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Experiments on Roll Waves in Air-Water Pipe Flow

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Abstract

Experiments on air-water two phase flow in inclined pipes have been made, with emphasis on the roll wave regime. The motivation for the work is the improving of 1D flow models for multiphase pipeline transport of oil and gas mixtures. Pressure and liquid fractions are recorded in time, together with video recordings. The results show that large amplitude roll waves have associated pressure jumps across the fronts. Some implications for the flow modelling are discussed.

Introduction

Multiphase flow simulators are very important tools for the design and operation of sub-sea pipelines carrying mixtures of oil and gas from wells to a processing facility on a floater, or onshore. Design considerations include both steady operation (pressure drop, liquid content, temperatures) and dynamic flow conditions (operational transients, unstable flows). The basic flow models in these simulators are one dimensional, and as the closure relations cover averaged physical phenomena (averaged wall friction, interface drag, cross sectional phase distribution etc.) they are normally empirically determined. Experimental data at realistic flow conditions then become an important basis for the modelling work.

Flow with large amplitude roll waves is a regime which occurs in gas condensate pipelines, in particular for high pressure systems (high gas densities). Although this regime has some similarities with slug flow, it is often treated as averaged stratified flow in the flow models.

In slug flow, liquid slugs block the pipe cross section and the slug lengths normally exceed 10 number of diameters. The slugs carry the major part of the liquid transport and they propagate faster than the total mixture velocity. The slug fronts propagate over a liquid layer, which is absorbed and accelerated to the liquid velocity in the slug front. Liquid is then shed at the tail of the slugs (which has the form of a bubble nose), and decelerated as the trailing bubble propagates over it.

Some similarities can be noted for flows with large amplitude roll waves. The waves have sharp propagating fronts overrunning a liquid layer. The liquid layer behind a wave can decelerate from a larger velocity in the wave, see Figure 1 for schematic drawings.

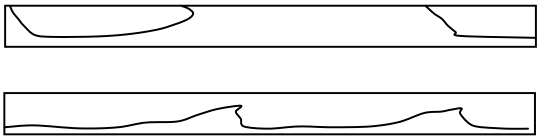

Figure 1. Sketch of a slug (top) and large amplitude waves (bottom)

Typical differences between the two flow regimes are the length scales (waves are in the order of a few diameters long) and the front velocities (waves propagate much slower than slugs). The wave regime is also more irregular, with larger spread in velocities and amplitudes. Waves can be seen to collapse and to merge with other waves, and the roll wave regime can indeed be speculated to be a transitional regime towards slug flow.

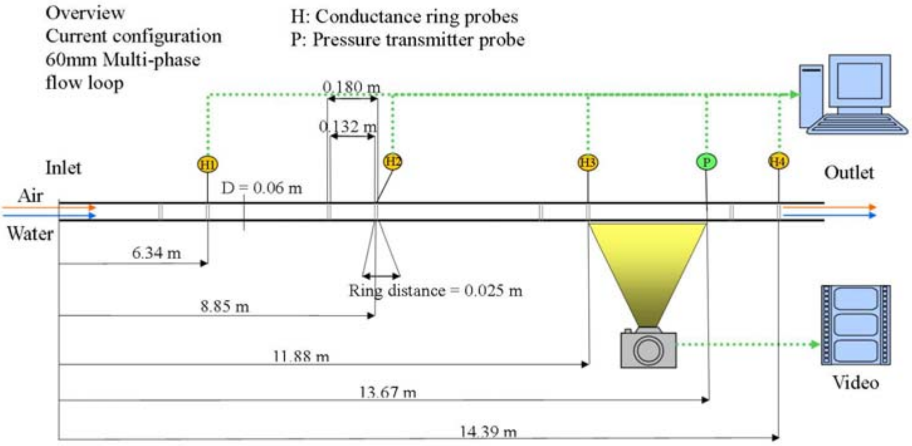

Figure 2. Location of liquid fraction probes, pressure sensor video and camera

Objectives

The objective of the work is to measure some characteristics of roll waves: pressures, amplitudes and propagation velocities. Some experimental studies have been made on roll waves before (10 cm internal diameter (I.D.) high gas densities, [1]). The added value of the present experiments will be the pressure response of individual waves, which is information lacking in most other previous experimental studies [1, 2, 3, 4, 5, 6]. An atmospheric flow loop with air and water is available for the experiments.

Experiments

Flow loop and instrumentation

The flow laboratory is located at the Norwegian University of Science and Technology. The experiments were made in a 16 m long acrylic pipe of 6 cm I.D. Pipe inclinations varied in the range of -1 to 3 degrees with the horizontal. The loop pressure was atmospheric.

The single phase flow rates are measured with electromagnetic meters (water) and vortex meters (air). The liquid fraction is recorded in time with impedance ring probes at 4 locations along the pipe, see Figure 2 and 3. Pressure is recorded with an absolute sensor located close to the last liquid fraction probe.

A video camera was used to monitor the flow at the position of the pressure sensor. The video has a time stamp, making it possible to identify the video picture of a wave with the time recordings of pressure and liquid fraction.

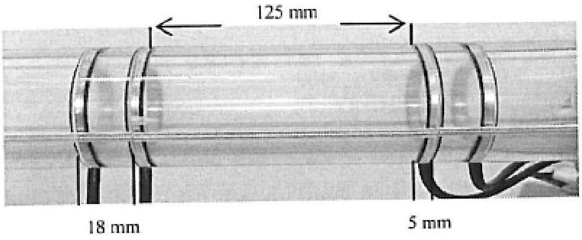

Figure 3. Image of internal flush mounted conductance ring probes for liquid fraction measurement. 6 cm I.D.

Experimental Procedure and Data Analysis

Qualitative observations were first made over quite a large range of air and water flow rates and pipe inclinations in search of the occurrence of roll waves at low frequencies. When several waves or slugs are present at the same time in the pipe, it becomes difficult to interpret the dynamics of the pressure recordings.
After the initial screening, measurements and video recordings were made at selected flow conditions.

The time trace analysis should provide velocities and amplitudes of liquid fractions and pressures variations relative to each wave phenomenon. Automatic data analysis for this purpose turned out to be difficult, because waves could decay or emerge in between the liquid fraction sensors, making the time traces non-coherent between the probes.

A simple first analysis was made by obtaining an averaged wave velocity from cross correlating the liquid fraction time traces from the four probes, giving three velocity measurements. The averaged amplitudes were taken as the 95% percentile value in the statistical distributions of all pressure and liquid fraction samples in a time series.

Results

The typical differences between a case with slug flow and a case with wavy flow are shown in Figures 4-6. The time traces have been shifted in time according to the cross correlation time, so that the waves should appear at the same location in the time plots. Usg and Usl are the superficial velocities of gas and liquid (volumetric flow rate pr. pipe area).

Overlapped liquid fraction time traces and the pressure time trace are matched to the corresponding video snapshot for an individual wave in Figure 6. The experiment has a cross correlated wave velocity of 1.86 m/s, a 95% percentile pressure value of 0.014 bar, and a 95% percentile liquid fraction of 0.28 from liquid fraction time trace 4. The individual wave moves with a velocity of 1.67 m/s, it has a peak pressure of 0.027 bar, and a peak liquid fraction of 0.32 in time trace 4.

The slug and the wave time traces have similarities with sharp fronts and a decaying tail. It can be difficult from liquid fraction time traces alone to discriminate between liquid waves and aerated slugs, so the synchronised video pictures were useful in the identification of the type of the phenomena which was recorded. The time traces in Figure 4 and 5 are predominantly waves and slugs. Other flow conditions could show a mixture of waves and slugs, making the averaged time trace analysis more uncertain.

Slugs travel faster than waves. Figure 7 shows the velocities from the cross correlations as function of total volumetric flow rates. Slug velocities increase with the flow rates, whereas the trends for the wave velocities are less clear.

Slugs exhibit a strong pressure jump across the liquid-gas front. The interesting results here is that waves also can show a pressure jump, although of a smaller magnitude than for slugs, Figure 8.

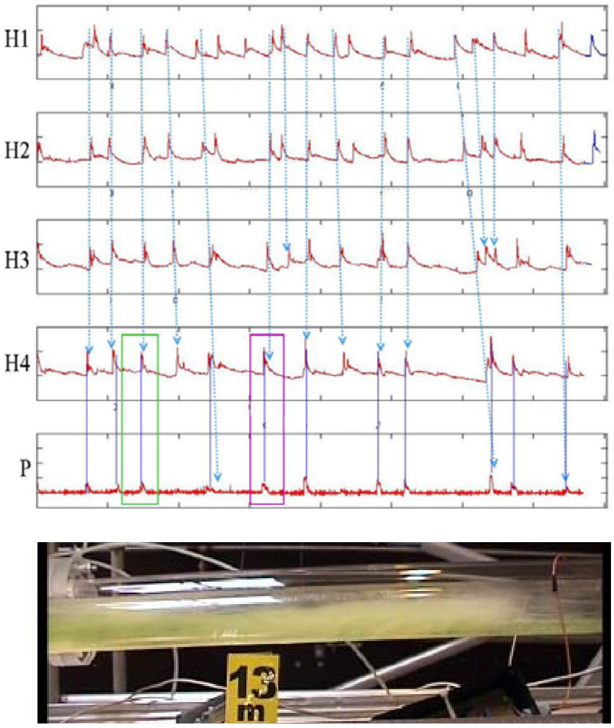

Figure 4. Time traces of liquid fraction probes (no. 1 at the top) and of pressure in bar (at the bottom). 1 degree upwards pipe inclination, Usg = 4.34 m/s and Usl = 0.13 m/s. The video snap shot is for the wave enclosed in the first rectangle (green).

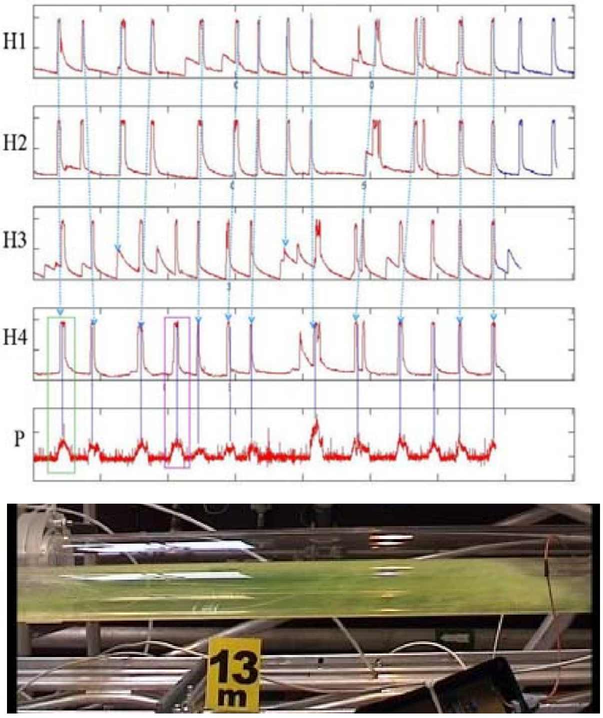

Figure 5. Time traces of liquid fraction probes (no. 1 at the top) and of pressure in bar (at the bottom). 0 degrees pipe inclination, Usg = 1.53 m/s and Usl = 0.34 m/s. The video snap shot is for the wave enclosed in the first rectangle (green).

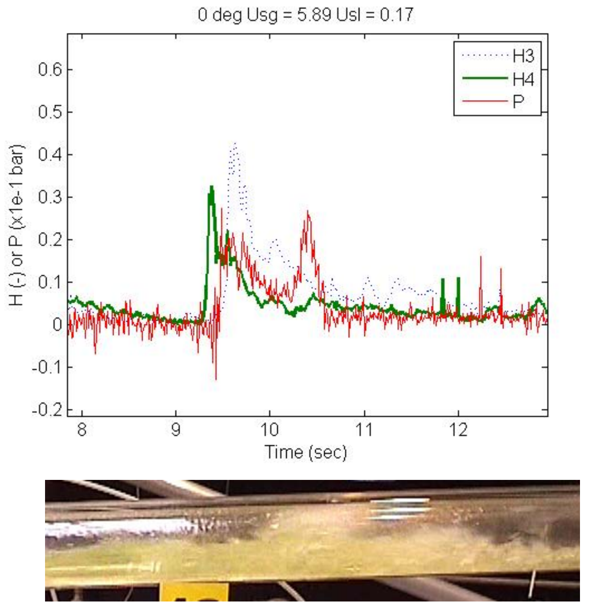

Figure 6: Overlapped signals for liquid fraction time trace 3 and 4 and the pressure time trace and the matching video snapshot for the 0 degrees, Usg = 5.89 m/s and Usl = 0.17 m/s. The pressure signal is multiplied by a factor of 10 so that it can be seen on the same plot as the liquid fraction.

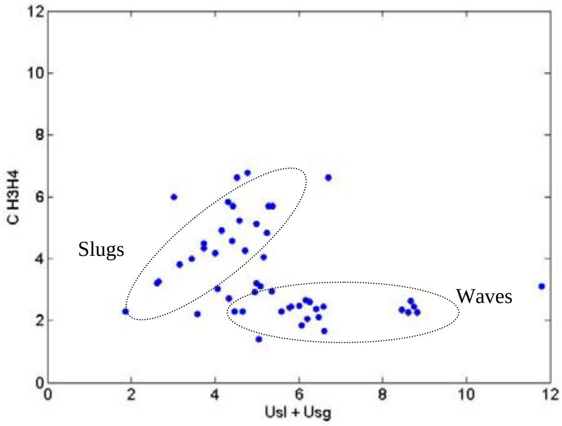

Figure 7: Velocities from cross correlation of time traces no. 3 and 4.

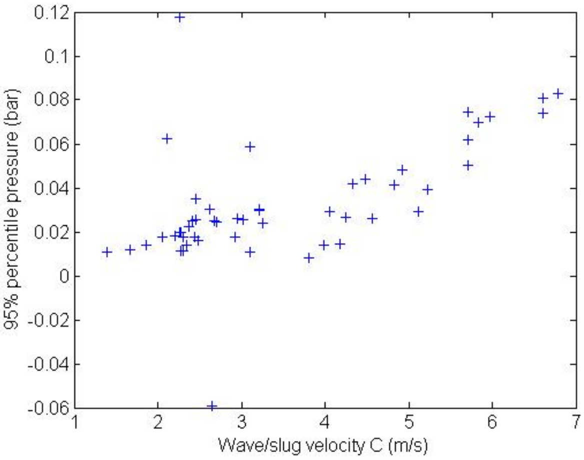

Figure 8: 95% percentile pressure in bar vs. the cross correlated disturbance velocity between liquid fraction time trace 3 and 4 in m/s for all experiments. Experiments with both waves and slugs are included in the plot.

Flow Models

On the length scale of a pipe diameter, slug flow and wavy flow appears as dynamic flows, with time fluctuations in the flow parameters. General 1D models can be solved numerically on a small grid, in order to capture the dynamics of individual slugs. This has been demonstrated using a two fluid model, with a set of conservation equations for both phases [7,8]. Such models are, however, very sensitive to the numerical scheme, and the computational times are prohibitive for simulation of long two phase flow pipelines.

Alternative schemes bases on slug tracking instead of capturing have been tested [9]. These schemes employ a grid moving with the fronts, allowing for computations with orders of magnitudes less grid points than with an Eulerian front capturing scheme. The grid velocities in such tracking schemes are the characteristic bubble propagation velocity in slug flow and the front velocities, as derived from mass balances across the fronts.

For simulation of long pipelines with lengths in the order of 10 or 100 kilometers, the small scale dynamics of slug flow is often of less importance, and slug flow is then treated as a quasi stationary flow, with averaged pressure drop and liquid fraction over several slug-bubble units. The numerical grid in such simulations would typically be much larger than slug-bubble units, and the dynamics of such simulations would typically be on pipeline scales (transport times and riser lengths) and not on diameter scales. Quasi steady state slug flow models "unit cell models" can be formulated as a combination of models for bubbly flow in the slug region and separated flow in the bubble region, with the two regions coupled with mass balances for gas and liquid [10]. Such "unit cell models" can be solved as a point model, and integrated into dynamic simulators for resolving the large scale dynamics.

Wavy flows

Wavy flow is often modelled as averaged separated flow, assuming flat interface geometry, and with empirically tuned wall and interface friction relations. This is probably a reasonable approach when the waves are small. For the roll wave regime, with breaking waves and significant liquid transport in the waves, the question is whether improvements can be made along the modelling lines similar as for slug flow.

As for slug flow, it has been demonstrated that numerical schemes can be designed to capture formation and propagation [8] of large amplitude waves. Point models have also been derived for the roll wave regime, based on the combination of discontinuous numerical solutions of the set of momentum and mass conservation equations for gas and liquid [1].

The present experiments have shown that a pressure jump over the waves constitutes a large part of the pressure drop in large amplitude wavy flows. This could suggest a modelling approach along similar lines as for slug flow, including both "unit cell" point models as well as dynamic tracking models. An integral wave model is then needed, providing in particular relations for the wave velocity, wave amplitude and pressure drop across the wave. The present experimental data needs further analysis to extract single wave data as a basis for the further modelling considerations.

Conclusions

Experiments have been made with air-water, near horizontal pipe flows in order to measure details in the pressure response related to large amplitude waves.

Time trace recordings of four liquid fraction probes and one pressure sensor, together with synchronised video recordings, show that large amplitude roll waves are associated with a pressure jump.

This suggests that further modelling efforts of roll waves could be made along similar lines as for slug flow, both regarding steady state and dynamic models.

Acknowledgments

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