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Characteristics of flowrate transients in slug flow

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Abstract

A study of the effect of flowrate transients within the slug flow regime was carried out in the WASP Facility at Imperial College. The test section consisted of a 36 m long, nominal 3-inch diameter stainless steel pipe. Air and water were used as the test fluids and the response to a change for flowrate of either phase was measured using a series of conductivity probes, pressure transducers and a gamma densitometer.

When the gas flowrate was increased, the pressure was found to peak above the new steady state value before recovering. In addition, a temporary period of intense slugging was observed, particularly at higher liquid superficial velocity, as well as a decrease in holdup. When the gas flowrate was decreased, a rarefaction in the inlet pressure was observed together with a period of stratified flow, even though conditions were such as to cause slug flow in both the initial and final steady states. The period of stratified flow was observed to be longer for lower liquid flowrates. For an increase or a decrease in the gas flowrate, the amplitude of the pressure peak was observed to increase with the ratio of the higher to the lower gas flowrate. In contrast, changes in liquid flowrate were accommodated by smooth transitions between the corresponding steady states. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Two-phase slug flow; Intermittent flow; Flowrate transients; Slug growth and decay

1. Introduction

Slug flow is an area of crucial industrial significance as a great number of multiphase transport lines are operated in this flow regime. Understanding of multiphase flow is essential in addressing key operational and safety issues relating to offshore developments. For steady state operations, parameters such as holdup and pressure gradient are important whereas under transient conditions, an understanding of additional parameters such as maximum slug length and peak pressure is also required. Transient conditions include operational upsets, start-up, shut-down, pigging and blowdown. This study looks at the effect of a step change in one of the

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flowrates for a pipe operated in the slug flow regime, the flowrate change being such that the new steady state is also in the slug flow regime (although a regime change can occur *during* the transient).

The effects of flowrate transients in horizontal pipes have been studied for a number of years. Probably the first study was that of Sakaguchi et al. (1973) who looked, in particular, at the formation of slugs in flowrate transients between two stratified flow steady states. A more detailed study was conducted by Taitel et al. (1978) who considered flowrate transients in a 38.1 mm internal diameter pipe using air and water. Their experimental results were compared with a simplified transient model using a quasi-steady state assumption for the behaviour of the gas phase. The model provided a good prediction of the appearance of ephemeral flow patterns in fast transients. For instance, it was able to predict the appearance of a smooth stratified flow between an initial steady state characterising an annular flow and a final steady state corresponding to intermittent flow.

More recently, the interest in flowrate transients has been spurred by the development and validation of transient computer codes based on either a drift-flux or separated flow model. Caussade et al. (1987) conducted experiments in an 89.9 m long pipeline of 53 mm internal diameter using air and water as the test fluids. Void fractions and pressures were recorded at five locations along the test section. The experiments were conducted within the slug flow regime with a total of seven steady state points used. All the flowrate transients were averaged over ensembles of between 70 and 200 step changes and were planned so the total variation in void fraction between the initial and final steady states was less than 10%. The results presented showed the propagation of both pressure and holdup waves along the pipe. For the gas flow transients, a pressure overshoot beyond the value of the new steady state was observed at the entrance to the test section, but was not apparent in the exit pressure. For liquid flowrate transients, the pressure was observed to change smoothly between the old and new steady states.

Minami (1991) conducted experiments on flowrate transients using air and kerosene in a 3-inch diameter pipeline of 420 m length operated in the slug flow regime. The exit pressure for this set of experiments was set at 2 bar. Time averaged values were obtained which resulted in the loss of detailed information on the local flow structure. From the results presented it is possible to identify an overshoot in the inlet pressure of around 30 kPa for an increasing gas flowrate transient. This was associated with an increased liquid discharge rate corresponding to a period of intense slugging and the new steady state took around 500 s to establish itself. In the case of a decreasing gas transient, the pressure undershoot below the new steady state was around 25 kPa and the liquid build-up in the separator appears to be consistent with the existence of a period of stratified flow. Liquid transients again exhibit no unusual features; the pressure rise to the new steady state appears smooth and asymptotic. The slug flow isograms presented for the same facility by Scott and Kouba (1990) indicate that the slug flows used for this series of experiments had a low slug frequency and were close to the stratified transition boundary.

De Henau (1992) used the transient data of Théron (1989) which was reported in Caussade et al. (1987) for comparison with his two-fluid model. No new data on flowrate transients in slug flow were collected for his work. Fabre et al. (1995) used the same facility as Théron (1989) to look further into this area, specifically to obtain validation data for the tracking of pressure and void waves in a drift flux model. Taking the ensemble-averaged results, the void wave propagating along the system can be identified as shape-conservative and moving at constant velocity but it is not possible to identify this wave from a single trace. Fabre et al. (1995) characterise this wave as a perturbation of the slug flow structure. In contrast, the pressure wave is identifiable from a single trace and attenuates severely along the pipe, being barely discernible near the pipe exit.

Finally, King et al. (1996) presented preliminary findings for flowrate transients within the slug flow regime in WASP, the experimental facility described in Section 2. They concluded that gas transients exhibit pressure and holdup effects and that decreasing gas transients caused the temporary formation of a stratified flow. Liquid transients caused changes in slug frequency with smooth pressure changes between the steady states. They also considered the effect of an upstream compressible volume on the duration of the transient response and concluded that the greater the volume, the more damped the response.

Present work has considered the large-scale (Minami, 1991) or ensemble-averaged (Fabre et al. 1995) response of a slug flow to inlet flowrate changes. In the experiments reported here, we have observed the response of individual slugs to flowrate changes using a series of conductivity probes along the test section. This allowed a detailed study of the growth and collapse of individual slugs under transient conditions to be undertaken.

This paper continues in Section 2 with a description of the experimental facility used for the present series of experiments, the High Pressure WASP Facility at Imperial College. The experimental results are then described in Section 3. The main set of experiments includes all four types of flowrate transient (increasing gas, decreasing gas, increasing liquid and decreasing liquid) and two subsidiary sets of experiments. The first of these considers the reproducibility of the results over a limited ensemble average. The second set considers gas flow transients with very high liquid flowrates to further investigate the mechanisms occurring in a transient slug flow. Conclusions drawn from the experiments are summarised in the final section.

2. Experimental method

The results presented in this paper were collected on the established WASP rig located in the Department of Chemical Engineering and Chemical Technology at Imperial College. The test section is a 36 m long inclineable stainless steel pipe of 3-inch nominal bore (77.92 mm) and is capable of carrying air-oil-water flows at pressures up to 30 bar. It consists of a number of 7 m sections supported at multiple locations to ensure that the deviations from horizontal are kept to a minimum. For the experiments presented, the rig was limited to air-water flow in a horizontal configuration with atmospheric pressure at the exit of the test section. A schematic diagram of the facility is shown in Fig. 1.

Water was supplied from a dedicated 5000 l tank and then passed through a centrifugal pump and a water flowmeter before entering the mixer section. The air came from 65 m^3 of storage tanks kept at 30 bar. The air, having been dried and cleaned of impurities, was metered with an orifice plate before entering the test section through the mixer. To ensure an initially stratified configuration, the mixer unit consisted of a horizontal plate with the gas introduced above and the liquid below, as illustrated in Fig. 2. At the downstream end of the test section

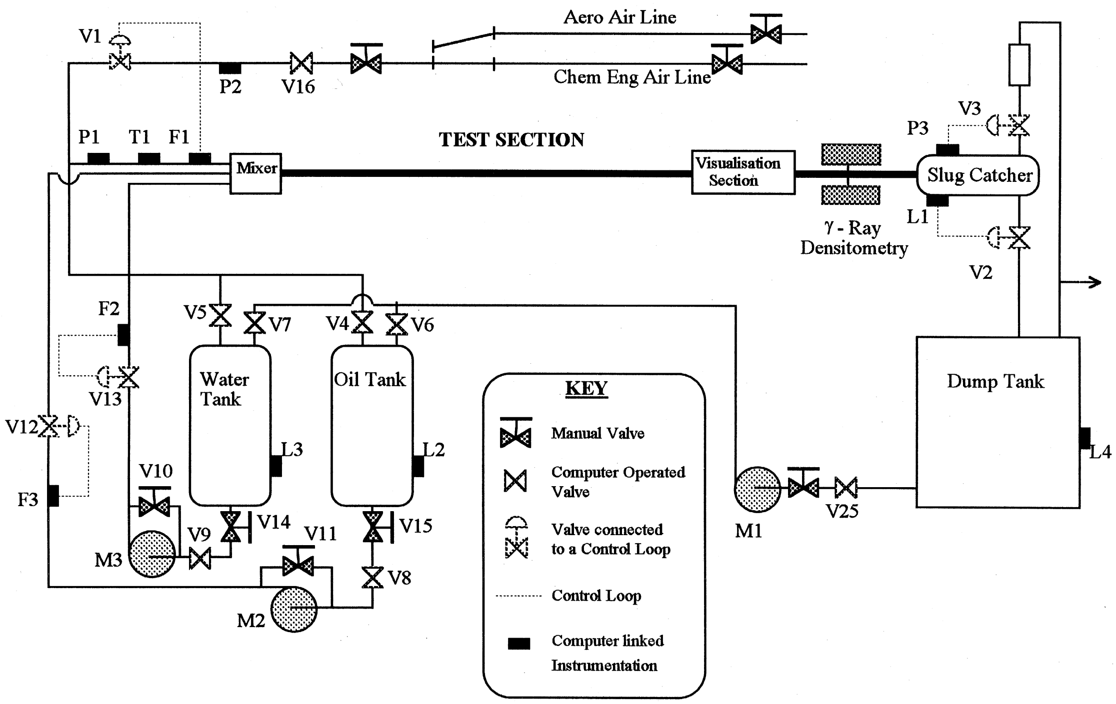

Fig. 1. Schematic of the WASP facility.

the flow passed into a slug catcher. This specially designed pressure vessel consisted of a series of welded annular rings onto which baffles were bolted to break up the slugs. The slug catcher also provided primary separation of the phases, with the gas leaving from the top into a silencer and was vented to atmosphere. The liquid was drained into the dump tank from which it was eventually pumped back to the water tank.

The rig was extensively instrumented with a series of conductivity probes located along the test section. These were located 7.2 m, 14.4 m, 20.5 m, 27.7 m and 28.3 m downstream of the mixer; each consisted of two vertical platinum wires of 0.5 mm diameter spaced 2 mm apart located symmetrically about the pipe axis. Calibration of these probes was performed by filling the test section to a known liquid height and sampling the probe output over 3 min. This was repeated twelve times for different liquid heights from completely full to completely empty. In addition to these probes, a number of pressure transducers were located along the pipe. Absolute pressure transducers were positioned before the air orifice plate, and 0.5 m and 36 m downstream of the mixer. A differential pressure transducer measured the pressure difference between points at 31 m and 33 m downstream of the mixer. The instrumentation also included a video camera at the visualisation section 33.5 m downstream of the mixer and a gamma densitometer at 35 m. The gamma beam was aligned vertically through the pipe centre.

The rig was fully automated with the control valves interfaced via an ANDS 4400 control unit to a flow sheet mimic on a Personal Computer. Information concerning flowrates, pressures and liquid levels was displayed on the screen. This allowed the flowrate transients to be actuated in a systematic and reproducible manner. To minimise upstream compressibility

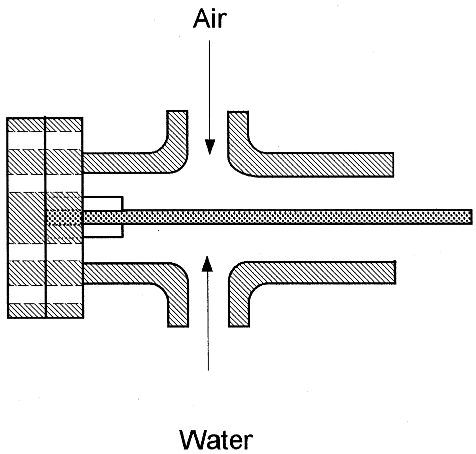

Fig. 2. Cross section of the mixer plate at the entrance to the test section.

effects on the gas flowrate transients, the gas flow was choked through the main air control valve (see valve V1 on Fig. 1) prior to being metered by the air orifice plate. This is an important point, as large upstream compressible volumes tend to damp out the effect of flowrate transients (King et al., 1996).

The experimental run commenced with the establishment of a steady state slug flow for 4 min before the flowrate change was initiated using the control computer. The system response to the transient was then monitored for a further 6 min before the next experimental run was set up. During the run, all their instrumentation was monitored; the conductivity probes were sampled at 500 Hz to allow accurate determination of the slug profiles, the gamma densitometer output was counted over successive periods of 40 ms and pressures and flowrates were recorded every 2.5 s. A typical (10 min) experimental run resulted in around 2,500,000 data points.

The parameter values investigated corresponded to

Liquid superficial velocity	0.4, 0.6, 0.8, 1.0 m/s
Gas superficial velocity	4, 6, 8, 10 m/s

This gave a total of sixteen steady state points and the capacity to perform 24 transients of each of the four types: "Up-gas", "Down-gas", "Up-liquid" and "Down-liquid".

A flow pattern map for the system is shown in Fig. 3 along with arrows denoting the flowrate transients described in Section 3 and the flow pattern transition predicted by the model of Taitel and Dukler (1976). The transition line for the stratified-slug transition agrees well with the experimental data but the slug-annular transition does not. The flow pattern map demonstrates that the steady state flows considered in this paper are all well within the slug flow regime. As was noted by Nydal et al. (1992), fully developed slug flow takes a considerable length of pipe to become established. This entrance length is a function of both the superficial liquid and superficial gas velocities. Fully developed flow exits in WASP for the

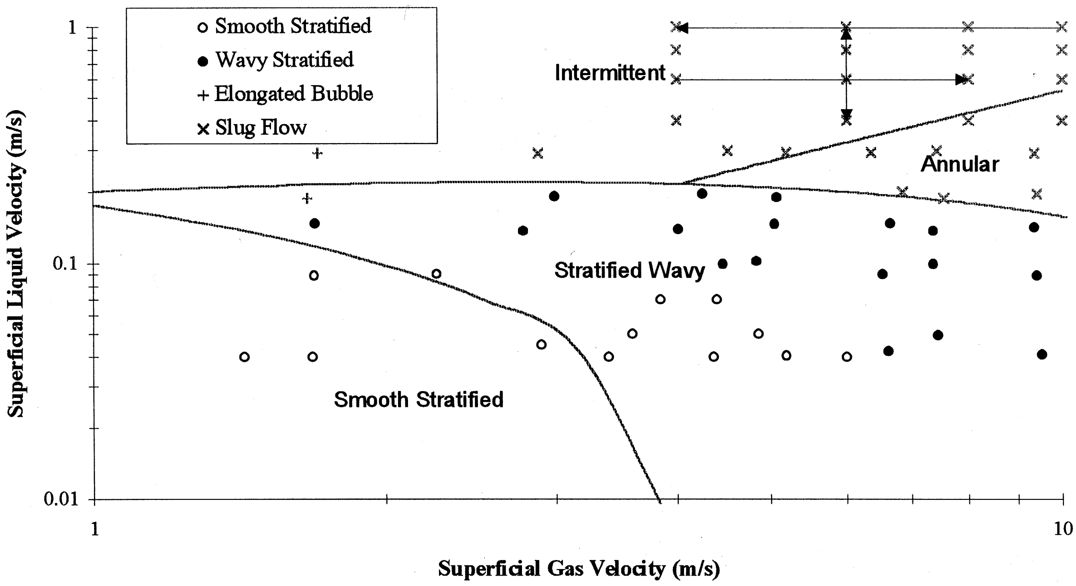

Fig. 3. A horizontal flow pattern map for the WASP facility at atmospheric pressure. The lines denote transitions calculated using the model of Taitel and Dukler (1976). Arrows denote the flowrate transients reported from the main block of experiments.

majority of the steady states considered in this set of experiments, although for some flowrate combinations this is not necessarily true. In the latter cases the flow is developing along the entire length of the test section.

In addition to this systematic test matrix, two further studies were performed. The first repeated a series of up and down gas transients ten times. This was to investigate the effect of the location of the slugs within the pipe on the phenomena observed. This series of experiments was carried out with a superficial liquid velocity of 0.8 m/s and the gas transients performed were

Increasing gas transients	4→6, 4→8, 4→10 m/s
Decreasing gas transients	10→4, 10→6 10→8 m/s

As this was intended to replicate experiments performed in the first set, all sixty of the runs were performed exactly as described above.

The second extension was to perform the limited experimental gas transient matrix (given above) at higher liquid flowrates. The liquid flowrates chosen were 1.5 m/s and 2 m/s. The steady state flow patterns for all these runs were in the slug flow regime. This was to further investigate phenomena in the limit of comparatively high slug frequency. Due to limitations in the runtime at these very high liquid flowrates, the total runtime was cut to 5 min. The transient was initiated after 2 min with data acquisition throughout the run. Two minutes was sufficient for a steady state to be established since the slug frequency was high and a minimum of ninety slugs travelled along the pipe in this period.

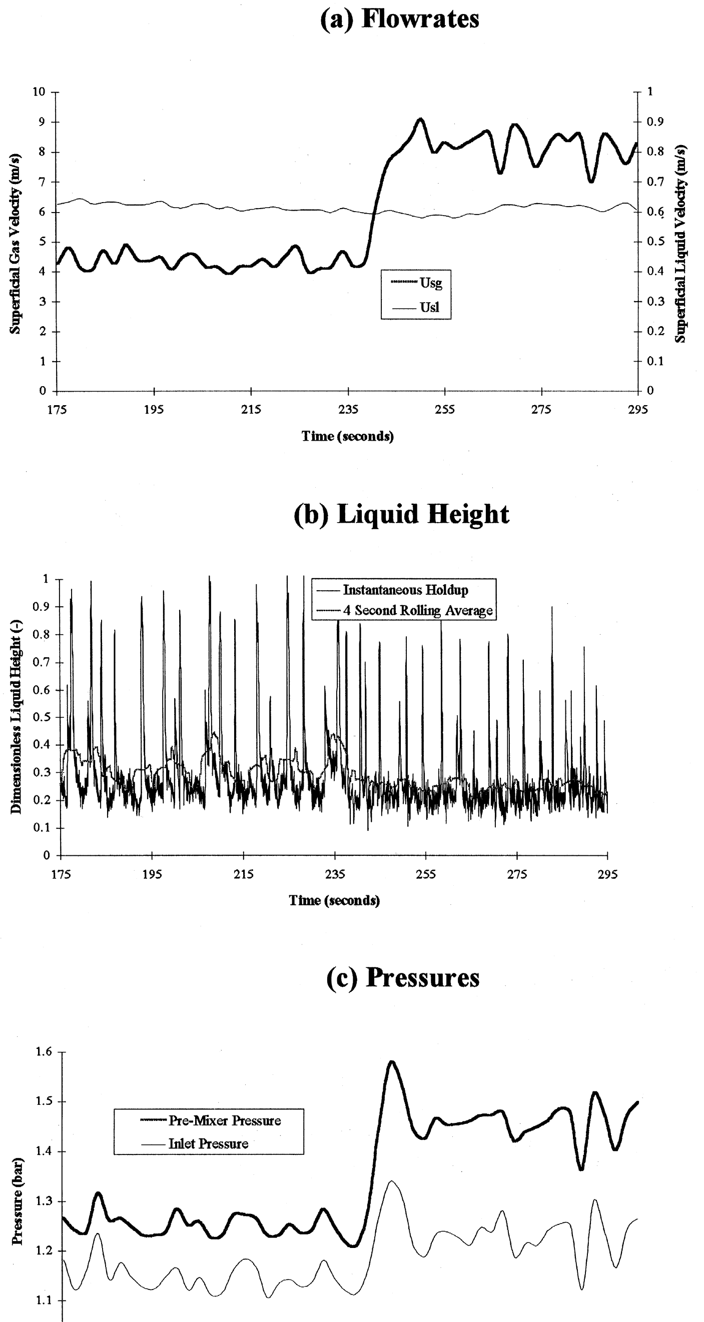

Fig. 4. Flowrate (a), liquid height after 35 m (b) and pressure (c) traces for an increasing gas transient. The gas superficial velocity increases from 4–8 m/s after 235 s. The liquid superficial velocity was 0.6 m/s.

3. Results and discussion

If the transient was conducted infinitely slowly, a number of features would be seen as the quasi-steady state changed. For a change of the gas flowrate, the major effect would be the change in the slug body holdup. This would increase for a decreasing gas flowrate transient and decrease for increasing gas flowrate (Gregory et al., 1978). The slug velocity is also a strong function of the gas velocity and so this too would change significantly (Bendiksen, 1984). Under steady state conditions, slug length is relatively unaffected by changes in gas and liquid velocities (Nydal et al., 1992). Slug frequency however is correlated in terms of both gas and liquid velocities (Manolis et al., 1995), although over the range considered the effect of changing the gas flowrate is minimal. For liquid flow changes, the slug body holdup would not change substantially and neither would the slug length or the slug velocity. Slug frequency, however, changes quite significantly for large changes in superficial liquid velocity as in this study. All of these quasi-steady effects are still to be expected when the flowrate undergoes a rapid change. Of particular interest in the present study are additional features of the transient response which are not directly associated with the new steady state.

3.1. "Up-gas" transients

Fig. 4 shows the principal results for an increasing gas transient from 4 m/s to 8 m/s. The liquid velocity for the case illustrated was 0.6 m/s. The transient was initiated after 235 s of runtime. A number of features are immediately obvious. From the gamma densitometer trace (Fig. 4b) it is clear that the slug frequency is relatively unchanged and that the slug body void fraction increased markedly. This decrease is also seen in the average holdup trace. These features all correspond to the expected results for a change of steady state slug flow; slug frequency is mainly dependent on superficial *liquid* velocity whereas slug body holdup depends primarily on the mixture velocity. The change in mixture velocity is much greater for the gas transients than the liquid transients investigated, as the gas flowrate changes in 2 m/s steps compared with 0.2 m/s for the liquid superficial velocities.

The rapid response of the system is in sharp contrast to the period of around 500 s (Minami 1991) needed for the new steady state to be established for a 420 m long pipe. If the wave propagated through the system at a constant velocity equal to that of the wave in Minami's system (the gas flowrate is comparable) then for a 36 m long pipe this would indicate a response of over 40 s. It is clear from the holdup trace that all features resulting from the flowrate change are over in around 10 s. This may indicate that the 'three interconnected large storage tanks' used by Minami (1991, p. 50) are interacting with the test section due to an insufficiently high pressure ratio across the pressure regulator valve to ensure critical flow. This upstream compressible volume could result in much longer transient response times (King et al., 1996). Fabre et al. (1995) suggested that the voidage wave in transient slug flow travels at a (constant) velocity equal to that of the new long bubble velocity and that the transient is over once this wave has cleared the system. However, the results shown in Fig. 4 (and of Minami, 1991) suggests that this significantly underpredicts the response time.

A major feature of an increasing gas flowrate in the slug flow regime is the pressure overshoot above the value of the new steady state inlet pressure. This feature was not visible in

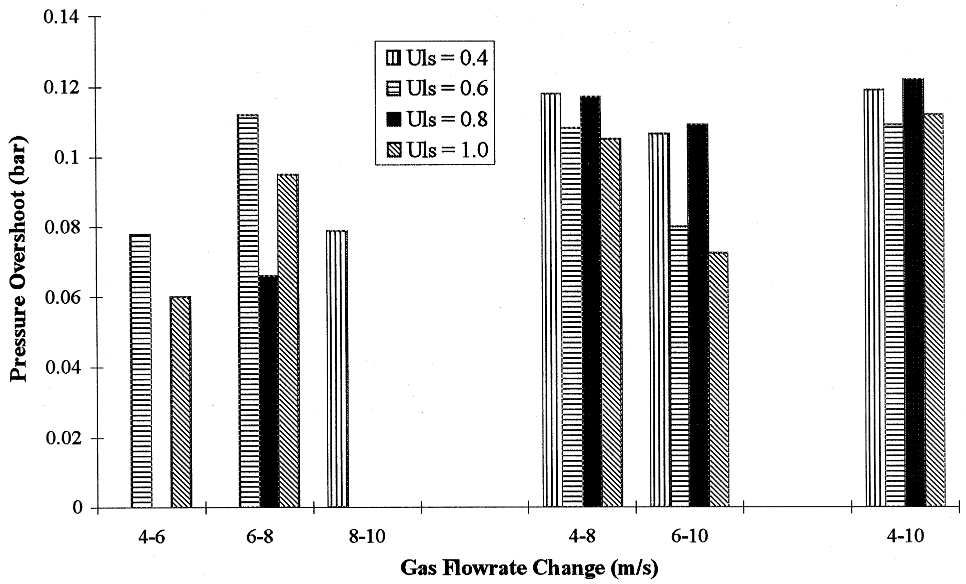

Fig. 5. Magnitude of the pressure overshoot above the new steady state at the entrance to the test section.

the exit pressure trace. For some cases, especially the transients with a larger flowrate change, there is a brief period of intensified slugging that includes two or three "extra" slugs. This feature arises from the different response speeds of the pressure build-up and the acceleration of the liquid slugs. This is unsurprisingly a function of the magnitude of the gas flowrate change. Fig. 5 shows the values of the pressure overshoots from all the "Up-gas" transient experiments. The highest observed value for the pressure peak above the new steady state is around 0.12 bar corresponding to the largest flowrate change from 4–10 m/s gas superficial velocity. The overshoot does not appear to be a strong function of the superficial liquid velocity indicating that the gas transient causes the same acceleration effect regardless of how quickly the next slug will form. The scatter and absence of some data for the smaller gas transients indicates that the pressure overshoot was swamped by the normal fluctuations present for this flow pattern.

An analysis of the conductivity traces around the transient region showed that the transient was often associated with the formation of a larger slug. This is consistent with the increased gas flowrate promoting the formation of a slug which sweeps down the pipe with the higher gas driving velocity behind forcing it over the relatively high holdup in front of the slug. Effectively a new steady state slug is being pushed over the (higher) film holdup corresponding to the old steady state conditions. Under these circumstances, the possibilities for extremely rapid slug growth are increased (Bendiksen and Espedal 1992; Woods and Hanratty 1996).

Fig. 6 shows the collected liquid holdup traces from the probes located in the test section. This clearly shows the progression of slugs along the pipe and the coalescence of waves with slugs. Merging of the waves and slugs is indicated by arrows connecting the waves and slugs involved. Four separate incidents are highlighted, one occurring during the transient and the others in the steady states either side of the transient. The transient illustrated by the traces is the same as that shown in Fig. 4 and thus the gas flowrate doubles after 235 s. At this instant a slug is located 20.5 m along the pipe (Slug 'A'). This slug passes out of the system moving at approximately 9 m/s. In the 7.2 m trace it is possible to identify two closely matched slugs after around 236 seconds (Slugs 'B' and 'C'). Following these along the pipe, Slug 'B' catches up and overtakes a wave whilst Slug 'C' shrinks due to the relatively fast moving liquid film shed out of Slug 'B'. The last two conductivity probes (after 27.7 m and 28.3 m) are located 0.6 m apart, so an accurate estimate of the slug front velocity may be obtained. A detail from this pair of conductivity probes is shown in Fig. 7. The front of the first slug (Slug 'B') is moving at 17.5 m/s and it has a total length of 5 m. This represents an increase of 225% in length compared to the average steady state slug length of 2.17 m. The velocity of the slug front is increased by the accretion of liquid from the thicker liquid layer ahead of it, though the tail velocity (9.4 m/s) is more typical of the new steady state. Fig. 7 shows that although the front of Slug 'B' moves very fast, the back velocity is similar to that of Slug 'A' and thus there may be a capacity for colossal slug growth in an industrial scale pipeline.

3.2. "Down-gas" transients

Fig. 8 shows the flowrates, pressures and holdup for a transient in which the gas flowrate was decreased from 10 m/s to 4 m/s after 240 s. The superficial liquid velocity was maintained at 1 m/s. This is approximately the reverse of the transient shown in Fig. 4 but with a higher liquid superficial velocity and a greater change in superficial gas velocity.

Again Fig. 8b shows no apparent change in slug frequency but a substantial increase in the average holdup and a decrease in the void fraction in the slug body region. As before, these changes correspond to the steady state conditions either side of the transient. However, for this case there is a substantial dip in pressure at the pipe entrance and the flow becomes quiescent during the transient. The pressure falls and a period of stratified flow is established within the pipe before slugging resumes. The length of this period is around 8 s for the case shown and is visible in the holdup trace presented as Fig. 8b. The slug velocity is rapidly reduced with the decrease in gas velocity. For slugs already present in the pipe as the transient is initiated, the liquid layer in front of them retains the low thickness characteristic of the previous higher gas velocity. These slugs pick up less liquid from this thin layer than they shed from their tails and thus rapidly collapse, leading to the short period of stratification observed.

The sensitivity of the pressure undershoot to the flow conditions and magnitude of the transient was investigated over the experimental matrix and the results are shown as Fig. 9. Again missing values correspond to conditions for which the undershoot was impossible to distinguish from the inherent fluctuations of the slug flow regime. Due to the missing information it is difficult to extract any firm trends from the data but it seems that the greater the transient, the more likely an effect will be noticeable. The largest observed value for the undershoot was around 0.12 bar, about the same value as the maximum observed overshoot for the up-gas transients.

As shown in Fig. 10, the greater the liquid superficial velocity, the shorter the stratified period appears to be. This is an extension of the natural slug frequency cycle; a higher superficial liquid velocity corresponds to higher slug frequency and thus the liquid layer recovers more quickly to the new equilibrium inlet holdup (Taitel and Dukler 1977). This period of stratified flow is not predicted by the application of steady state models although the

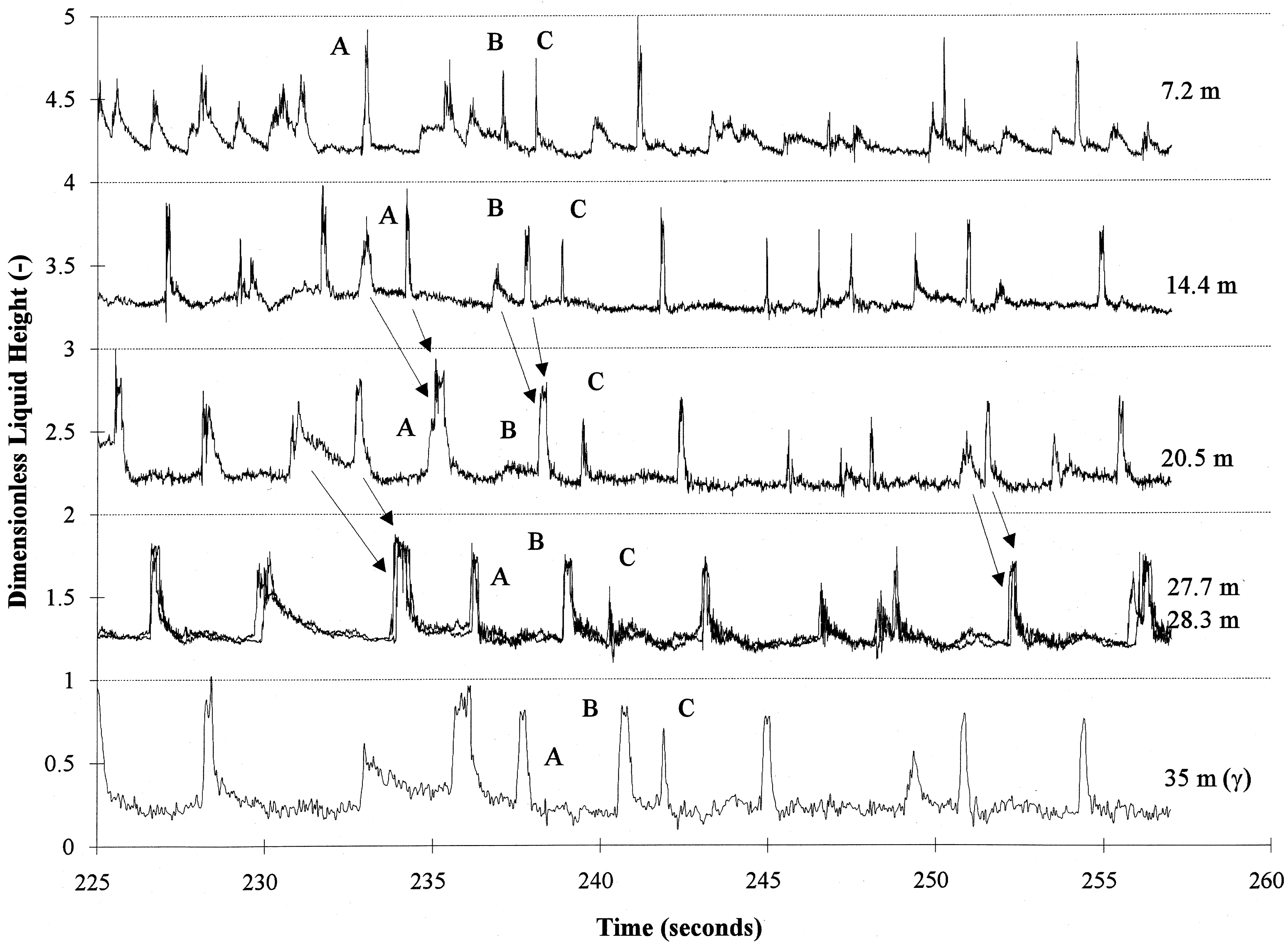

Fig. 6. Conductivity probe traces for an increasing gas transient. This for the same experiment as represented in Fig. 4. Arrows indicate incidences of slug-wave coalescence and labels indicate slugs discussed in the text. Note that in this and subsequent figures, the traces are offset by one unit of liquid height, except that the traces at 27.7 m and 28.3 m are shown superimposed to allow estimation of slug velocities.

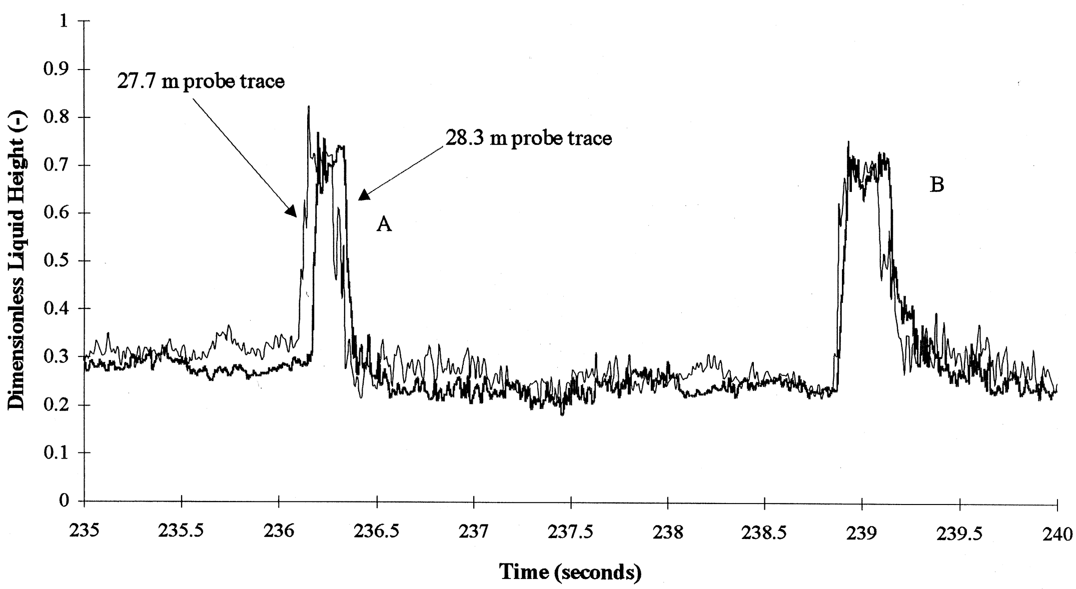

Fig. 7. Detail of the conductivity probe traces for the probes located 27.7 m and 28.3 m downstream of the mixer. These traces show a fast moving slug trailing a slow moving slug.

transient flow pattern map of Taitel et al. (1978) does predict the existence of other flow patterns during fast transients. The trace of a decreasing gas flowrate transient presented by Minami (1991) shows a similar effect but this was not commented upon by the author. It is anticipated that this effect may be substantially enhanced for slug flow under inclined conditions.

If the hypothesis of Taitel et al. (1978) for "fast" transients, that in the liquid level is essentially unaffected by a quick change in gas velocity, is adopted, then it is possible to predict the period of stratified flow. The paths of this hypothetical 'no response' case and of a succession of small changes in flowrate have been plotted in Fig. 11. The transition line is based on the model of Taitel and Dukler (1976). The Froude number/liquid height axes adopted by Fan et al. (1993) have been used for improved clarity. The temporary change to stratified flow is predicted for a "fast" transient, whereas the flow pattern remains in slug flow throughout a slow change in flowrate.

An indication of the slug decay process can be seen from the succession of conductivity probe traces presented together with the gamma densitometer trace in Fig. 12. The decay of slug flow is unidentifiable in the two most upstream probes but thereafter becomes more and more apparent. In the 20.5 m probe trace, the beginnings of the quiescent period can be seen with a longer film profile behind the slug encountering the probe after 242 s (Slug 'A'). This slug subsequently decays into a slow moving wave (Slug 'B') and is absorbed into the front of another slug (Slug 'C') before the 35 m gamma densitometer trace. The next slug through the system (Slug 'C') travels over a relatively high liquid level and grows quite markedly. The last four positions (20.5 m, 27.7 m, 28.3 m and 35 m) show that the new steady state is established quickly after the passage of Slug 'C'.

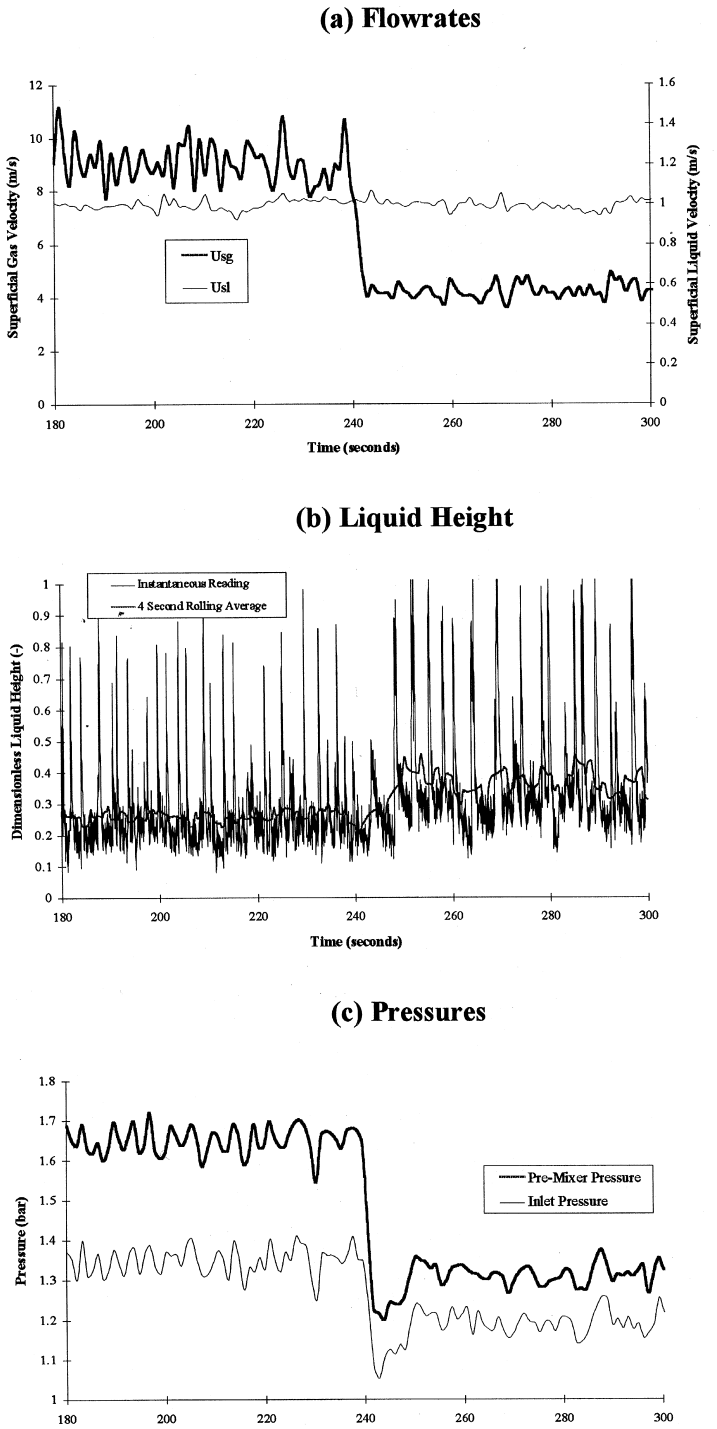

Fig. 8. Flowrate (a), liquid height after 35 m (b) and pressure (c) traces for a decreasing gas transient. The gas superficial velocity decreases from 10–4 m/s after 240 s. The liquid superficial velocity was 1.0 m/s.

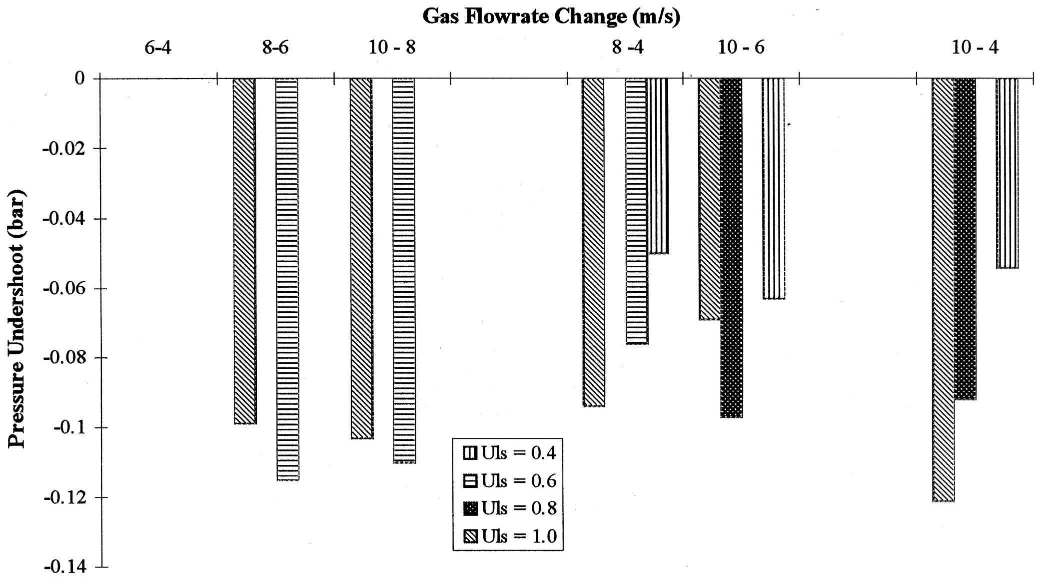

Fig. 9. Magnitude of the pressure undershoot below the new steady state at the entrance to the test section.

3.3. "Up-liquid" transients

The results presented in Fig. 13 show the effect of a liquid flowrate increase from 0.4 m/s to 1.0 m/s for a fixed superficial gas velocity of 6.0 m/s. The transient occurred after 240 s of runtime. Compared to the gas transients, the liquid transients are rather limited in effect. There is no overshoot in the inlet pressure and no flow pattern transition. The holdup effects that were very obvious for the gas transients do not happen and there is no promotion of intense slugging. In fact, the only effect that characterises the transient appears to be the rapid change in the slug frequency. This corresponds to the strong dependence of steady state slug frequency on the superficial liquid velocity (Manolis et al. 1995). The new steady state is established quickly with typically two or three slugs needed to bridge the period. This suggests that the liquid level near the inlet responds quickly to the change in liquid flowrate and hence the slug formation mechanism for the new steady state is established in a similar period (Taitel and Dukler 1977). The absence of other effects justifies the application of extended steady state and simplified transient models (see Minami 1991) to these transients and the efficacy of their use.

The liquid height traces displayed in Fig. 14 for this run showed that the slug frequency for the new steady state is established in around 5 s and that no other unexpected features occur. It is also clear from the traces that the slug body holdup does not change appreciably.

3.4. "Down-liquid" transients

Fig. 15 shows the response for a system operated with a gas superficial velocity of 6 m/s with the liquid flowrate decreased from 1.0 to 0.4 m/s after 240 s. A rather large number of large holdup features can be resolved in the new steady state. This demonstrates that the new steady

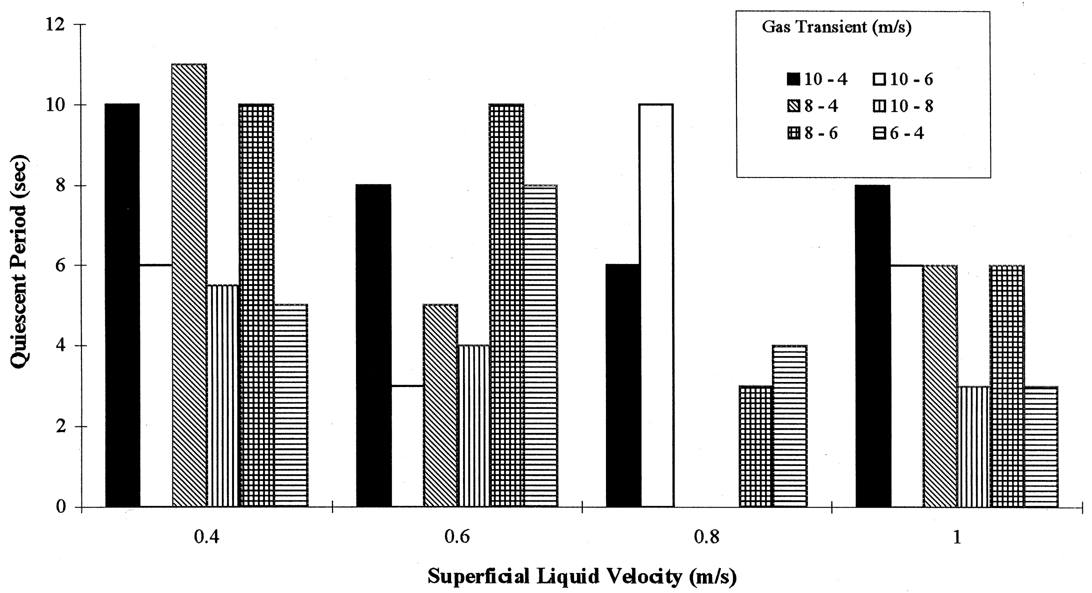

Fig. 10. Duration of the quiescent period for decreasing gas transients.

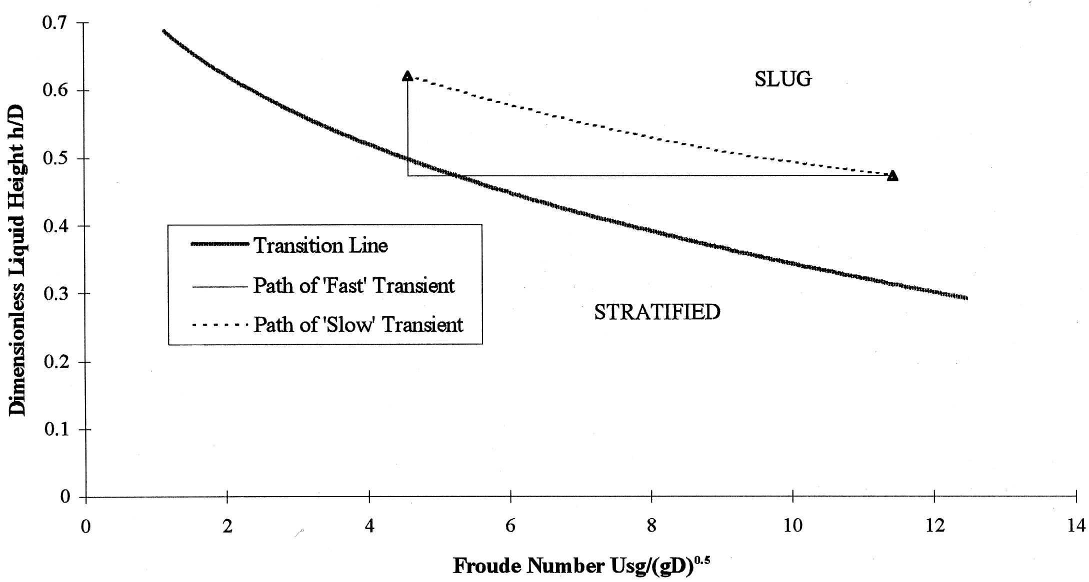

Fig. 11. Flow pattern map plotted on the axes suggested by Fan et al. (1993) showing the stratified-to-slug transition line (Taitel and Dukler 1976). Two possible paths are illustrated for a decreasing gas flowrate transient (same flowrate transient as illustrated in Fig. 8); one for a series of steady states (– –) and one for an extremely fast response (—).

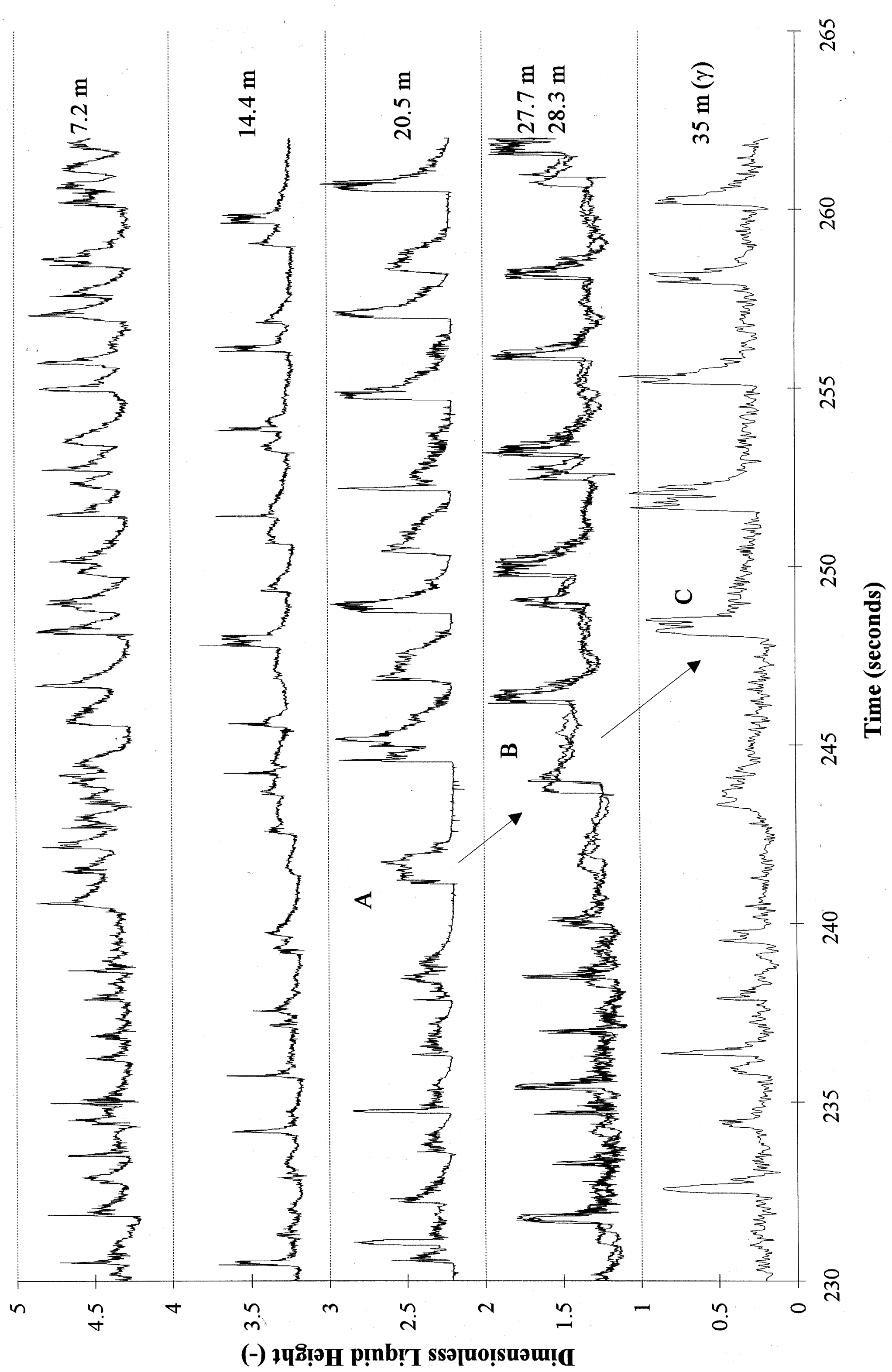

Fig. 12. Conductivity probe and gamma densitometer traces for a decreasing gas transient. This is the same experiment as represented in Fig. 8. Labels relate to slugs considered in the text.

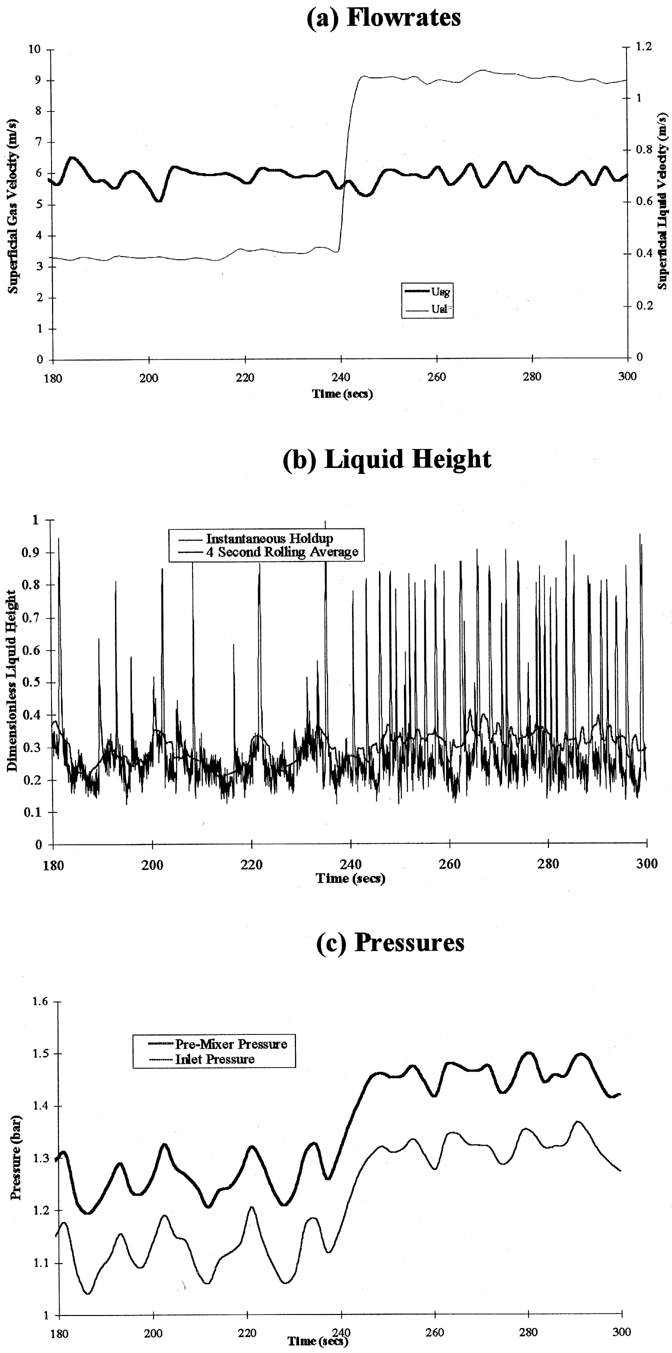

Fig. 13. Flowrate (a), liquid height after 35 m (b) and pressure (c) traces for an increasing liquid transient. The liquid superficial velocity increases from 0.4–1.0 m/s after 240 s. The superficial gas velocity was 6 m/s.

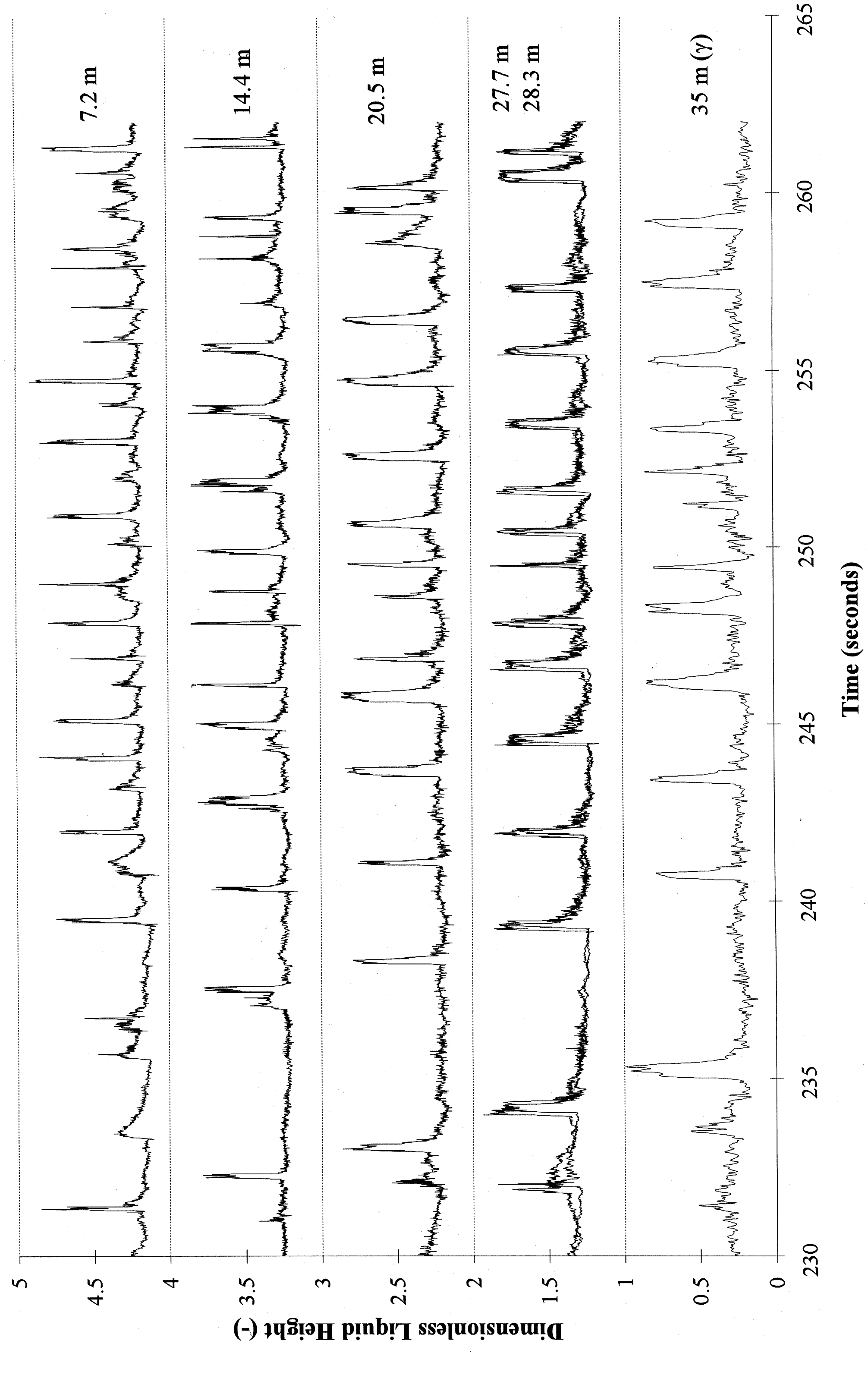

Fig. 14. Conductivity probe traces for an increasing liquid transient. This is the same experiment as shown in Fig. 13.

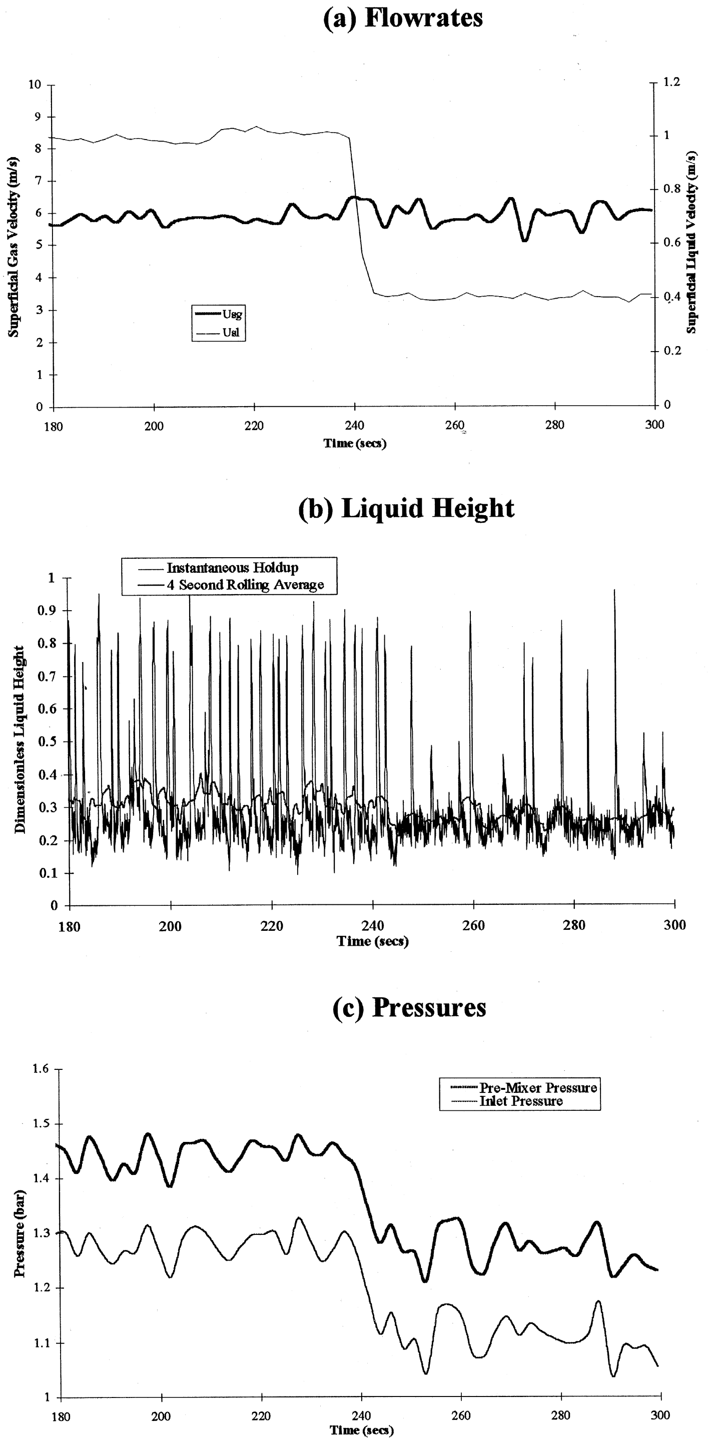

Fig. 15. Flowrate (a), liquid height after 35 m (b) and pressure (c) traces for a decreasing liquid transient. The liquid superficial velocity decreases from 1.0–0.4 m/s after 240 s. The superficial gas velocity was 6 m/s.

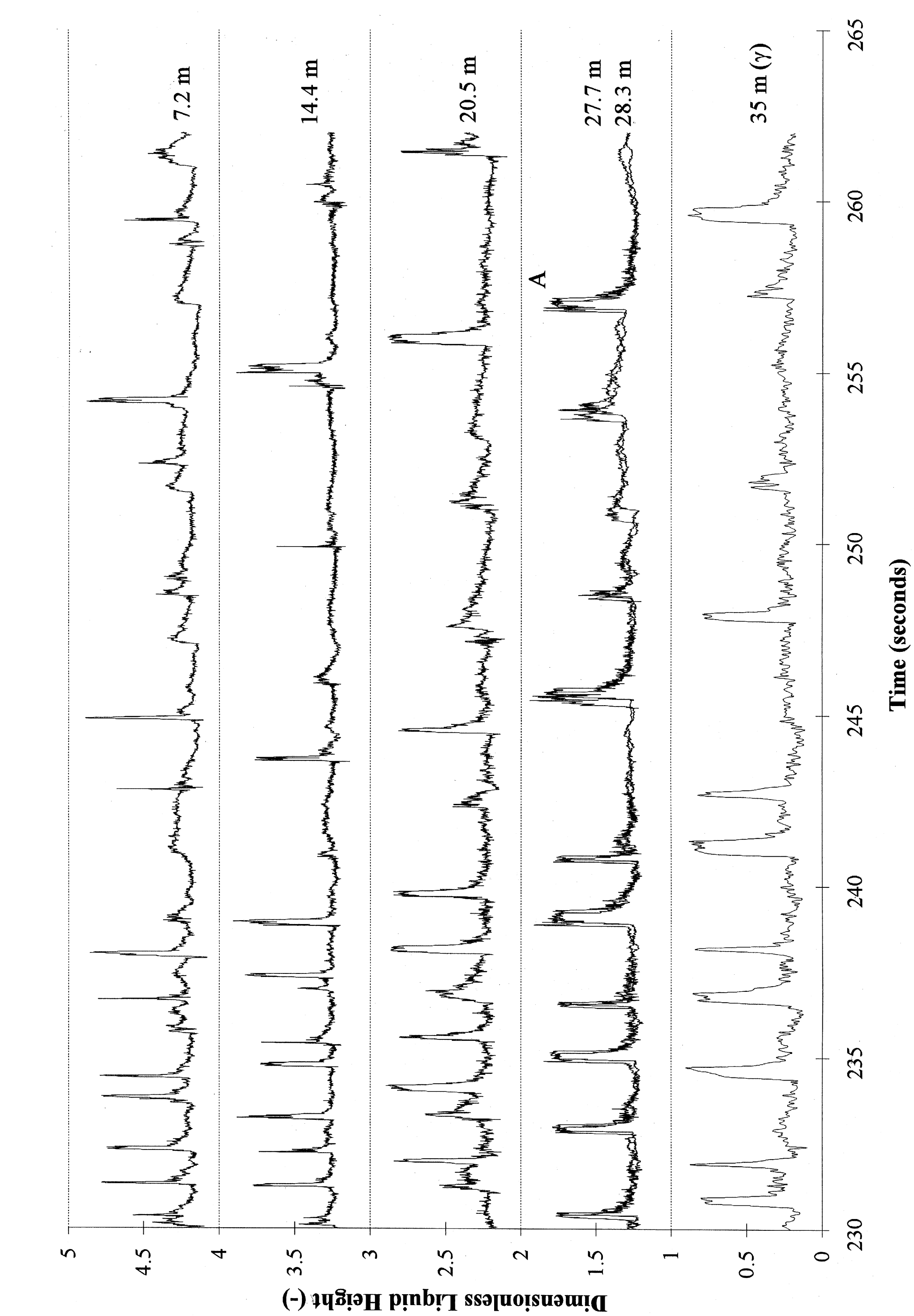

Fig. 16. Conductivity probe traces for a decreasing liquid transient. This is the same experiment as shown in Fig. 15. The label denotes a slug discussed in the text.

state is a developing slug flow rather than a fully developed one and this is consistent with the results of Nydal et al. (1992). These holdup features vary in character from pseudo-slugs (aerated slugs moving at approximately the slug translational velocity) to large amplitude waves. Resolution of these features is supplied, in part, by careful examination of the video recording of the flow.

As with the "Up-liquid" transient, the characteristics of the down liquid transient are relatively straight forward. Again no changes in flow pattern or pressure overshoots are evident. The only obvious change is a conspicuous decrease in frequency. As such, the application of steady state models is still justified and the predictions generated should match the experiment quite closely.

Fig. 16 shows the sharp decrease in slug frequency associated with the decrease in superficial liquid velocity. Before the flowrate transient, the conductivity trace corresponding to the probe located 7.2 m downstream of the inlet shows quite a large number of slugs; afterwards slugs rarely form and the number of waves is quite high. As the waves propagate along the pipe they are overtaken and merged into slugs. The 27.7 m and 28.3 m traces show this quite clearly with obvious distinction between slugs formed near the inlet and slugs formed further along the pipe from growing waves. Since the velocity of the slug located 27.7 m downstream after 257 s (Slug 'A') is larger than the velocities of the holdup waves preceding it, so it is inevitable that further coalescence effects would occur if the pipe was longer.

3.5. Ensemble averaging

A series of ten nominally identical experiments was carried out at each of six pairs of initial and final conditions. For the increasing gas transients, all the features discussed earlier were repeatable across the entire set of experiments. The main benefit of the averaging was to remove some of the inherent randomness of the slug flow regime. Fig. 17 shows the average pressure overshoot as a function of the magnitude of the flowrate transient. This shows that larger transients cause bigger overshoots. The standard deviations for the pressure overpeak were 0.01 bar for the 4–6 m/s change, 0.014 bar for the 4–8 m/s change and 0.022 bar for the largest transient.

Fig. 18 is the equivalent of Fig. 4 for the averaged case but with a slightly higher superficial liquid velocity of 0.8 m/s. The ensemble average over ten runs removes the sharp peaks due to the slugs themselves, although large fluctuations are still evident in the holdup trace. Although the individual experiments typically show larger slugs and possibly intensified slugging; no remnant of this feature is discernible in the averaged trace. This seems to indicate that the intensification is short lived and depends on the location of the slugs in the pipe. The average pressure trace shows a clear overshoot and a damped oscillation in the approach to the new steady state inlet pressure. This overcompensation, although consistent with a mass-spring slug flow model (see Akagawa et al., 1982) is not present in any of the other averaged traces and so may be just an artefact of this particular collection of runs. The slow sampling rate of the pressure transducers means that this feature would be unidentifiable in the majority of the traces.

Unlike the increasing gas transient case, the decreasing gas transient features are less reproducible over a number of runs. The same features still occur but the magnitudes are less

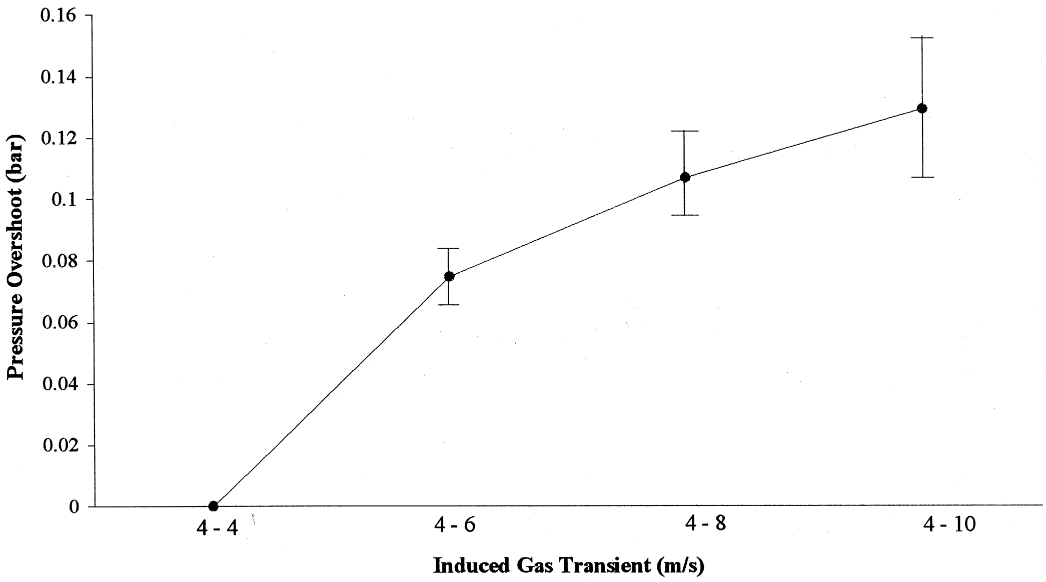

Fig. 17. Average pressure overshoot above the new steady state for the ensemble averaged increasing gas transients. The error bars show the standard deviation of the pressure overshoot. The liquid superficial velocity was 0.8 m/s.

consistent. For instance, the average duration of the quiescent period is around $8\frac{1}{2}$ s for the 10–4 m/s gas decrease and $3\frac{1}{2}$ s for the 10–6 m/s decrease but the effect for the smallest transient (10–8 m/s) is mainly manifest as a local suppression of the slug frequency and so not immediately quantifiable. It appears that the actual location of the slugs with respect to the inlet *does* matter for the decreasing gas transients. This observation is supported by the variation of the quiescent period duration; for the 6 m/s decrease in gas flowrate the quiescent period varies between 6 s and 13 s and has a standard deviation of 2.2 s. The traces for this set of experiments all show evidence of slug decay just after the decrease in gas superficial velocity.

3.6. High-liquid flowrates

To further investigate the kinematic features of the flow, a series of experiments was carried out at higher liquid flowrates, namely 1.5 and 2.0 m/s. For the increasing gas flow transients, a sample set of traces is presented in Fig. 19. The superficial liquid velocity was 1.5 m/s and the superficial gas velocity was increased from 4 m/s to 10 m/s after 120 s for this experiment. The features that are immediately obvious in comparison to Fig. 4 are that both the slug frequency and the inlet pressure to the test section are a lot higher. This is consistent with steady state predictions in this region. The transient produces a pressure overpeak as for the lower liquid velocities and there is a period of more intense slugging evident in the holdup trace after a 4 s delay.

Fig. 20 shows the conductivity probe and gamma densitometer traces in the time period of interest. The traces from the probes 27.7 m and 28.3 m downstream of the inlet slow a local enhancement of the frequency that lasts for approximately five slugs and represents an

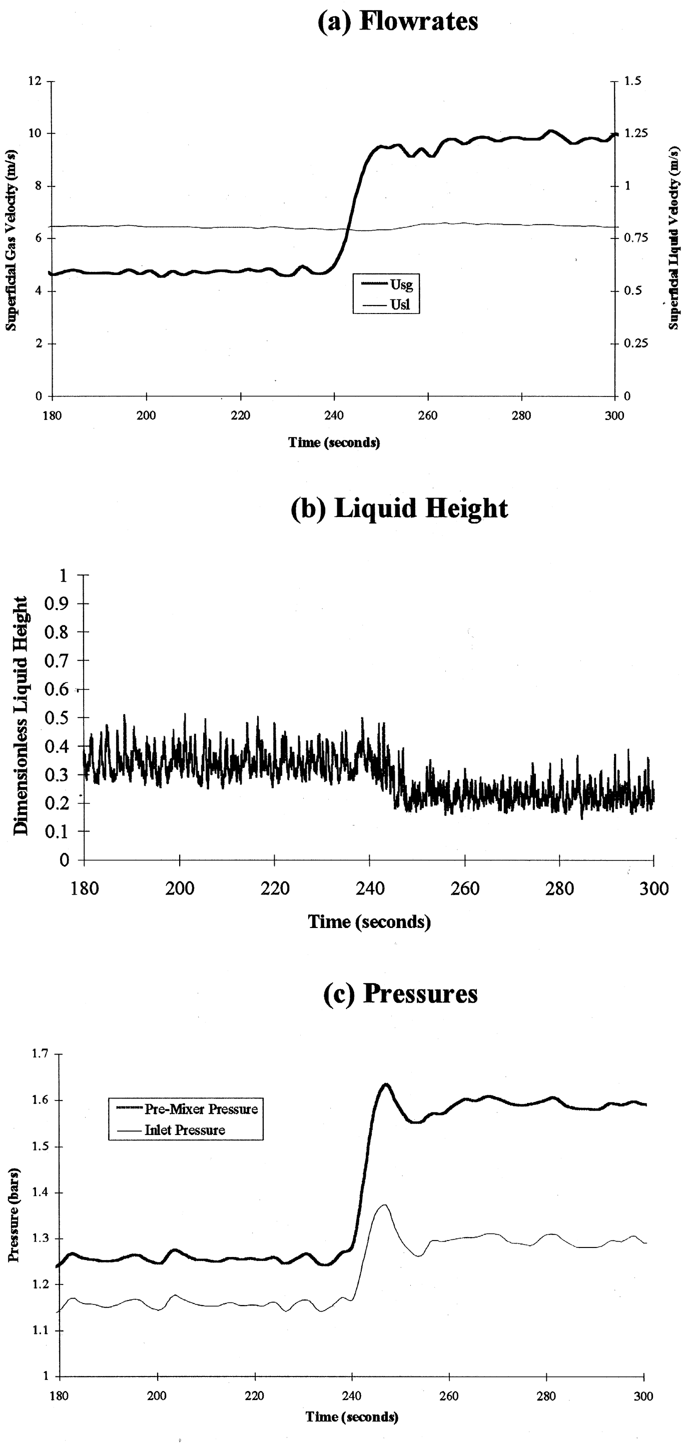

Fig. 18. Ensemble averaged (over 10 runs) flowrate (a), liquid height after 35 m (b) and pressure (c) traces for an increasing gas transient. The gas superficial velocity increases from 4–10 m/s after 240 s. The superficial gas velocity was 0.8 m/s.

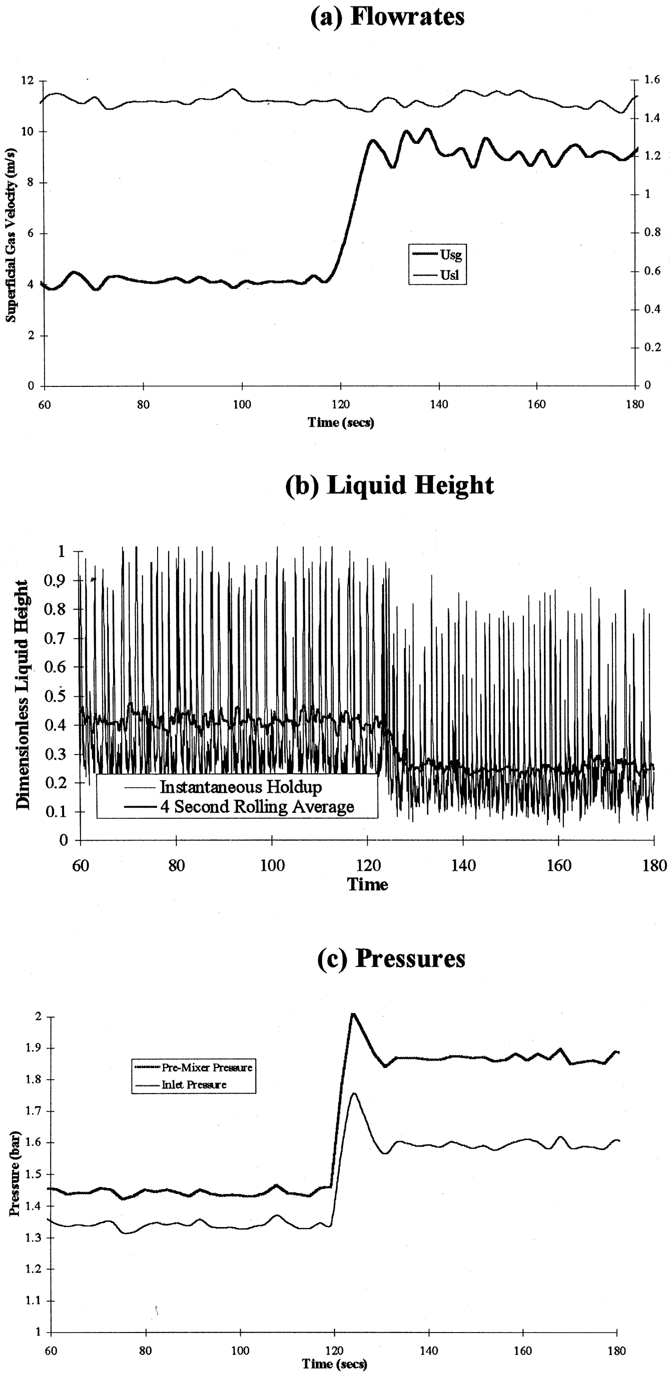

Fig. 19. Flowrate (a), liquid height after 35 m (b) and pressure (c) traces for an increasing gas transient at high liquid flowrate. The superficial gas velocity increases from 4–10 m/s after 120 s. The superficial liquid velocity was 1.5 m/s.

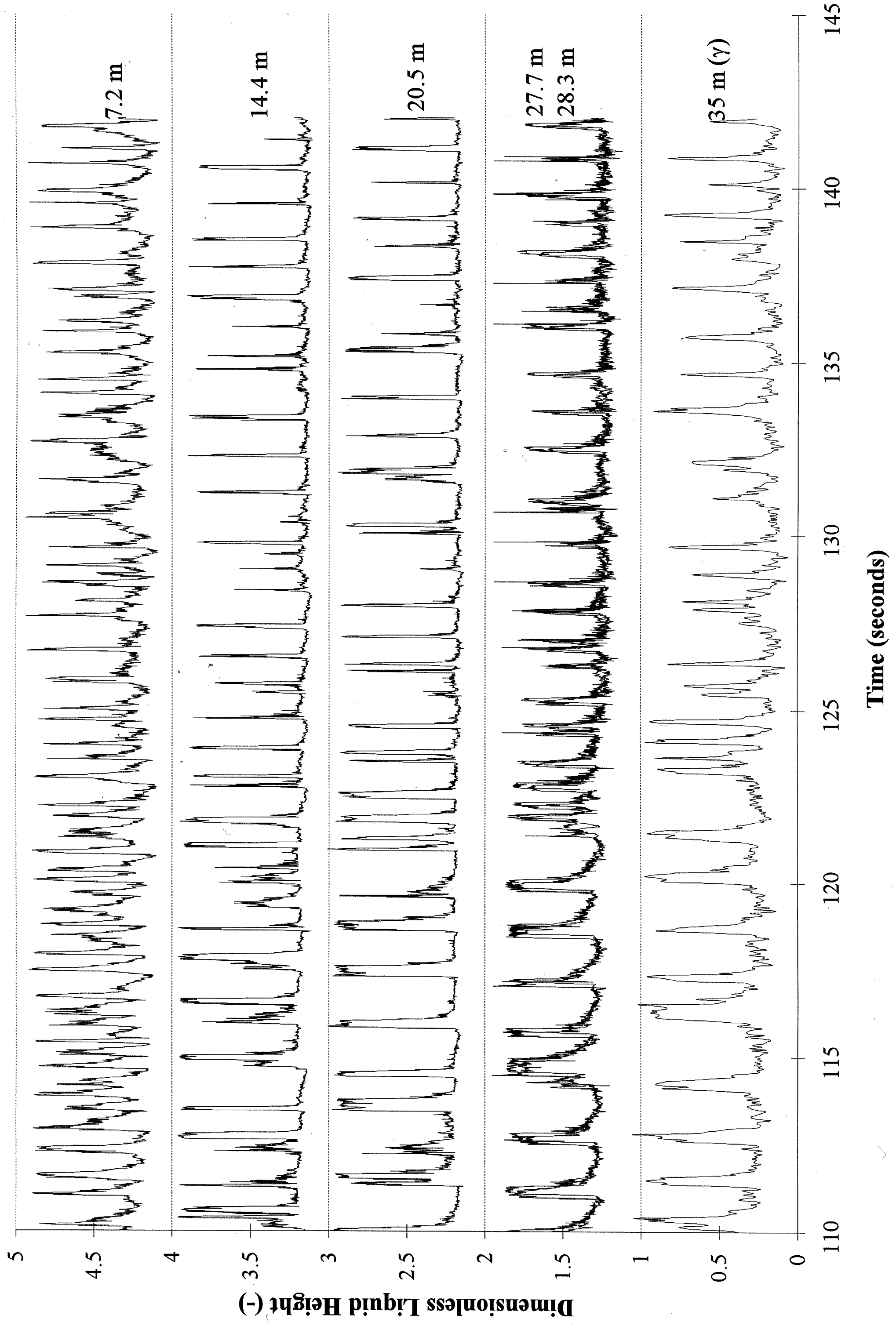

Fig. 20. Conductivity probe traces for an increasing gas transient at high (1.5 m/s) liquid flowrate. This is the same experiment as shown in Fig. 19.

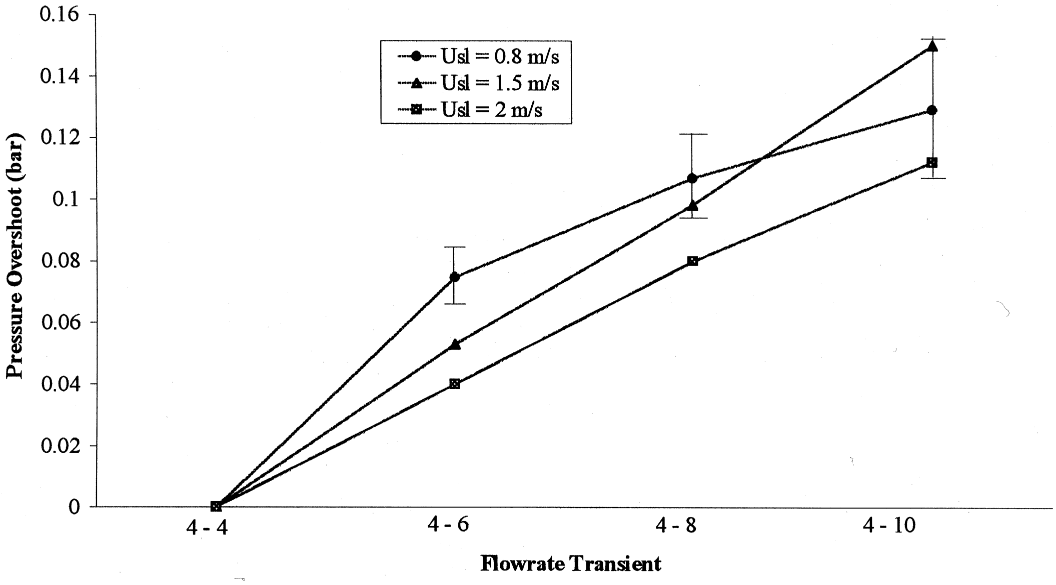

Fig. 21. Maximum pressure overshoot above the new steady state for high liquid flowrates.

amplification of around 60% above the final steady state frequency. It seems that these slugs are only initiated halfway along the pipe as the extra slugs are not obvious in either of the two upstream probes. If the pipe were longer, it is foreseeable that these slugs would coalesce into one large slug, especially as they are moving faster than the slug directly downstream of them. Intense slugging is more likely at high liquid flowrates as it is evident in all the traces. This is primarily due to the increased rate of slugs forming at the inlet.

The magnitude of the pressure overshoot depends on the extent of the flowrate transient as shown in Fig. 21. As can be seen, the overshoot is greater for a bigger flowrate change. The overshoot for the 2 m/s liquid velocity was consistently about 80% of the value for 1.5 m/s liquid velocity but comparison with ensemble averaged results show that this may not be statistically significant. As a result, there appears to be no systematic effect of superficial liquid velocity on the magnitude of the pressure peak.

Decreasing gas transients, at high liquid flowrate, produce much the same effects as for the lower superficial liquid velocities. Fig. 22 shows the collected traces for the case of a decrease from 10 m/s superficial gas velocity to 4 m/s for a constant 1.5 m/s liquid velocity. The transient occurs after 2 min of runtime. The pressure undershoots the new steady state inlet pressure and there is a suppression of slug frequency after the transient. However both features are muted due to the fast rebuilding of the liquid layer at the pipe inlet. For some of the higher liquid flowrates, no stratified period is identifiable but the local frequency is reduced indicating the longer time needed for slugs to form over a lower film height.

Fig. 23 shows the conductivity traces for this experiment and, as expected, the character of the flow does not change very much. Around 124 s, a reduction of the local slug frequency is visible in the 27.7 m and 28.3 m conductivity probe traces for two slugs. This can also be seen in the last trace (35 m) where two slugs (Slugs ‘A’ and ‘B’) are decaying. The slug at 28.3 m

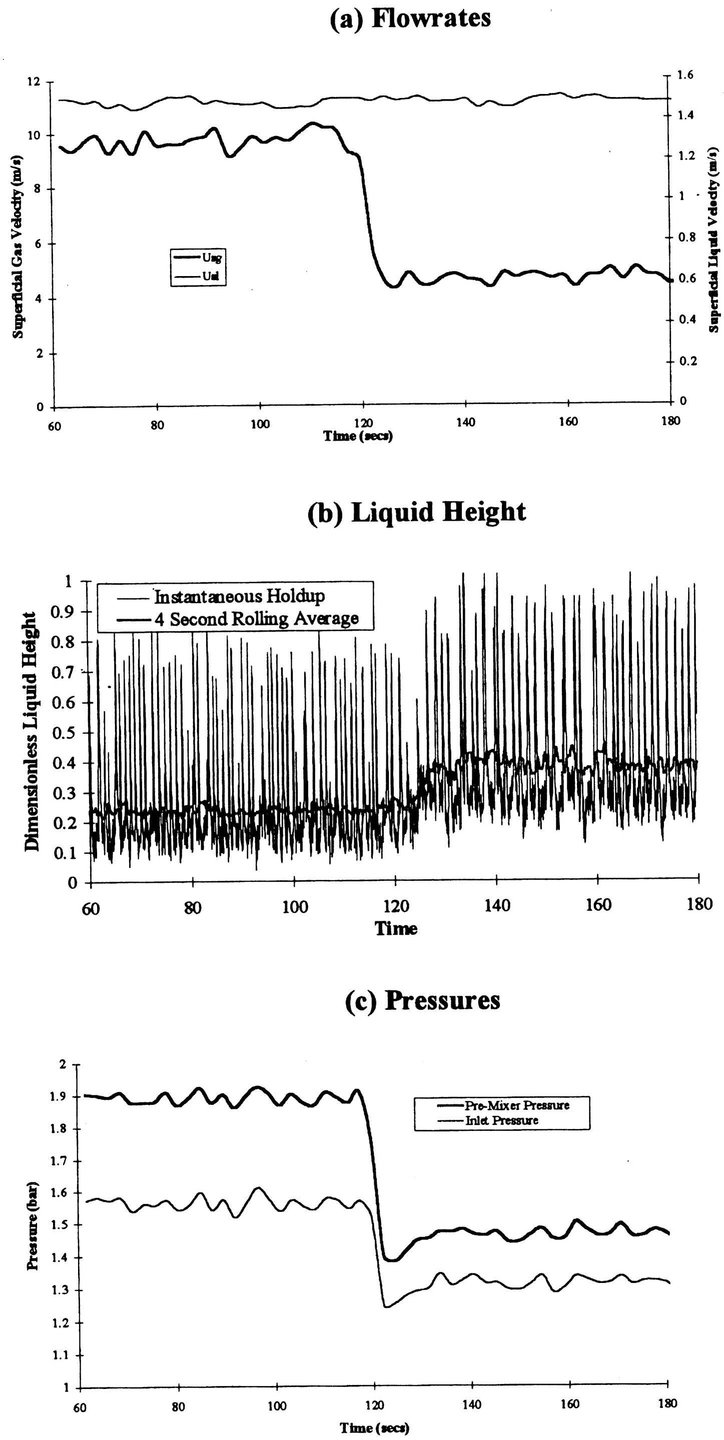

Fig. 22. Flowrate (a), liquid height after 35 m (b) and pressure (c) traces for a decreasing gas transient at high liquid flowrate. The superficial gas velocity decreases from 10–4 m/s after 120 s. The liquid superficial velocity was 1.5 m/s.

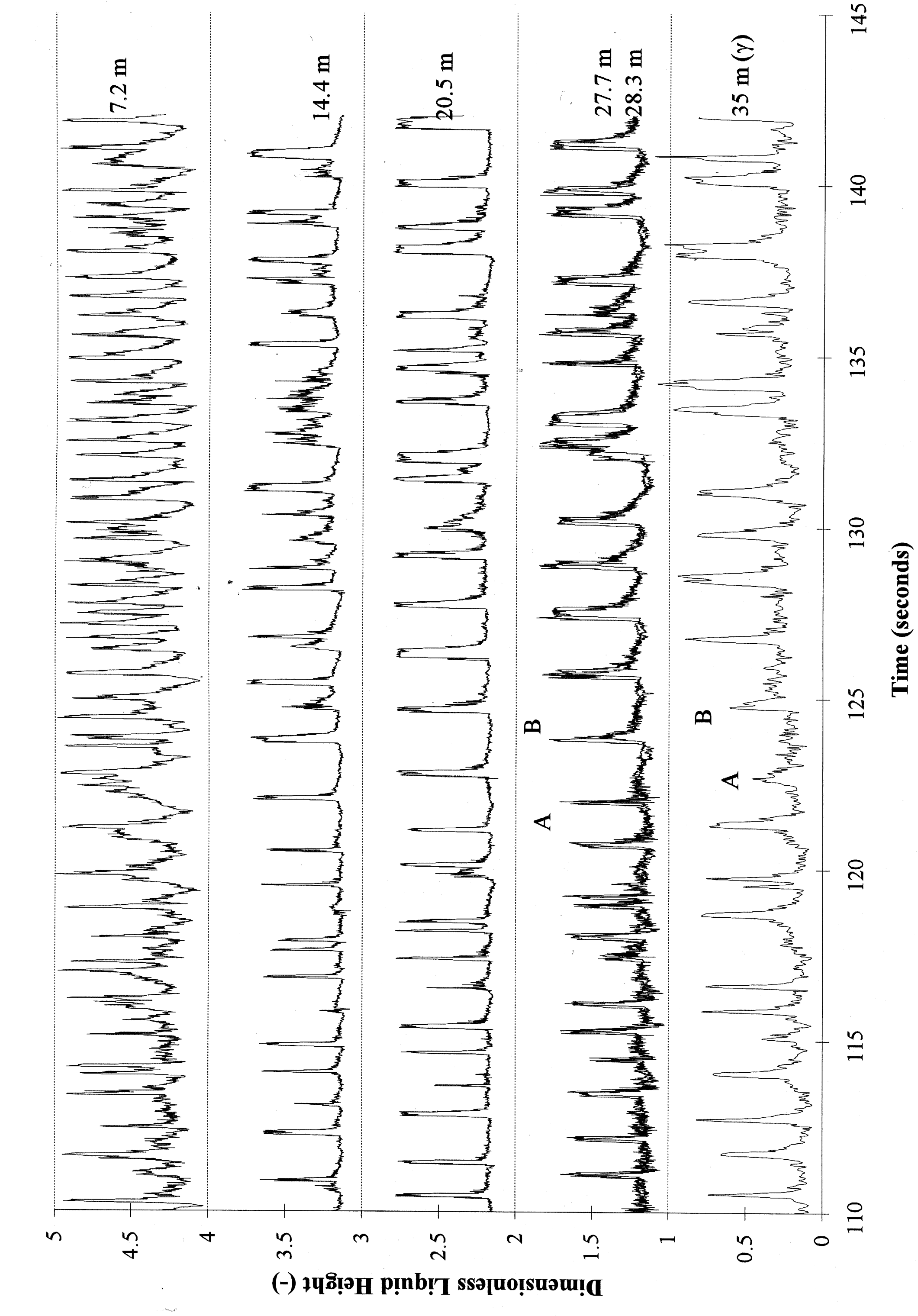

Fig. 23. Conductivity probe traces for a decreasing gas transient at high liquid flowrate. This is the same experiment as shown in Fig. 22. Labels denote slugs mentioned in the text.

after 124 s (Slug ‘B’) is travelling over a thin liquid layer shed from the previous slug whilst the film holdup behind it is higher. Decay thus occurs due to an imbalance between liquid pickup and shedding.

4. Conclusions

The results presented in this paper demonstrate that transients within the slug flow regime cannot, in general, be modelled by a quasi-steady state approach since some features of gas transients are not predicted by considering the flow as a succession of steady states. The foremost of these features is the overshoot in the inlet pressure in response to an increase in the gas velocity. Furthermore, the observed period of intense slugging is not a feature of steady state models.

Of equal interest is the case of a decreasing gas transient for which the flow becomes quiescent and slug decay is promoted. The pressure undershoot below the new steady state pressure is caused by a decreased pressure drop along the test section and the becalmed period persists until the equilibrium liquid level rebuilds to cause resumed slug formation at the inlet.

For liquid transients, steady state models can be used with impunity as the flowrate change causes no noticeable effects except the increase or decrease in the slug frequency and a limited change in holdup.

The kinematic effects of the transient can be successfully interpreted using the approaches adopted by Bendiksen and Espedal (1992) and Woods and Hanratty (1996). They both assigned a slug tail velocity based on inlet conditions and allowed the velocity of the slug front to depend on the properties of the film in front of the slug. The resultant slug growth was determined by the difference in velocity (Bendiksen and Espedal 1992) or volumetric pickup and shedding (Woods and Hanratty 1996). This philosophy can be extended to transient situations were the rapid slug growth for increasing gas flowrate transients or the slug decay for decreasing gas flowrate transients can be predicted.

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