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BUBBLE-BUBBLE INTERACTION IN HORIZONTAL TWO-PHASE SLUG FLOW

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Abstract. *Modelling of the slug structure requires a new effort on fundamental research. To clarify some aspects of the horizontal slug flow, an experimental study of the behaviour of two isolated bubbles in a single-phase liquid flow was performed. This procedure was adopted to avoid the overlap of different phenomena induced by a train of long bubbles.*
The experimental facility consists of a 90-m horizontal PVC pipe with internal diameter of 0,053 m. The behaviour of two single air bubbles travelling in a water flow was studied. Focus was given on the influence of the distance between the bubbles on the velocity of the second bubble. This study allows the understanding of the mechanism of overtaking that takes place right after the slug formation and that precedes the coalescence of bubbles in a slug flow.
The results show that bubbles placed behind a liquid slug smaller than a critical value move faster than the leading one. Otherwise, they move slower than the leading one.

Key words: *Two-phase flow, Slug flow, Flow structure, Interaction between bubbles*

1. INTRODUCTION

Horizontal slug flow has been object of studies for at least 30 years. Models to predict phase velocities and pressure gradient were developed based on the unit cell concept described initially by Wallis (1969). Dukler & Hubbard (1975) proposed the first comprehensive model and further papers were variations upon the same concept. Later on, Taitel & Barnea (1990) proposed an unified approach for the vertical, horizontal and inclined flow. Two years later, Fabre & Liné (1992) presented a different approach based on a statistical cell concept. All these developments improved the ability to predict important flow parameters such as pressure gradient, mean phase velocities and mean volume fractions. But in no way they improved the knowledge of the slug structure itself, i.e., very little advance was made on the prediction of the lengths of each phase, their statistical distribution as a function of flow parameters and their evolution along the pipe.

Owing to the exhaustion of current oil reserves, the petroleum industry turns to the exploitation of deep and ultra deep-water reservoirs. The use of new production technologies has been then considered, in particular, the use of subsea multiphase pumping systems and subsea separation systems. To optimise the application of these new technologies, a better knowledge of the multiphase flow structure is required.

Some interesting experimental works were made recently by Dhulesia *et al.* (1991), Nydal *et al.* (1992) and Grenier (1997), which provided statistical description of slug flows. Recent attempts to predict the evolution of the slug structure were made using two different approaches. The most popular is the “slug-tracking” method, where the volume and position of each individual bubble and liquid slug are followed systematically along the pipe. The bubbles are allowed to expand as pressure decreases and coalescence may occur. Straume *et al.* (1992), Barnea & Taitel (1993) and Nydal & Banerjee (1995) applied this method to describe the slug flow evolution along the pipe. The second approach uses transport equations for the bubble and liquid slug lengths distribution. The first attempt to use this method was made by Grenier (1997). It was limited to the pipe region where the interaction between bubbles is supposed weak and depressurisation is the only cause of structure evolution. Fagundes Netto (1999) presented a complete model to predict the evolution of the flow structure taking into account gas depressurisation, interaction between bubbles and coalescence. In any of the proposed methods, the relation between the bubble velocity and the previous liquid slug length is required to predict the coalescence process.

The bubble velocity in a developed slug flow was object of several experimental and theoretical works. The equation proposed by Nicklin *et al.* (1962) for the vertical case has been successfully used for the horizontal flow. The bubble velocity V_S is written as a function of the mean mixture velocity U, the pipe diameter D and the gravity g:

$$V_S = C_0\, U + C_\infty \sqrt{g\, D} \tag{1}$$

The coefficients C_0 and C_∞ are usually chosen as (Bendiksen, 1984):

$$\begin{aligned} C_0 &= 1{,}0 \quad \text{and} \quad C_\infty = 0{,}54 \quad \text{if} \quad U < 3{,}5 \sqrt{g\, D} \\ C_0 &= 1{,}2 \quad \text{and} \quad C_\infty = 0 \qquad \text{if} \quad U \geq 3{,}5 \sqrt{g\, D} \end{aligned} \tag{2}$$

In our knowledge, Moissis & Griffith (1962) presented the only study of the influence of the liquid slug length on the bubble velocity. Their paper is dedicated to the vertical ascendant flow and they proposed the following relation:

$$V = V_S \left(1 + 8\, exp(-1{,}06\, L_S / D\,) \right) \tag{3}$$

where V_S is the velocity of a bubble following a long slug and L_S is the actual length of the liquid slug. Barnea & Taitel (1993) used a similar relation with different coefficients for the horizontal case.

To verify if this relation is also valid to the horizontal case, the behaviour of two single air bubbles travelling in a horizontal water flow was studied experimentally. Focus was given on the influence of the distance between the bubbles on the velocity of the second bubble. This study allows the understanding of the overtaking mechanism that takes place right after the formation of the slug pattern and that precedes the coalescence of bubbles in a slug flow.

The paper is organised as follows: the first part presents the experimental facility which allows: (1) the injection of two bubbles with known volumes; (2) the control of the distance between them and (3) the measurement of this distance and of both bubbles velocity. In the second part, the experimental results are presented: it will be seen how the distance between bubbles changes along the pipe. A correlation between the velocity of the trailing bubble and its distance to the leading one is proposed. The consequences of these original results are analysed at the end of the paper.

2. EXPERIMENTAL FACILITIES

The test facility was designed and built at the *Institut de Mécanique des Fluides de Toulouse (IMFT)* to study the structure of the horizontal slug flow and its evolution along the pipe (Grenier *et al.*, 1997). Air and water are injected in a horizontal 90 meters long PVC pipe with internal diameter of 0,053 m. The water flows in a closed loop and a pump provides liquid velocities up to 2,0 m/s. The liquid flow rate is measured in a set of diaphragms and the flow is controlled by valves commanded by the *Control and Data Acquisition System (CDAS)*. In this study we are not interested on a regular two-phase slug flow, but on the study of the interaction between two isolated bubbles in a single-phase liquid flow.

Figure 1 presents a scheme of the test facility. The liquid is supplied into the test pipe through the inclined branch "A". A predetermined air volume is introduced in the other two branches, where the pneumatic valves "B" and "C" are kept closed. Controlled by the *CDAS*, valve "B" opens at the same time that valve "A" closes. The liquid flow is deviated into the vertical branch and it pushes the first gas pocket into the test pipe. After a pre-set time delay, valve "B" is closed while valve "C" is, at its turn, opened. The second bubble is then pushed into the test pipe, the distance between the bubbles being controlled by the time that valve "B" is kept open.

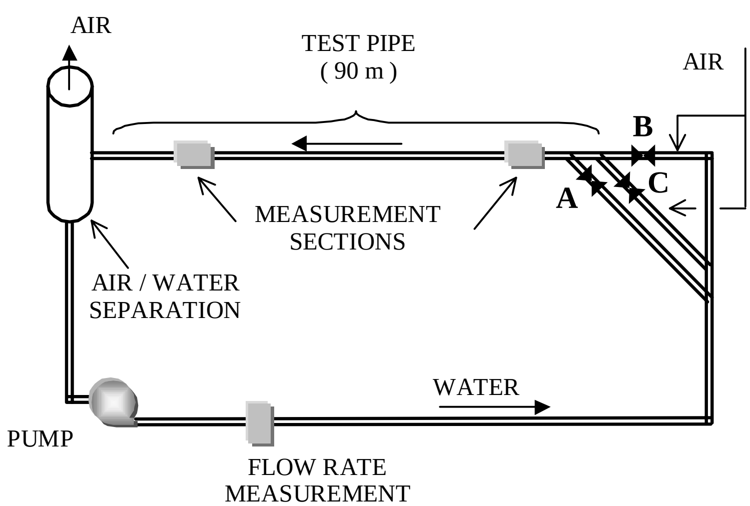


Figure 1 - Test loop scheme

At two meters from the inlet, the gas pockets have already reached their fully developed shape. Two measurement sections were installed, the first at 3 meters from the inlet, the second 65 meters further. Each section is composed of a set of five sensors, distant one meter from each other. Each sensor consists of a metallic wire electrically isolated by a Teflon layer. The isolated wire, with an external diameter of 0,29 mm is installed vertically at the centreline of the pipe section. The capacitance of the wire is linearly proportional to the height of the liquid around it. An electronic device converts the wire capacitance into a voltage signal. Data from the five sensors allow the determination of bubbles velocity and the evaluation of the distance between them.

3. EXPERIMENTAL RESULTS

An extensive test campaign was held to determine the influence of the length of the liquid slug on the velocity of trailing bubbles. Experiments were made at four different flow rates, from 1,3 *m/s* to 2,0 *m/s*. At each flow rate, two different leading bubble lengths were used: 25 and 45 times the pipe diameter D. In each case, several bubble pairs were launched, varying the distance between them from 0 to 50 D. The trailing bubbles have a fixed length of 30 D.

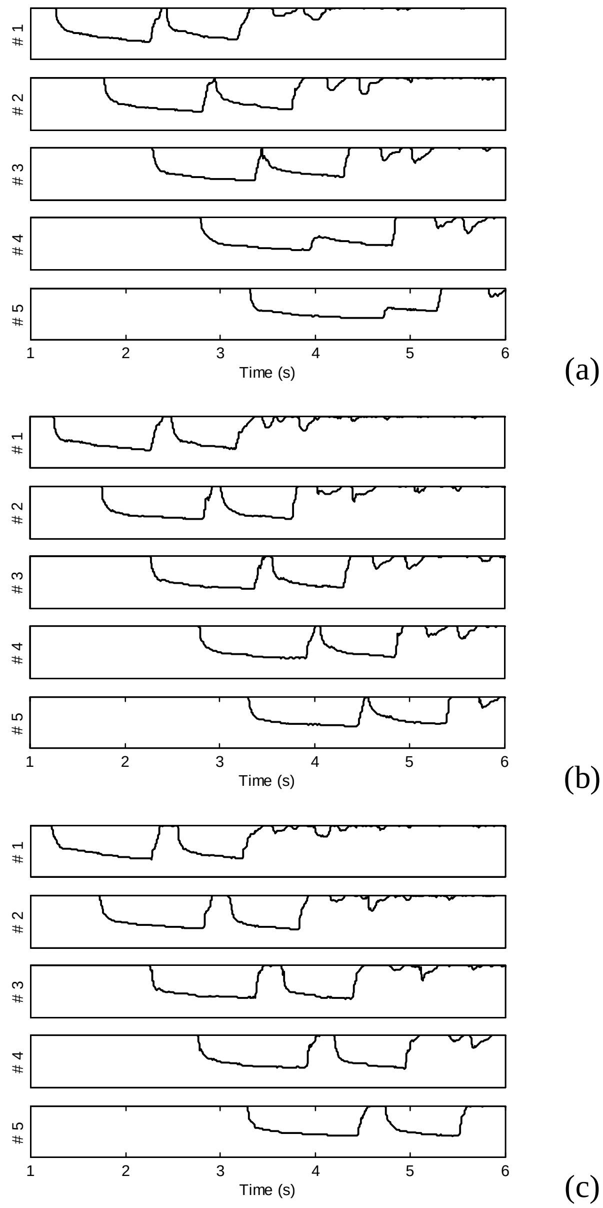


Figure 2 - Time signal at the first section.
Liquid velocity: 1,5 m/s Leading bubble length: 45 *D*

Typical time signals obtained at the first measurement section are shown in Figure 2. Figure 2a shows a pair of bubbles that merge just after the third wire. In Figure 2b, coalescence occurs, but it takes place downstream in the pipe. The pair of bubbles pictured in Figure 2c will not merge. In those cases when the liquid slug "survives", the distance between the bubbles was also measured at the second section, located 65-m downstream.

The set of five sensors gives the time of passage of all four interfaces: the nose and the tail of the leading and trailing bubbles. This information may be plotted as shown in Figure 3.

The first bubble is supposed in uniform motion and its nose and tail velocities are determined by linear regression. The second bubble may be in an accelerated motion and its velocities are determined through a parabolic regression. The distance between bubbles is easily determined once we know the position of the leading bubble tail and of the trailing bubble nose at any time.

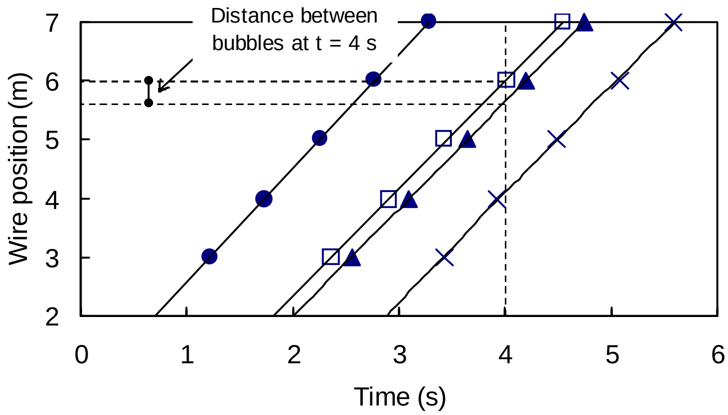


Figure 3 - Interfaces positions with time.
● Nose (bubble 1) ❐ Tail (bubble 1) ▲ Nose (bubble 2) X Tail (bubble 2)

Figure 4 presents the evolution of the length of the liquid slug along the pipe for all cases. It compares the distance between the bubbles measured at both sections. The flow velocity and the size of the leading bubble seem to play a minor role in the liquid slug evolution. It is evident that there is a critical length L_{crit}, around 6,3 D, which determines the evolution of the liquid slug downstream. Slugs smaller than this threshold collapse and coalescence occurs. When the distance between the bubbles is initially longer than the critical length, it grows in size showing that the bubbles move away one from the other.

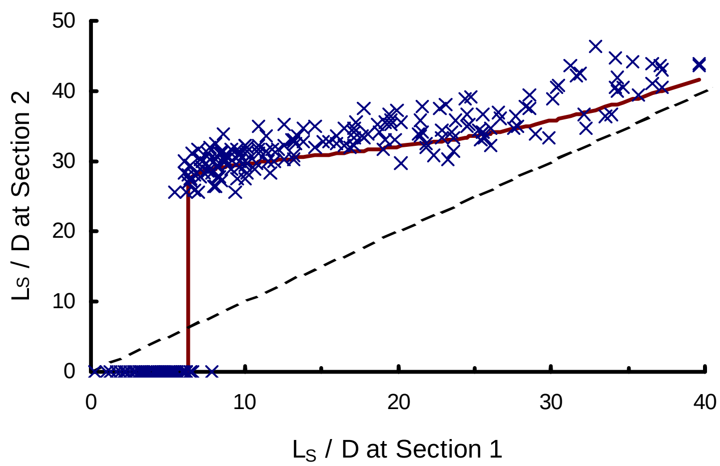


Figure 4 - Evolution of the distance between the bubbles.
Symbol: Experimental data (all runs) - Solid line: Solution of Eq. (7)

The analysis of Figure 4 suggests that bubbles placed behind a liquid slug smaller than the critical value move faster than the leading ones. Otherwise, as the slug lengths increase, they seem to move slower than the leading ones.

The evolution of the bubble velocity with the length of the liquid slug is shown in Figure 5. Bubble velocity is replaced by $v = \left(V - V_S\right) / V_S$, where V_S is the measured velocity of a bubble following a very long slug ($L_S / D > 100$). The figure presents data of all runs, liquid velocities varying from 1,3 *m/s* up to 2,0 *m/s*. It is clear that there is a range of slug size where the trailing bubble moves slower than an isolated one. The critical value L_{crit} is the same observed in the previous figure.

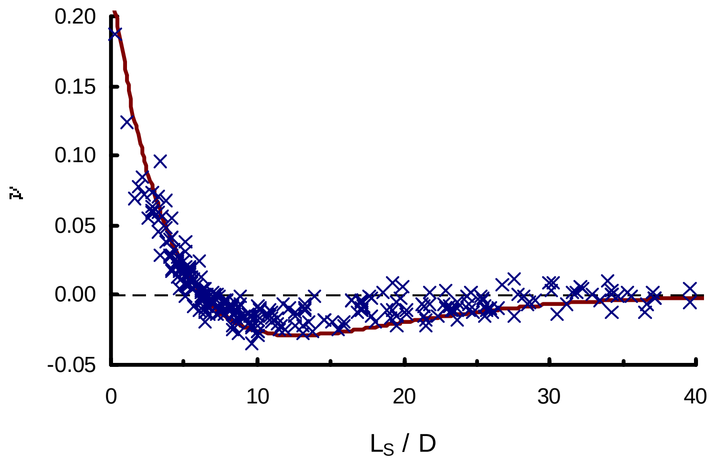


Figure 5 - Bubble velocity x liquid slug length.
Symbol: Experimental data (all runs) - Solid line: Eq. (4)

Figure 5 also shows the proposed correlation between bubble velocity and length of the liquid slug:

$$v\left(L_S\right) = v_0\left(1 - L_S / L_{crit}\right) exp\left(-k\,L_S / D\right) \tag{4}$$

where L_S and L_{crit} are measured in meters. The best fit was observed with $v_0 = 0{,}22$, $L_{crit} = 6{,}3\ D$ and $k = 0{,}16$.

The evolution of the distance between the bubbles along the pipe may be estimated by:

$$\frac{d\,L_S}{d\,X} = \frac{1}{V_S}\frac{d\,L_S}{d\,t} = \frac{\Delta V}{V_S} = v\left(L_{S1}\right) - v\left(L_S\right) \tag{5}$$

where L_{S1} is the length of the liquid slug that precedes the first bubble and X is the axial position in the pipe.

As the leading bubble moves behind a very long slug, Eq. (5) reduces to:

$$\frac{d\,L_S}{d\,X} = -v\left(L_S\right) \tag{6}$$

The slug length measured at the second section $L_S^{(2)}$ is given by the solution of the integral:

$$\int_{L_S(1)}^{L_S(2)} \frac{exp(\,k\,L / D\,)}{(\,L / L_{crit} - 1\,)}\, dL = v_0\ \Delta X \tag{7}$$

where $L_S^{(1)}$ is the length of the same liquid slug measured at the first section and the distance between the two sections ΔX is 65-m. Equation (7) is solved numerically and its solution is also plotted in Figure 4. It reasonably predicts the evolution of the length of the liquid slug, showing that Eq.(4), determined experimentally near the pipe inlet, is representative of the motion of the trailing bubble along the entire pipe.

4. CONSEQUENCES TO THE SLUG STRUCTURE

Three mechanisms are responsible for the evolution of the structure (Grenier, 1997) in a hydrodynamic horizontal slug flow:

- Gas expansion due to pipe depressurisation;
- Mass exchange due to gas entrainment;
- Bubble-bubble interaction through short liquid slugs.

The present analysis applies to flow conditions in which gas expansion and gas entrainment are negligible, i.e., low mixture velocities. It is assumed that the bubble-bubble interaction is described by a law of the type

$$V = V_S \, (1 + \nu (L_S)) \tag{8}$$

Let us consider two bubbles "A" and "B" as shown in Figure 6. The liquid slugs that precede each bubble have lengths L_{SA} and L_{SB} respectively. Actual bubble velocities are V_A and V_B.

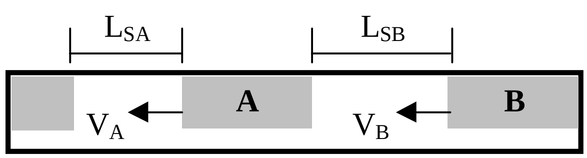


Figure 6 - Bubbles scheme

When function ν has the form shown in Figure 5, there are two different situations:

4.1. Near the slug formation

In this region, both bubble and slug lengths are small. We may consider that all liquid slugs are shorter than L_m, the length where $\nu(L)$ reaches its minimum.

Figure 7a shows the case where L_{SA} is shorter than L_{SB}. In this case, bubble "B" moves slower than "A" and the longer slug increases. The opposite case is shown in Figure 7b, where $L_{SB} < L_{SA}$. In this case, bubble "B" moves faster than "A" and the distance between them decreases.

Near the pipe inlet, the dispersion of the slug length distribution increases. The standard deviation increases with pipe position and, as coalescence takes place, the mean slug length also increases.

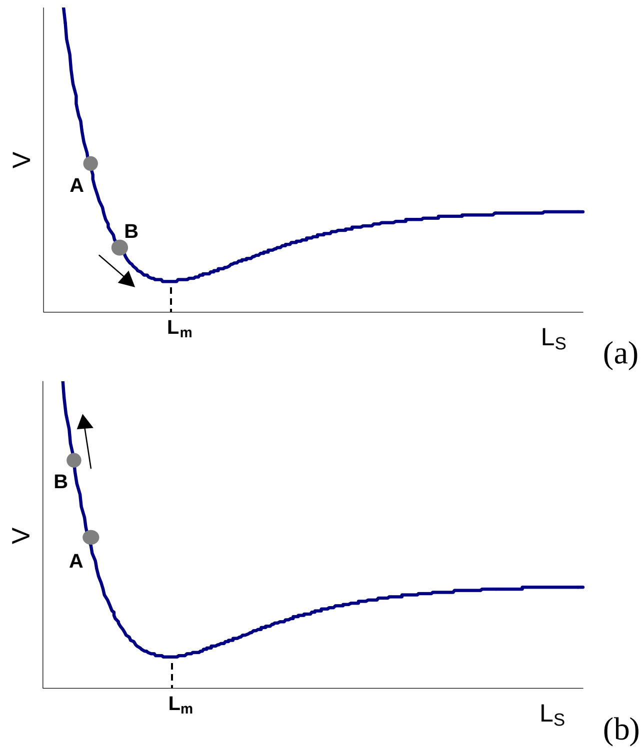


Figure 7 - Bubble-bubble interaction near the pipe inlet

4.2. Fully developed slug flow

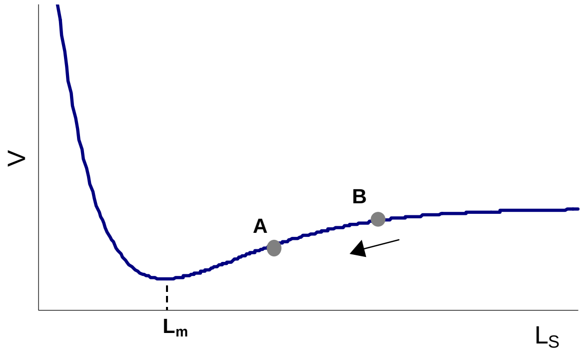
Far from the pipe inlet, the slug length distribution is such that, in this domain, function v increases monotonically. Using the same reasoning as above, if $L_{SB} > L_{SA}$, bubble "B" moves faster than "A" and the longer slug decreases, as shown in Figure 8a. Conversely, when the liquid slug preceding "B" is shorter, bubble "B" is slower and L_{SB} increases (Figure 8b).

For fully developed slug flow, dispersion of the slug length decreases with pipe position, while the mean slug length remains unchanged, as coalescence no longer occurs.

This analysis agrees with the experimental observation reported by Grenier (1997). He did observe that the mean slug length initially increases as well as its dispersion. Further in the pipe, liquid slugs seem to interact in order to "calibrate" their length around a stable mean value. In this region, Grenier observed that short slugs increase while longer ones decrease, dispersion decreasing with pipe position.

When v is a monotonically decreasing function, as the exponential relation proposed by Moissis & Griffith (1962), the liquid slugs grow endless and dispersion always increases with pipe position.

The correlation - Eq.(4) - proposed in this paper is valid for water and air flowing in a horizontal pipe with 0,053-m internal diameter, and for a total mixture flow of up to 2,0 m/s. Calibration of the slug length distribution was observed by Grenier using the same experimental facility, with mixture flow velocities up to 5,0 m/s. Further extrapolation should be made with care. The role of the pipe diameter in the form of function v, for instance, was not studied.



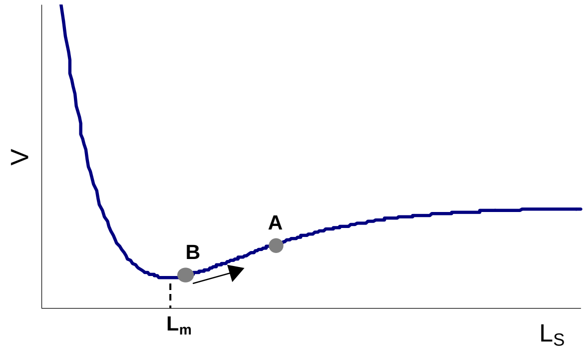


Figure 8 - Bubble-bubble interaction far from the pipe inlet

5. CONCLUSION

An experimental campaign to study the interaction bubble-bubble was performed. The behaviour of two isolated air bubbles in a horizontal water flow was measured. We were interested in the dependence of the trailing bubble velocity on the distance between the two bubbles. The study shows that their relation can not be described by a classical exponential law. An original correlation resulted instead, and it takes into account that short liquid slugs collapse while long slugs grow along the pipe.

The consequences of this experimental result provide the understanding of the evolution of the slug structure reported by Grenier (1997) at the same test facility.

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