrial processes employing pipeline transport.

The dependence of the flow behaviour on different parameters, such as fluid properties, makes it difficult to predict the flow characteristics when one of these parameters is changed. In order to characterise slug flow in more industry relevant fluids, an experimental campaign has been carried out using air and silicone oil as the gas and liquid fluids, respectively. This paper reports the results of an analysis performed on experimental data to determine parameters that characterise the vertical slug flow phenomena observed. A comparison of the experimental results obtained against previously published empirical relationships is presented.

Theoretical background

The occurrence of slug flow in a vertical riser is a very common phenomenon under normal operating conditions of a two-phase flow facility, such as in an oil production riser. A large number of research studies have been carried out in this field over the past three decades. One of the earliest contributions to slug flow characterization was carried out by Nicklin et al. (1962), who proposed an empirical relationship to describe the rise velocity of single Taylor bubble in a static water column. Nicklin's empirical relationship, given by equation 1, describes the rise velocity of the Taylor bubble as a linear function of the mixture velocity. For the air-water system considered the value of the constant C_o was determined to be 1.2.

$$U_N = C_o U_{LLS} + 0.35\sqrt{gD} \tag{1}$$

Rise velocity of a Taylor bubble (Structure velocity)

A cross-correlation was performed on the time varying void fraction data measured by the twin ECT- planes located at 5.0 and 5.089 m above the mixer section at the base of the riser. This allows the determination of the delay time as individual slugs passed between the two planes; and this together with the distance between the planes enabled the calculation of the structure velocity, U_N . Details of the cross-correlation function used may be found in Hernandez-Perez (2007).

Slug frequency

The slug frequency is defined as the number of slugs passing through a defined pipe cross-section in a given time period. To determine the frequency of periodic structures (slugs) the methodology of Power Spectral Density (PSD) was applied. The Power Spectral Density, PSD, is a measure of how the power in a signal changes over frequency and therefore, it describes how the power (or variance) of a time series is distributed with frequency. Mathematically, it is defined as the Fourier Transform of the autocorrelation sequence of the time series. The DFT can be computed efficiently in practice using a Fast Fourier Transform (FFT) algorithm. Details can be found in Hernandez-Perez (2007).

Lengths of slug unit, Taylor bubble and liquid slug

The length of a slug unit may be determined from a knowledge of the rise velocity of the Taylor bubble and the slug frequency, as indicated in equation 5. The Lengths of the different zones of the slug unit have been determined for a range of different liquid and gas rates. The time of passage of the slug unit, Taylor bubble and liquid slug have been determined from performing an analysis of the output time series from the twin-planes of the ECT signals. These times were assumed to be proportional to the respective lengths. Relationships were then obtained to estimate the respective lengths, as briefly described below. Equations 8, 9 and 10 have been employed to determine the lengths of the slug unit, liquid slug and Taylor bubble, respectively.

$$U_N = \frac{L_{SU}}{Time} \tag{2}$$

Where,

$$\frac{1}{Time} = frequency = f \tag{3}$$

$$U_N = L_{SU} f \tag{4}$$

$$L_{SU} = \frac{U_N}{f} \tag{5}$$

Assumimng that

$L_{SU} \propto t_{SU}$, $L_{TB} \propto t_{TB}$, $L_S \propto t_S$, incompressibility and Mach number < 1

Dividing L_{TB} by L_S

$$\frac{L_{TB}}{L_S} = \frac{kt_{TB}}{kt_S} = c \tag{6}$$

and taking into account that,

$$L_{SU} = L_{TB} + L_S \tag{7}$$

The following relationships can be obtained

$$L_{SU} = cL_S + L_S \tag{8}$$

$$L_S = \frac{L_{SU}}{c+1} \tag{9}$$

$$L_{TB} = L_{SU} - L_S \tag{10}$$

Experimental arrangement

All experiments were carried out on an inclinable pipe flow rig within the Engineering Laboratories of the Department of Chemical and Environmental Engineering at University of Nottingham. Figure 1 shows a schematic diagram of the experimental facility. This rig has been employed for a series of earlier published annular flow studies by Azzopardi et al (1997), Geraci et al. (2007a) and Geraci et al. (2007b), Hernandez Perez et al (2007), and Abdulkadir et al. (2010). In brief, the experimental facility consists of a main test pipe section constructed from transparent acrylic glass. The 6 m test pipe section is of a 0.067 m internal diameter. The test pipe section may be rotated on the rig to allow it to incline between -5 ^{o} to 90 ^{o} degree. For the experiments reported in this paper the rig test pipe section was mounted as a vertical riser. Details can be found in Abdulkadir et al. (2010).

The resultant flow regimes obtained from the test matrix of air-oil flow rates were recorded using electrical capacitance tomography (ECT). The ECT system is shown in Figure 2. This technology, described by Hammer (1983), Huang (1995), and Zhu et al. (2003), can scan the distribution of the dielectric fluids in the pipe by measuring the capacitances of the passing flow across several pairs of electrodes mounted uniformly around an imaging section. Then, the sequential variation of the spatial distribution of the dielectric constants representing the different phases of the flow can be determined. In this study, a ring of electrodes was placed along the circumference of the riser, so the instantaneous distribution of the phases over the cross-section of the pipe could be determined. By using two such rings, it was possible to determine the rise velocity of the Taylor bubbles and the liquid slugs. The twin-plane ECT was placed at about 5.0 and 5.089 m upstream of the air-silicon oil mixer section located at the base of the riser.

Results and discussion

Time series of cross-sectional average void fraction have been obtained directly from the ECT system. In order to extract useful information about the characteristics of slug flow in the riser, statistical analysis was applied. A very frequently used statistical function is the Probability Density Function (PDF). In multiphase flow, it can be employed as a tool for flow pattern identification, based on the shape of the PDF graph. According to Costigan and Whalley (1996), twin peaked PDFs of recorded void fractions represents slug flow. The low void fraction peak corresponds to liquid slug while the high peak void fraction is for Taylor bubble.

Experimental conditions cover slug flow regime having liquid superficial velocity of $0.047 \leq U_{SL} \leq 0.38$m/ s and the gas superficial velocity is $0.344 \leq U_{SG} \leq 0.745$m/ s. In addition to the flow pattern, the structure velocity, slug frequency, lengths of liquid slug, and Taylor bubble were determined as outlined in the background section. These paremeters are reported as follows: The results for the structure velocity as a function of the mixture superficial velocity are presented in Figure 3. Both the void fraction in liquid slug and the Taylor bubble are plotted against the gas superficial velocity, in Figures 3 to 5. The slug frequency and lengths of liquid slug, Taylor bubble and slug unit are shown in Figures 6 to 8.

Structure velocity of the Taylor bubble

A linear relationship is obtained, as shown in Figure 3, between structure velocity and mixture velocity. This is in disagreement with the result of Nicklin (1962). The difference can be observed at all mixture velocities, this could be due to the assumptions made by Nicklin (1962) regarding the condition of single Taylor bubble moving in static liquid which is in contrast with the situation in the present experiment, where continuous moving liquid has been used. In addition, fluid properties are different. This therefore accounts for an increase in the rise velocity of the Taylor bubble.

Void fraction in liquid slug and Taylor bubble

Figure 4, shows that the void fractions in liquid slug and Taylor bubble increase with gas superficial velocity at constant liquid superficial velocity. This can be explained by the fact that an increase in gas flow rate increases bubble production, thereby bringing about an increase in void fraction. This is similar to the result reported by other authors such as Nydal (1991) for 38 mm pipe. In addition, it follows the same trend as the correlation of Gregory and Scot (1978).

Figure 5 shows that the void fraction in Taylor bubble in general increases with gas superficial velocity. At liquid superficial velocity of 0.38 m/ s, the void fraction in the Taylor bubble increases with gas superficial velocity. Contrary to this at liquid superficial velocity of 0.14 m/ s, the void fraction in Taylor bubble increases from 0.62 to 0.68 until the terminal gas superficial velocity is reached. As the gas flow rate is increased, there is an increase in bubble population in the liquid slug, which then merges with the Taylor bubble and as a consequence may be responsible for the increase in void fraction. At liquid superficial velocity of 0.047 m/ s, the void fraction increases linearly with gas superficial velocity from 0.62 to 0.72 and then dropped to 0.6. This drop can be due to collapsing of the Taylor bubble and can be regarded as a transition to spherical cap bubble.

Slug frequency

The slug frequency is found to increase with liquid superficial velocity. The frequency according to Figure 6 is varying between 3.8 to 1.5 Hz. The data show that the liquid superficial velocity strongly affects the frequency of the periodical structures in intermittent flows such as cap bubbles and Taylor bubbles. It can be observed that for each liquid superficial velocity, there is a different trend from the plot. For the lowest liquid superficial velocity, the frequency slightly increases with gas superficial velocity. Then as the liquid superficial velocity increased to 0.14 m/ s, the frequency remains constant. However, at the highest liquid superficial velocity, the frequency decreased and then increased, having a minimum at 0.6 m/ s. This behaviour might be attributed to the change in flow pattern with liquid superficial velocity. This has been found by many researchers to hold true (Hubbard (1965), Taitel and Dukler (1977), Jepson and Taylor (1993), Manolis (1995).

Lengths of liquid slug, Taylor bubble and slug unit

The lengths of liquid slug, and Taylor bubble are found to increase with gas superficial velocity with liquid superficial velocity as a parameter. The lengths of liquid slug as a function of the gas superficial velocity at various liquid flow rates has been shown in Figure 7. It can be observed that there is no clearly defined trend for the variation of liquid slug length with gas superficial velocity. It is interesting, however, to note that at liquid superficial velocity of 0.38 m/ s, the length of the liquid slug increases from about 0.396 to 0.584 m (6 to 9 D) and then decreased finally to about 0.408 m (6 D). The shape of the trend is like a triangle; having a maximum at the top vertex. The stable liquid slug length is reported to be between 10 to 20 D (Akagawa and Sakaguchi (1966); Fernandes (1981) and Barnea and Shemer (1989). The drop in length could be attributed to a transition to churn flow; bigger bubbles in the liquid slug merge with succeeding Taylor bubble, thereby reducing its void fraction and length. A similar trend can be observed for 0.14 m/ s, liquid superficial velocity. Which means the length is changing constantly due to interaction at the tail of the Taylor bubble between dispersed bubbles and the wake of the Taylor bubble as a result different velocities are observed for different sections of the liquid slug.

At a certain liquid flow rate an almost linear relationship seems to exist between Taylor bubble length and gas superficial velocity as shown in Figure 8. Furthermore, an increase in gas superficial velocity leads to a proportional increase in Taylor bubble length. However, at liquid superficial velocity of 0.047 m/ s, the length of the Taylor bubble increased from 0.142 to 0.442 m and then decreased to about 0.428 m. The increase in Taylor bubble length could be due to an increase in bubble coalescence as a consequence of an increase in gas flow rate. The drop in length on the other hand might me due to inertia forces overcoming low surface tension forces leading to bubble collapsing.

Conclusions

Slug flow characterization with non-intrusive instrumentation, such as electrical capacitance tomography, has being successfully carried out. The results show that:

(1) A linear relationship was obtained between structure velocity and mixture superficial velocity. Comparison between Nicklin et al. (1962) empirical equation with present experimental data showed that agreement was not satisfactory.

(2) For a given liquid flow rate, the experimentally measured values of average void fractions in liquid slug and Taylor bubble were found to become greater as the gas flow rate was increased. The liquid superficial velocity was found to have an influence on void fractions in liquid slug and Taylor bubble.

(3) Slug frequency was found to increase with an increase in liquid superficial velocity.

(4) The lengths of the liquid slug and Taylor bubble, were found to increase with an increase with gas superficial velocity. However, the length of liquid slug was found to be changing due to interaction at the tail of the Taylor bubble between dispersed bubbles and the wake of the Taylor bubble.

With the experiments done in the current study, more insight is gained in the physical phenomena behind the slug properties and the way they behave under various flow conditions. A more fundamental approach is used for improving the general knowledge on slug flow.

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Nomenclature

D	Diameter of the tube, mm
F	Frequency, Hz
g	Gravity constant, 9.81 m/ s^2
U_M	Mixture superficial velocity, m/ s
U_N	Structure velocity or nose velocity of a Taylor bubble, m/ s
U_{SG}	Gas superficial velocity, m/ s
U_{SL}	Liquid superficial velocity, m/ s
U_{GLS}	Gas superficial velocity in liquid slug, m/ s
U_{LLS}	Liquid superficial velocity in liquid slug, m/ s
U_O	Terminal velocity of a bubble rising through fluid, m/ s
C_O	Distribution coefficient, dimensionless
ρ	Density, kg/m^3
μ	Viscosity, kg/ms
σ	Surface tension, N/m
ΔU_N	Increment of U_{ST} as defined in equation 1.1, m/ s
$\frac{\Delta P}{\Delta L}$	Pressure drop, N/m
α_S	Void fraction in liquid slug, dimensionless
α_{TB}	Void fraction in Taylor bubble, dimensionless
∂	Liquid film thickness, mm
β	Ratio of void fraction in liquid slug and Taylor bubble, dimensionless
α_M	Mean void fraction, dimensionless

Subscript

G	Gas phase
L	Liquid phase
LLS	Liquid in liquid slug
GLS	Gas in liquid slug
s	Slug
M	Mixture

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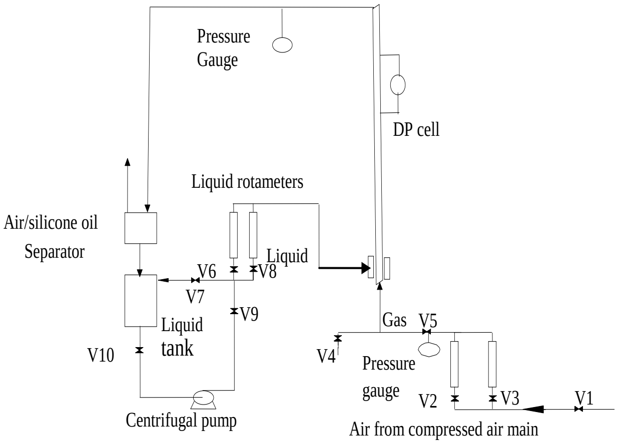

Figure 1: Schematic diagram of riser rig. This rig was instrumental to take physical measurements that could be used to characterise the flow regime existing the vertical pipe when the flow rates of both the oil and the air injection were varied.

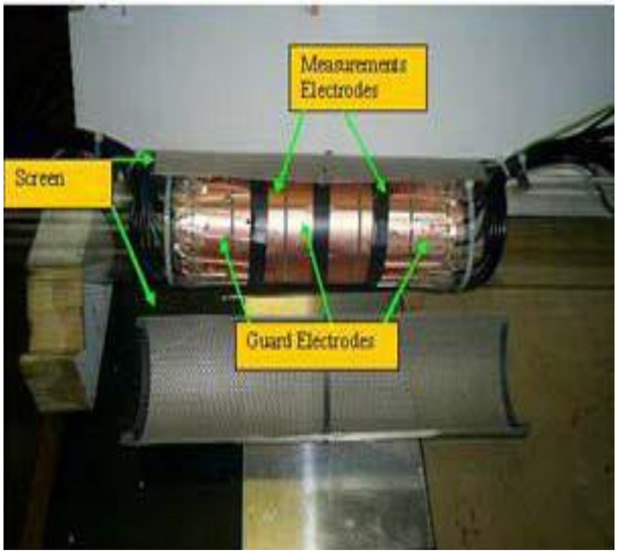

Figure 2: Electrical capacitance tomography (ECT)

Table 1: Properties of the fluids

Fluid	Density (kg/ m^3)	Viscosity (kg/ ms)	Surface tension (N/ m)
Air	1.18	0.000018	
Silicone oil	900	0.0053	0.02

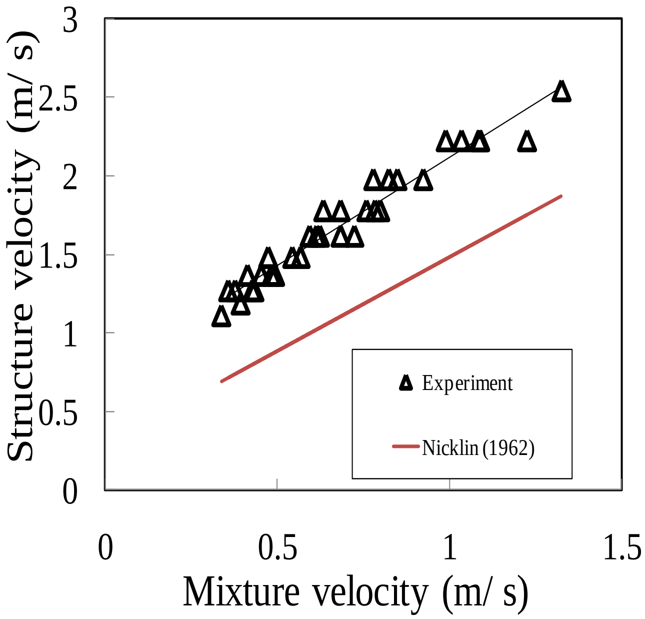

Figure 3: a plot of the experimentally measured structure velocity vs mixture velocity. The empirical equation proposed by Nicklin (1962) was recalculated using the physical properties of air and silicone oil.

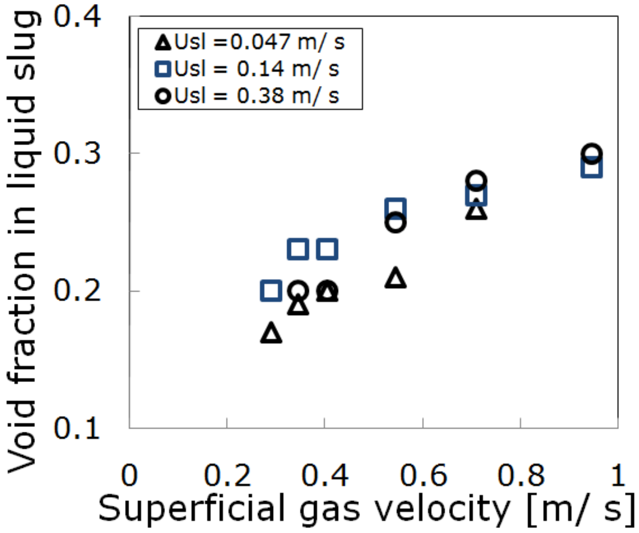

Figure 4: Mean void fractions in liquid slug

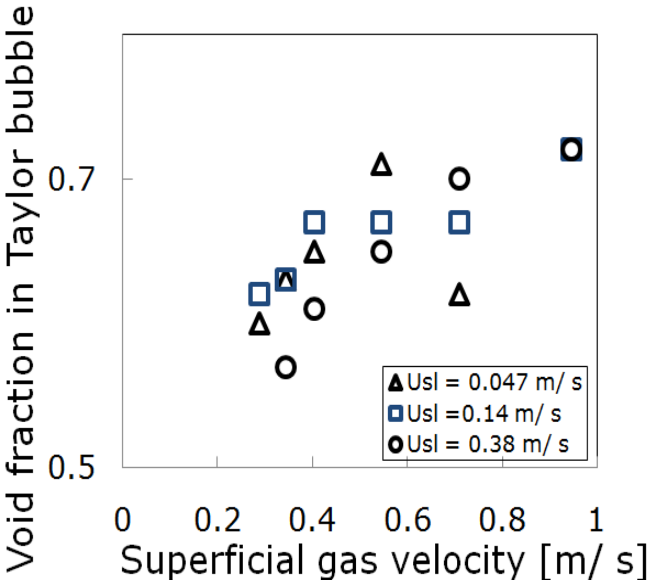

Figure 5: Mean void fractions in Taylor bubble

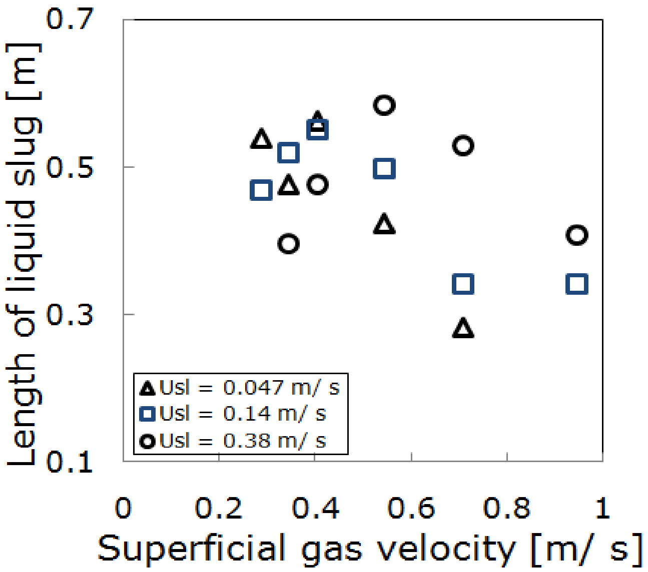

Figure 7: Influence of superficial gas velocity on the average lengths of liquid slug. The lengths were obtained for an average of 60 seconds

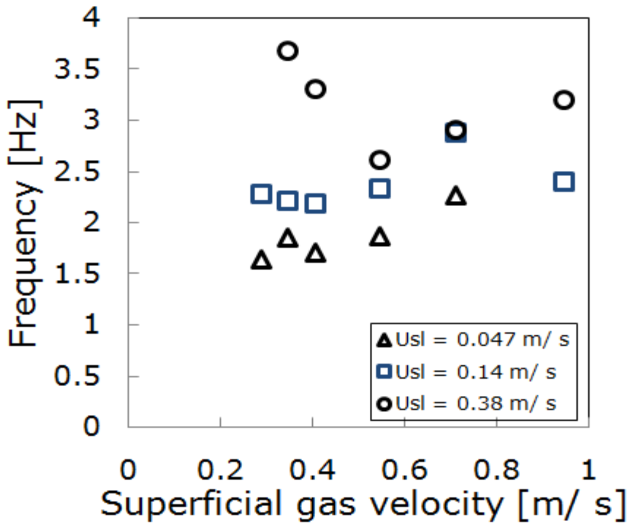

Figure 6: Frequency vs superficial gas velocity

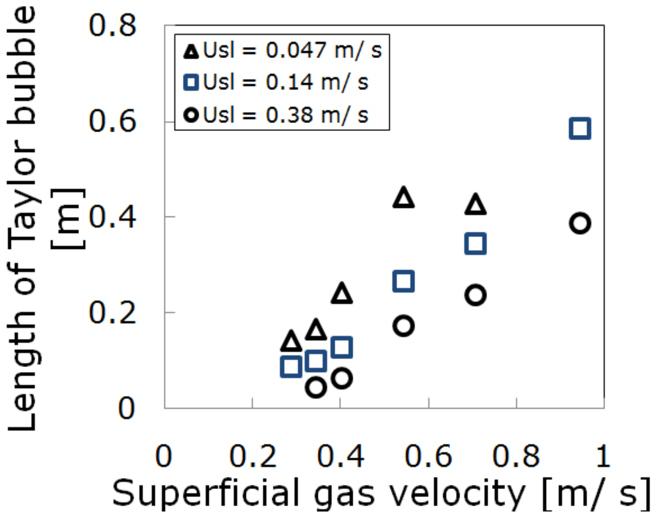

Figure 8: Influence of superficial gas velocity on the average lengths of Taylor bubble. The lengths were obtained for an average of 60 seconds