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DETECTION OF SLUG FLOW FROM PRESSURE MEASUREMENTS

P. Y. LIN and T. J. HANRATTY
Department of Chemical Engineering, University of Illinois, Urbana, IL 61801, U.S.A.

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Abstract—A slug pattern for gas–liquid flow in horizontal pipelines is observed when slugs of liquid block the whole pipeline and move as a coherent mass downstream at a velocity approximately equal to the gas velocity. At low gas velocities they are easily observed in a transparent pipe. However, at high gas velocities it is difficult to differentiate slugs from large amplitude waves which momentarily close off the pipe cross section. This paper shows how the pressure measurements at two locations, separated from each other in the flow direction, can be used to detect slugs.

1. INTRODUCTION

Gas and liquid flowing in a horizontal pipeline show a number of interfacial configurations, called flow patterns, which have received considerable attention in the literature. One of these is slug flow, in which liquid slugs, filling the whole pipe cross section, are intermittently propelled down the pipe. This paper describes how a pair of pressure transducers can be used to detect the presence of these slugs.

The motivation for this work came from a recent study in which the flow regimes were defined for air and water flowing in horizontal 2.54 and 9.53 cm i.d. transparent pipes. At low gas velocities a transition to slug flow was quite easy to detect visually. At high gas velocities this was not the case. The slugs became much shorter and highly aerated, so it was not possible to detect whether they filled the whole pipe cross section or whether they were durable. Therefore, it was necessary to use an instrumental rather than a visual detection technique.

A summary of the different types of flow-regime detection techniques has been given by Hewitt (1978) and by Jones (1979). The X-ray absorption measurements, used by Jones & Zuber (1974), have the disadvantages of high cost and the need for safeguards. Barnea *et al.* (1980), Reimann *et al.* (1981), and others have used conductance probes which detect the presence of a particular phase by making use of the large difference in electrical conductivity between the gas phase and the liquid phase. Jones & Zuber (1978) made use of a hot-film anemometer, but its fragility and short lifetime have limited its acceptance. Hubbard & Dukler (1966), who first recognized the value of instrumental techniques, used the power spectra of the fluctuations in the local pressure to characterize different flow patterns. However, it is not at all certain that the frequency domain is an appropriate basis to distinguish between slugs and large amplitude waves that close off the pipe momentarily. Weisman *et al.* (1979) used the real-time differential pressure signal. They suggested a scheme that uses the amplitude and frequency of the signal to characterize a particular pattern. Tutu (1982) proposed using the probability density of the fluctuations in the pressure difference for vertical systems.

We initially explored the use of conductance techniques (Lin 1985) to detect the slug–annular transition. Because the slugs are highly aerated it was difficult, with this technique, to differentiate a slug from a large-amplitude wave which does not block the pipe cross section. We, therefore, decided to explore the possible use of a pair of pressure transducers 1.3–5 m apart in the flow direction as a detection device. The technique is different from that used by Weisman *et al.* (1979) in that the local pressures at two different locations were measured instead of the differential pressure drop over a short distance. It is felt that the analysis of differential pressure drop is more suited for flow patterns which are steady with respect to time rather than for intermittent flows. The interpretation of the measurements is also quite different from that of Weisman *et al.*

The picture of a slug used in this analysis is that it blocks the pipe cross section, that it keeps its identity until it reaches the exit of the pipe and that it moves approximately at the gas velocity. Large disturbances, which from visual observations look like a slug, that do not have all of the above characteristics are called pseudo-slugs. Dukler & Hubbard (1975) reported that the pressure drop in horizontal slug flow takes the form of a steep jump when a slug is between the two taps. The pressure in front of the slug is low and increases sharply to a much higher value behind the slug. The pressure gradient behind the slug is small, but the pressure remains high. This, then, is the type of pressure behavior that was used to identify slugs. The upstream pressure measurement detected blockage from the characteristics of the pressure signal. The downstream pressure measurement was used to determine whether the slug remained coherent.

2. DESCRIPTION OF THE EXPERIMENTS

The experiments were conducted in two horizontal pipelines of 2.54 and 9.53 cm i.d. The phase-mixing section were simple tees. The air was introduced in the branch and the water in the run of the tee.

The experimental setup used to detect slugs is sketched in figure 1. Two Viatran Model 218 strain gauge pressure transducers with a flat frequency response up to 2 kHz and a range of 0–1.03 b were used. The reference pressure to these transducers is adjustable to allow for increased pipeline pressures at high flow rates. The transducers were located 200 pipe diameters away from the entry so as to allow the slugs to develop. They were connected to pressure taps at the bottom of the pipe located 1.35–5 m apart, depending on the flow conditions. The lines to the transducers were filled with liquid and frequently purged of air bubbles.

Two sets of parallel wire conductance probes, that extended over the pipe cross section were used to measure the heights and velocities of waves and pseudo-slugs. These provided a better understanding of the flow but are not necessary for the interpretation of the pressure signals.

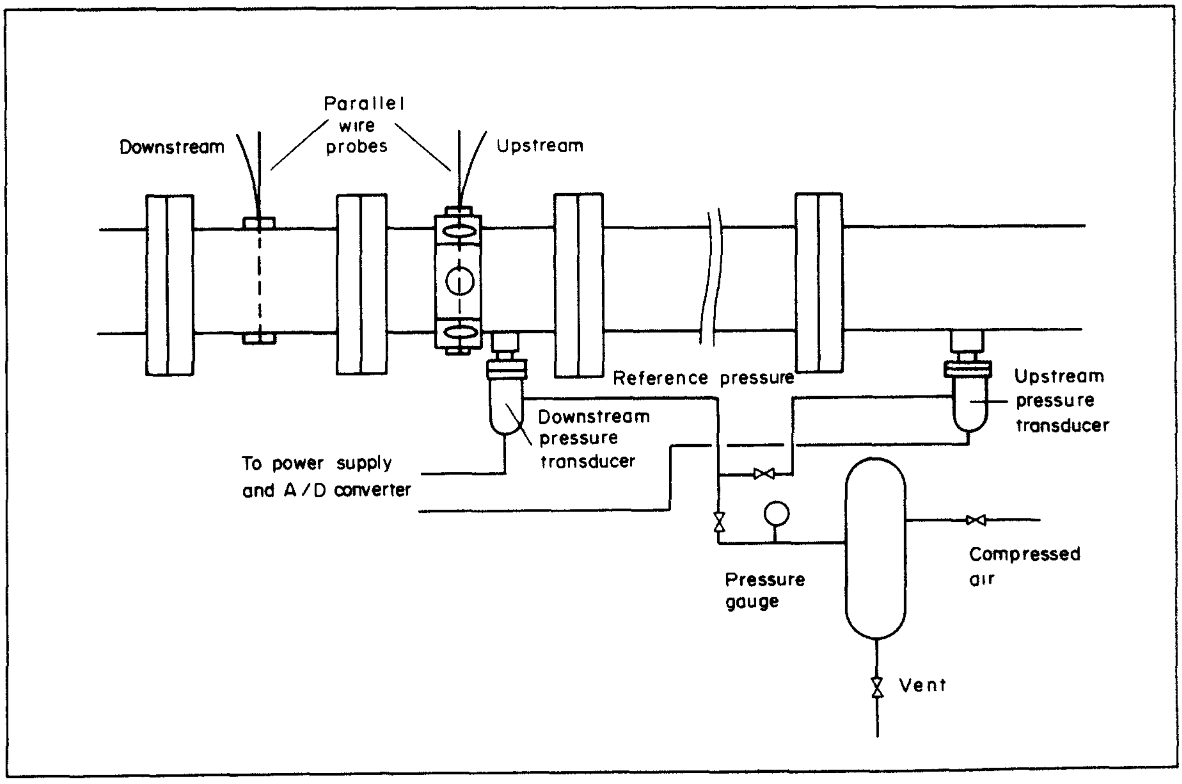


Figure 1. The experimental setup.

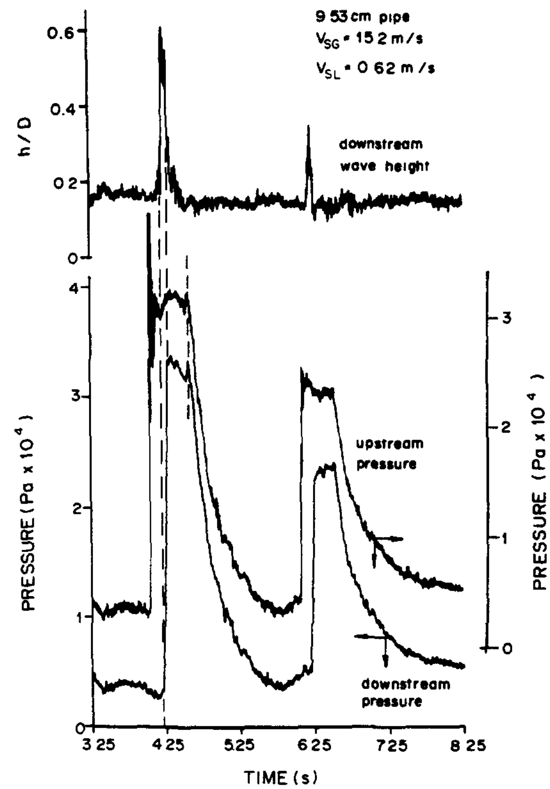


Figure 2. Wave-height and pressure-fluctuation measurements in slug flow.

Signals from the measuring devices were recorded simultaneously in two different ways: a Honeywell Model 1508 C Visicorder with a frequency response of 1 kHz was used to print out a trace representing the signal. This recorder produces the traces by deflecting high-intensity light beams that are focused on a moving light-sensitive chart. The signals were also digitized and stored in a microcomputer for later analysis.

3. RESULTS

(*a*) *Pressure signals for slugs*

Figure 2 shows a typical set of recorded pressure measurements and the signal from the upstream pair of parallel wire probes, located 3.9 cm downstream from the downstream pressure transducer, which gives the ratio of the height of the liquid to the pipe diameter, h/D. It can be seen that at about $t = 4.05$ s a slug arrived at the upstream tap. This causes the pressure at that point to increase sharply because the cross section of the pipe is plugged. The slug has not reached the downstram pressure tap, as evidenced by a low h/D at that location. The downstream pressure does not experience any increase in pressure at this time because the upstream slug blocks the high pressure air behind it. When the slug reaches the downstream pressure tap the pressure and h/D simultaneously experience a sudden increase. A comparison of the h/D and downstream pressure signal shows that the pressure increase commences at the front of the slug and reaches a maximum at the tail of the slug (indicated by the drop in h/D) and then remains almost constant.

The pressures at both taps remain high until the slug leaves the pipe, at which point the two pressures drop simultaneously. This behavior indicates the slug sustains a competent blockage of the pipe throughout its existence.

Another distinctive feature of slug flow is that slugs travel approximately at the gas velocity, as shown by Hubbard (1965), Nicholson *et al.* (1977) and others. Pseudo-slugs and large waves, on the other hand, do not maintain a pipe blockage and are expected to travel at a speed much lower

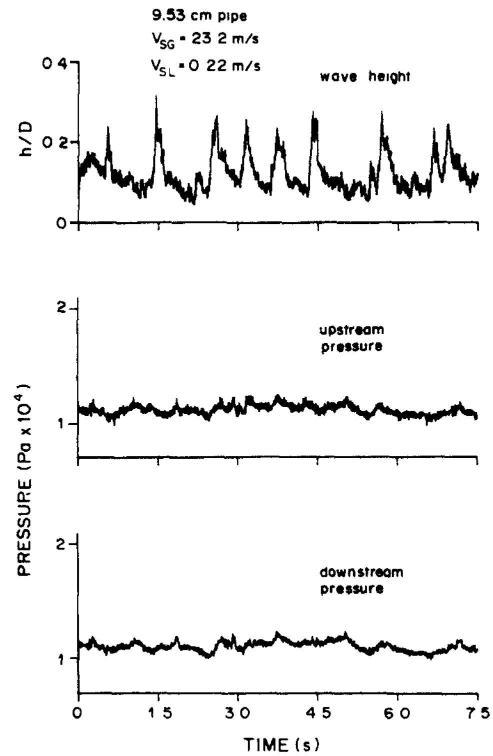


Figure 3. Wave-height and pressure-fluctuation measurements for pseudo-slugs.

than the gas velocity. The delay time between the arrivals of the two pressure signals gives a means of measuring the slug velocity. For the signals shown in figure 2, the delays for the two slugs are 0.1625 and 0.1500 s. The pressure taps were 2.25 m apart, so slug velocities of 13.8 and 14.9 m/s are to be compared with a superficial gas velocity, V_{SG}, of 15.2 m/s.

(*b*) *Pressure signals for pseudo-slugs*

Figure 3 shows pressure signals observed in the pseudo-slug regime. Large peaks in the h/D signal correspond to the observation of pseudo-slugs moving along the pipe. However, no large pressure pulses, of the type in figure 2, are observed. The reason is that the gas phase can flow through the pseudo-slug so that a huge pressure build up behind it is not possible. A measurement of the time delay in the wave-height signals shows that the pseudo-slug velocity is 2.83 m/s compared to a value of V_{SG} of 23.2 m/s.

For most cases slugs can be distinguished from pseudo-slugs by examining the amplitude of the pressure fluctuation at a single location. However, in some cases, especially when both the gas and liquid throughputs are high, the distinction is not so clear-cut. In these cases, pseudo-slugs plug the pipe momentarily and cause considerable pressure fluctuations. Since the blockage is only momentary, the pressure is not sustained for the entire duration of the existence of the pseudo-slug, as would have been the case for slugs. The second pressure transducer distinguishes whether the blockage of the pipe remains coherent through a long section of the pipe. Furthermore, the use of dual pressure transducers gives the direction of travel of the pressure wave, hence eliminating ambiguities caused by possible pressure reflections from downstream.

Figures 4a,b show the pressure signals obtained for annular and wavy stratified flows. The pressure fluctuations are much smaller than those observed for slugs and pseudo-slugs.

(*c*) *Cross-correlation functions*

A convenient way to represent the pressure signals for slug flows is to compute the cross-correlation function of the two pressure signals.

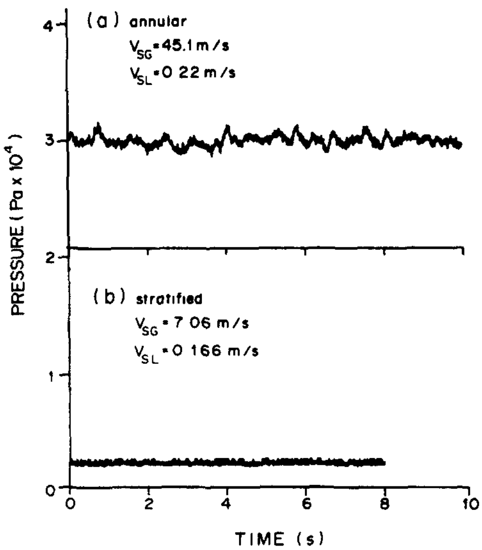


Figure 4. Pressure signals in (a) annular and (b) stratified flow in a 9.53 cm pipe.

If the pressure records as a function of time t at the upstream and downstream locations are represented by $P_U(t)$ and $P_D(t)$, respectively, then the means $\overline{P_U}$ and $\overline{P_D}$ are given by

$$\overline{P_U} = \lim_{T\to\infty} \frac{1}{T} \int_0^T P_U(t)\,dt$$

and

$$\overline{P_D} = \lim_{T\to\infty} \frac{1}{T} \int_0^T P_D(t)\,dt.$$

The cross-covariance C_{UD} of the two signals at delay time τ is then given as

$$C_{UD}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T [P_U(t) - \overline{P_U}][P_D(t+\tau) - \overline{P_D}]\,dt.$$

The autocorrelations at time delay zero, $R_U(0)$ and $R_D(0)$, of the two signals are given by

$$R_U(0) = \lim_{T\to\infty} \frac{1}{T} \int_0^T [P_U(t) - \overline{P_U}]^2\,dt$$

and

$$R_D(0) = \lim_{T\to\infty} \frac{1}{T} \int_0^T [P_D(t) - \overline{P_D}]^2\,dt.$$

The cross-correlation function, $R_{UD}(\tau)$, of the two pressure signals, $P_U(t)$ and $P_D(t)$, is obtained by normalizing $C_{UD}(\tau)$ with $R_U(0)$ and $R_D(0)$:

$$R_{UD}(\tau) = \frac{C_{UD}(\tau)}{R_U(0)R_D(0)}.$$

The cross-correlation function is hence dimensionless and has a value of between -1 and $+1$.

Figure 5a is a cross-correlation of the pressure signals in slug flow, a portion of which is presented in figure 2. A characteristic peak at a time delay of 0.145 s can be observed in the cross-correlation. This represents an average of the time delays of all the slugs in the record, including those shown

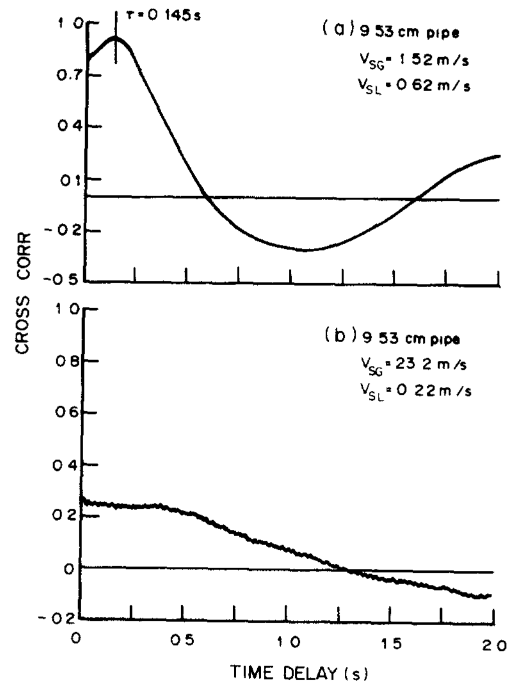
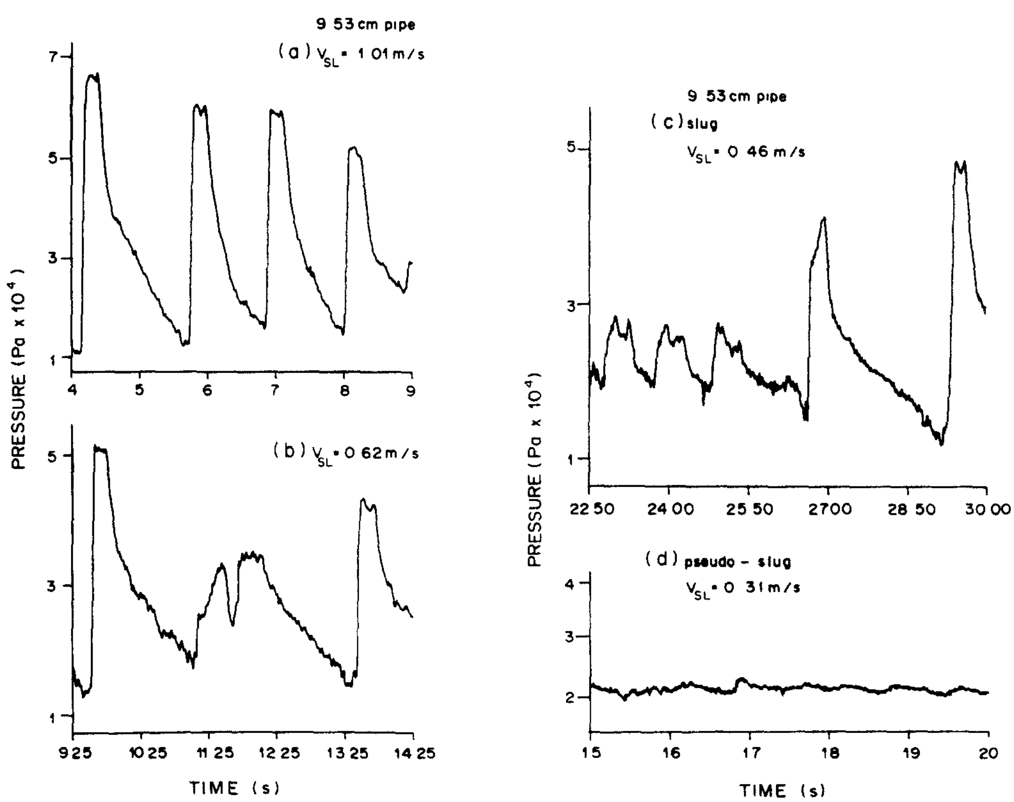


Figure 5



Figures 6a–d. Pressure signals in slug flow at $V_{SG} = 33$ m/s.

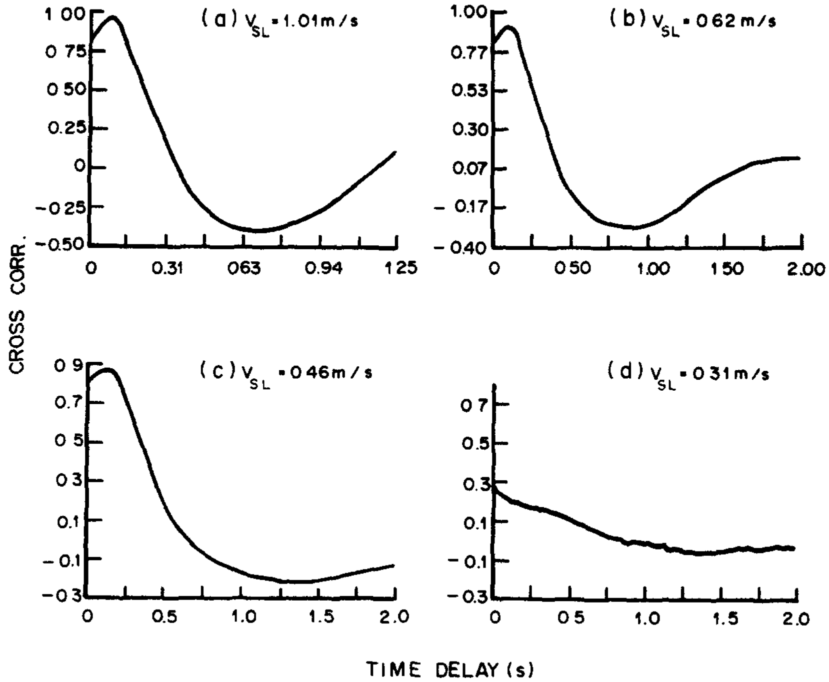


Figure 7. Cross-correlation in slug flow at $V_{SG} = 33$ m/s.

in figure 2. As discussed previously, this time delay compares well with the superficial gas velocity at the measurement points.

Figure 5b is a cross-correlation of the pressure signals in the pseudo-slug flow represented in figure 3. This cross-correlation function does not show a high degree of correlation except at zero time delay and, hence, is distinctively different from that for slug flow.

Figures 6a–d are portions of the pressure signals obtained at a constant V_{SG} of 33 m/s in the 9.53 cm pipe that illustrate the transition from slug to pseudo-slug flow. The corresponding cross-correlations of these measurements are presented in figures 7a–d. The transition from slug to pseudo-slug flow is distinctive in both the pressure signals and the cross-correlations.

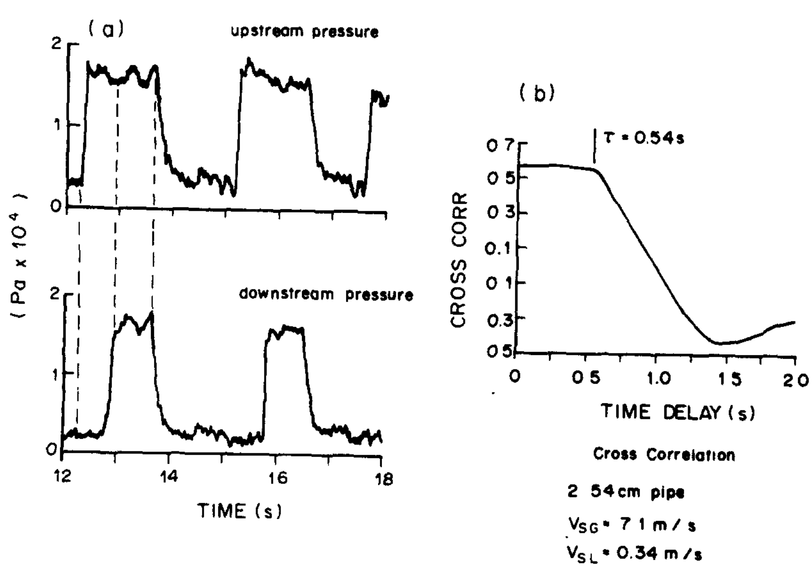


Figure 8. Cross-correlation of pressure signals for slug flow at low gas velocities.

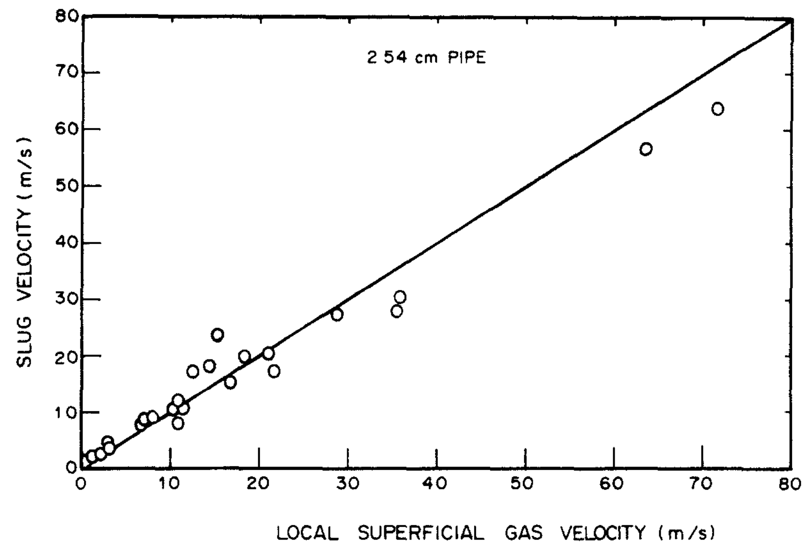


Figure 9. Slug velocity vs V_{SG} for the 2.54 cm pipe.

The shapes of the cross-correlation functions presented in figures 7a–d are typical of most of the slug flows observed in the 2.54 and 9.53 cm pipes. However, at low gas velocities the cross-correlation function may have a shape such as that shown in figure 8b. Figure 8a shows a portion of the pressure signals from which figure 8b was computed. The reason for this behavior is that the pressure signals are not "true" time-delay signals. Once the slug passes through both pressure taps, the pressures at both taps are almost identical. Provided the pressure signals on both sides of the pressure plateau for each probe are identical, as is the case in figure 8a, the signals for the two pressure taps will give the same degree of cross-correlation for all time delays from zero up to that which corresponds to the slug velocity. The pressure signals for slug flows at higher gas flow rates are not so symmetrical about the pressure plateau as for the case in figure 8a and hence do not generate a cross-correlation of the shape shown in figure 8b.

(*d*) *Slug and pseudo-slug velocities*

The slug velocities obtained from the cross-correlation of the pressure signals at various flow conditions are summarized in figure 9 for the 2.54 cm pipe and in figure 10 for the 9.53 cm pipe.

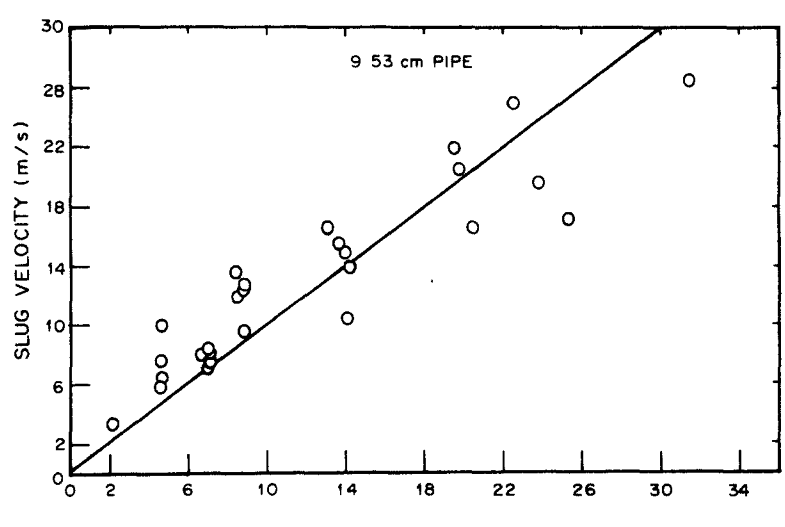


Figure 10. Slug velocity vs V_{SG} for the 9.53 cm pipe.

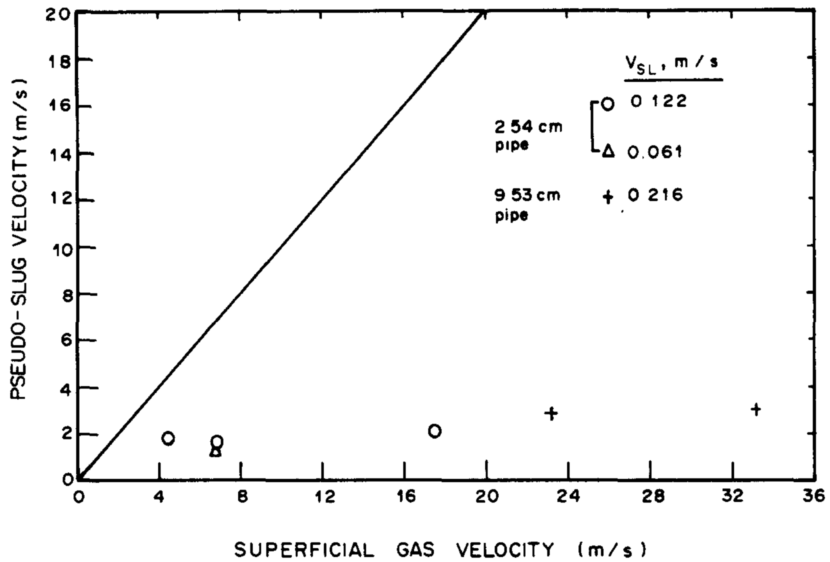


Figure 11. Pseudo-slug velocity vs V_{SG}.

In both cases, the slug velocity is plotted against the superficial gas velocity at the pressure taps. The agreement between the slug velocity and V_{SG} is quite good for both cases. Figure 11 presents some pseudo-slug velocities measured from the cross-correlation of the parallel-wire conductance probes. The velocities of pseudo-slugs are much lower than the gas velocities, as expected.

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