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INVESTIGATION OF INTERFACIAL WAVES ON STRATIFIED TWO PHASE FLOW

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Abstract. *The evolution of interfacial waves on a stratified flow is investigated experimentally for air water flow in a horizontal pipe. The waves are introduced in the liquid level of stratified flow near the pipe entrance using an oscillating plate. Mean height of liquid layer and fluctuations superimposed to this mean level are captured using high speed cameras. Digital image processing techniques are used to detect instantaneous interfaces along the pipe length. The driving signal of the oscillating plate is controlled by a DA board that was synchronized with the acquisitions. This enabled to perform phase locked acquisitions and to use ensemble average procedures. Thereby, it was possible to measure the temporal and the spatial evolution of the disturbances introduced in the flow. The assessment of the set-up is an important stage in the development of the experimental methodology because the results must be reproducible to enable further comparisons with theoretical models and numerical simulations. Therefore, this paper focuses on the validation of a new methodology developed to study instabilities of stratified two phase flow. Results show that under controlled conditions the wave development can be well captured and reproduced. In addition, the results shed some light on the physical explanation for differences between theoretical predictions and experimental data for the transition limit between stratified and intermittent flow regimes.*

Keywords: *Kelvin Helmholtz Instability, Controlled disturbances, Stratified flow, Slug initiation*

1. INTRODUCTION

The simultaneous flow of a liquid film and high-velocity gas stream occurs in a variety of industrial equipment. Due to variations in the gas shear stress and pressure along the pipe, complex wavy structures can appear on the film and phases can be organized into different flow regimes or patterns. If the amplitude of these oscillations are large enough, transition to slug flow regime can appear, leading a successive passage of liquid slugs followed by gas bubbles. Due to sudden increase of pressure drops the operation can require a production shutdown (Harvre, 2000). Thus, the prediction of the slug onset is a well-known challenge and crucial for design and operation of pipelines.

According to Kordyban and Ranov (1970), the transition from stratified flow to slug flow can occur by growth of small perturbations generated by hydrodynamic instabilities in the liquid interface. A criterion for transition based on inviscid linear stability analysis was implemented and were observed discrepancies with experimental results of Wallis and Dobson (1973). Later, Lin and Hanratty (1986), Barnea and Taitel (1989), and Barnea and Taitel (1993) extended the linear stability analysis to include viscous effects. They derived theoretical expression and showed reasonable agreement with reported low-pressure, small-scale data for low and medium gas flow rates. On other hand, for pipes with large diameters and high flow rates there is still a discrepancy between the experimental findings and the theoretical predictions (Bendiksen and Espedal,1991 and Kadri et al.,2009).

Andreussi et al. (1985) suggested that the appearance of roll waves would be related to the slug initiation and are possible solutions of the one-dimensional mass and momentum equations for gas and liquid. Later approaches to predict the initiation of roll-waves and the slug onset were developed by Soleimani and Hanratty (2003) using viscous long wavelength theory. Although many other subsequent works have been devoted to model the slug initiation (Fan et al., 1993, Ujang et al., 2005, Valluri et al., 2006, Ansari and Shokri, 2011), many aspects of the problem are still not capable to accurately predict the slug onset for a wide range of pipe diameters and flow rates. Bontozoglou (1991) argued that non-linear effects, which are not included in the majority of models, are also relevant in transition process. Indeed, Sanchis et al (2011) have shown a fast growth of fluctuations in the liquid level in the presence of nonlinear wave interactions. The mechanism would be responsible for fast initiation of slugs.

In the last decades numerical tools for simulation of two phase flows has experienced notable progress (Issa, 2003). Simulation tools are capable to predict flow transition, but they often fail in predicting the formation of hydrodynamic slugs. Simulation tools widely used commercially, such as OLGA ®, are still not capable to predict with reasonable accuracy the formation of hydrodynamic slugs (Sanchis et al. 2011).

Given the complexity of numerical simulation, it was difficult to define a single model that can be use for all operational flow conditions. So that, experimental data is the common alternative for theoretical and numerical models validations (see Sanchis, 2011 for a review). To this end, statistical data about the shedding frequency of slugs have been extensively used. For instance, the works Barnea and Taitel (1989), Barnea and Taitel (1993), Kadri et.al. (2009) and Sanchis (2011) did use such approach. Although, the slug statistics can be somehow influenced by the growth of disturbances that causes the slug initiation, it is not clear whether these disturbances are directly related to its shedding frequency. For a straightforward validation of models and simulations, it would be more convenient to have an experimental data base about the development of interfacial waves, since most of models are derived from stability analysis of well-defined disturbances. However, the set-up for such experiments is hard to implement and therefore it is not found in the literature.

The aim of the current work is to address this problem by introducing controlled waves at the interface of the liquid in a stratified gas-liquid flow. The disturbances are introduced near the pipe entrance and their evolution is analyzed for different mixture Froude numbers

2. EXPERIMENTAL SET-UP

A schematic view of the test rig used in the experiment is presented in Figure 1. The pipe line was fabricated from Fluorinated Ethylene Propylene (FEP) with internal diameter (D) of 0.0508 m and length (L) of 8m, yielding 150-diameter-long tube. FEP material has nearly the same refractive index as water providing reduced light scattering and allowing the liquid film visualization at regions very close to the pipe wall (Hewitt, et al., 1990).

Air was supplied to the test section by a centrifugal compressor with velocities up to 40 m/s. Superficial liquid velocities up to 0.5 m/s is provided by a progressive cavity pump. Air and water flow rates were measured using calibrated turbines, CONTECH® models SVTG G19 and SVTL L19, with experimental uncertainties estimated to be within 1% and 0.5%, respectively. Air and water were injected by special mixer designed using concepts employed in low turbulence water tunnel facilities (Wetzel and Arndt, 1994). The mixer was located at the inlet section of the tube. The flow conditioners are introduced downstream of the settling chamber in order to remove swirl and fluctuations of high amplitude. Further downstream a contraction with cubic shape, designed according to Wetzel and Arndt (1994), provides a smooth acceleration of both fluids toward the pipe inlet. At the end of the line, air–water mixture flow was directed to a high volume separator vessel from where fluctuations are damped. The water returned to the pump inlet, while the air was vented out of the laboratory space.

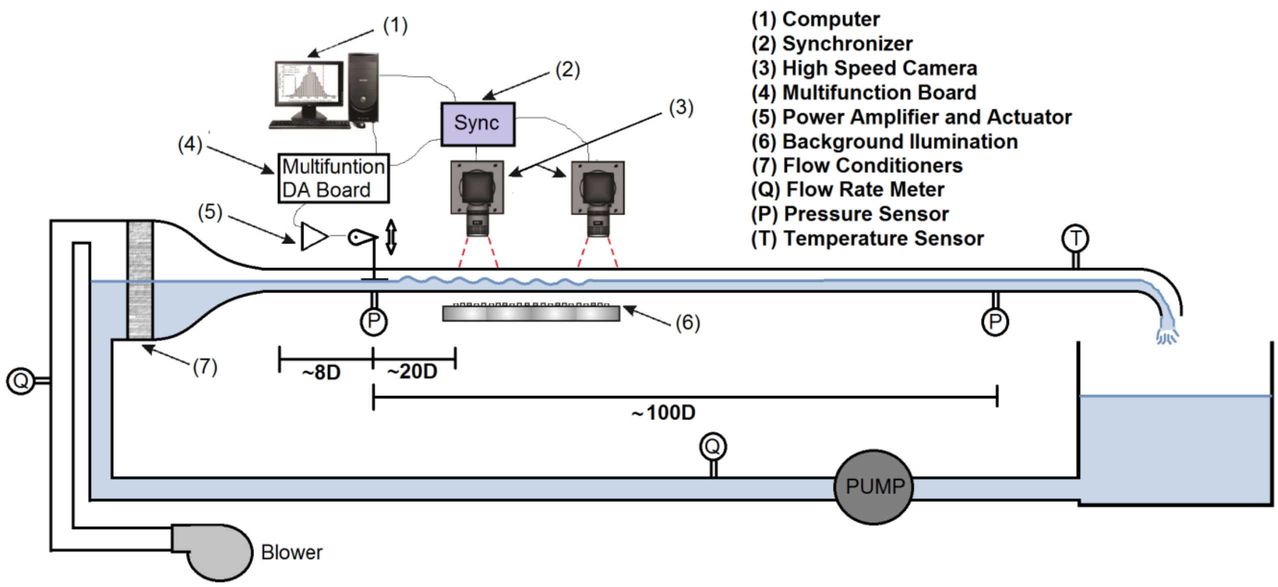

Figure 1: Schematic view of the test section.

Controlled disturbances are generated at the liquid-gas interface near the pipe entrance using an oscillating plate. At the interface the energy required to excite the disturbances in the liquid level is lower, hence the range of movement of the plate is reduced. Thereby, the disturbances are introduced mainly in the liquid level and not in the components of the base flow velocities.

A multifunction D/A board NI AT-MIO-16X was used to control the movement of the oscillating plate. This setup is capable to generate arbitrary waveforms. A power amplifier with unity gain was used to drive the actuator, that consists of a head positioning system of a common hard disk drive. The axis of rotation of the actuator was coupled to the knob of a radial potentiometer to monitor in real time the movement of the actuator and transform it into a displacement in mm. In present work, waves at frequencies of 4,6,8,10 and 12 Hz were generated by the controlled system implemented.

Images of the liquid film were captured using two IDT Motion Pro X3 high frame rate cameras with 1.3MPixels. Approximately 20 pipe diameters from the wave generation source, the cameras were mounted orthogonally to a high power white LEDs light sheet panel, which provide with proper contrast background illumination for image acquisition. A synchronizer BNC 575 allowed the synchronization between the generation of disturbances and the image acquisition. An image processing algorithm was developed to automatically detect the position of the air–water interface in each image frame.

3. IMAGE PROCESSING

Image processing techniques were employed to extract the liquid film height information from the set of captured images, as shown in Figure 2. Longitudinal images of the liquid film were captured using a high speed digital video camera synchronized with the signal of the actuator. The syncronization of the system allows for acquiring temporal and spatial evolution of the disturbances generated by the oscillating plate. This enabled to perform phase locked acquisitions.

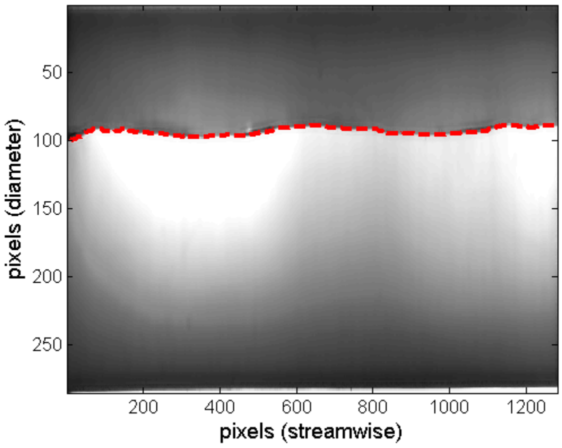

Figure 2- Example of interface detection on typical captured image.

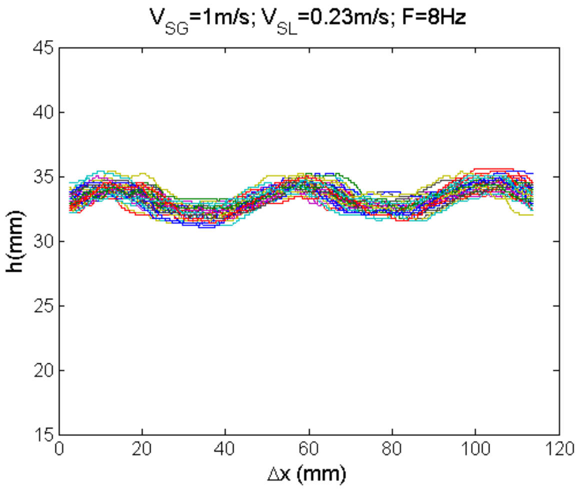

Figure 3- Example of interface detection from 60 different images.

Instantaneous images were pre-processed with the objective of enhancing contrast by an intensity histogram smoothing and equalization procedure. This procedure not only removes any bias that could have been introduced by differences in illumination intensity, but also facilitates the determination of the binarization threshold for identifying liquid-gas interface contours (see Gonzales, et al., 2009 for a review of the standard image processing routines).

A non-intrusive shadow technique based on the work of Nogueira et.al., 2003 was employed to provide time-resolved data of liquid heights. The technique relies on the acquisition of images with an intense and uniform background light that passes through the flow and is captured by a digital camera. At interface between the two fluids, the passage of light is attenuated, creating a shadow on the acquired image. In figure 2 a red thick line corresponding to the measured film height is overlaid on the original image in order to illustrate the accuracy of the interface detection. A calibration operation was necessary to convert from pixels to real dimensions. The edges of pipe were used as a reference. Before every set of measurements the calibrations were checked.

The synchronization between acquisition and disturbance generation is demonstrated in figure 3. The figure shows a set of contours obtained from 60 different images. An excellent agreement is found.

4. ASSESSMENT OF THE METHODOLOGY

In view of the very high sensitivity of wave development to the flow conditions, a series of preliminary tests were performed to assess the quality of the results obtained with the new test rig. This is an important part of the experiment, because the results must be reproducible for further comparisons with simulations and theoretical models.

One of most influent parameters on the development of the interfacial waves is the mean liquid level. Thus, this parameter must be kept accurately constant during the measurements. However, there is an inconvenient for maintaining the liquid height constant when waves are introduced in the flow. Depending on liquid and gas superficial velocities, waves can grow and initiate slugs downstream of the excitation location. Such slugs are capable to capture a high amount of liquid from the pipe as they propagate along the pipe. Therefore, even stations far upstream from the point of slug initiation can be considerably affected by its presence.

In order to avoid influence of slugs, the disturbances were introduced in the flow as wavetrains and not as continuous waves. Image acquisitions were synchronized with the central part of the wavetrain, where the waves display constant amplitude and spectral content. Blocks of only 20 images were collected per wavetrain at constant frame rate of 40Hz. Thereby, the acquired images would appear as a continuous movie if displayed in a sequence.

The time elapsed between consecutive wavetrains had to be long enough to enable a complete recovery of the base flow conditions even in the presence of slugs. Preliminary tests have shown that 30 seconds after the slug initiation the flow was completely recovered.

Prior to the measurements, it was necessary to define the minimum number of blocks required for convergence of wave statistics. At every repetition a block containing 20 images was acquired. This test was important to observe whether variations in flow conditions during the tests would avoid convergence of the results. First and second order statistical parameters were analyzed for increasingly higher number of acquired blocks and the results are presented in Figures 4 and 5. For this test, the liquid and the gas velocities were set to 0.21m/s and 1m/s, respectively, and the excitation frequency was set to 8HZ. The statistics were evaluated at three distances $\Delta X/D$=3.6, 5.4 and 7.2. According to the image reference frame these positions corresponds to 1000, 1500 and 2000pixels. The location $\Delta X/D$ equals to 0 corresponds to the first pixel of the first camera. The figures suggest a remarkable variation of the statistics when less than 50 repetitions are considered.

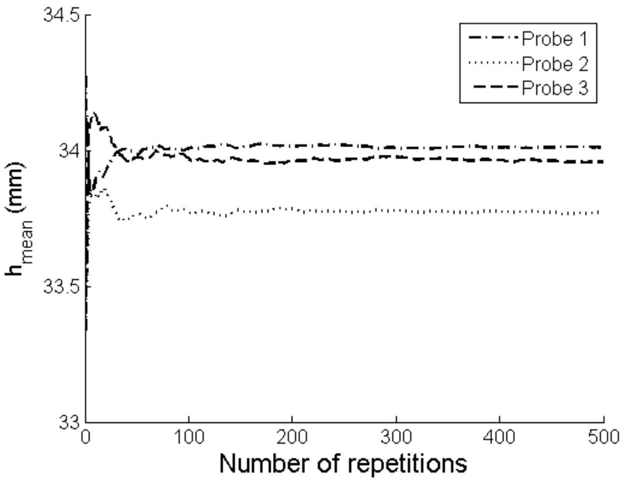

Figure 4- Convergence of the mean liquid height with the number of acquired images blocks.

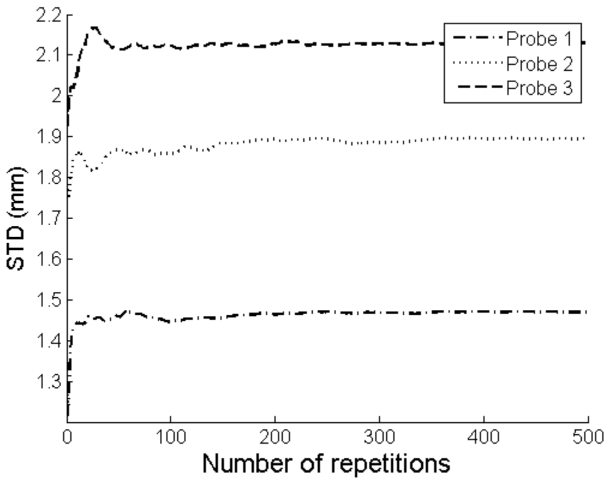

Figure 5- Convergence of the STD of the liquid height with the number of acquired images blocks.

In Figure 6, the RMS liquid height fluctuation is plotted as a function of the longitudinal image axis, for the same superficial liquid and gas velocities used in cases of figures 4 and 5. Since the distance between the cameras is a known parameter, the RMS of liquid height can be merged and presented in Figure 6 as unique graph. A convergence of data is seen when more than 32 blocks were considered. In summary, Figures 4, 5 and 6 present stable statistics when the number of blocks is higher than 80. Therefore, this value was considered as a reference and all further measurements were made with 80 blocks.

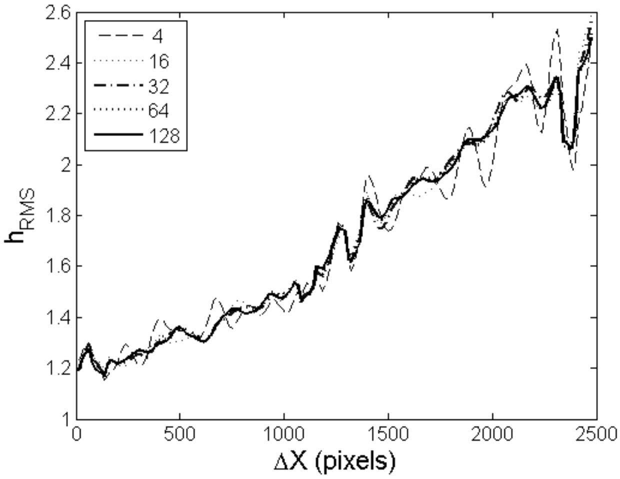

Figure 6- Convergence with the number of blocks of the evolution of the waves observed downstream from the excitation.

In view of sensitivity of the wave development to the flow conditions it was necessary to verify the reproducibility of amplification curves for different ambient conditions. This was tested by comparing experiments performed in different days. The results of the evolution of the waves are presented is Figure 7 for three different runs under fixed gas and liquid superficial velocities of 1m/s and 0.16m/s, respectively. The Figure 7 illustrates that all runs have the same amplification curve behavior and successful demonstrates that the experiment is reproducible.

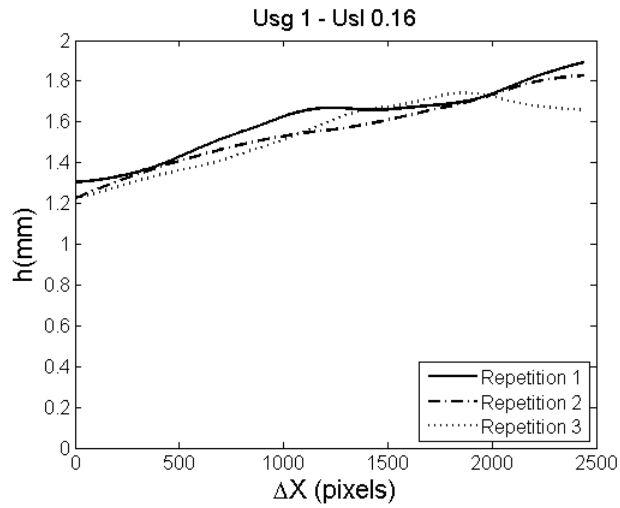

Figure 7- Liquid height measurements tests performed in different days. Reproducibility of amplification rate checked for fixed frequency of excitation 8Hz and liquid and gas superficial velocity of 0.16 and 1m/s.

In order to evaluate the behaviour of measured waves with respect to theoretical predictions, amplification rates given by linear stability calculations were considered and the results are depicted in Figure 8. The model used is based on the Kelvin-Helmholtz Viscous Linear Stability described in the work of Barnea and Taitel (1993). Although it is not clear how accurate such models predictions can be, it is expected that it might roughly reflect the behavior of the disturbances. According to the figure, the model predictions show that within a range from 0.01 to 14Hz, there is no variation of the amplification rates. In addition within this a range all waves are unstable and are expected to be amplified. These considerations are valid only for superficial liquid and gas velocities equals to 0.16 and 1m/s respectively.

The experimental results of Figure 9, show the amplitude evolution of the excited interfacial waves along the streamwise direction. Frequencies of 4, 6, 8, 10 and 12Hz were analyzed for a fixed pair of liquid and gas flow velocities. A significant change in the evolution of the disturbances was observed for increasingly higher frequencies of excitation. Waves with frequencies of 4, 6 and 8Hz have a noticeable amplification behaviour, while the wave excited at 10 and 12Hz were damped. Although, the model predicts amplification of disturbances up to 14Hz, it can be seen that most inner frequencies within the unstable area of Figure 8, are at the same range of the most amplified waves observed in the experiments. This result shows a rough agreement between model predictions and experiments.

The methodology adopted in the current work seems promising as a tool for exploring the physics of transition from stratified to slug flow regime under controlled conditions.

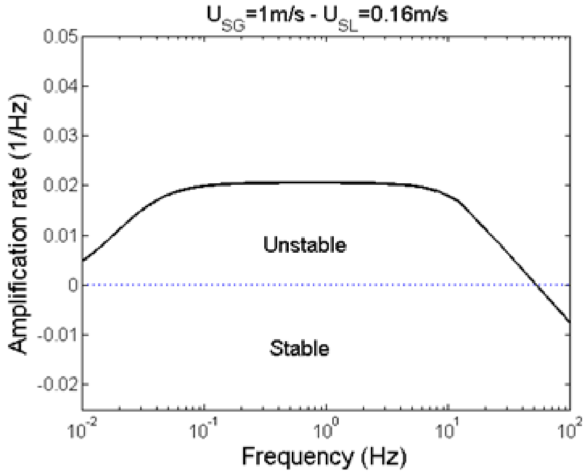

Figure 8- Theoretical amplification rates for waves at different liquid velocities and a fixed gas velocity.

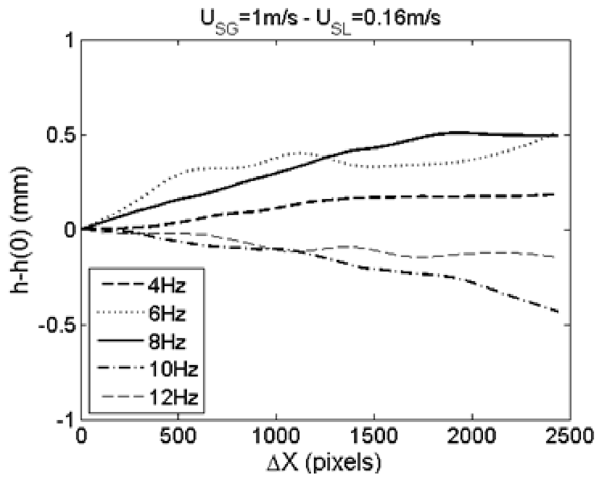

Figure 9- Evolution along the streamwise direction of the amplitude of waves at different frequencies.

5. INFLUENCE OF DISTURBANCES ON THE TRANSITTION FROM STRATIFIED TO SLUG FLOW

Due to the complexity of the problem it is, indeed, very difficult to establish a unique model which can be used for a wide range of flow parameters. From a literature survey, one can observe that several models and empirical correlations are available for the predicting flow regimes in two phase pipe flows (Wallis & Dobson 1973, Mandhane et.al 1974, Lin & Hanratty 1986,Barnea & Taitel 1993, Kadri et. al 2009). Typically, maps of flow regimes were presented in those papers as a quick guide for identification of flow regime. However, close to the transition of regimes, specially the transition from stratified to slug flow, significant variation of the transition limits for stratified and intermittent flow regimes can be observed. A comparison between experimental results from different test rigs often do also display discrepancies. The reason for such discrepancies is controversy and motivated the development of many models. The development of theoretical models often involves stability calculations. For the estimation of the stability of two phase flows two main approaches are be found in the literature, one that use the variation of energy of the disturbed flow and other based on classical linear stability analysis using normal modes.

The sketch shown in Figure 10, illustrate how the definition of critical Reynolds numbers can affect the interpretation of flow instability. This figure is merely illustrative and a similar sketch can be found in many books, e.g. Schmid & Henningson (2001). According to the figure, the region I, which is below all critical Reynolds numbers is stable and all disturbances would decay monotonically. The right end of this region is defined by a critical Reynolds given by energy approach (Re_E). Between Re_E, and Re_G there is a region II where disturbances can grow for a while, but for infinitely long time they would decay. Thus, disturbances are stable independently of their initial energy (E_0). The right end of this region is delimited by the critical Reynolds given by global stability analysis (Re_G). For Reynolds numbers higher than Re_G the disturbances can either be damped (region III) or be amplified (region IV) according to their initial energy. Above the critical Reynolds given by linear stability calculations (Re_L) even infinitesimal waves are unstable and might exhibit amplification. The situations described by the figure have been already observed for many canonical flows such as Hagen-Poiseuille, Plane Couette and others (see Schmid & Henningson).

A picture similar to Figure 11 has not yet been observed for stratified flow. Thus, a very simple test case was designed in order to examine the influence of initial disturbances on the slug initiation. In this test, the transition conditions were detected in two situations, one with the source switched off and other with disturbances of high amplitude being introduced in the flow. Since the most unstable frequencies were, in principle, not known for the different velocities, it was chosen to introduce a very short wavepacket. This kind of wavepackets have a rich spectral content, therefore fluctuations in a broad range of frequencies were excited with high initial amplitude. In Figure 11, the transition points observed here are compared against the map given by Mandhane et. al. (1974) and the linear stability predictions given by the model of Barnea & Taitel (1993).

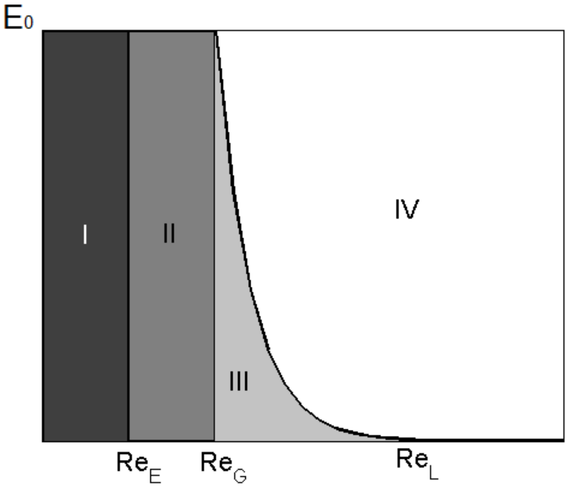

Figure 10- Theoretical amplification rates for waves at different liquid velocities and a fixed gas velocity

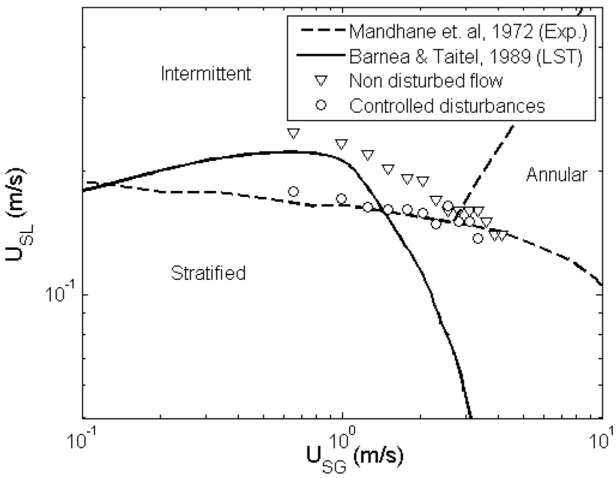

Figure 11- Evolution along the streamwise direction of the amplitude of waves at different frequencies

The map found in Mandhane's work, was based on an experimental database from different apparatus. None of the test rigs selected by Mandhane have a specially designed section for mixture of gas and liquid aiming at the reduction disturbances at the pipe inlet. Therefore very energetic fluctuations are expected to be present in such cases. On the other hand, Barnea & Taitel have developed a model based on Linear Stability Theory (LST), which predicts the onset of instability for infinitesimal disturbances. Surprisingly the experimental results obtained here, fits very nicely to Mandhane's map when the flow was disturbed, and approach the LST predictions for non-disturbed flow. This picture is very similar to the sketch of Figure 10. For high gas velocities the disturbances generated by shear at the interface are so strong that is impossible to have a condition of non disturbed flow. This is the reason why the experimental points merge at high gas velocities.

From a practical point of view, the results of Figures 10 e 11 suggests the use of Mandhane's criteria for a conservative prediction of slug initiation. If flow conditioners are used at the inlet, then criteria of Barnea and Taitel is more suitable.

6. CONCLUSIONS

The concepts of shadow technique, controlled disturbances and phase locked image acquisitions were applied to investigate the instability of stratified flow in regimes close to the transition to slug flow. The work focused on the assessment of a methodology adopted to measure the evolution of disturbances at gas-liquid interface in a horizontal pipe.

A set-up was developed to introduce controlled disturbances in the flow. Phase locked acquisitions were performed and ensemble average techniques were employed to measure the fluctuations in the liquid level. The results show a very reproducible evolution of the excited waves. The experimental findings were compared with model predictions given by Barnea and Taitel (1993) and a qualitative agreement was found. Measurements were also carried out close to the transition from stratified to intermittent flow. Cases with and without excitation of disturbances were observed. For low superficial gas velocities it could be seen a significant influence of the disturbances on the reduction of the critical liquid velocity for initiation of slugs. On the other hand, for high gas velocities, the interfacial waves generated by shear were so high that slugs were initiated independently of the disturbances introduced in the flow. Moreover, transitions of non disturbed cases are in agreement agrees with predictions given by linear stability theory, while disturbed cases are in closer agreement with maps based on experimental databases. Thus, in practical situations, with non-controlled disturbances at the inlet, it might be interesting to consider maps based on experimental findings for a more conservative prediction of slug initiation.

7. ACKNOWLEDGEMENTS

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