Int. J. Multiphase Flow Vol. 11, No. 1, pp. 31–41, 1985
Printed in the U.S.A.

0301-9322/85 $3.00 + .00
Pergamon/Elsevier

TRANSITION FROM STRATIFIED TO SLUG REGIME IN COUNTERCURRENT FLOW

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(*Received* 21 *November* 1983; *in revised form* 8 *May* 1984)

Abstract—In many two-phase flow situations the prediction on the conditions likely to instigate the change of flow pattern from the stratified regime to the slug flow condition is important. Since published material on such predictions for countercurrent flow is scarce this paper considers the influencing parameters for these conditions and then uses the data recorded from an experimental test rig to quantify the developed instability criterion equation.

1. INTRODUCTION

There has been extensive experimental and analytical studies to predict the regime of flow in two phase pipelines. These have shown that a good understanding can be gained from a two dimensional map of gas velocity versus liquid velocity in which the areas of different flow regime are identified. Clearly, this type of map can provide the design engineer with a good indication of the regime of flow he is likely to encounter. Also, sometimes of more importance to him is the chance that the regime of flow might change during the operation of his designed structure. In some cases this situation cannot be tolerated because such a change could unbalance the pressures and instigate an increased dynamic loading on a structure beyond an acceptable limit. An example of this is the design of certain two-phase natural gas pipelines since controlled stratified conditions are desired to make conditions more stable and to assist in the separation of the two phases at the terminal. By maintaining this stability the possibility of slug flow conditions and the resulting extra dynamic loading at the terminal is avoided.

Most of the previous work in this area has concentrated on the stability of the stratified flow condition in co-current flow (i.e. where both phases travel in the same direction). In contrast to this, published details on similar work on countercurrent flow (phases in different directions) is relatively scarce. There are some applications where such conditions prevail and the determination of the stability of the stratified regime is critical in the design of the system. An illustration of this is the flow in certain inlet pipes of a parallel bottle slugcatcher where the instigation of a slug, or bridging of the pipe by the liquid phase, could facilitate the dumping of a significant volume of liquid in the gas header system. This effect is often referred to as carryover and is obviously very undesirable and may indeed control the capacity of the downstream processing facilities. The countercurrent flow in these inlet pipes is brought about because in certain circumstances during the terminal's operation large volumes of condensate are introduced to the network and as this liquid fills up the main body of the slugcatcher displaced gas flows in an opposite direction to the incoming liquid.

Hence, to improve the general understanding of this instability, dimensionless groups were identified and then examined with the aid of experimental results to provide a numerical criterion for instability in countercurrent flow conditions.

2. THEORY

Baker (1954) carried out initial work where he outlined regime maps for two-phase flow which are still used today. Subsequent work of Govier & Omer (1962) and Al-Sheikh *et al.* (1970) concentrated on defining the appropriate dimensionless groups to predict these areas more accurately. Mandhane (1974) also produced an experimentally based map in terms of the superficial phase velocities. One of the main difficulties experienced when trying to correlate the work which has been completed in this area, is that the classification of the regimes is subjective and therefore susceptible to variation.

Stratified flow conditions have, in general, received most attention in the past because these conditions are probably the most commonly found in practical situations. Taitel & Dukler (1976) developed relationships based on a momentum balance to predict the various fluid parameters associated with two-phase stratified co-current flows in near horizontal pipes. Johnston (1983) conducted similar studies into co and countercurrent conditions and quantified these relationships by completing tests using two different fluid systems for a range of pipe gradients from level to 1/10.

The transition between stratified and slug flow (as defined in figure 1) has been described by Butterworth (1972) and Dukler & Hubbard (1975) as where at low gas and liquid flowrates stratified conditions are expected but as the liquid flowrate is increased the interfacial level rises and instigates a wave on the interfacial surface which continues to grow until a temporary blockage of the pipe occurs. This manifests the change from stratified to slug flow as described in figure 1.

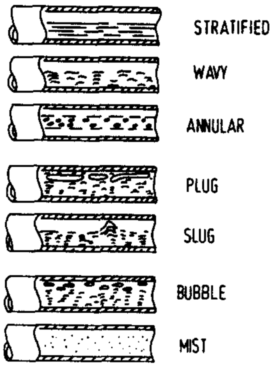

Figure 1. Two phase flow regimes.

It can be argued that using the Kelvin–Helmholtz theory described in Milne–Thomson (1960) that these infinitesimal waves if the liquid phase is between two plates which are parallel and horizontal will grow if:

$$U_G > \left[\frac{g(\rho_L - \rho_G)h_G}{\rho_G}\right]^{1/2} \qquad [1]$$

where U_G is the gas velocity in stratified condition; g is the gravitational acceleration; h_G is the gas depth; ρ_L is the density of liquid; and ρ_G is the density of gas.

A similar stability criterion can be applied to conditions where a finite wave is considered as shown in figure 2 where,

$$P - P' > (h_G - h'_G)(\rho_L - \rho_G)g \qquad [2]$$

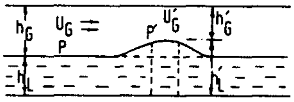

Figure 2. Interfacial wave.

where P is the pressure for stratified condition; P' is the pressure for interfacial wave condition; h'_G is the gas depth above interfacial wave, and where

$$P - P' = \tfrac{1}{2}\rho_G[U'^2_G - U_G^2] \qquad [3]$$

where U'_G is the gas velocity in interfacial wave condition.
The criterion for instability becomes;

$$U_G > C_1\left[\frac{g(\rho_L - \rho_G)h_G}{\rho_G}\right]^{1/2} \qquad [4]$$

in which

$$C_1 = \left[\frac{2}{\dfrac{h_G}{h'_G}\left(\dfrac{h_G}{h'_G} + 1\right)}\right]^{1/2} \qquad [5]$$

where C_1 is a parameter which reflects the size of the interfacial wave.

Comparing [1] and [4] the instability of finite waves is reached before the condition predicted by the infinitesimal waves since the value of C_1 must be less than unity. Therefore, [4] becomes the controlling criterion.

Using the same type of analysis, conditions for general pipe geometry where the pipe is inclined can be investigated and give,

$$U_G > \left[\frac{2(\rho_L - \rho_G)g\cos\alpha(h'_L - {}^hL)}{\rho_G}\right]\frac{A'^2_G}{A_G{}^2 - A'^2_G} \qquad [6]$$

where α is the gradient of pipe; h_L is the liquid depth to top of interfacial wave; h_L is the liquid depth; A'_G is the cross sectional area of gas above the interfacial wave; and A_G is the cross sectional area of gas.

Taitel & Dukler (1976) showed how this relationship could be expressed in a dimensionless form,

$$\underbrace{F^2\left[\frac{1}{C_2{}^2}\frac{U_G{}^2 d\tilde{A}_L/d\tilde{h}_L}{A_G}\right]}_{\text{(STAB)}} \geqslant 1 \qquad [7]$$

where F is a modified Froude number,

$$F = \sqrt{\rho_G/(\rho_L - \rho_G)}\cdot\frac{U_G^s}{\sqrt{Dg\cos\alpha}}$$

$$\frac{\mathrm{d}\tilde{A}_L}{\mathrm{d}\tilde{h}_L} = \sqrt{1 - (2\tilde{h}_L - 1)^2}$$

$C_2 = (1 - {}^hL/_D)$ is a parameter reflecting the position of the interfacial boundary; U_G^s is the superficial gas velocity; D is the diameter of pipe; and $\tilde{A}_L$ is the non dimensional area of liquid

$$= 0.25[\pi - \cos^{-1}(2\tilde{h}_L - 1) + (2\tilde{h}_L - 1)\sqrt{1 - (2\tilde{h}_L - 1)^2}]$$

$\tilde{A}_G$ is the non dimensional area of gas

$$\tilde{A}_G = 0.25[\cos^{-1}(2\tilde{h}_L - 1) - (2\tilde{h}_L - 1)\sqrt{1 - (2\tilde{h}_L - 1)^2}]$$

where $\tilde{h}_L$ is the non dimensional interfacial depth $= h_L/D$; and h_L is the liquid depth.

It is this stability criterion (STAB) which was examined using experimental data from the present study.

3. EXPERIMENTAL STUDY

To quantify the stability relationship introduced in[7] and to provide a better understanding of the flow conditions in two-phase countercurrent flow a test rig was constructed (figure 3) which facilitated the study of conditions for different, phase flowrates, pipe diameters and gradients of pipe. Since one of the objectives of the study was to provide information for a natural gas/condensate system which has a density ratio of 1/13 consideration had to be given to this ratio since it must have an effect on the flow regime. Modelling of these fluids is very difficult, firstly because the fluids themselves cannot normally be used due to their combustibility, and secondly, that other inexpensive more manageable fluids cannot achieve a similar density ratio. One solution to the problem is to use *two liquids* of varying density to simulate the two-phase gas liquid system. The selection of these liquids is not easy because there is the problem that many of the suitable liquids are incompatible with perspex and other construction materials used in models. The two liquids which were chosen were Kerosene (a liquid having a density of 800 kg/m^3) to represent the gas phase and zinc chloride solution (density up to 4000 kg/m^3) to simulate the liquid phase. Zinc chloride has the unusual quality that when added to water it goes into solution forming a mixture which can, if enough material is added, have the density of up to three to four times that of the original water. Consequently, a density ratio of over 4 is possible with this system which is of the same order of magnitude of that in the prototype.

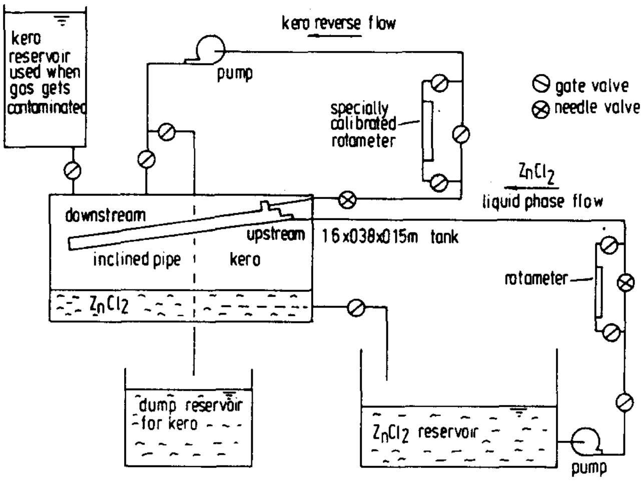

Figure 3. Experimental rig to study countercurrent flow conditions.

The experimental rig which was built to house these fluids and facilitate their interaction in a pipe of varying diameter and gradient is illustrated in figure 3 where the pipe is located in a rectangular bath (1.6 × 0.38 × 0.15 m). The bottom quarter of this tank was filled with the $ZnCl_2$ solution then the remaining volume was topped up with kerosene. A specially fabricated perspex pipe was immersed in this bath and hinged at entry end. To facilitate its change in gradient a vertical threaded bar was attached to the downstream end of the pipe. The performance of this perspex pipe unfortunately was not satisfactory due to the fact that kerosene slowly interacted with it and finally caused it to fail, consequently a glass tube was made and used for the final tests.

To instigate two-phase countercurrent flow conditions in the inclined pipe two circuits were used. The first involved the controlled free draining of the $ZnCl_2$ solution from the tank into a reservoir which fed a centrifugal pump. This reservoir was needed to let any kerosene which accidentally entered the drain to be separated out before entry to the pump. It was found that if the two fluids were fed to the pump simultaneously the high speed action of the impeller caused the fluids to be mixed which was extremely undesirable in these tests. The uncontaminated $ZnCl_2$ was therefore pumped through a control valve and then a specially calibrated rotameter bypass which was used to set the "liquid" phase flowrate at the entry of the inclined submerged pipe. Problems were also encountered with the pump in that either the fluids as they were, or when mixed, attacked the seals in the pump consequently the insides of both pumps were treated with lead paint. After the $ZnCl_2$ solution entered the inclined pipe it flowed down the pipe before returning to the base of the bath.

To instigate countercurrent flow in the pipe a second circuit was needed where a small tapping close to the entry of the inclined pipe was connected to the suction side of a centrifugal pump. Again this "gas" phase flow was controlled by a needle valve and its flowrate set by a specially calibrated rotameter before entering the pump. The accidental mixing of the two fluids at this pump again required attention since if the resulting cloudy mixture was returned directly to the bath it very quickly affected the whole top part of the bath thereby masking the required observations of the fluid interactions in the inclined pipe. It was found that this unwanted effect could be controlled using the two reservoirs shown in figure 3 where if the kerosene was clear, it could be fed directly back to the bath. However if it became contaminated it could be transferred to the bottom reservoir for eventual gravitational separation and the top reservoir opened to maintain steady conditions in the bath. When the contamination had cleared in the delivery from the pump the system could be returned to its initial mode.

Using the described system the changing from stratified two-phase flow conditions to slug conditions was studied for three pipe diameters (0.057, 0.069 and 0.095 m) for inclinations from level to 1/10.

4. DISCUSSION OF RESULTS

As implied in section 2 the different regimes of flow as outlined in figure 1 in two-phase situations and more specifically the actual threshold between one regime and another is open to a certain amount of subjective interpretation. Therefore, to allow the present results to be related to other work and to try to ensure consistency in this experimental study the following procedure was adopted.

A particular pipe diameter and gradient of the inclined pipe was set then the liquid phase pump was switched on and a small initial flow was set using the needle control valve. After the system stabilised a record of the interfacial depth was recorded using a carefully mounted camera. The next step was to instigate countercurrent flow in the pipe by starting the "gas" phase or kerosene pump and then slowly opening the needle valve. In general, with only the liquid phase switched on there would be a fairly level steady interfacial depth along the length of the pipe and as the back flow was introduced, waves were instigated along the interface from the downstream end of the pipe which then tended to grow and move towards the upstream end as the flow was increased. With further backflow increase these waves grew in amplitude at the downstream end until they bridged the pipe. When this occurred either the liquid slug moved quickly towards the entry or the bridging continued in a random manner with no net upstream movement of the slug. It was the former condition (sometimes called choking) which was taken as the point of demarcation between slug and stratified flow. It should be noted that in some cases if the liquid flowrate was sufficiently high it was possible that immediate slug conditions could be instigated.

In total 147 flow conditions were examined with a view to quantifying the stability criterion developed and expressed in [7]. To assist in this a Fortran program was used where essentially the pipe and phase geometries and the fluid characteristics were input and the resulting stability criterion was output; i.e.

input:
  density of fluid phases
  initial interfacial depth
  phase flowrates
  diameter of pipe
  gradient of pipe
intermediate parameters calculated:
  actual and dimensionless areas of phases
  actual and dimensionless phase velocities
  superficial velocity
  modified Froude number
final parameter calculated:
  stability criterion (STAB).

Figure 4 illustrates the results which were obtained with the 0.057 m diameter pipe

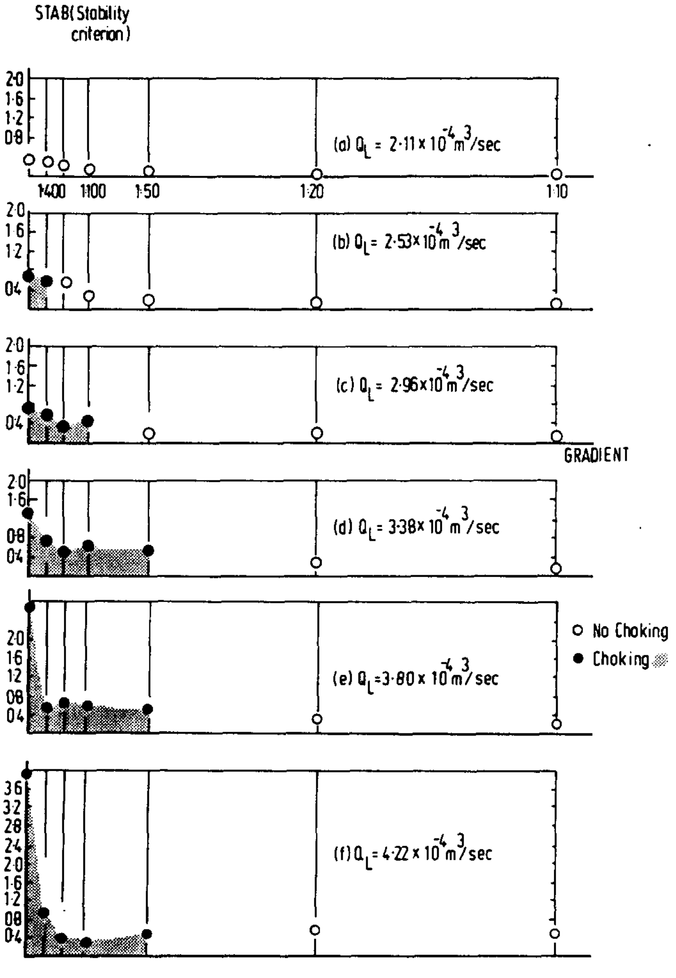

Figure 4. Instability of countercurrent flow in 0.057 m pipe.

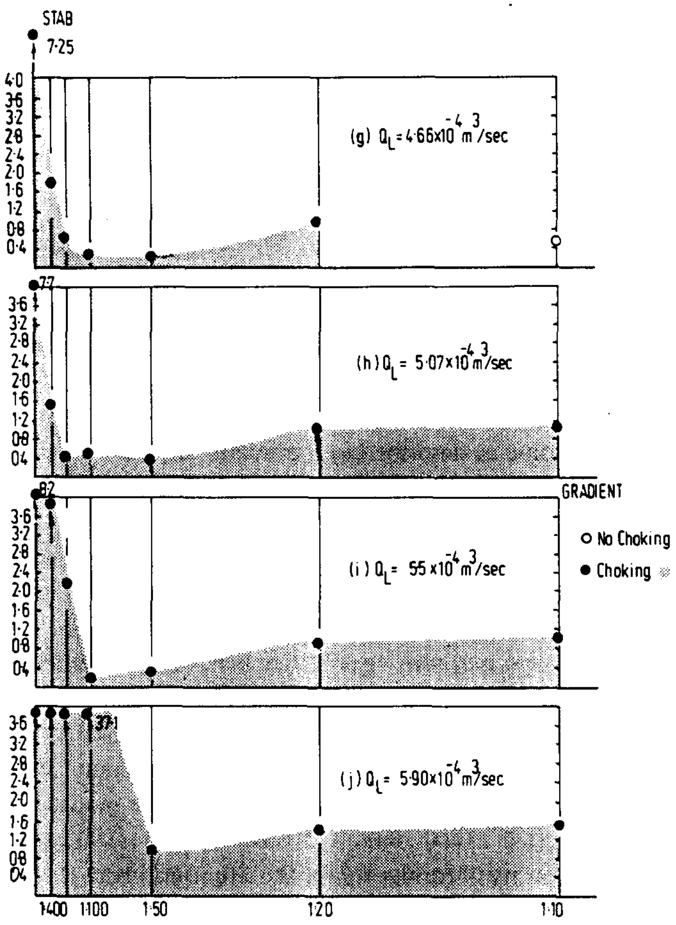

Figure 4. (cont)

when the liquid flowrate, (2.11 – 5.91 × 10^{-4} m^3/sec) the gas flowrate (2.11 – 5.91 × 10^{-4} m^3/sec) and the gradient of the pipe were varied. The open symbol (o) in this figure indicates that no choking was achieved with gas flowrate up to the magnitude of the corresponding liquid flowrate while the closed symbol (●) indicates that choking was possible at a gas flowrate less than or equal to the liquid flowrate. Consequently, figure 4(a) describes that at the initial liquid flowrate of 2.11 × 10^{-4} m^3/sec no choking was observed at any of the gradients for gas flowrates up to 2.11 × 10^{-4} m^3/sec. However, figure 4(b) indicates that choking was only possible at the level and 1/400 gradients. This initial trend of choking being closely related to the gradient continued as shown in figure 4(c)–(j) increased, until at a liquid flowrate of 5.07 × 10^{-4} m^3/sec the pipe was choked at the 1/10 gradient. As would be expected at these larger liquid flowrates the choking of the pipe at flatter gradients was facilitated by fairly small gas flowrates.

The reason for displaying these results in this format, instead of in a conventional two-phase map is that it is considered that the process in the countercurrent situation in the interfacial region of flow is relatively more complicated than the co-current situation, in that, there is a zone of gas phase entrainment as illustrated in figure 5. To allow for these processes and also to take account of the difficulties in measuring the interfacial depth when both phases are in operation the stability criterion is based on the initial interfacial depth with only the liquid phase in motion.

Figure 4 overall shows a number of interesting features regarding the location of the boundary between stratified and slug flow when the pipe choked. The first is that choking at all gradients is in general, observed at values of the stability number well below that

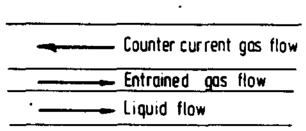

Figure 5. Gas entrainment in countercurrent flow.

of unity as perhaps suggested by [7]. Secondly, that the values of the choking stability number for different liquid flowrates at the same gradient and for different gradients is not constant. Table 1 gives details of these results. It is suggested that this variation is strongly related to the changing influence of gravity acting on the system. At the level gradient a mean stability number of 4.00, which is significantly greater than; the 1/400 value of 2.60, the 1/200 value of 0.65 and the 1/100 value of 0.15. This trend can perhaps be explained in that the choking of the pipe as described in a previous section is initially caused by the growth of a wave and in the four gradients named upstream and downstream conditions have a major influence in the growth of this wave. At the level gradient both phases enter the pipe in a direction parallel to the longitudinal axis of the pipe and so the flow remains in a stratified condition until a relatively high stability number is reached. However, when the pipe gradient is slightly changed the liquid phase enters the pipe in a direction slightly different to the axis of the pipe and also "gas" entry is not as streamlined as before. Both effects combine to encourage the growth of the choking wave resulting in the lower choking stability numbers at the 1/400, 1/200 and 1/100 gradients. However this trend is changed after the 1/100 gradient because gravity becomes the dominant force and in effect suppresses the growth of the choking wave. This results in the gradual increasing of the choking stability numbers (i.e. 1/100 : 039, 1/50 : 0.40, 1/20 : 0.93, and 1/10 : 0.97). It should be noted that the majority of results are for the situation where the gas flowrate is less than the magnitude of the liquid flowrate which is due to the fact that the main thrust of this work was to find a solution for a particular applied situation where these conditions were prevalent. To generalise this investigation a number of results were taken with

Table 1. Choking stability numbers (STAB) recorded in 0.057 m pipe

Liquid Flowrate m^3/sec $X10^{-4}$	Gradient of Pipe Level	1/400	1/200	1/100	1/50	1/20	1/10
2.11	n.c.(0.50)	n.c.(0.48)	n.c.(0.46)	n.c.(0.41)	n.c.(0.36)	n.c.(0.33)	n.c.(0.28)
2.53	0.65(0.52)	0.55(0.50)	n.c.(0.49)	n.c.(0.44)	n.c.(0.40)	n.c.(0.39)	n.c.(0.32)
2.96	0.73(0.54)	0.58(0.51)	0.37(0.46)	0.43(0.45)	n.c.(0.39)	n.c.(0.38)	n.c.(0.36)
3.38	1.26(0.59)	0.73(0.54)	0.48(0.49)	0.55(0.49)	0.51(0.44)	n.c.(0.39)	n.c.(0.32)
3.80	2.35(0.65)	0.48(0.51)	0.65(0.52)	0.59(0.46)	0.52(0.44)	n.c.(0.38)	n.c.(0.35)
4.22	3.98(0.69)	0.83(0.59)	0.37(0.52)	0.28(0.48)	0.41(0.42)	n.c.(0.41)	n.c.(0.40)
4.64	7.25(0.72)	1.77(0.64)	0.62(0.56)	0.31(0.49)	0.23(0.41)	0.88(0.43)	n.c.(0.38)
5.07	7.68(0.78)	1.50(0.64)	0.40(0.54)	0.41(0.50)	0.38(0.43)	1.06(0.44)	0.95(0.42)
5.49	8.16(0.77)	8.16(0.77)	2.17(0.66)	0.17(0.47)	0.34(0.49)	0.86(0.47)	0.98(0.44)
Mean Result	4.00	1.83	0.72	0.39	0.40	0.93	0.97
Standard Deviation	3.24	2.60	0.65	0.15	0.11	0.11	0.02

- n.c. no choking
- figures in brackets after stability number indicate the initial interfacial depths

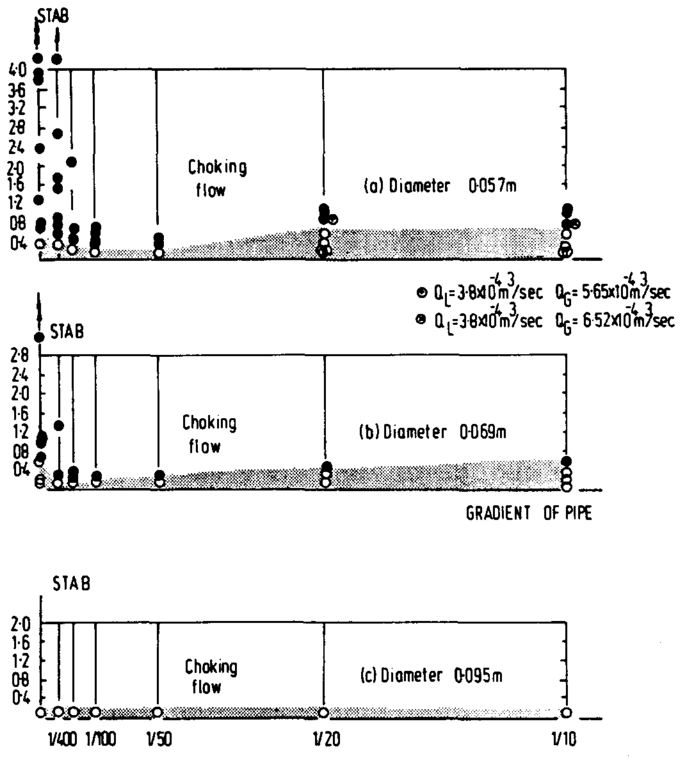

Figure 6. Instability of countercurrent flow in 0.057, 0.069 and 0.095 m pipes.

increased gas flowrate component as shown in figure 6a, and they seem to agree with the rest of the results in their definition of the demarcation boundary.

Another feature of these results is the variation in the choking stability number at particular gradients which is quantified in table 1 were the standard deviation of the results at each gradient is calculated. These show larger variations at the flatter gradients compared to the steeper gradients and this again is attributed to the increased influence of gravity as it tends to control the wave growth at the steeper gradients.

The above trends were also observed when the other two pipes were tested (diameter = 0.069, 0.095 m) as shown in figure 6 although only a few results could be obtained with the 0.095 m pipe because of insufficient capacity of the pumps. In turn *all* these results are shown in figure 7 in addition to a number of results from Wallis & Dobson (1973) and Kordyban & Ranov (1970). Both these results were for water/air systems where Wallis and Dobson studies were in a rectangular duct while Kordyban & Ranov were in

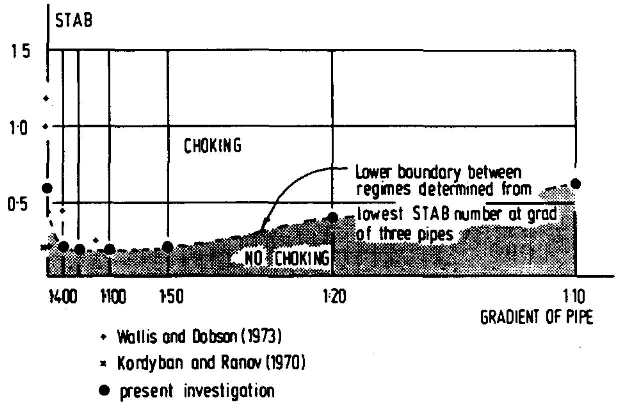

Figure 7. Comparison of present results and previous investigators.

circular pipes. However, both results seem to agree with the present investigation in identifying the stability criterion numbers thereby perhaps indicating their acceptance for any two phase countercurrent system. Clearly more results in such systems need to be taken to verify this observation.

5. CONCLUSIONS

On the basis of the theoretical and experimental study completed the following conclusions were reached.

(1) The prediction of the changing of the regime of flow from stratified to slug flow in countercurrent flow can be made using a stability criterion (or number) which is based on the growth and collapse of the interfacial wave.

(2) The experimental results showed that the stability criterion number to be well below (down to 0.17) that perhaps expected from theoretical considerations (1.0). Furthermore, these results also showed that there is quite a variation in the stability number and that care should be taken if using a constant value in calculations.

(3) At fairly gentle gradients (level to 1/100) this criterion is influenced by; viscous forces, inlet conditions and gravity to varying degrees. Combinations of the effects of these forces result in the rather unusual trend of the stability number decreasing with increasing gradient i.e.

Gradient	Mean stability number
Level	4.00
1/400	1.83
1/100	0.72
1/100	0.39

(4) At steeper gradients the stability is predominantly affected by the gravitational force consequently the larger the gradient, the larger the stability number, i.e.

Gradient	Mean stability number (STAB)
1/100	0.39
1/50	0.40
1/20	0.93
1/10	0.97

(5) The choking stability criterion is observed to be within narrower limits at the steeper gradients, i.e.

Gradient	Standard deviation of stability number (STAB)
Level	3.24
1/400	2.60
1/200	0.65
1/20	0.11
1/10	0.02

It is believed that this is due to the increasing influence of gravity, in that, as the gradient increases gravity tends to suppress the growth of the choking wave and thereby makes the system more controllable.

(6) Although more results are needed from countercurrent flow of fluids of different density several results analysed from previous investigators indicate that the defined choking stability number boundary could be used for general two phase conditions.

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