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Development and statistical characterization of slug in two-phase flow along horizontal pipeline

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Abstract – In many industrial processes, the presence of liquid and gas mixtures creates a slug flow. This kind of regime is observed when slug's liquid blocks the whole pipeline and moves as a coherent mass downstream at a velocity approximately equal to the gas velocity. The aim of this study is to provide statistical information on slug in two-phase flow in horizontal pipe. Experiments were conducted in a pipe of 0.04 m diameter and a length of 14 m. First of all, a flow regime map is compiled for air/water two phase flows. Data on pressure gradient, slug frequency and liquid holdup are presented. It was found that mean slug frequency clearly increases as the superficial liquid velocity increases but it weakly depends on the superficial gas velocity.

Key words: Slug / stratified transition / pressure gradient / liquid holdup / frequency / transitional velocity

Nomenclature

J	Superficial velocity of phase j (m.s^{-1})
d	Pipe diameter (m)
t	Time (s)
f	Slug frequency (1/s)
x	Distance from the inlet (m)
X	Liquid volume fraction
V	Velocity of elongated bubble
H/D	Liquid holdup
St	Strouhal number
Sub and super scripts	
max	Maximum value
l	For liquid
g	For gas
t	Translational
m	Mixture

1 Introduction

Two-phase gas/liquid flows occur in numerous pieces of engineering equipment's such as boiler, condensers, reactor, heat exchanger and oil/gas pipelines. In gas-liquid flow the two phases can be distributed in different configurations, recognized as flow patterns. Each flow pattern in a system depends on the operational variables (gas and liquid flow rates), geometry (pipe diameter and inclination angle), and physical properties of the fluids. In horizontal and near horizontal pipelines, flow patterns are usually classified into the following categories, stratified (smooth and wavy), intermittent (plug and slug), annular, and dispersed bubble.

Of all flow patterns encountered in field operations, slug flow is the dominant one in horizontal and near horizontal pipelines, and is also the most complicated one. Classical flow maps (e.g. [1–3]), show that the intermittent regime exists for a wide range of gas and liquid flow rates in a horizontal two-phase flow configuration. It is characterized by an alternate flow of liquid slugs and gas pockets, resulting in an inherently unsteady hydrodynamic behavior. All the important design variables, such as gas and liquid velocity profiles, liquid holdup distribution, and pressure drop vary axially and radially and exhibit fluctuations, even when the inlet liquid and gas flow rates are constant. This makes prediction of slug flow characteristics difficult and challenging. Therefore, such flow is considered as an extremely complicated flow pattern. The complexity evolves from the intermittency of the flow and the large velocity gaps between the various slug regions, also the phases usually have very different

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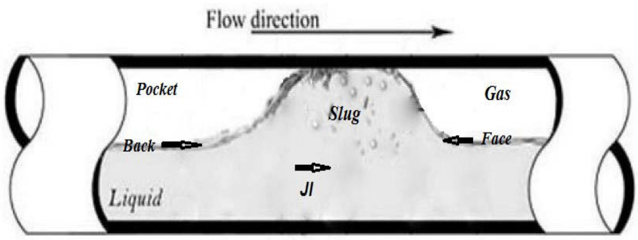

Fig. 1. Schematic representation of basic slug unit.

properties and can be arranged in a variety of geometrical pattern in the duct. In Figure 1 the phase's distribution of gas and liquid encountered in slug flow is depicted schematically.

Several studies have been carried out during the past fifty years in an attempt to describe slug flow in horizontal pipelines. The earliest attempt to model horizontal slug flow was by Kordyban [4]. Slugs were visualized as sliding at the gas phase velocity over a liquid film with no interaction between the slugs and the film. The slug unit consists of large gas bubbles flow alternately with liquid slugs at randomly fluctuating frequency [5]. The liquid slug may be either of pure liquid or aerated as a result of gas entrainment (in the form of small dispersed bubbles) from the large bubbles [6,7]. Many authors have addressed the mechanism of slug formation and established approximate criteria for the transition from stratified to slug flow. Visual observations of wave growth and slug formation show that the slugs are formed from long waves, when they become large enough to bridge the pipe cross-section via a classical Kelvin-Helmholtz instability to occupy the entire pipe cross section [3,8–11], or/and by accumulation of liquid at valleys of irregular terrains [12]. Wave coalescence has also been observed as an important mechanism in the slug formation, especially at high gas flow rates in horizontal pipes [13].

Despite a large amount of research focused on predicting the transition boundaries between two phase flow regimes and in particular the behavior of slugs, there are still large holes in our understanding. Therefore, this work was undertaken to provide statistical informations of two-phase flow in horizontal tube especially for slug flow pattern. At first, it aims to build a flow regime map. Then, the development of slug and some parameters including pressure, frequency, and liquid holdup are investigated.

1.1 Experimental facility and measurement techniques

The experiments were conducted in a horizontal pipe of 0.04 m diameter and a 14 m length. The experimental setup used to detect slugs is sketched in Figure 2; our experimental loop is adapted to generate a gas-liquid two phase flow concurrently. It operates in closed circuit for the liquid component, open for the gas component. The liquid flow is provided by a centrifugal Noryle pump, the nominal operating point gives a volume flow-rate 10 $m^3.h^{-1}$ for a delivery height of 9 m. The air is provided from a compressor. Both fluids air/water

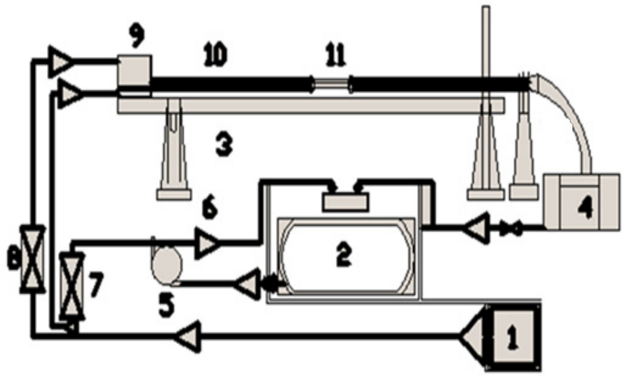

Fig. 2. Description of the experimental setup. 1: compressor, 2: liquid tank, 3: Frame, 4: liquid-gas separator, 5: centrifugal pump, 6: liquid by pass line, 7: Liquid debimeter, 8: Gas debimeter, 9: liquid-gas mixer, 10: visual section, 11: Test section.

arrive in a cylindrical mixing chamber which is fed the pipe made of Plexiglas with the resulting two-phase component. Prior to the experiments, we first set the horizontal line; to avoid transition which is due to the effect of the inclination of the pipe [14]. Therefore, it is imperative to remove all traces of oil in the air using air filters to maintain good experimental conditions. Visualization of the flow regime is achieved at 7m from the inlet of the pipe using a Canon HG20 camera (1920 × 1080 full HD24 bits/s) with high resolution. Gas flow measurement is performed by two Rota meters VMRP010092 and VMRP010083 type, our measuring range lies between 10 $l.mn^{-1}$ up to 400 $l.mn^{-1}$, while the liquid rate ranging from 10 $l.mn^{-1}$ to 68 $l.mn^{-1}$ is measured by an ultrasonic flow meter type PT878 portable.

2 Results and discussion

2.1 Flow regime map

In order to enhance the confidence level of our experimental investigation, a flow regime map was compiled. In industrial applications the prediction of flow regimes in horizontal multiphase pipe flow is important for reliable design of transportation system. In this work, detection of flow was carried using two methods visualization and wall pressure fluctuations analysis [15]. For given superficial water velocity (J_l) a range of superficial air velocities (J_g) was swept, the flow regime determination was carried visually. Figure 3 exhibits the predicted flow regime type (shown as points) on a flow regime map in comparison to the Mandhane et al. [2] transition lines for horizontal flow.

Following the flow regime map, a study of the characteristics of slug flow in the 0.04 m pipeline was carried out.

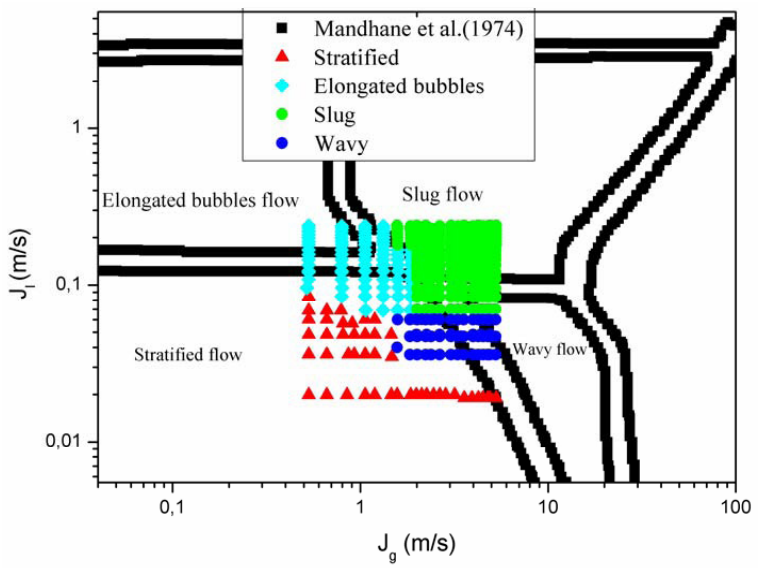

Fig. 3. Flow pattern map for $D = 0.04$ m horizontal pipeline.

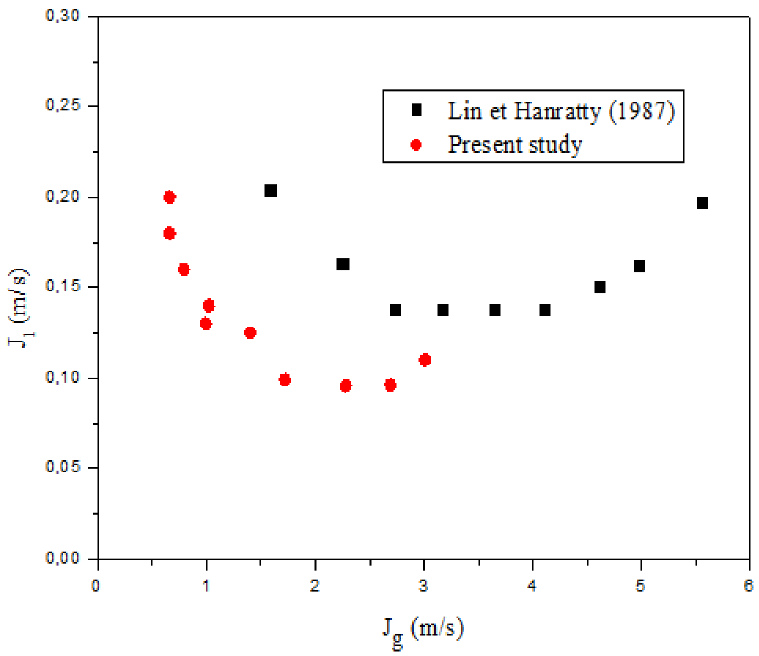

Fig. 4. Conditions for the transition from stratified flow to a slug flow.

2.2 Slug initiation

In many two-phase flow situations the prediction of the conditions likely to investigate the change of flow pattern from stratified regime to slug flow conditions is important. The conditions observed in these experiments for the initiation of slugging are presented in Figure 4, which gives the critical superficial liquid velocity as a function of the superficial gas velocity (slug flow exists above and stratified flow, below the points). For comparison, results obtained by Lin and Hanratty [9] are also given. It is shown that there is discrepancy between our experimental data and the results of Lin and Hanratty [9]. This is due to the intrinsic conditions of each experimental test loop (diameter, length...).

2.3 Slug evolution

Consider a fixed gas flow with $J_g < 3$ m.s^{-1}, at low liquid flows $J_l < 0.1$ m.s^{-1}, the interface was observed to be smooth with an increase in liquid flow, long wavelength waves appear.

For superficial gas velocity of 3.5 m.s^{-1} the first slug will appear at a distance downstream from the entry of 102 pipe diameter. With small increases in liquid flow ($J_l < 0.1$ m.s^{-1}) the location at which slugs appear is

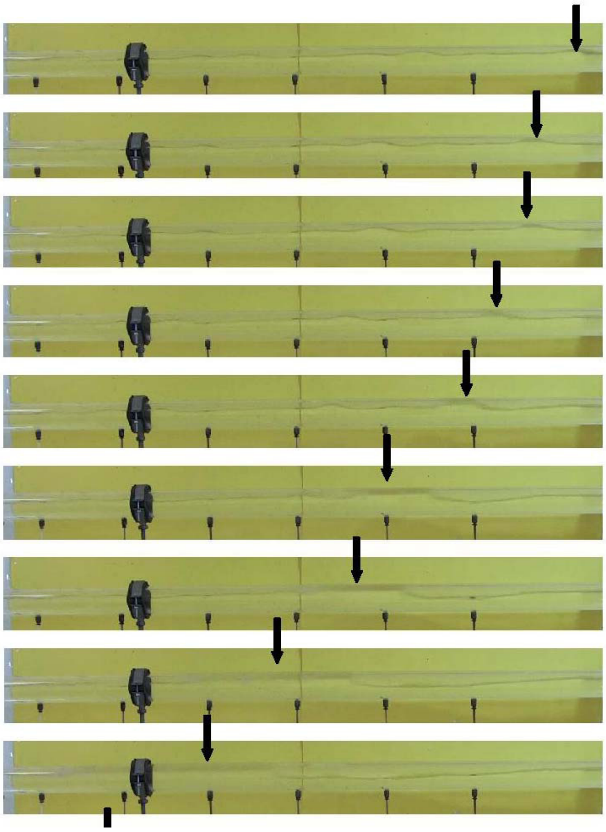

Fig. 5. Video images of slug formation.

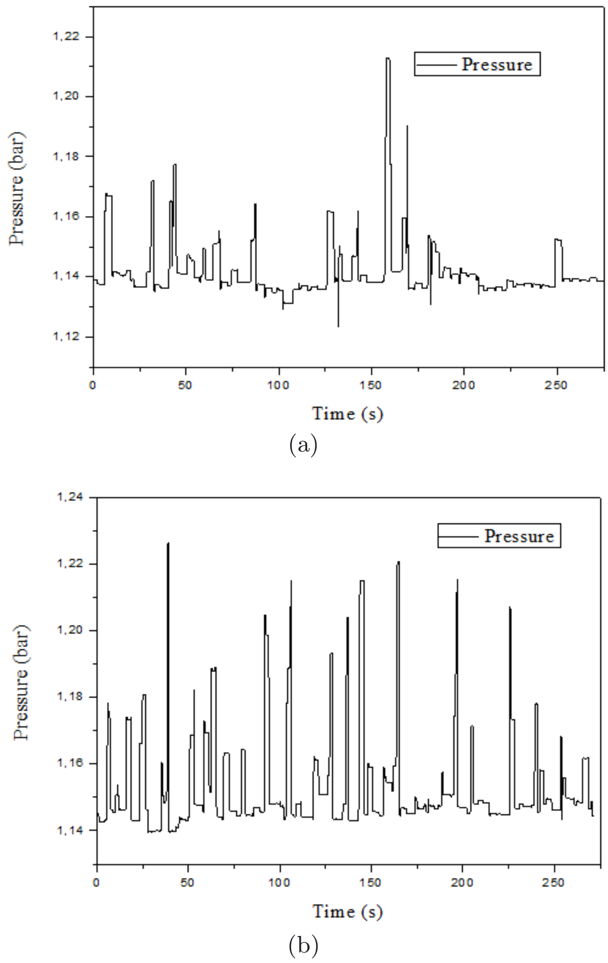

Fig. 6. Evolution of the pressure for various superficial gas velocities. (a) $J_l = 0.18$ m.s^{-1}; $J_g = 0.79$ m.s^{-1}. (b) $J_l = 0.18$ m.s^{-1}; $J_g = 1.83$ m.s^{-1}.

much closer to the inlet. In addition, more than one slug exists in the pipe at a given time. Figure 5 shows the evolution of slug for $J_l = 0.18$ m.s^{-1} and $J_g = 4.5$ m.s^{-1}.

2.4 Pressure variation

Pressure gradients were measured with a capacitive differential pressure transducer. The taps were placed at 5.29 m from the entrance of the test section. Measurements of the pressure fluctuations according to the superficial gas velocity, presented in Figure 6, prove that the reduction in J_g is accompanied by a progressive reduction in the amplitude of the pressure fluctuation. Analysis of the signals of pressure shows that the fall of pressure of the film zone between two slugs can be neglected compared with that produced in the zone of mixture [16].

2.5 Slug frequency

The frequency of slugging defined as the number of slugs passing a stationary observer per unit time was determined by treatment of the electric signal tension delivered by the piezoelectric pressure pick-up using a method similar to that proposed by Lin and Hanratty [9], Fan et al. [17] and Wood and Hanratty [11]. According to these authors the arrival of a slug in a point is accompanied by a sudden increase in the level of liquid as well as pressure. Knowing the linear relation which binds the pressure to the electric tension delivered by the sensor, it follows from there that the peaks of tension observed reveal the passage of the slugs. Consequently, the counting of the peaks for one duration of 272 (s) enabled us to measure the frequencies of the slugs. It should be noticed that the results obtained by this method were corroborated by counting the slugs during the visioning of the videos recorded simultaneously with the acquisition of the signal delivered by the sensor. Figures 7a and 7b show clearly that slug frequency increases as the superficial liquid velocity increases but it weakly depends on the superficial gas velocity.

The measured slug frequency data at $x/D = 132.24$ are calculated with dimensionless parameters and plotted in Figure 7c, in which the Strouhal number St is shown as a function of the liquid volume fraction X_l. It is observed that the relation can be correlated by the equation of the following form, as reported by Fossa et al. [18].

$$\mathrm{St} = \frac{0.05X_l}{1 - 1.675X_l + 0.768X_l^2} \tag{1}$$

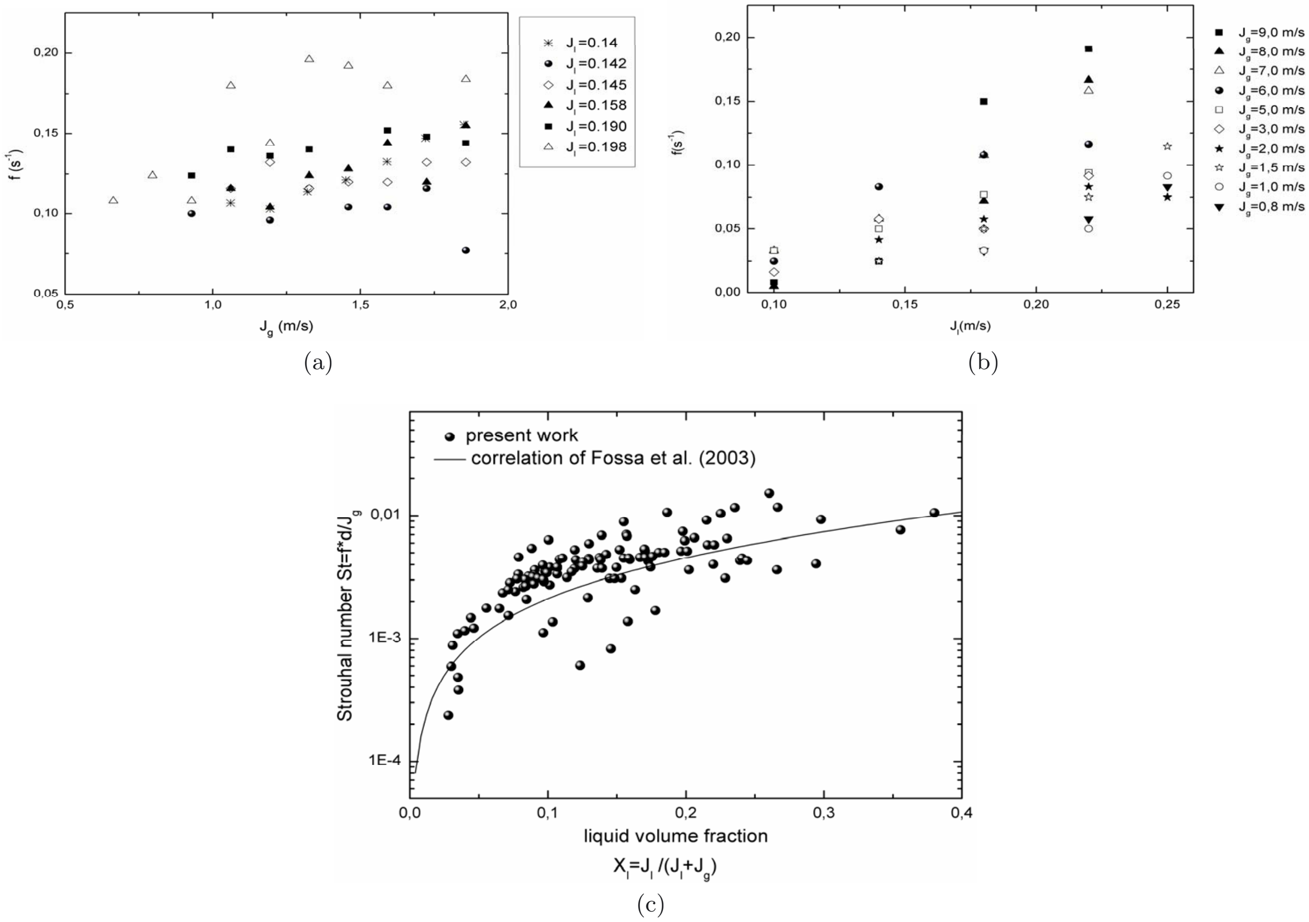

Fig. 7. (a) Frequency of the slugs according to the superficial gas velocity for various superficial liquid velocities. (b) Frequency of the slugs according to the superficial liquid velocity for various superficial gas velocities. (c) Correlation of slug frequency measured. Comparison with the correlation of Fossa et al. [18].

2.6 Holdup of slug

Figure 8 shows measurements of liquid holdup (H/D) at a distance $x/D = 132.24$ for a superficial liquid velocity $J_l = 0.14$ m.s^{-1} and three superficial gas velocities.

The H/D measured with the pressure probes does not reach a value of unity when a slug passes because of the presence of gas bubbles. The average value of $(H/D)_{\max}$ is ~0.8.

2.7 Translational velocity of elongated bubble

The translational velocity of elongated bubble (V_t) as a function of the local mixture velocity (V_m) is shown in Figure 9. It is observed that the mean value of V_t increases linearly with the mixture velocity. The measured translational velocities of elongated bubble are compared with the predicted values from the model proposed by Nicklin et al. [19] with good agreement.

$$V_t = C_0\,V_m + V_0 \tag{2}$$

3 Conclusion

In this work, an experimental study of the slug flow in horizontal pipe is presented. The interest was focused in the mechanical aspect by measuring the variations of pressure at time of slug's passage, and in the physical aspect by determination of the flow parameters.

The following conclusions may be drawn:

- The reduction in superficial gas velocity is accompanied by a progressive reduction in the amplitude of the fluctuations in pressure.
- The slug frequency is not variant with the pressure.
- The frequency of the slug's increases linearly with the superficial liquid velocities and it is weakly affected by the superficial gas velocity.
- The mean value of the translational velocity of elongated bubble increases linearly with the mixture velocity.

The characteristic parameters, such as translational velocity of elongated bubble, liquid slug holdup, and slug frequency determined in this study agree quite well with the correlation in literature.

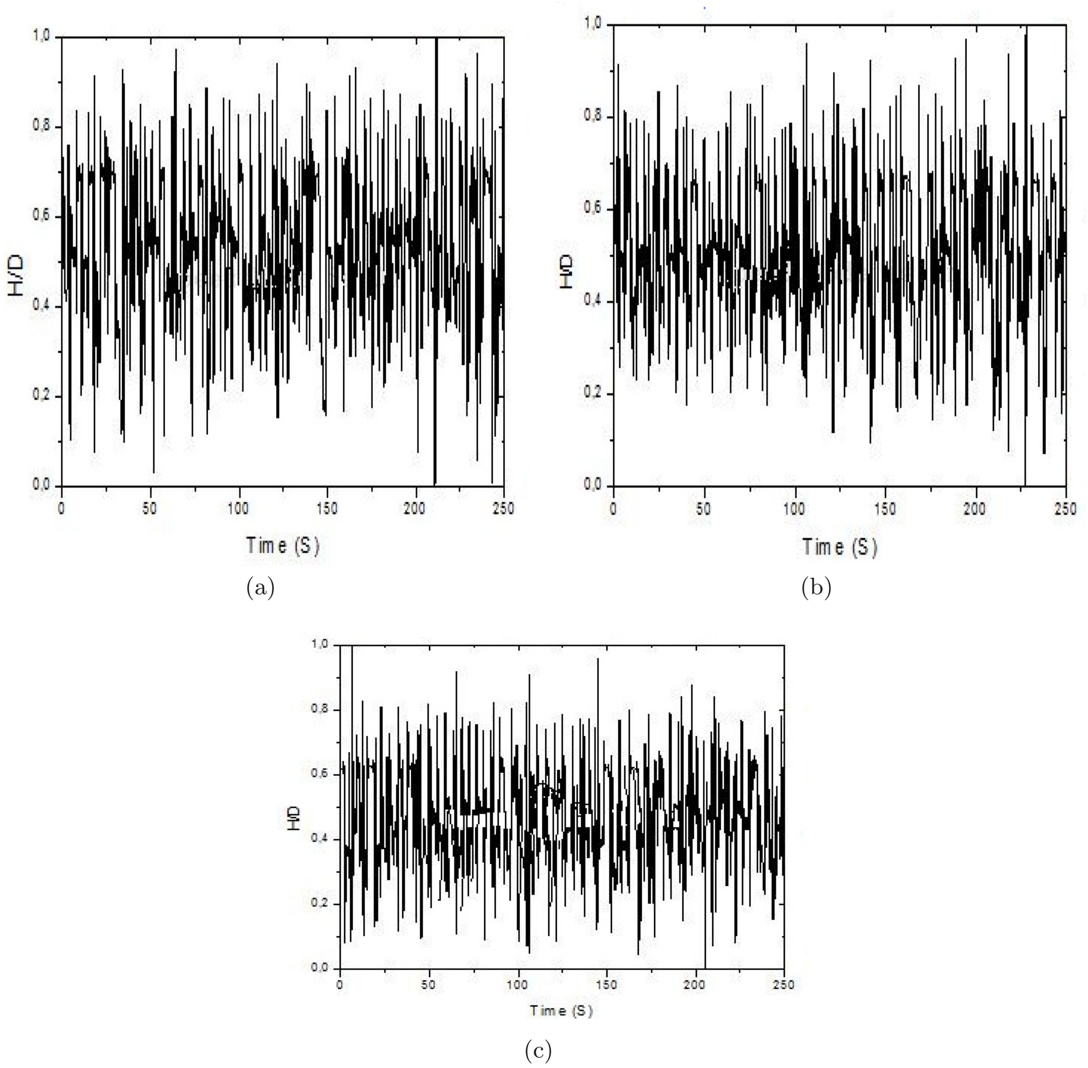

Fig. 8. Holdup measurements at $x/D = 132.24$ for $J_l = 0.14$ m.s^{-1}. (a) Measurements for $J_g = 2.19$ m.s^{-1}. (b) Measurements for $J_g = 2.65$ m.s^{-1}. (c) Measurements for $J_g = 3.95$ m.s^{-1}.

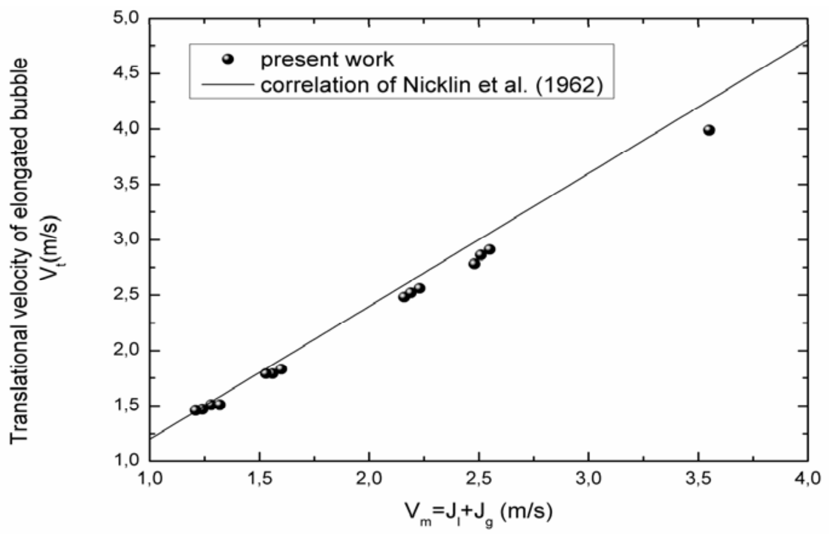

Fig. 9. Translational velocity of elongated bubble as a function of mixture velocity: comparison of measurements with Nicklin et al. [19] model.

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