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International Journal of Multiphase Flow 31 (2005) 337–357

International Journal of Multiphase Flow

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Investigation of slug flow characteristics in the valley of a hilly-terrain pipeline

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Received 24 June 2003; received in revised form 13 October 2004

Abstract

The objective of this study is to improve the current phenomenological understanding of slug flow characteristics over an entire hilly-terrain section, and in particular, the slug initiation mechanism at the lower dip.

The experimental part of this study revealed that five possible flow behavior categories exist along a hilly-terrain section. In these categories, the flow behavior at the dip is coupled with flow conditions of the upstream downhill section. This qualitative classification was superimposed on steady-state flow pattern maps for the upstream downhill section in an attempt to relate the qualitative flow behavior at a dip to the flow pattern maps through the flow behavior in the downhill section.

Statistical analyses of mean slug length, maximum slug length, slug frequency, and slug length variation across the hilly-terrain pipeline revealed that slug length distribution characteristics change across a symmetrical hilly-terrain pipeline. Physical modeling of the slug initiation mechanism and the characteristics of initiated slugs at the lower dip indicated two main mechanisms, namely, wave growth and wave coalescence initiation mechanisms. The initiated "pseudo slugs" or slug characteristics of each mechanism differ significantly with respect to frequency, length, liquid holdup and velocity. It was observed that pseudo slugs initiated by the wave coalescence mechanism have velocities less than the mixture velocity due to gas blowing through the slug body.

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0301-9322/$ - see front matter
doi:10.1016/j.ijmultiphaseflow.2004.11.002

Keywords: Hilly-terrain; Slug initiation; Lower elbow; Slug length distribution

1. Introduction

Rothe and Crowley (1986) investigated slug flow in uphill and downhill pipes. They found that slug flow could persist in a downhill section with an inclination angle of −15° to −20°. This was observed only for a very narrow range of superficial gas and liquid velocities. However, their study was inconclusive.

In studies by Zheng et al. (1994, 1995) and Zheng (1991), the effects of a hilly-terrain pipeline configuration on flow characteristics were clearly demonstrated. Zheng et al. (1994) proposed a simple slug-tracking model that follows the behavior of all individual slugs for a rather simple geometry consisting of a single hilly-terrain unit (one upward and one downward inclined section).

Henau and Raithby (1995) conducted an experimental study and model validation on induced terrain slugging in multiple hills and valleys. An available transient two-phase flow model was improved by introducing a new correlation for drag coefficient and the virtual mass force. This improvement included the frictional force, which was neglected in previous hilly-terrain transient models.

Barratt et al. (1998) investigated slug decay phenomena in the downhill section of a hilly-terrain pipeline for proper pressure drop prediction. The pressure drop prediction based on the flow pattern predicted by a steady-state flow pattern map may not be accurate if slugs persist in the downhill section while flow pattern maps predict stratified flow to occur. The proposed work superimposes a fully consistent decaying slug regime on incorrectly predicted stratified flow in the downhill section. Slugs will then decay at a rate based on their position and the film thickness in front of them. The resulting film thickness must be equivalent to the stratified flow liquid layer if slugs have not been superimposed. This model was incorporated into a mechanistic steady-state model to enhance the accuracy of pressure drop predictions. When compared with experimental data, the new model showed an improvement at low and intermediate velocities and comparable results with a full head recovery version of Beggs and Brill (1973) correlation at high velocities.

Scott and Kouba (1990) studied the changes in slug flow characteristics in hilly-terrain pipelines. They proposed a model for slug length change as slugs pass a bottom elbow (dip), assuming no change in the liquid holdup in the slug and an equilibrium film thickness. However, they did not consider slug initiation or dissipation in their model. Furthermore, they used isograms of slug length superimposed on a flow pattern map to visually examine the change of slug length with respect to flow conditions and slug flow boundaries. From this technique they concluded that the assumption of uniform film thickness is not justifiable for a reasonable portion of slug operational conditions.

Wood (1991) developed a mechanistic model of induced terrain slugs in a gas condensate pipeline. The model determined the critical gas velocity for liquid removal from the bottom elbow (dip), the maximum stable liquid accumulation, and characteristics of initiated slugs. The model was based on experimental work, and a theoretical quasi-steady-state approach was considered, assuming one dimensional flow. A co-current liquid film must exist to predict the critical gas velocity at which no slug initiation will take place. The combined momentum equation for gas and liquid layers was adopted to predict the liquid layer depth at which counter-current flow will exist, thus beginning the slug initiation process. For a generated slug to survive and exit the uphill section downstream of an elbow, the shedding rate and picking rate at the back and front of the slug, respectively, have to be balanced. Prediction of initiation frequency was attempted by equating the critical liquid volume found at the stratified/intermittent flow pattern boundary to the time integrated flow rate into the uphill section. When compared with experimental data, this model under-predicted the slug frequency by a factor of two.

Zhang et al. (2000) modeled slug dissipation and growth along a hilly-terrain pipeline using a steady-state approach with the liquid film as the control volume to solve the mechanistic equations. This model predicts the average slug length and slug frequency at any location along a hilly-terrain pipeline, given the average slug length or slug frequency at the entrance. The model validation with part of the data of this project shows a reasonable match.

The literature review on hilly-terrain studies confirms the significant impact of hilly-terrain pipeline geometry on slug flow characteristics. Also, it shows that available slug-tracking models are important tools to operate and design a pipeline with hilly-terrain geometry. Yet, existing slug-tracking models lack accurate closure relationships for slug length distribution or slug frequency at the entrance and lower dips.

2. Experimental setup

The test facility was a 420-m long smooth ($\varepsilon = 0$) steel pipe flow loop. The gas phase (compressed air) was supplied by a two-stage compressor, while a centrifugal pump was used to pump the liquid phase (lubspar 107, paraffinic mineral oil) from a storage tank. At the nominal operating temperature (37.8 °C), the oil density, viscosity and surface tension are approximately 890.6 kg/m^3, 0.0102 kg/m s and 0.0284 N/m, respectively. Both the gas and liquid were metered in the metering section using Micro Motion mass flow meters. The two fluids were then filtered and flowed to the mixing tee where they mixed to form a two-phase flow. After the air–oil mixture flowed through the test section, it entered a separator where the two phases were separated. The oil flowed back to the storage tank, while the air was vented to the atmosphere. Fig. 1 illustrates the overall test facility.

Fig. 2 shows a schematic of the test section design. The test section was made of 50.8-mm diameter smooth ($\varepsilon = 0$) transparent acrylic pipe, which simulates a single hilly-terrain unit of 21.34-m downhill and 21.34-m uphill sections. The 42.7-m length is equivalent to an L/D ratio of 840. The range of the investigated inclination angles was $\pm 0.915°$ and $\pm 1.93°$, valley configuration. Fig. 2 identifies 11 capacitance sensors that were installed in the test section: two upstream of the downhill section, three in the downhill section, one at the elbow, three in the uphill section, and two downstream of the uphill section. These CSs were used to measure the slug flow characteristics in this pipeline.

The capacitance sensors can be used to measure the liquid holdup of the pipe flow. Other characteristics such as slug length, frequency, and velocity are calculated using the CSs signals. These sensors are improved versions of those used by Zheng (1991). All the capacitance sensors used in the experimental study of this project were tested, tuned, and calibrated both statically and dynamically. A more detailed description of the experimental program is found in Al-Safran (1999).

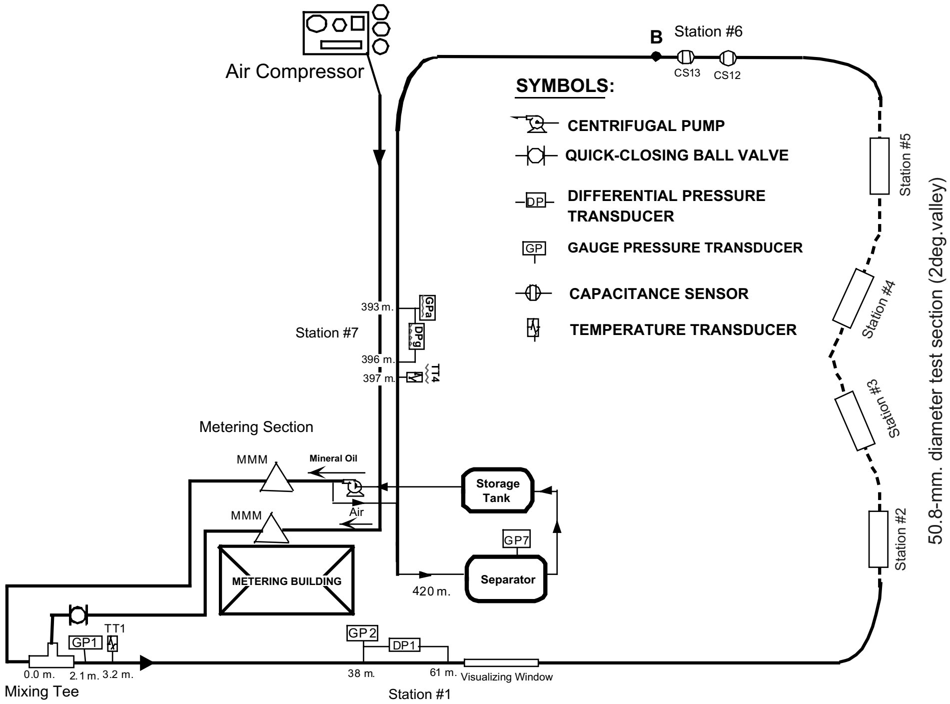

Fig. 1. Test facility.

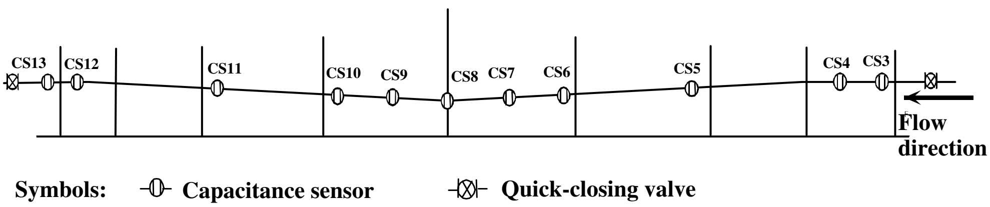

Fig. 2. Test section.

The lower elbow configuration is reasonably smooth (not a "V" shape) to resemble a real life elbow configuration. The downhill and uphill sections are connected by a 0.3-m long horizontal pipe section to create this smoothness.

3. Physical modeling

3.1. Flow behavior categories

Figs. 3 and 4 show five categories of flow behavior at the dip as a function of superficial liquid velocity (v_{SL}) and superficial gas velocity (v_{SG}) for 1.93° and 0.915° valley configurations, respectively. The liquid accumulation at the elbow comes from the mass influx from the downhill section

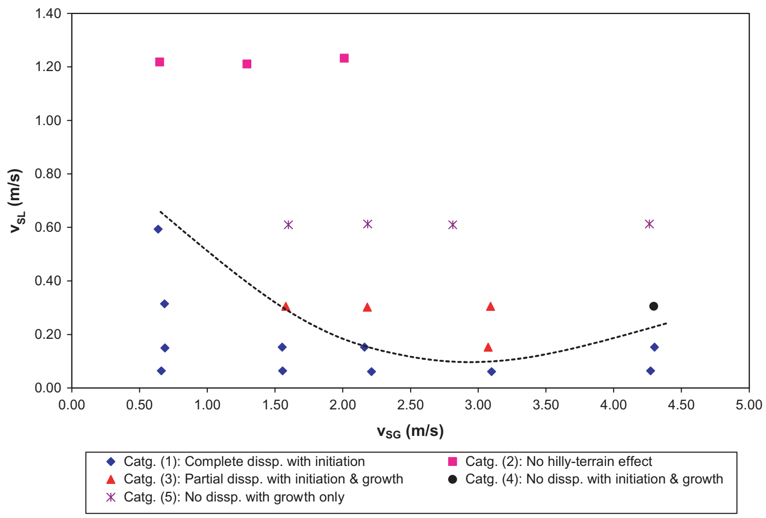

Fig. 3. Bottom elbow flow behavior map (1.93° valley configuration).

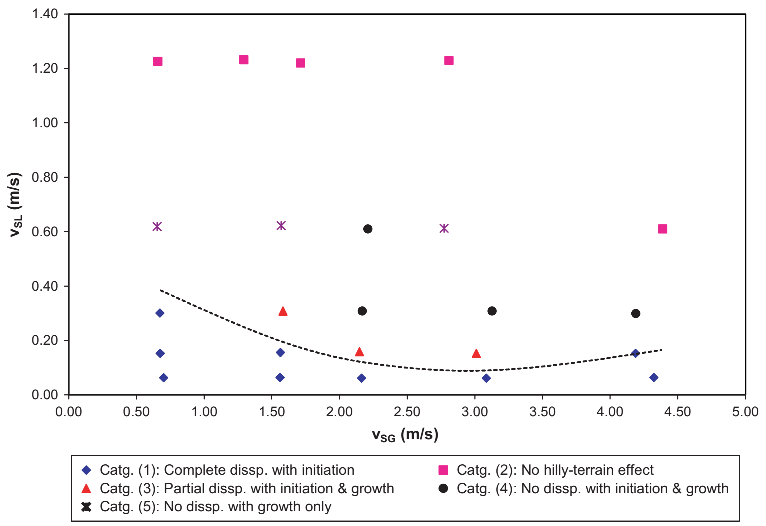

Fig. 4. Bottom elbow flow behavior map (0.915° valley configuration).

and backward flow from the uphill section (Zheng, 1991). Therefore, the flow behavior at the elbow is coupled with the flow conditions of the upstream downhill section and the downstream uphill section. However, qualitative flow behavior (i.e. whether slug initiation only, slug initiation and slug growth or no hilly-terrain effect) is coupled with the flow behavior in the downhill section only. Conversely, the characteristics of the initiated slugs in term of slug length, frequency or liquid holdup depend on both the uphill and downhill sections upstream.

3.1.1. Complete slug dissipation in downhill section with slug initiation at elbow (category-1)

Fig. 5 illustrates, schematically, the case of complete slug dissipation in the downhill section with slug initiation at the elbow. This is the predominant case over a wide range of operational conditions. This behavior yields zero slug frequency along the downhill section and is observed for the conditions of low and moderate v_{SL} and low v_{SG}. Fig. 3 illustrates the general trend where this behavior decreases with increasing v_{SG} to a minimum value, then increases again at high v_{SG}. Physically, at low to moderate v_{SL} and low v_{SG}, short and slow moving slugs are observed in the pipeline, which are easily dissipated in the downhill section. As the v_{SG} increases, the hilly-terrain effect is suppressed because of the increase in slug velocity, which minimizes the gravity effect in dissipation. This behavior persists until v_{SG} is high enough to create highly aerated and foamy slugs. Although these slugs are fast, they are easy to collapse as they enter the downhill section. For the case of 0.915° inclination angle (Fig. 4), a similar trend is observed but with a suppressed area of this flow behavior. This is perhaps due to the reduction in the gravity force at the smaller inclination angle that contributes to the dissipation mechanism. In this case, stratified flow is observed in the downhill section. Thus, a relatively high liquid layer flows into the elbow, resulting in liquid accumulation and slug initiation.

3.1.2. No hilly-terrain effect on slug flow characteristics (category-2)

The no hilly-terrain effect is the case where neither slug dissipation is observed in the downhill section nor slug initiation or growth at the elbow. Fig. 3 shows that this behavior occurs at high v_{SG} and v_{SL}. In this case, high liquid holdup slugs with high frequency persist in the downhill section. At the elbow, because of the high frequency slugs, insufficient time exists for the liquid to accumulate for slug initiation or growth. As the inclination angle decreases to 0.915° (Fig. 4), this flow behavior is observed even at moderate v_{SL} ($v_{SL} = 0.61$ m/s) and high v_{SG}.

3.1.3. Partial slug dissipation in downhill section with slug initiation and slug growth at elbow (category-3)

The flow behavior of partial slug dissipation in the downhill section and slug initiation and growth at the elbow is observed at moderate v_{SL} and v_{SG} (Fig. 3). The slug frequency decreases in the downhill section, but slug flow persists. Consequently, the behavior in the elbow is both slug initiation and slug growth. In this case of low slug frequency in the downhill section, liquid accumulates at the elbow and either a new slug initiates or a persistent slug picks up the accumulated liquid. Fewer experimental tests of this category are observed for the case of 0.915° configuration (shown in Fig. 4) because of the reduced slug dissipation at the lower angle.

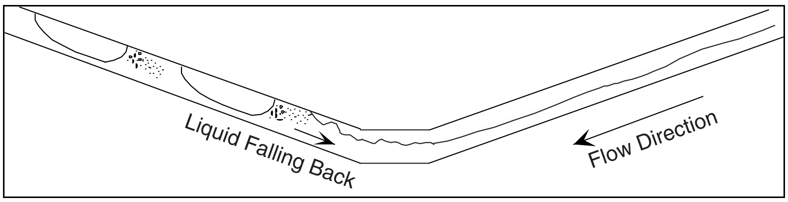

Fig. 5. Complete dissipation in downhill section with slug initiation at the elbow (category-1).

3.1.4. No slug dissipation in downhill section with slug initiation and slug growth at elbow (category-4)

No slug dissipation in the downhill section with slug initiation and slug growth at the lower elbow was observed only once at a moderate v_{SL} and a high v_{SG} for the 1.93° inclination angle (Fig. 3). As the inclination angle was lowered to 0.915° (Fig. 4) this flow category was more widely observed, showing its sensitivity to inclination angle. In the 0.915° configuration, this behavior is observed at moderate v_{SL} and both moderate and high v_{SG}. At the higher inclination angle where dissipation is promoted, the case of no slug dissipation in the downhill section occurs only when the slugs move sufficiently fast (high v_{SG}).

3.1.5. No slug dissipation in downhill section with slug growth at elbow (category-5)

No dissipation at the downhill section and slug growth in the bottom elbow is schematically illustrated in Fig. 6. This case is experimentally observed at moderate v_{SL} ($v_{SL} = 0.61$ m/s) at inclination angles of both 1.93° and 0.915°. However, as the inclination angle increases, this category shifts towards higher v_{SG}, as one compares Figs. 3 and 4. The relatively high slug frequency in the downhill section allows liquid accumulation at the elbow, which is picked up by a persistent slug before a slug is initiated.

3.2. Bottom elbow flow behavior in terms of flow pattern maps

Figs. 7 and 8 show the experimental data plotted on Taitel and Dukler (1976) flow pattern maps for 1.93° and 0.915° downward flows, respectively. Each flow behavior at the bottom elbow is discussed below in terms of the flow pattern maps.

3.2.1. Flow pattern map (−1.93°)

Fig. 7 shows the experimental data plotted on a flow pattern map generated for 1.93° downward flow. All the experimentally observed cases of complete dissipation in the downhill section and initiation at the elbow fall in the stratified and stratified wavy regions. This suggests that the flow pattern map could be used to predict the flow behavior at the elbow. Furthermore, the flow pattern map may give insight into the slug initiation mechanism for this category of flow behavior.

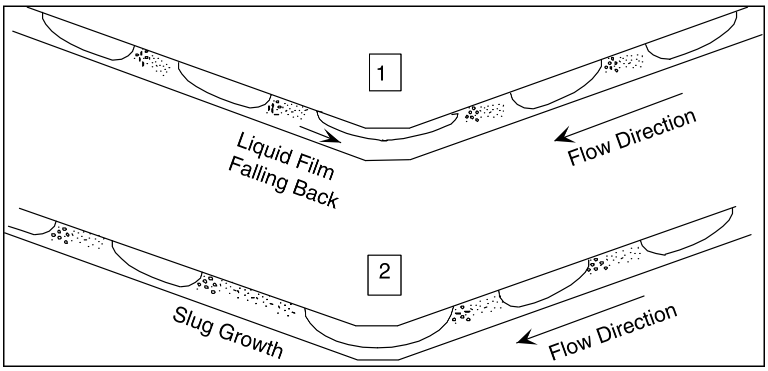

Fig. 6. No dissipation in downhill section with slug growth (category-5).

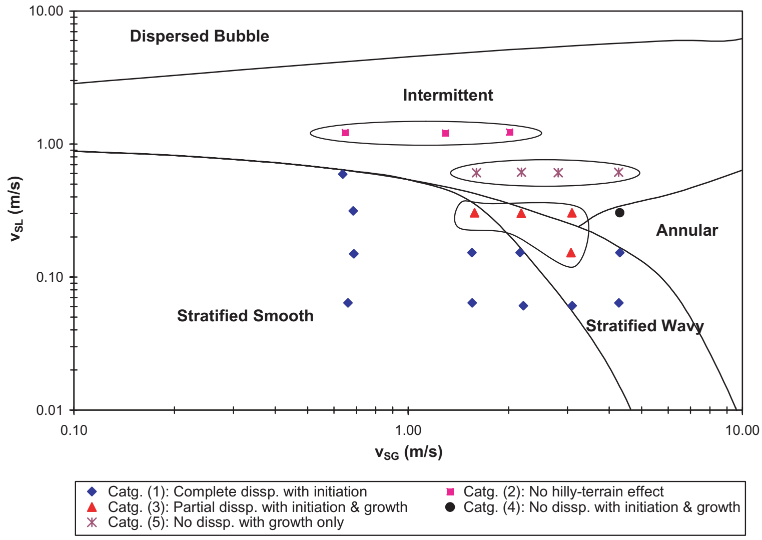

Fig. 7. Test data on flow pattern map (−1.93°).

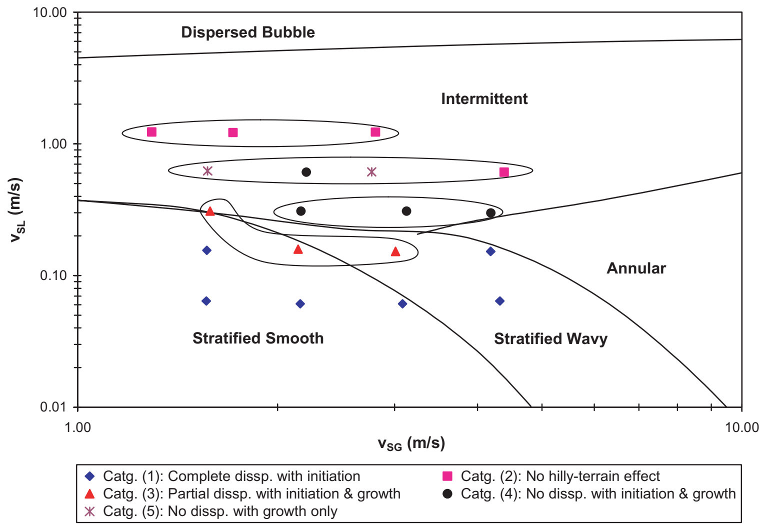

Fig. 8. Test data on flow pattern map (−0.915°).

The slug initiation mechanism differs for the experimental points in the stratified flow region compared to those in the stratified wavy region. The initiation mechanism related to tests in the stratified smooth region is mainly due to partial liquid blockage of the elbow and an increase of gas velocity as its flow area is reduced. Thus, small amplitude waves are formed locally (i.e. at the elbow), and propagate to form slugs in the uphill section (wave growth mechanism as will be described latter). Conversely, slug initiation in the tests that fall in the stratified wavy region has a different mechanism. Basically, the waves that trigger the slug are not formed locally, but are transferred with the stratified wavy flow coming from the downhill section. In this case, less accumulated liquid is required to initiate slugs.

Fig. 7 shows that the test points for partial dissipation in the downhill section with slug initiation and growth are close to the transition boundary of stratified wavy and slug flow. Indirectly, this suggests that slug initiation and growth at the bottom elbow occur at operating condition close to this boundary. In the slug flow region, the category of no hilly-terrain effect is observed at relatively high v_{SL}. Also, the category of no slug dissipation in the downhill section with slug growth at the elbow falls in the slug flow region, but at lower v_{SL}. In both categories, slug flow persists, while the no hilly-terrain effect category is more stable than the slug growth category.

The category of no slug dissipation in the downhill section with slug initiation and slug growth at the elbow appears for only one data point that is close to the transition between slug and annular flow.

3.2.2. Flow pattern map (−0.915°)

Fig. 8 shows the experimental data plotted on a flow pattern map for 0.915° downward flow. As the inclination angle decreases, all the experimentally observed cases of complete dissipation for this configuration still fall in the stratified smooth and stratified wavy regions. Similarly, the category of partial dissipation with initiation and growth remains close to the transition between stratified wavy and slug flow. However, in the slug flow region, three categories appear instead of two as observed for the 1.93° configuration. At low v_{SL} in the slug flow region, a well-defined category exists of no slug dissipation in the downhill section with slug initiation and slug growth at the elbow. At high v_{SL} slug flow, no hilly-terrain effect is observed. At moderate v_{SL}, a combination of all three categories is observed, showing the complexity of the flow under these operational and geometrical conditions. They all lead to slug growth and initiation at the elbow.

The above data analysis is an attempt to relate the qualitative flow behavior at a bottom elbow to a flow pattern map through the flow behavior in the downhill section. By this analysis, one can see that a steady-state flow pattern map could be redefined in terms of the flow behavior in a lower elbow. Thus, a flow pattern map could be used to qualitatively predict the flow behavior in a lower elbow.

3.3. Hilly-terrain effect on slug flow characteristics in terms of the flow behavior categories

The above approach of utilizing a steady-state flow pattern map to qualitatively predict the flow mechanism in the elbow is extended to predict the hilly-terrain effect on slug flow parameters. For each category described in Section 3.1, the change of the average slug length, slug frequency, maximum slug length and slug length variation between the hilly-terrain entrance and exit were investigated to relate each category to a specific hilly-terrain effect. The experimental data were further analyzed at the near entrance of the hilly-terrain section (measurement station # 2) and the far exit of the hilly-terrain section (measurement station # 6). Measurement station # 6 is located 182.5-ft (1095 L/d) downstream of the exit of the upward inclined section of the hilly-terrain pipeline, which assures a fully developed flow. Figs. 9–13 show slug length distribution plots for each category for which the results are summarized in Table 1.

The data from category-1 (complete slug dissipation with slug initiation at lower elbow) revealed that, in general, the mean slug length decreases from the entrance to the exit of the

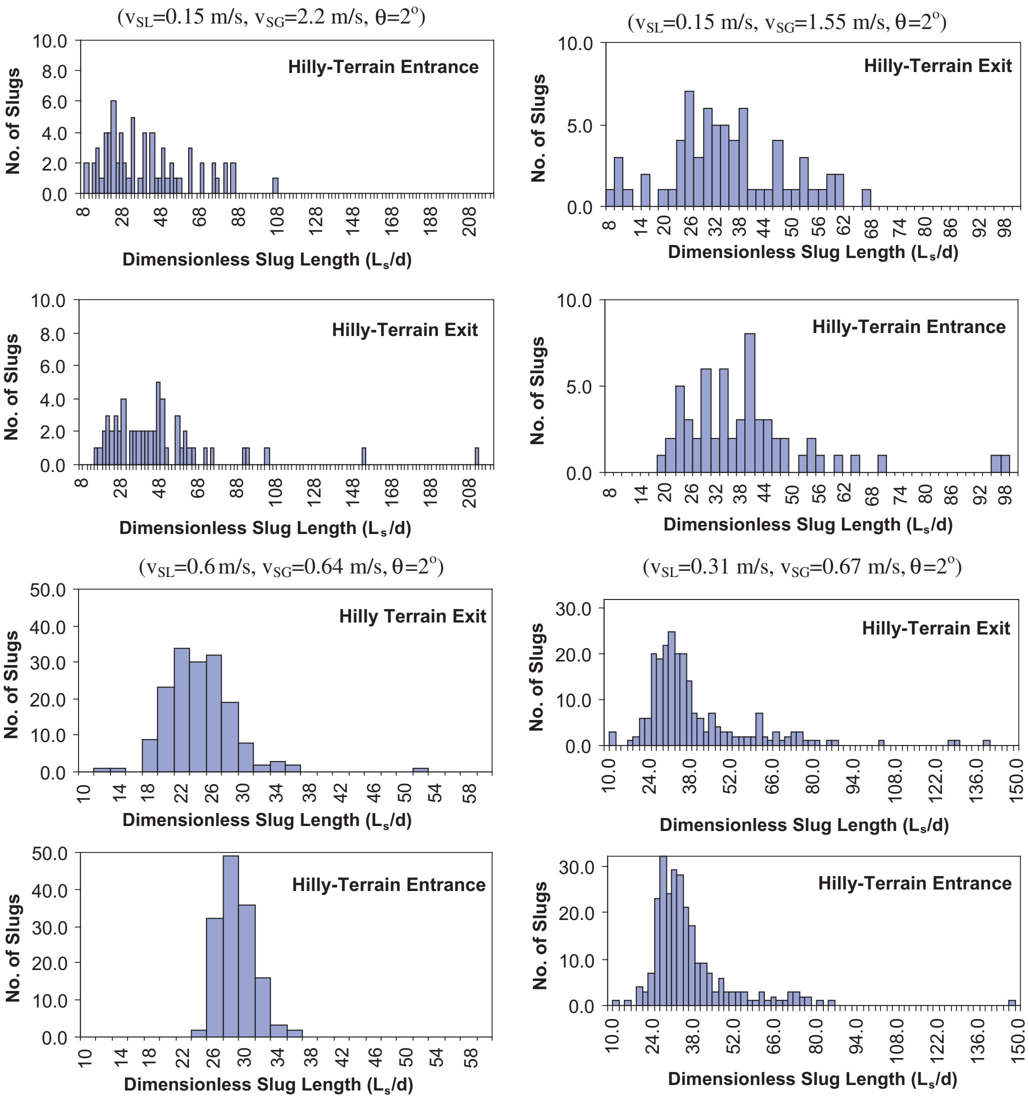

Fig. 9. Category-1 slug length distribution across hilly-terrain section.

hilly-terrain section, especially for relatively low superficial velocities (up to $v_{SL} = 0.15$ m/s and $v_{SG} = 1.5$ m/s). However, an increase of the mean slug length across the hilly-terrain section is observed as the v_{SG} increases. This observation confirms the notion that slug length depends strongly on the inlet condition (Hall et al., 2001; Nydal et al., 1992). The fully developed mean slug length resulting from dip initiation is smaller than the fully developed mean slug length that was initiated in horizontal flow. The slug length distribution variance increases across the hilly-terrain section. Similar to the mean slug length, maximum slug length decreases across the hilly-terrain section, which may imply the physical interconnection between the mean slug length and maximum slug length. The slug frequency across the hilly-terrain for category-1 did not show a specific trend.

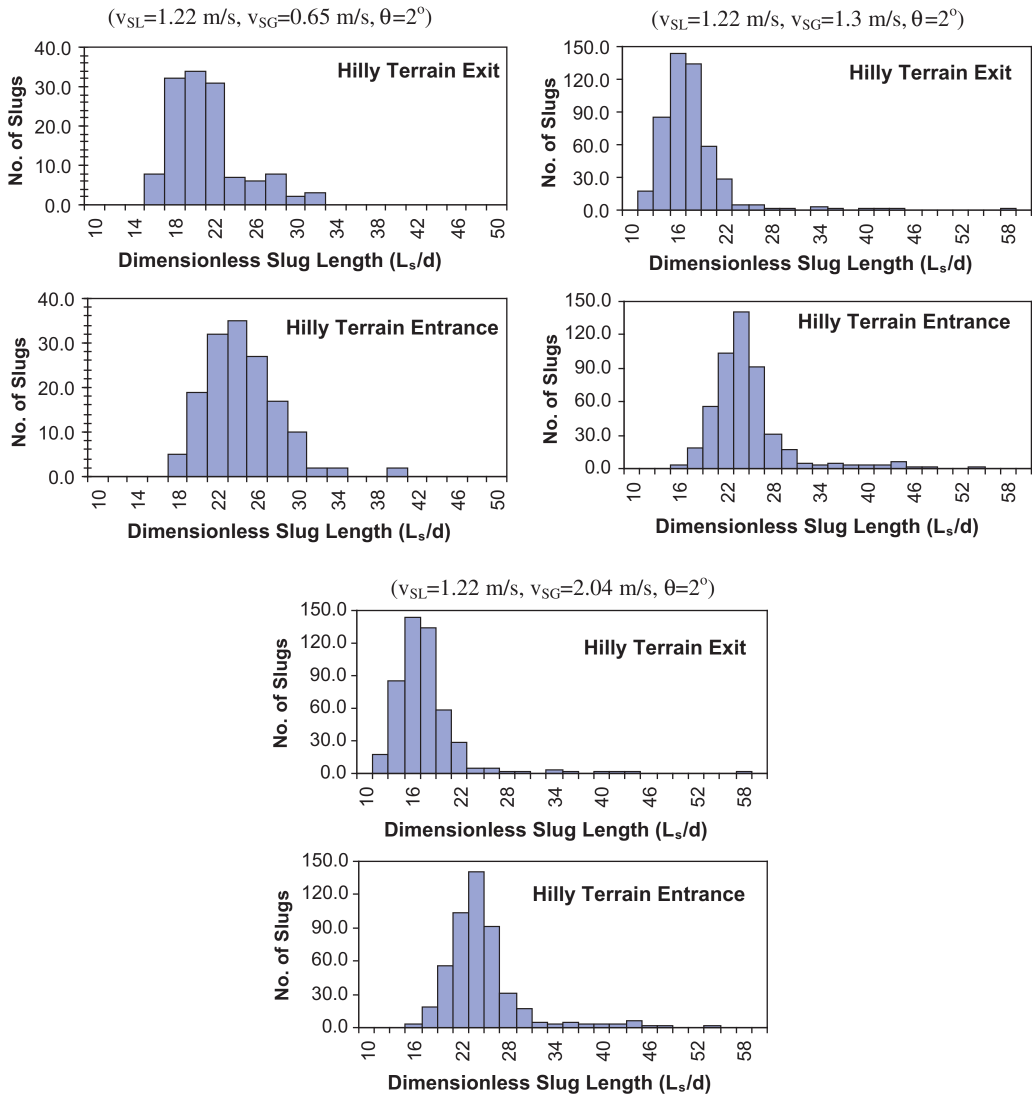

Fig. 10. Category-2 slug length distribution across hilly-terrain section.

However, in general the frequency decreases in high v_{SG} cases and increases in low v_{SG} cases, due to the different structure of the initiated slugs with the high and low v_{SG} values as will be discussed later.

In category-2 (no hilly-terrain effect), the mean slug length is always decreasing across the hilly-terrain section, which indicates that the slug dissipation in the downhill section is not compensated by the slug growth in the uphill section, even for a symmetrical hilly-terrain section such as the one in this experiment. Similarly, the maximum slug length mostly decreases across the hilly-terrain section. Both the slug frequency and slug length variance show constant values across the hilly-terrain section.

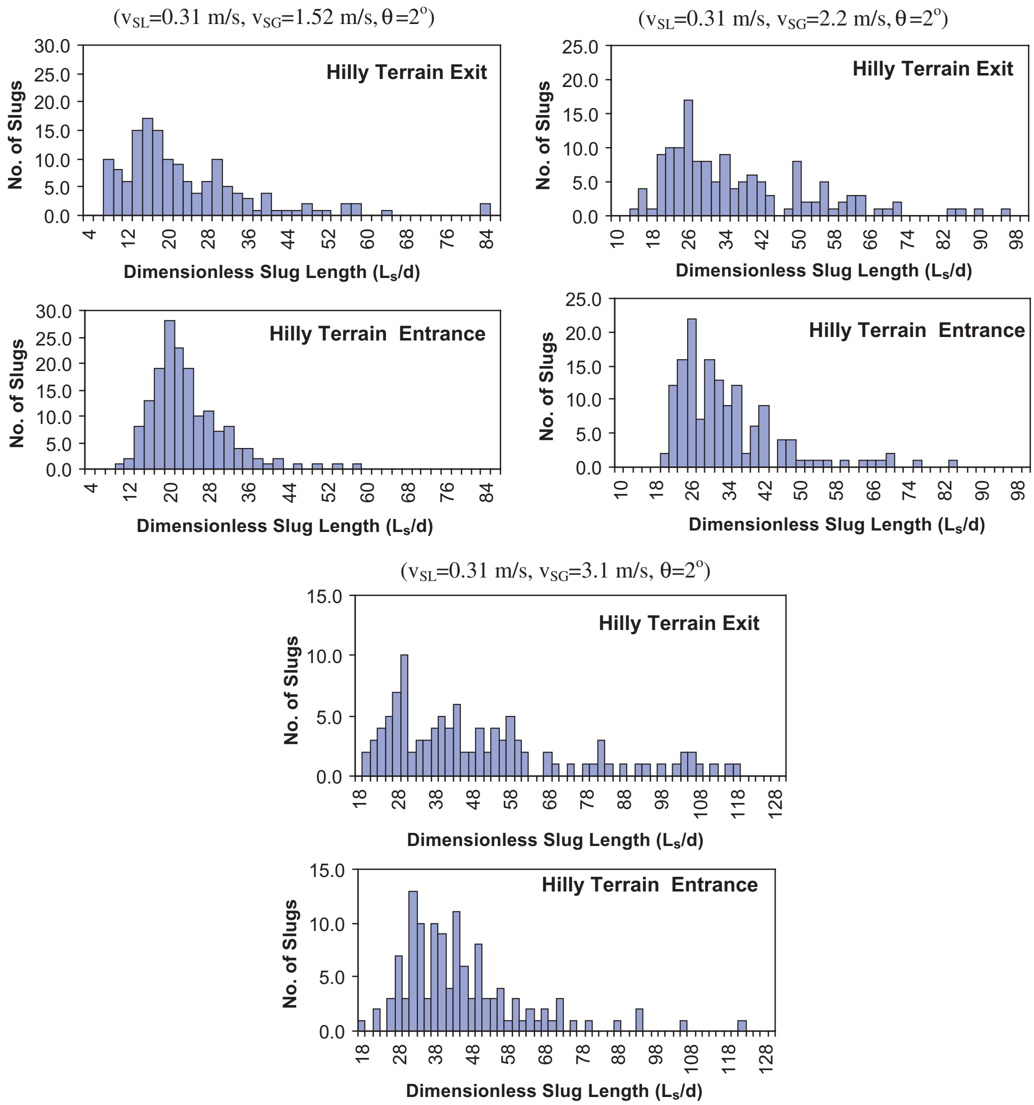

Fig. 11. Category-3 slug length distribution across hilly-terrain section.

The flow behavior at the elbow of category-3 (partial slug dissipation with slug initiation and slug growth at lower elbow) impacts the slug flow characteristics across the hilly-terrain section. In general, mean slug length, slug frequency and slug length variance increase across the hilly-terrain section in this category. The slug length variance and slug frequency increase are clearly related to the slug initiation at the elbow. The increase of mean slug length is physically related to the phenomenon of long persistent slugs from the downhill section overriding initiated shorter and slower slugs along the uphill, leading to longer slugs. However, not all the initiated slugs are overridden as in category-4. The maximum slug length across the hilly-terrain section was found to have no specific increasing or decreasing trends.

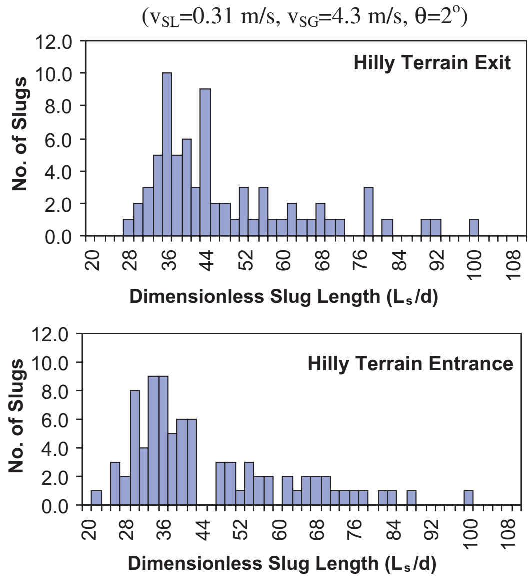

Fig. 12. Category-4 slug length distribution across hilly-terrain section.

In category-4 (no slug dissipation with slug initiation and slug growth at low elbow), all the initiated slugs at the elbow are overridden by the persistent slugs coming from the downhill section. Therefore, the mean slug length increases across the hilly-terrain section while the frequency stays constant. Also, both the maximum slug length and slug length variance stay constant across the hilly-terrain section. This finding may not be completely valid due to the limited data sets of category-4.

Category-5 (no slug dissipation with only slug growth at lower elbow) is characterized by no slug dissipation in the downhill section with slug growth at the lower elbow. Amazingly, the mean slug length, in general, decreases across the hilly-terrain section in this category which could be interpreted as follows. The slug growth (mass gain) at the elbow and along the uphill section is less than the slug dissipation (mass lost) at the top elbow located at the exit of the uphill section (Fig. 2) resulting in shorter slugs, and thus decrease in mean slug length. Another explanation is that the loss of mass during the dissipation process in the downhill section as the slugs become shorter is not being off set by mass gain across the bottom elbow. This observation suggests that slug growth across the lower dip does not necessarily lead to an increase of mean slug length across a hilly-terrain pipeline. However, mean slug length increases across a hilly-terrain pipeline when there is slug initiation at the lower dip coupled with slug flow persistence in the downhill section as in categories 3 and 4. Slug frequency in category-5 stays the same across the hilly-terrain section, except in the case of high v_{SG}, where it decreases. This observation could be related to slugs merging in the uphill section because of the fast moving slugs.

Overall, the above analysis adds more insight to the observed categories in the hilly-terrain section. The approach of categorizing flow behavior, regardless of the operational and geometrical conditions, and the use of steady-state flow pattern maps, is now more meaningful and complete when related to the change in slug flow characteristics across the hilly-terrain section. Although

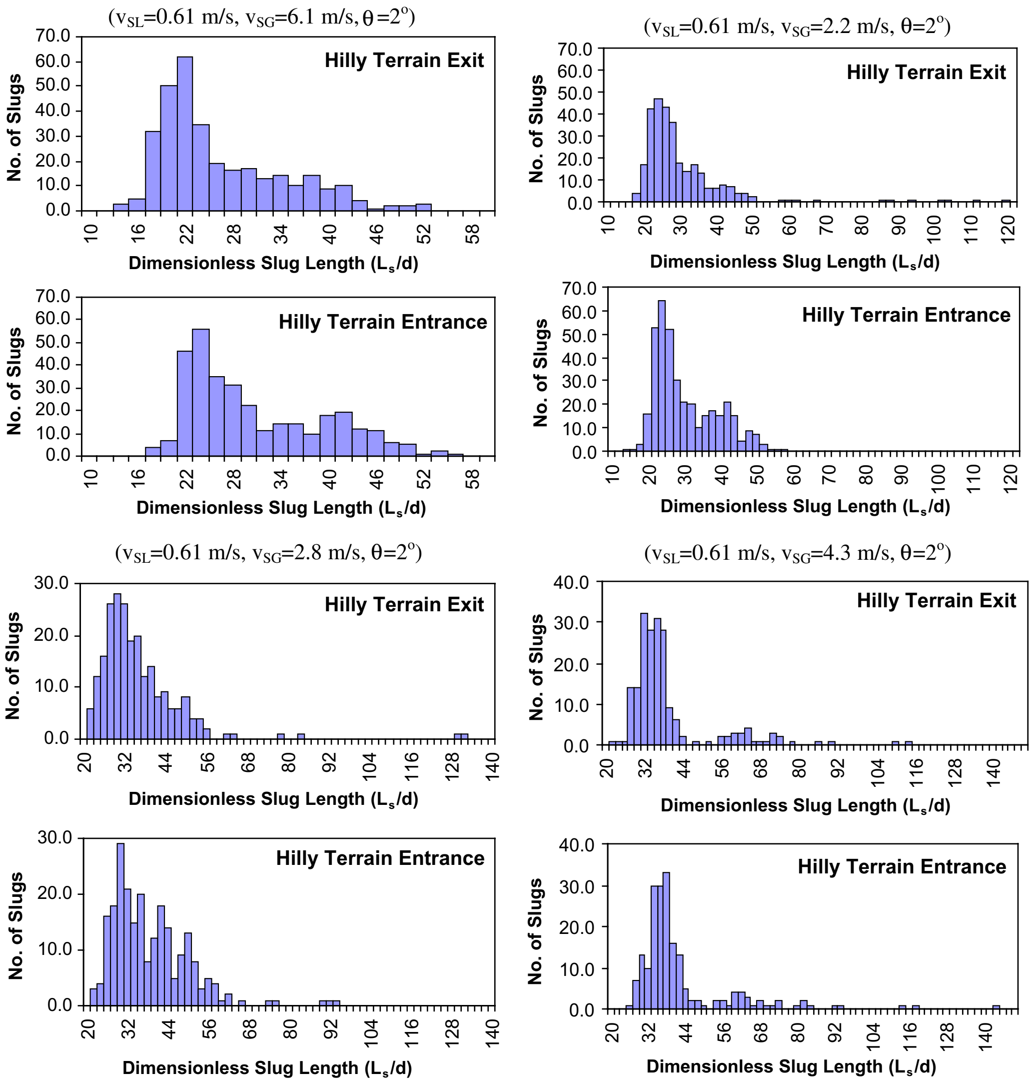

Fig. 13. Category-5 slug length distribution across hilly-terrain section.

Table 1
Summary of slug flow characteristics trend across hilly-terrain section

Flow behavior categories	Dimensionless mean slug length	Dimensionless max. slug length	Slug freq. (1/s)	Slug length variance
1	Decrease	Decrease	No trend	Increase
2	Decrease	Decrease	Same	Same
3	Increase	No trend	Increase	Increase
4	Increase	Same	Same	Decrease
5	Decrease	Increase	Same	Decrease

this approach is a qualitative analysis, it provides some understanding of occurring phenomena that may lend itself for future modeling work.

3.4. Initiation mechanism and initiated slug characteristics at bottom elbow

An extensive data analysis of the slug initiation phenomenon was carried out, which revealed an interesting observation and important physical understanding of this complicated phenomenon. This analysis was conducted on both valley inclination angles of $+2°$ and $+1°$ and only for category-1, in which stratified flow exists in the downhill section and slug initiation occurs at the dip. However, the slug initiation in other categories should exhibit similar physical behavior, but with an additional phenomenon taking place, i.e. slug growth. The key instruments used in this analysis are the three capacitance sensors in the uphill section and the sensor located at the elbow. The experimental data showed that there are two types of slug initiation mechanisms at the dip, each producing totally different slug characteristics as described below.

3.4.1. Wave growth initiation mechanism

This initiation mechanism in which the liquid phase slowly accumulates at the dip from downstream and upstream under the effect of gravity, has been reported by several investigators (Al-Safran, 1999; Zheng et al., 1994; Wood, 1991). Consequently, the gas flowing area at the top of the liquid is reduced, leading to a local increase in gas velocity. The pressure reduction due to the gas acceleration will result in a suction force acting on the liquid phase, called the Bernoulli effect. This mechanism is the Kelvin–Helmholtz (K–H) stability criterion for transition to slug flow (Taitel and Dukler, 1976). In our experimental data, this mechanism was observed for the cases of low v_{SG} ($v_{SG} = 0.61$ m/s) and different v_{SL} values ($v_{SL} = 0.061$, 0.15, 0.305, 0.61 m/s). Fig. 14 illustrates the time series of liquid holdup of this initiation mechanism along the uphill section. The velocities of the initiated slugs fall in the range of Nicklin et al. (1962) correlation ($1.2 * v_m$), and maintains high liquid holdup values around 0.95. Examining the slug frequency along the uphill section shows a constant slug frequency, indicating slug persistence along the uphill section. Thus, the previous analysis of slug flow characteristics across the hilly-terrain section shows an increase in slug frequency in category-1. In this initiation mechanism, the frequency of the initiated slugs decreases as v_{SG} increases, owing to the low liquid accumulation rate at the elbow, which requires a longer time for a slug to be triggered. Fig. 15 shows this trend for all the investigated v_{SL} values with v_{SG} less than 1.83 m/s. A major characteristic of the initiated slug flow in the uphill section is the smooth and relatively high liquid film holdup in the bubble region. Because the initiation mechanism is due to K–H wave growth, the initiation is located exactly at the elbow, as shown by the elbow CS signal in Fig. 14.

3.4.2. Wave coalescence initiation mechanism

Fig. 16 is the time series plot of liquid holdups of the initiated slugs along the uphill section and at the elbow. Unlike the wave growth initiation mechanism, this slug initiation mechanism is visually observed to be merely related to the coalescence of the very small waves initiated at the elbow, which are unable to partially block the elbow. These tiny waves are then moved by the high gas velocity along the uphill section, where they coalesce to form a slug. This is clearly observed by the signal of the elbow capacitance sensor (CS8) in Fig. 16, which does not show any liquid

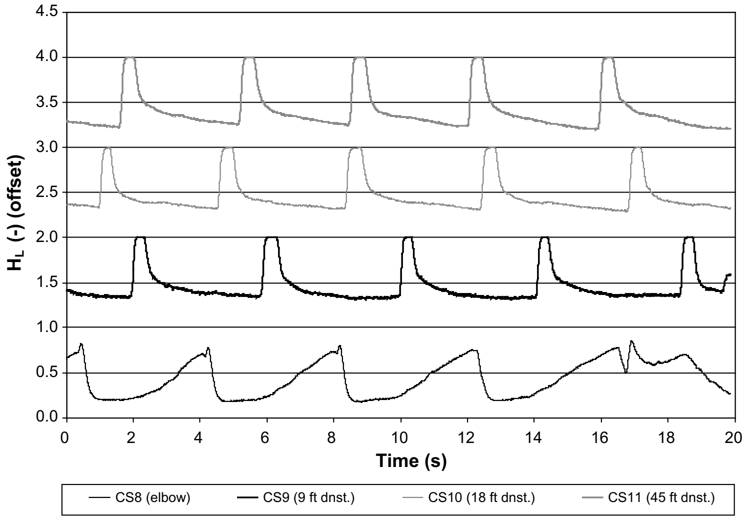

Fig. 14. Liquid holdup time series along uphill section (wave growth initiation mechanism).

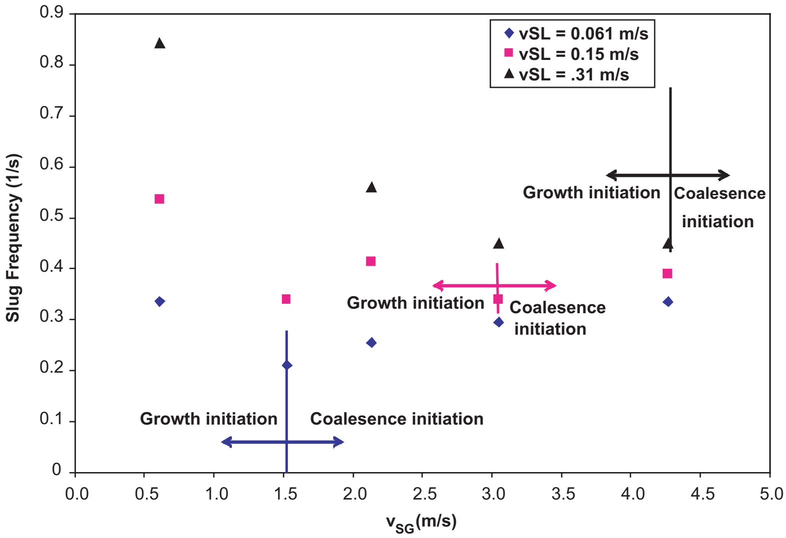

Fig. 15. Initiation slug frequency trend of both initiation mechanisms.

accumulation, but the slugs appear at the 9-ft downstream capacitance sensor (CS9) after the wave had coalesced. This unexplored initiation mechanism was observed at relatively high v_{SG} values ranging from 1.5 to 4.3 m/s, and low v_{SL} in the range of 0.061–0.15 m/s. This mechanism was investigated by Lin and Hanratty (1986) as a transition to intermittent flow in horizontal pipes at high gas velocity.

A unique, yet experimentally verified characteristic of the slugs initiated under this mechanism, is that the average slug translational velocity was found to be less than the mixture velocity. Fig.

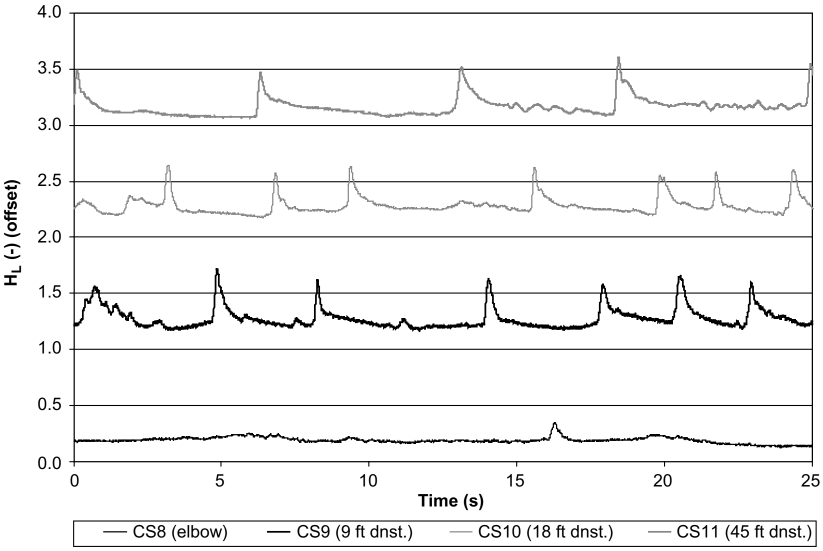

Fig. 16. Liquid holdup time series along uphill section (wave coalescence initiation mechanism).

17 shows the translational velocity distribution of one case with $v_{SL} = 0.15$ m/s and $v_{SG} = 4.3$ m/s. Fig. 17 shows that about 95% of the initiated slugs have translational velocities less than the mixture velocities, with an average translational velocity around 60% of the mixture velocity. The skewed shape of the slug velocity distribution disagrees with the normal distribution findings of Nydal et al. (1992), Dhulesia et al. (1993) (in horizontal pipe) and Bernicot et al. (1993) (in a dip). A closer look at the initiated slugs indicated that, although the initiated slugs are not fully structured slugs, they are also not waves. The slow motion visual recording of these cases shows that, although these slugs block the entire pipe cross section, distinguishing them from waves, they are a foamy and frothy type of slug leading to the notion of gas blowing through the slug body.

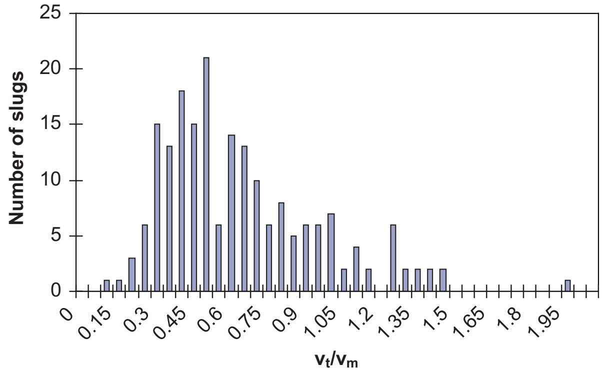

Fig. 17. Translational velocity distribution of initiated slugs at elbow ($v_{SL} = 0.15$ m/s, $v_{SG} = 4.3$ m/s).

Therefore, the discrepancy of the translational velocity being less than the mixture velocity could be attributed to the violation of the major assumption of fully developed slug flow, i.e. no phase slippage occurs in the slug body. Nydal et al. (1992) observed similar slug characteristics of short, highly aerated slugs that fully block the pipe cross sectional area at the entrance of a horizontal test section. However, these slugs were observed to travel at the same velocity as the developed slugs. Conversely, van Hout et al. (2001) observed the opposite trend of slug velocity at the entrance of an upward inclined section. They reported that the average as well as the individual slug translational velocities of the newly initiated slugs exceed the prediction of Nicklin et al. (1962) velocity ($1.2v_m$) by at least 20% under different operational conditions.

Fig. 18 is a plot of the average translational velocity normalized with mixture velocity 2.75-m downstream of the elbow as a function of v_{SG}. This plot shows a decreasing trend of the slug translational velocity as the v_{SG} increases. This trend is illustrated further in Fig. 19 when this phenomenon was coupled with the average slug liquid holdup. Fig. 19 shows that the decreasing trend of the ratio of slug translational to mixture velocity is related to phase slippage taking place in the slug body.

This characteristic of the initiated slugs is a major difference between the initiation mechanisms. In some cases both types of slugs were observed, i.e. those with translational velocity greater than v_m and those with translational velocity less than v_m. These cases have a moderate v_{SG} around 1.5 m/s. Fig. 20 illustrates a bi-modal distribution of initiated slug translational velocity, indicating the existence of both types of slugs and thus both initiation mechanisms.

The frequency of the slugs initiated under the second mechanism decreases along the uphill section as opposed to the first initiation mechanism. Furthermore, when the frequency of these slugs is related to the above investigation of frequency change across the hilly-terrain section, it was found that most of the slugs do not survive in the uphill section, resulting in less slug frequency at the exit than at the entrance. Therefore, this type of slugs should not impose any concerns related to system design, but may impact the pressure drop calculation and erosion/corrosion concerns along the uphill section. Fig. 15 illustrates the trend of the slug frequency in terms of v_{SG} and v_{SL}. For example for v_{SG} greater than 1.5 m/s and v_{SL} of 0.061 m/s, slug frequency increases with

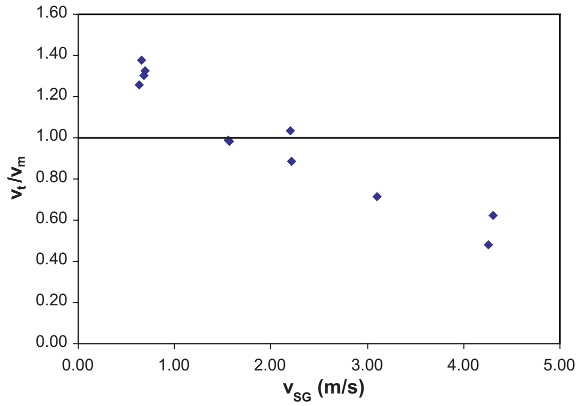

Fig. 18. Initiated slugs translational to mixture velocities ratio trend.

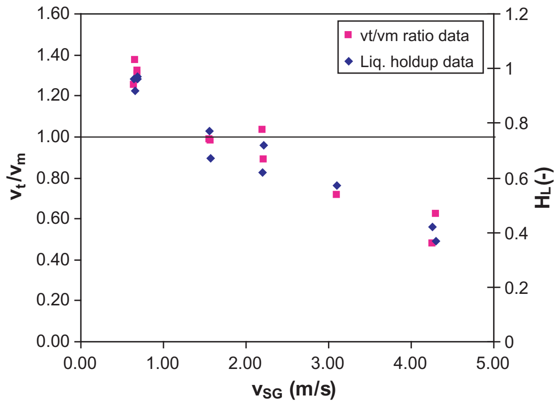

Fig. 19. Initiated slugs translational to mixture velocities and slug liquid holdup trend.

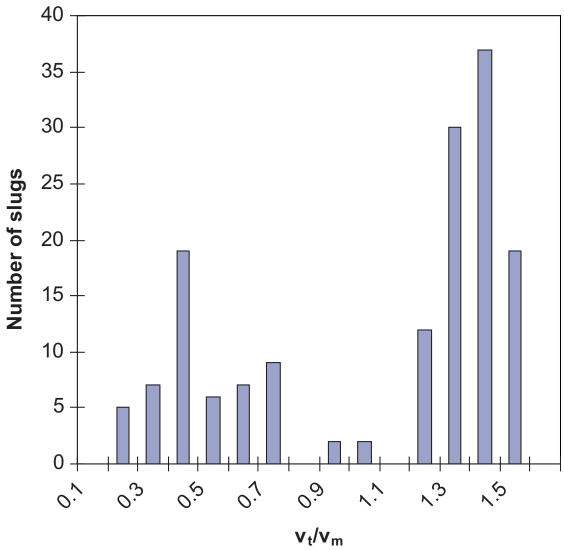

Fig. 20. Translational to mixture velocities ratio bi-modal distribution of initiated slugs ($v_{SL} = 0.15$ m/s, $v_{SG} = 1.52$ m/s).

increasing v_{SG}. This observation confirms the finding that wave coalescence is the primary mechanism of slug initiation because, as v_{SG} increases, more small amplitude waves will coalesce to form slugs. A final note on Fig. 15 is that a similar trend of slug frequency is observed in horizontal co-current two-phase slug flow (Gregory and Scott, 1969). This similarity in frequency trend between horizontal and dip flow implies that for low v_{SG} values in horizontal flow, a local flooding phenomenon (local liquid flow reversal) may exist which results in a wave growth slug initiation mechanism.

4. Concluding remarks

- Five flow behavior categories were observed over the entire hilly-terrain test section. Namely, (1) complete slug dissipation in the downhill section with slug initiation only at the dip, (2) partial slug dissipation in the downhill section with slug initiation and slug growth at the dip, (3) no slug dissipation in the downhill section with slug initiation and slug growth at the dip, (4) no hilly-terrain effect, and (5) no slug dissipation in the downhill section with slug growth only at the dip.
- The five flow behavior categories were superimposed on steady-state flow pattern maps for the conditions in the downhill section. This approach may be used to relate the qualitative flow behavior at a bottom elbow to locations on flow pattern maps for the downhill section. This approach is case specific and may not be valid for other data.
- For each above category, the change of the average slug length, slug frequency, maximum slug length and slug length distribution variability between the hilly-terrain entrance and exit were investigated to relate each category to a specific hilly-terrain effect. This analysis revealed that slug length distribution characteristics change across a symmetrical hilly-terrain pipeline, and this change is related to the flow behavior that exists along the hilly-terrain section.
- Two initiation mechanisms were observed at the lower dip, namely, wave growth and wave coalescence mechanisms. In the wave growth mechanism, is controlled by the Kelvin–Helmholtz (K–H) stability criterion for transition to slug flow (Taitel and Dukler, 1976). This mechanism was observed for the cases of low v_{SG} ($v_{SG} = 0.61$ m/s) and different values of v_{SL} ($v_{SL} = 0.061$, 0.15, 0.305, 0.61 m/s). The initiated slugs of this mechanism are characterized by high liquid holdup, high slug frequency which stays constant as slugs travel downstream, and slug velocities in the range of the Nicklin approximation ($1.2\,v_m$).
- The wave coalescence initiation mechanism is related to the coalescence of very small waves initiated at the elbow, which are unable to partially block the elbow. These tiny waves are then moved by the high gas velocity along the uphill section, where they coalesce to form a slug under K–H instability. This initiation mechanism was observed in relatively high v_{SG} values ranging from 1.5 to 4.3 m/s, and low v_{SL} values in the range of 0.061–0.15 m/s. The initiated pseudo slugs of this mechanism are characterized by low liquid holdup, low slugging frequency which decreases as pseudo slugs travel downstream due to pseudo slug decay, and slug velocities less than mixture velocity due to gas blowing through the pseudo slug body.

Acknowledgment

The main author wishes to express his thanks to Kuwait University for providing a full scholarship during his entire graduate program. The authors are also grateful to the TUFFP member companies for their financial support of this research.

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