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THE ELIMINATION OF SEVERE SLUGGING—EXPERIMENTS AND MODELING

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Abstract—Severe slugging can occur in a pipeline–riser system operating at low liquid and gas rates. The flow of gas into the riser can be blocked by liquid accumulation at the base of the riser. This can cause formation of liquid slugs of a length equal to or longer than the height of the riser. A cyclic process results in which a period of no liquid production into the separator occurs, followed by a period of very high liquid production. This study is an experimental and theoretical investigation of two methods for eliminating this undesirable phenomenon, using choking and gas lift. Choking was found to effectively eliminate or reduce the severity of the slugging. However, the system pressure might increase to some extent. Gas lift can also eliminate severe slugging. While choking reduces the velocities in the riser, gas lift increases the velocities, approaching annular flow. It was found that a relatively large amount of gas was needed before gas injection would completely stabilize the flow through the riser. However, gas injection reduces the slug length and cycle time, causing a more continuous production and a lower system pressure. Theoretical models for the elimination of severe slugging by gas lift and choking have been developed. The models enable the prediction of the flow behavior in the riser. One model is capable of predicting the unstable flow conditions for severe slugging based on a static force balance. The second method is a simplified transient model based on the assumption of a quasi-equilibrium force balance. This model can be used to estimate the characteristics of the flow, such as slug length and cycle time. The models were tested against new severe slugging data acquired in this study. An excellent agreement between the experimental data and the theoretical models was found. Copyright © 1996 Elsevier Science Ltd.

Key Words: severe slugging, pipeline–riser system, Bøe criterion

1. INTRODUCTION

Severe slugging is a phenomenon which may occur in a pipeline–riser system where a downward inclined or undulating pipeline is flowing into a vertical riser. For such a system, at low liquid and gas rates, liquid accumulates in the riser and the pipeline, blocking the passage of the gas flow. This results in a compression of the gas in the pipeline. When the gas pressure in the pipeline has increased enough to counter the hydrostatic head of the liquid column, the gas will expand and push the liquid column out of the riser and into the separator.

Severe slugging causes periods of no liquid or gas production into the separator followed by very high liquid and gas rates, when the liquid slug is being produced. This phenomenon is highly undesirable due to the large pressure and flow rate fluctuations it causes. The large liquid production might cause overflow and shut down of the separator. Fluctuations in gas production might cause operational problems during flaring, and the high pressure fluctuations might reduce the production capacity of the field.

Severe slugging is by definition the buildup of liquid slugs equal to or longer than one riser height and is normally described as consisting of four phases: slug formation; slug production; blowout, and liquid fall back. It should be noted that cyclic flow instability in the riser with the buildup of slugs shorter than one riser height can also occur, but these are normally of a less severe nature since a complete blockage of the gas does not occur.

The basic unrestricted (no elimination) severe slugging cycle has been studied and explained by several investigators (Bøe 1981; Fabre *et al.* 1987; Fuchs 1987; Pots *et al.* 1987; Schmidt *et al.* 1980, 1985; Taitel *et al.* 1986, 1990; Vierkandt 1988; Yocum 1973). However, few systematic studies have been conducted to account for the changes in the operational conditions when applying methods to eliminate severe slugging (Hill 1989, 1990; Jansen *et al.* 1990, 1994; Pots *et al.* 1987; Schmidt *et al.* 1979; Yocum 1973).

Schmidt *et al.* (1979) recognized that choking can eliminate severe slugging. However, no complete analysis of the choke behavior was presented. The choke has been found to eliminate severe slugging by increasing the back pressure proportionally to the velocity increase at the choke. If the acceleration of the gas front up the riser is stabilized before reaching the choke, steady flow will eventually occur.

Another method of elimination that has been looked upon with interest is gas lift. Although Schmidt *et al.* (1979) and Yocum (1973) considered gas lift to be too expensive, Pots *et al.* (1987) and Hill (1989, 1990) have studied the effect of gas injection on severe slugging characteristics in a pipeline–riser system. The drawback of gas lift is the large gas volumes needed to obtain a satisfactory stability of the flow in the riser. The primary benefit of gas injection is to reduce the hydrostatic head in the riser and thus, reduce the pipeline pressure. The injected gas also tends to carry the liquid and, thus, keep the liquid moving up the riser. When sufficient gas is injected the liquid will be continuously lifted and a steady flow will occur.

The objective of this paper is to study theoretically and experimentally two methods for the elimination of severe slugging: choking and gas lift. In the analytical development two theoretical approaches are used. The first approach is a stability analysis of the system. This analysis utilizes the stability concept presented by Taitel (1986) and performs an overall force balance including the effects of the choke and gas lift. The second approach is an extension of the quasi-equilibrium model presented by Taitel *et al.* (1990) to include the performance of the choke and gas lift. While the stability model is a time independent force balance assuming severe slugging to occur for unstable riser flow conditions, the quasi-equilibrium model is a transient model. Both models are tested against new experimental data for both choking and gas lift.

2. ANALYSIS

2.1. *Stability model*

2.1.1. Choking. The stability model predicts the boundary between stable (steady flow) and unstable riser flow (severe slugging). Under stable flow conditions no blockage occurs at the bottom of the riser and a steady state flow, in the form of bubble or slug flow, occurs. For unstable conditions a liquid blockage and build up will occur, resulting in a cyclic process. The model is based on the assumption that the blowout mechanism of severe slugging is initially gravity dominated. To define the boundary conditions for the stability analysis, a slug is assumed fully developed and ready to be blown out of the riser ($Z = H$), but no pipeline penetration occurs ($x = 0$) (see figure 1). The pipeline pressure is countering the hydrostatic pressure and the gas front is just about to enter the riser. At the initial conditions, the liquid influx into the riser should be equal to the superficial liquid velocity (i.e. no gas penetration into the riser and no liquid penetration into the pipeline). This means that the liquid in the riser and at the top should be moving with a velocity close to U_{LS} when no gas injection occurs. The pressure drop across the choke is given by [A2]. The back pressure upstream of the choke is then:

$$P_B = P_S + CU_{LS}^2, \tag{1}$$

where C is the choke coefficient. For single-phase liquid flow, C is a function of the bean size only and can be measured directly.

When the gas pressure in the pipeline exceeds that of the liquid hydrostatic head in the riser, the gas phase starts expanding and entering the base of the riser with an intruding gas front of height y. This action is assumed to cause an instantaneously increase of the pressure at the choke (assuming the riser to be completely liquid filled and in incompressible conditions). This additional pressure is assumed to be proportional to the intrusion height, Ky, where K is a proportionality

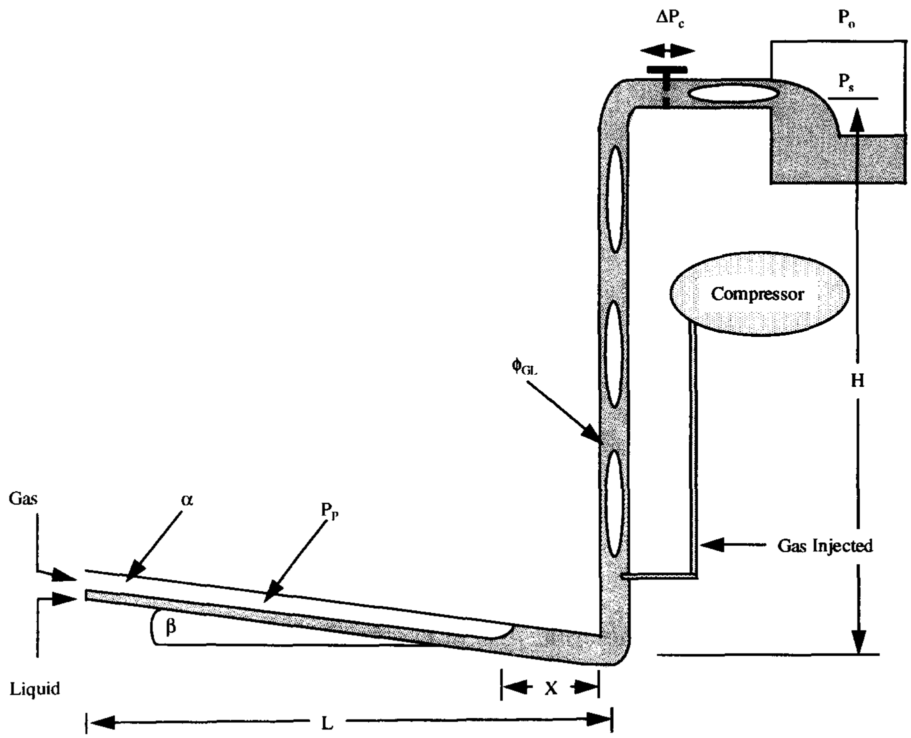

Figure 1. Pipeline–riser configuration with choking and gas lift.

constant (proof is given later). The increase in pressure upstream of the choke can be written as:

$$P_B - (P_S + CU_{LS}^2) = Ky. \qquad [2]$$

Using the same stability analysis, as given by Taitel (1986), the onset of severe slugging is determined by the difference between the buildup of the pressure force in the gas phase and the increase of the hydrostatic head. When the gas front has just started to penetrate the riser with a height y, the net force per unit area acting on the interface between the end of the liquid slug and the front of the penetrating gas phase (assuming isothermal expansion) can be given by:

$$\Delta F = F_1 - F_2 = \left[(P_S + CU_{LS}^2 + \rho_L gH)\frac{\alpha L}{\alpha L + \alpha' y}\right] - [P_S + CU_{LS}^2 + Ky + \rho_L g(H-y)]. \qquad [3]$$

The first term on the right hand side is the gas pressure force caused by the expansion of the gas in the pipeline. The second term on the right hand side is the back pressure force caused by the liquid column of height $H - y$, the separator pressure and the choke. The gas–liquid interface at the base of the riser will be in equilibrium ($\Delta F = 0$) for $y = 0$. The void fraction of the gas front entering the liquid column is α'. The value of α' for the experiments conducted was found to be in the range of 0.5–0.75. If the gas driving force increases relative to the hydrostatic pressure with respect to the intruding gas front, the gas front will be accelerated up the riser, blowing out the liquid and causing an instability in the riser. The frictional losses are neglected since only the instantaneous change in the force balance, where the velocity is still small, is considered. Thus, the criterion for stable flow in the riser is given as:

$$\frac{d(\Delta F)}{dy} < 0 \quad \text{and} \quad y = 0. \qquad [4]$$

If this criterion is satisfied, the intruding bubble will not be accelerated up the riser and no blowout will occur. This will lead to a stable flow in the riser. Differentiating [4], the stability criterion can be written as:

$$\frac{P_S + CU_{LS}^2}{P_O} > \frac{\dfrac{\alpha L}{\alpha'}\left(1 - \dfrac{K}{\rho_L g}\right) - H}{\dfrac{P_O}{\rho_L g}}. \qquad [5]$$

This criterion is independent of U_{GS} and gives a straight line as shown in figure 2 (stability of severe slugging), overlapping the top of the Bøe criterion for the case of no elimination. The solution of the stability criterion is based on the assumption that there exists a direct relationship between the choke coefficient, C, and the proportionality constant, K. To find this relationship it is assumed that the excess force imbalance in [3] causes an acceleration of the gas front up the riser. This acceleration term can be expressed in the form of Newton's law as follows:

$$A\Delta F = \frac{d(A(H-y)\rho_L U)}{dt}, \qquad [6]$$

where U is the total velocity of the liquid slug due to the velocity increase caused by the penetration of the gas front, instantaneously pushing the liquid slug ahead.

The pressure drop across the choke can also be expressed as a function of the velocity increase of the liquid slug in the riser:

$$P_B - P_S = CU^2. \qquad [7]$$

The initial assumption was that the pressure increase due to the penetration of the gas front into the base of the riser is proportional to the height of the gas penetration. Substituting [3] for ΔF in [6] and noticing that $U = \alpha'(dy/dt)$ results in a differential equation for U as a function of y. The solution for small y is (i.e. $y/H \ll 1$):

$$U^2 = U_{LS}^2 + \frac{2}{H}U_{LS}^2 y. \qquad [8]$$

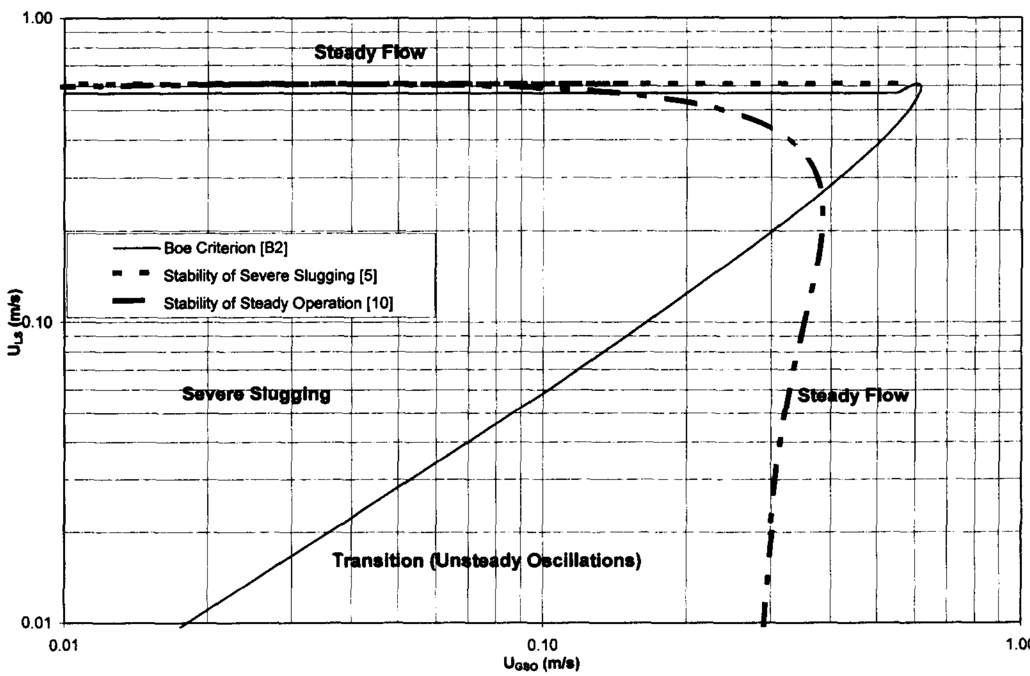

Figure 2. Severe slugging map—no elimination.

Substituting [8] into [7] and comparing to [2] show that:

$$K = \frac{2CU_{LS}^2}{H}. \quad [9]$$

For the case where a steady state operation occurs, a steady flow of gas up the riser can be assumed (i.e. total blockage of the pipeline does not occur). If the average holdup in the riser is Φ, the average density in the riser (neglecting the gas density) can be expressed as $\Phi\rho_L$. Replacing the liquid density with this average density, the stability criterion can be rewritten as:

$$\frac{P_S + CU_{LS}^2}{P_O} > \frac{\frac{\alpha L}{\alpha'}\left(\Phi - \frac{K}{\rho_L g}\right) - \Phi H}{\frac{P_O}{\rho_L g}}. \quad [10]$$

The decrease in the riser density reduces the value of the right hand side. It must also be noticed that the pressure drop across the choke is no longer due to single-phase liquid flow. Thus, both C and K are now variables, depending on the relative mixture of gas and liquid. However, to simplify the expression, the single-phase choking relationship in [A2] is used as an approximation in the equation for the time averaged operational conditions. Based on this assumption, the two-phase pressure drop across the choke is still given by [A2].

The stability criterion for steady operation will identify an unstable area which is outside the severe slugging area given by the Bøe criterion (1981). It should be noted that the Bøe criterion applies to severe slugging without elimination (see figure 2 for the case of no elimination). The cyclic flow in the area bounded by the stability criterion outside the Bøe criterion has been called unstable oscillations.

Unstable oscillations is a cyclic flow phenomenon where the liquid slugs are shorter than one riser height, no penetration occurs into the pipeline and gas continuously flows into the riser. This cyclic motion may or may not be damped into steady state. Severe slugging and indefinite oscillations are assumed to occur when the riser flow is unstable. The unstable region is given by the stability criterion and the Bøe criterion. Below the stability criterion line, unstable flow occurs, and above this line stable and steady flow occurs. Unstable oscillations occur in the area outside the region given by the Bøe criterion and below the line given by the stability of the steady operation criterion.

The stability criterion is a function of the pipeline gas volume which is represented by the length of the pipeline, L. This criterion can be applied directly to a real pipeline riser system as long as stratified flow occurs in the pipeline.

2.1.2. Gas lift. The stability model has also been extended by assuming a constant gas injection rate at the base of the riser. Gas injection reduces the average liquid holdup in the riser. For the case where only gas from the gas lift flows in the riser and no pipeline gas penetrates the riser, the stability criterion is given as (subscript GL designates gas lift):

$$\frac{P_S}{P_O} > \frac{\frac{\alpha L}{\alpha'} - H}{\frac{P_O}{\Phi_{GL}\rho_L g}}, \quad [11]$$

where:

$$\Phi_{GL} = 1 - \frac{U_{GSGL}}{U_T} \quad [12]$$

$$U_T = C_O U_S + U_O \quad [13]$$

and where the values for C_O and U_O are 1.2 and $0.35\sqrt{gD}$, respectively, for fully developed Taylor bubbles. For bubble flow the values are $C_O = 1.0$ and U_O is given by the Harmathy equation (1960).

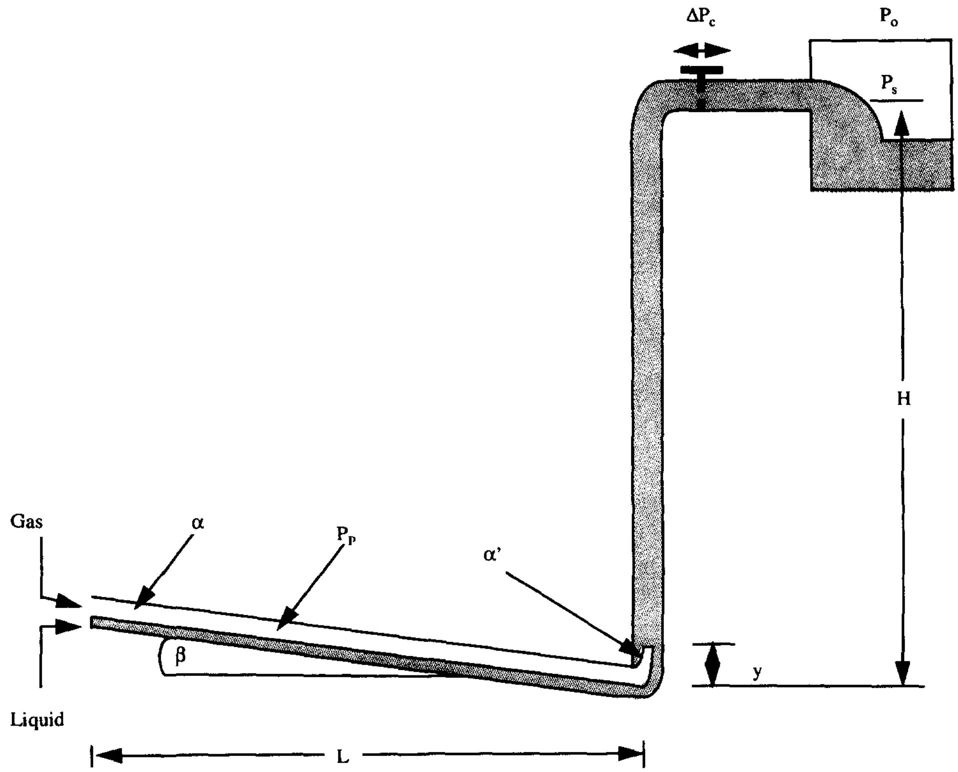

Figure 3. Pipeline–riser configuration with choking and gas penetration.

When a steady operation occurs and a steady stream of gas flows from the pipeline into the base of the riser in addition to the gas lift, the stability criterion is written as:

$$\frac{P_S}{P_O} > \frac{\frac{\alpha L}{\alpha'} - H}{\frac{P_O}{\Phi_T \rho_L g}}, \qquad [14]$$

where Φ_T is the total average liquid holdup in the riser due to both the pipeline gas and the injected gas ($\Phi_T < \Phi_{GL}$):

$$\Phi_T = 1 - \frac{(U_{GSGL} + U_{GS})}{U_T} \qquad [15]$$

and:

$$U_S = U_{LS} + U_{GSGL} + U_{GS}. \qquad [16]$$

The equations for choking ([5] and [10]) can easily be combined with the equations from the gas lift ([11] and [14]) to form a combined equation for both gas lift and choking.

2.2. *Quasi-equilibrium model*

2.2.1. Process description. A method to predict different flow types and calculating slug lengths and cycle times was presented by Vierkandt (1988) and Taitel *et al.* (1990). This analysis is based on the assumption of quasi-equilibrium and is a simplified transient analysis, where the system is assumed to be in equilibrium at each new time step. During the process the gas phase front is being tracked and the local holdup and phase velocities are determined along the riser for each new time step. A detailed derivation of this model is given in Taitel *et al.* (1990) and Vierkandt (1988). The following section presents a modification of this work, where the effects of a riser top choke and riser base gas injection have been incorporated.

The quasi-steady process can be described as follows. The process begins when the riser is full of liquid and the gas penetrates into the riser. It is assumed that the gas is penetrating under stable equilibrium conditions; thus, no blowout occurs. As a result of gas penetrating into the riser, the void fraction increases and the hydrostatic pressure decreases. Because of the pressure decrease and the subsequent expansion of the gas in the pipeline, the mass flow rate of the gas into the riser increases. This continues until the riser is completely aerated and the riser bottom pressure reaches a minimum. When the minimum riser bottom pressure is reached, the gas rate into the riser decreases. This, in turn, causes an increase of the liquid holdup in the riser. As the liquid accumulates in the riser, the incoming gas rate can become zero or negative, causing the liquid to penetrate into the pipeline, resulting in a cyclic process. The process will become steady state if the rate of penetration of gas into the riser is always positive.

When the penetration of gas into the riser becomes zero, liquid blocks the bottom of the riser. This is followed by a movement of the liquid interface into the pipeline, which blocks the gas passage into the riser until the liquid interface again reaches the bottom of the riser. At this point, penetration of gas into the riser starts and a new cycle begins.

Three different flow configurations can occur as a result of gas penetration into the liquid column in a quasi-steady process (Vierkandt 1988), as described below:

1. The penetration of the gas into the riser leads to oscillation, ending in a stable steady state two-phase flow.
2. The penetration of the gas into the riser leads to a cyclic operation without fall back of liquid.
3. The penetration of the gas into the riser leads to a cyclic operation with fall back of liquid.

Processes 2 and 3 are both severe slugging cycles. The difference between the two cycles is that for process 2, the liquid velocity in the liquid slug buildup phase is high enough to carry the liquid up the riser. For process 3, the liquid velocity is not sufficient to carry the liquid up the riser, resulting in a liquid fall back and the creation of a clear interface between gas and liquid as the liquid interface is propagating towards the top of the riser.

2.2.2. Incorporation of choking and gas lift. The quasi-equilibrium model is modified in this section to account for the increased pressure in the riser due to the choking. Since the quasi-equilibrium model is a transient model, it is important to be able to accurately model the choke behavior during the transient process. To model the choke behavior, it is necessary to correct the choking coefficient for two-phase flow and to estimate the liquid velocity at the choke (see appendix A).

The assumption for the modifications to the quasi-equilibrium model with respect to gas lift is similar to the one made for the modifications to the stability model. A steady flow of gas is being injected at the base of the riser. This steady gas flow moves up the riser with a constant average superficial velocity and reduces the liquid holdup along the length of the riser, contributing to a reduced hydrostatic head.

The analysis starts with the riser full of liquid, with gas just beginning to enter the riser ($Z = H$, $x = 0$, $P_P = P_{MAX}$). The pressure in the pipeline, P_P, is equal to the separator pressure, P_S, plus the weight of the hydrostatic column, $\Phi \rho_L g y$, and the pressure drop across the choke, ΔP_C:

$$P_P = P_S + \Delta P_C + \int_0^H \phi \rho_L g \, dy, \qquad [17]$$

where ϕ is the local holdup in the riser. From the expansion of the gas in the pipeline, the mass flow rate of gas, m_G, into the riser can be determined from:

$$m_G = m_{GO} - \frac{\alpha L A}{RT} \frac{dP_P}{dt}, \qquad [18]$$

where m_{GO} is the mass flow rate of the gas from the pipeline into the system at standard conditions. The pressure derivative with respect to time can be estimated by:

$$\frac{dP_P}{dt} = \frac{P_{new} - P_{old}}{\Delta t}. \qquad [19]$$

Since transient two-phase flow occurs, the two-phase choking coefficient, C', [A4], should be used. Rewriting [18], the average superficial gas velocity entering the riser is given by:

$$U_{GS} = \frac{m_{GO}}{\rho_G A} - \frac{\alpha L}{\rho_G RT}\frac{(P_S + \Phi\rho_L gH + C'U_S^2 - P_{old})}{\Delta t}. \quad [20]$$

Since U_S is a function of both the superficial liquid and gas velocities, this becomes a quadratic expression where the positive root is:

$$U_{GS} = -U_{LS} + \sqrt{U_{LS}^2 - \frac{1}{C'}\left[(P_S + \Phi\rho_L gH + C'U_{LS}^2 - P_{old})\left\{\frac{m_{GO}RT\Delta t}{\alpha LA}\right\}\right]}. \quad [21]$$

When gas lift also occurs, a constant rate of gas is assumed to be injected at the base of the riser. This decreases the liquid holdup in the riser and increases the total gas velocity. The total liquid holdup is given by [15].

The average superficial gas injection velocity based on average gas density can be written as:

$$U_{GSGL} = \frac{m_{GGL}}{\rho_G A}. \quad [22]$$

2.2.3. Cyclic flow without fall back. The previous analysis is valid for the case of no liquid penetration into the pipeline and for conditions where m_G is positive. When no liquid fall back occurs, the pipeline pressure at any time can be given as (neglecting friction and acceleration terms):

$$P_P = P_S + \Delta P_C + \rho_L g(\Phi H - x\sin\beta), \quad [23]$$

where x is the distance of liquid penetration into the pipeline. Applying a mass balance on the gas volume in the pipeline, and assuming an ideal gas behavior gives:

$$\left[\frac{P_S + \Delta P_C + \rho_L g(\Phi H - x\sin\beta)}{RT}\right](L - x)\alpha A = \left[\frac{P_S + \Delta P_C + \rho_L g\Phi_i H}{RT}\right]L\alpha A + \int_{t_i}^{t} m_{GIN}\,dt. \quad [24]$$

The mixture velocity is calculated on the basis of the liquid mass balance:

$$U_S = U_{LS} + U_{GSGL} - \alpha\frac{dx}{dt}. \quad [25]$$

Thus, at time t_i when there is no gas flow into the riser, $U_S = U_{LS} + U_{GSGL}$, $(m_G = U_{GS} = 0)$. The liquid velocity at the top of the riser can also be obtained from a mass balance:

$$U_L = \frac{U_S - U_T(1 - \phi_{top})}{\phi_{top}}. \quad [26]$$

2.2.4. Cyclic flow with fall back. If U_L in [26] is less than zero, fall back occurs and the interface between liquid and gas is established at height Z. The values of $x(t)$ and $z(t)$ can be found from a similar mass balance as [24].

When fall back occurs, the top of the riser becomes clear of liquid and a liquid slug builds up in the riser and the pipeline, while the liquid slug moves towards the top of the riser. The initial apparent liquid height in the riser is calculated by $Z = \Phi_T H$, where Φ_T is given by [15]. The liquid penetration into the pipeline is free of gas. However, the liquid slug in the riser has a constant reduced holdup, Φ_{GL}, due to the injected gas. The value of Φ_{GL} is given by [12], and will add a volume to the liquid slug in the riser, thus, the liquid height can be determined as:

$$Z = Z_i = \frac{H\Phi_{Ti-1}}{\Phi_{GLi}}. \quad [27]$$

A mass balance on the gas yields:

$$\left[\frac{P_S + \Delta P_C + \rho_L g(\Phi_{GL} Z - x \sin\beta)}{RT}\right](L - x)\alpha A$$

$$= \left[\frac{P_S + \Delta P_C + \rho_L g(\Phi_{GL} Z_i - x_i \sin\beta)}{RT}\right](L - x_i)\alpha A + \int_{t_i}^{t} m_{GIN} \mathrm{d}t \quad [28]$$

and a mass balance on the liquid gives:

$$Z = Z_i - \frac{\alpha(x - x_i)}{\Phi_{GL}} + \frac{\int_{t_i}^{t} U_{LS} \mathrm{d}t}{\Phi_{GL}}. \quad [29]$$

Equations [28] and [29] are solved simultaneously to calculate Z and x when $Z < H$. In the case of no gas injection, Φ_{GL} is one, and single-phase liquid flows in the riser until a new blowout occurs and gas penetrates into the riser from the pipeline.

3. EXPERIMENTAL PROGRAM

The test facility shown in figure 4, consists of a 9.1 m long pipeline, connected to a 3 m high riser. Both the pipeline and the riser are made of 2.54 cm diameter clear R-4000 PVC pipe and are mounted on aluminum I-beams. The pipeline is connected to the riser by a flexible hose and can be inclined from $+5°$ to $-5°$ from the horizontal.

Fluids exiting the riser flow into a 4.6 m high, 20.3 cm diameter PVC pipe, that serves as a separator. The large internal diameter of the separator eliminates any siphon effects. The separator can either be open or closed for back pressure control.

Additional pipe lengths are simulated by two variable volume tanks. The tanks can either be used separately or in parallel. For these experiments, only the smallest variable volume tank was

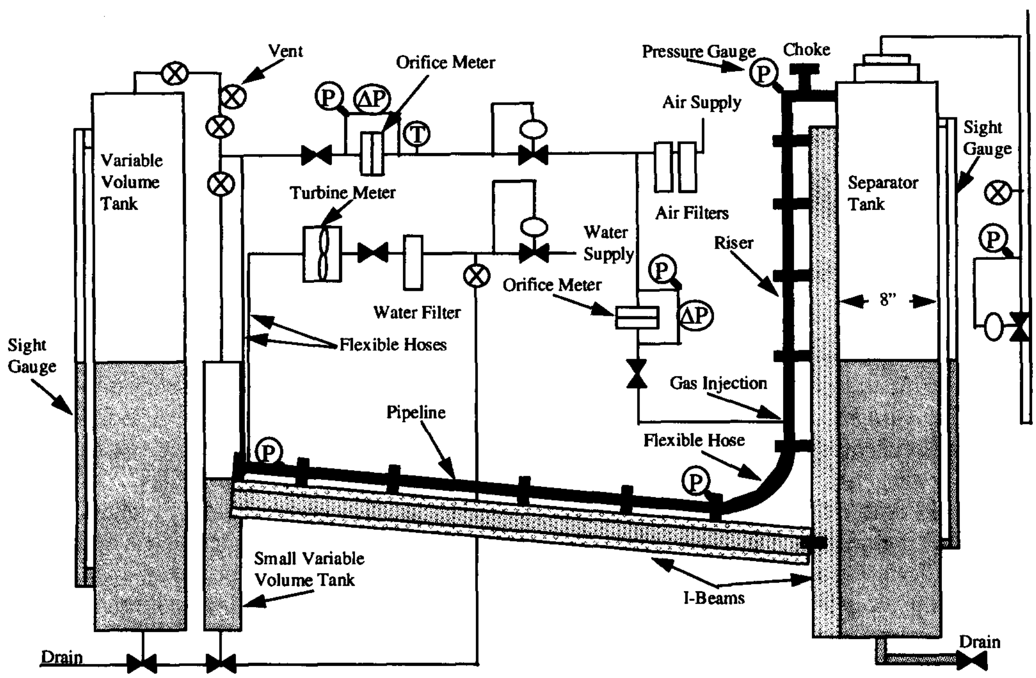

Figure 4. Schematic of experimental facility.

used. The gas volume can be adjusted easily by changing the water level in the tanks. Details of the test facility, the fluid handling system and the instrumentation are given by Jansen (1990).

The experimental program was limited to only one inclination angle, -1°. One equivalent pipe-length of 10 m, filled with gas was used to simulate additional pipeline length. No back pressure was used when choking or gas lift were applied. Thus, the same facility configuration for all the elimination experiments was used, except for the tests with increased back pressure.

For the gas lift experiments, two different procedures were used. The first method was to keep the inlet gas and liquid rates constant, while increasing the gas injection rates until steady state was achieved. The second method was to keep the gas injection rate constant while varying the inlet gas and liquid rates to observe the extent of the severe slugging operational area.

The range of liquid choke coefficients used in the experiments was from 62,600 $\mathrm{Pas^2/m^2}$ to 1,180,000 $\mathrm{Pas^2/m^2}$. Two different experimental procedures were also used for the choke tests. The first method was to keep constant inlet flow rates, while increasing the choking setting. This way the effect of the choking on the system pressure and the riser stability could be observed. The second method was to keep a constant choke setting, while varying the inlet flow rates to observe the effect of the choke size on the extent of the severe slugging operational area.

The liquid and gas flow rates varied in the range of 0.05–0.35 m/s and 0.05–0.5 m/s, respectively. The lower limits were due to limitations in the flow metering accuracy and the higher limits were due to slug formation and surging limitations. The gas and the liquid were allowed to flow for about 10–15 min, until constant operational conditions were reached, at which point the data acquisition was initiated to collect transient data for 6 min.

Data collection was performed by a LabMaster data acquisition package, gathering pressure and flow rate data every second. While the computer collected flow rate and pressure data, visual observations and measurements of the liquid slug length, penetration, cycle time and blow out time were performed. In addition, a visual identification of flow type and other visible trends of the flow were recorded, together with changes in flowline pressure and temperature.

4. RESULTS AND DISCUSSION

The Bøe criterion (1981) (see appendix B) was used as a basis for the comparison of the reduction of the range of occurrence of severe slugging for each elimination method. Both the theoretical boundary lines and the experimental data points are plotted together with the line given by the Bøe criterion. When all the other variables except the flow rates and the back pressure are kept constant, the line given by the Bøe criterion will be the same for all experimental runs, independent of any elimination method used. The effect of the elimination method can be observed by the size of the stable flow area inside the region given by the Bøe criterion as shown in figure 5.

Four different types of flow were found to exist; (1) steady flow; (2) cyclic flow without fall back; (3) cyclic flow with fall back, and (4) unstable oscillations. The stability criteria distinguishes between steady, oscillatory and severe slug flow, while the quasi-equilibrium model distinguishes between type (2) and (3) severe slugging, but cannot identify unstable oscillations (assuming no pipeline penetration will lead eventually to stable flow).

4.1. *Choking*

The experimental data, together with the theoretical lines given by the stability analysis and the quasi-equilibrium model are given in figures 5–7. These figures show the prediction of the flow regimes and separates the stable and the unstable flow areas. As can be seen, increasing the degree of choke setting will move the stability lines down along the superficial liquid velocity axis, increasing the stable flow area inside the region given by the Bøe criterion. An excellent agreement between the theoretical lines given by the new models and the experimental data is observed.

The stability criterion seems to be able to define the upper stability boundary during choking, while the transition between stable and unstable flow in the direction of increasing superficial gas velocity is not as clearly defined (Jansen 1990, 1994). While there is a relatively sharp line between stable and unstable flow in the direction of increasing liquid velocity (y-axis on the flow maps), the transition between stable and unstable flow in the direction of increasing gas velocity is gradual.

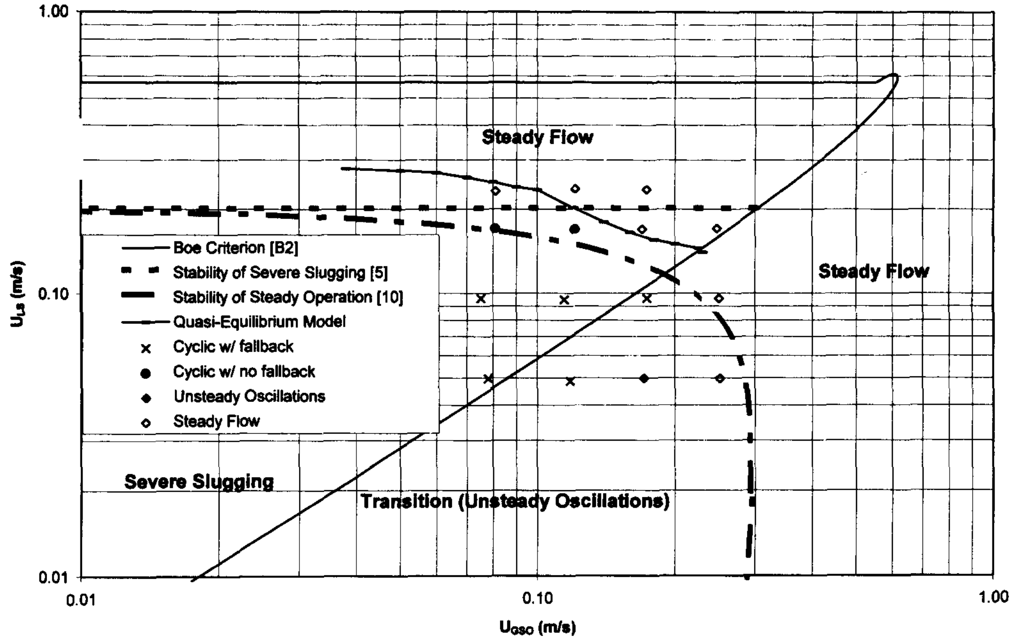

Figure 5. Flow pattern map—choking (C = 120,000 Pas^2/m^2).

This is assumed to be due to the performance of the choke. Since the choke is mainly responding to increases in liquid velocity, the boundary in this direction will be well defined, while increases in the gas velocity will have only a small effect on the stability.

The transient effect of cyclic flow is presented in figure 8. The pressure at the choke is given as the thin line at the bottom of these figures, while the thick line gives the pressure at the bottom of the riser. It should be noted that the choke responds directly to the increase in the mixture velocity until the liquid slug is produced and the gas front reaches the choke. When the liquid holdup at the choke is decreased and gas enters the choke, the pressure drop across the choke starts to decrease until no liquid flows through the choke. An additional effect of choking is to increase

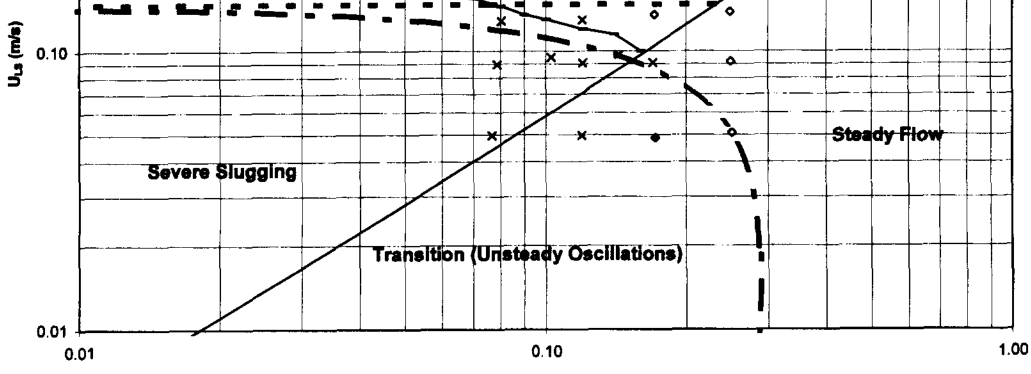

Figure 6. Flow pattern map—choking (C = 245,000 Pas^2/m^2).

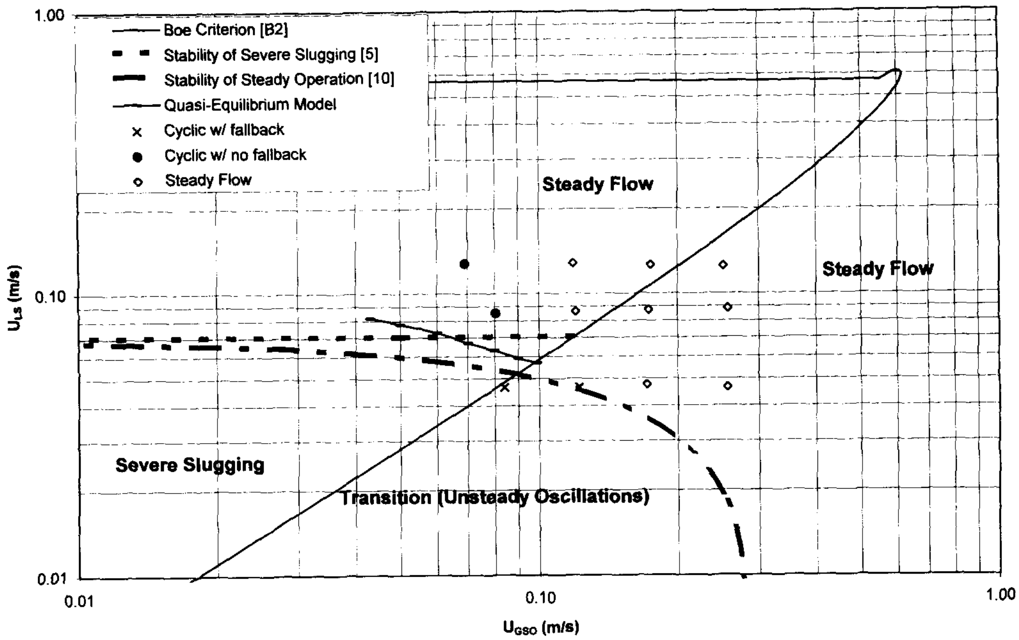

Figure 7. Flow pattern map—choking ($C = 1{,}180{,}000$ Pas²/m²).

the cycle time by reducing the blowout velocity in the riser. This reduces the violence of the blowout and causes a more continuous liquid production into the separator.

The main purpose of the stability criteria is to generate flow maps as seen in figures 5–7. The quasi-equilibrium model can, in addition to predict the type of flow, also estimate features such as the slug length and cycle time. Table 1 shows an example of comparison between the experimental results and the prediction using the quasi-equilibrium model.

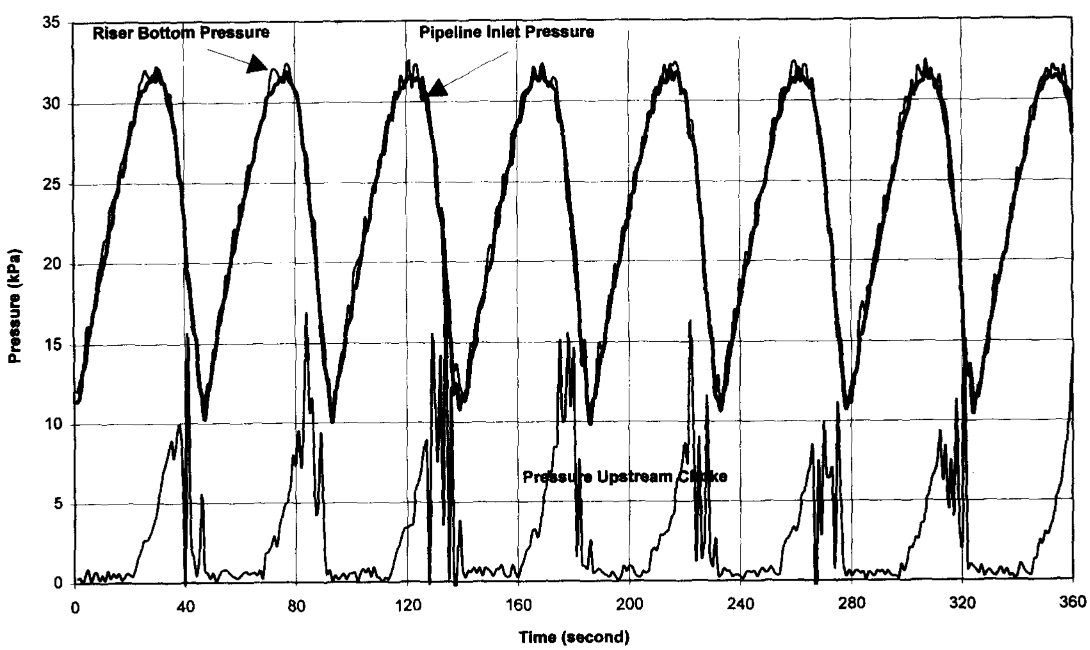

Figure 8. Transient pressure performance for choking.

Table 1. Comparison between experimental and theoretical data

		Experimental			Theoretical			Error	
ULS (m/s)	UGSO (m/s)	Flow type	SL_{max} (m)	t (sec)	Flow type	SL_{max} (m)	t (sec)	SL_{max} (%)	t (%)
0.0959	0.0753	Cycl + fall back	3.53	46.6	3	3.55	44.9	1	−4
0.0949	0.1147	Cycl + fall back	*	37.6	3	3.28	38.1		1
0.0959	0.1739	Cycl + fall back	*	31.8	4	<3	0		
0.0497	0.0781	Cycl + fall back	*	47.5	3	3.09	50.7		6
0.0487	0.1181	Cycl + fall back	*	38.5	4	<3	0		
0.1704	0.0809	Cycl no fall back	3.97	45	2	3.41	35	−16	−29
0.1693	0.1209	Cycl no fall back	3.74	39.9	2	3.36	31	−11	−29
0.0497	0.1713	Unst. oscill	<3	31.5	4	<3	0		
0.2365	0.1209	Steady	0	0	1	0	0		
0.2354	0.1734	Steady	0	0	1	0	0		
0.2386	0.2493	Steady	0	0	1	0	0		
0.1693	0.1698	Steady	0	0	1	0	0		
0.1704	0.2474	Steady	0	0	1	0	0		
0.0959	0.2502	Steady	0	0	4	0	0		
0.0497	0.251	Steady	0	0	4	0	0		

*SL_{max} < 3.5 m could not be measured.
Constant choke setting, C = 120,000 Pas²/m², Cs = 6.5.

4.2. *Gas lift*

For all the gas lift experiments, gas was injected into the base of the riser. These experiments were conducted following two different procedures. The first method was to keep the inlet rates constant while increasing the injected gas rate. Three data sets were acquired for U_{GSO} = 0.07, 0.135 and 0.185 m/s. The results given in figure 9 show the effect of increasing the gas injection rate. The amount injected can be several times higher than the inlet gas rate. The second procedure was to keep the injected gas rate constant while changing the inlet flow rates. By doing this the extent of the unstable flow area can be investigated (see figures 10 and 11). These plots are generated using an average α' value of 0.75. Deviation between the theoretical results and the experimental data is attributed to the increased flow resistance at the riser base and the fact that annular flow is approached.

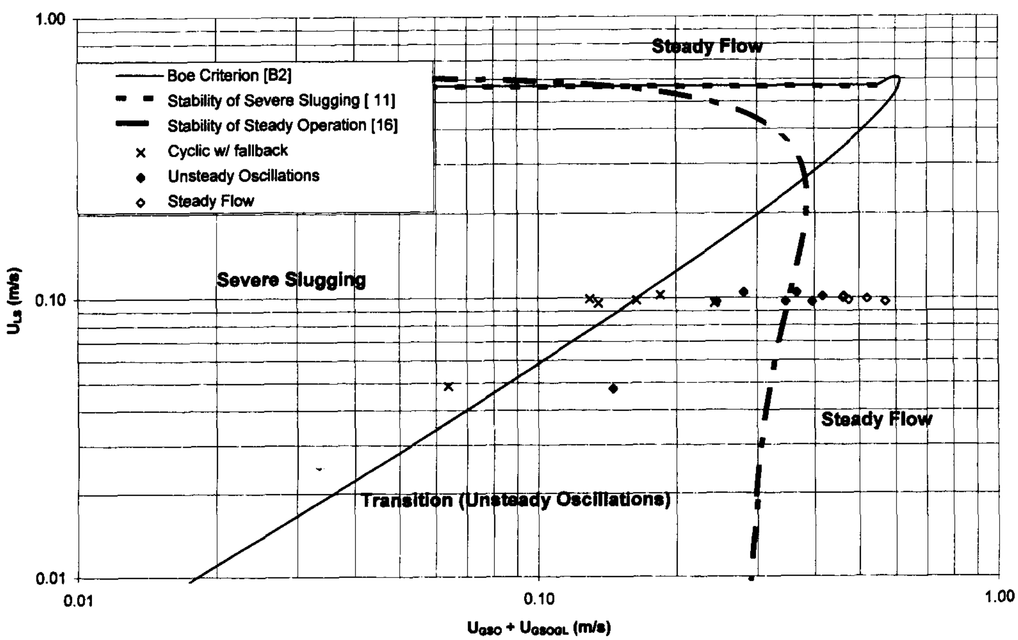

Figure 9. Flow pattern map—variable injection rate.

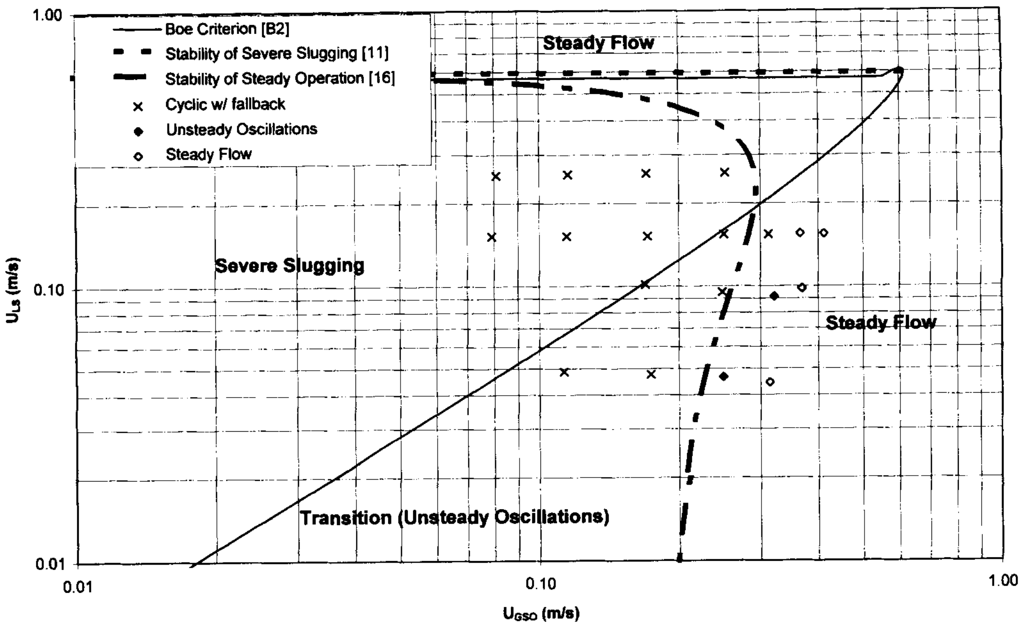

Figure 10. Flow pattern map—gas lift ($U_{GSGL} = 0.091$ m/s).

It can be seen from the figures that gas lift is mainly increasing the stability along the axis of the superficial gas velocity. Only a small degree of increased stability along the axis of the superficial liquid velocity is observed. An example of a comparison between the quasi-equilibrium model and experimental data for calculating slug lengths and cycle time is given in table 2. Limitations of the model are that the flow resistance through the injection point is not accounted for and that the model assumes fully developed Taylor bubbles, whereas in reality the flow may be approaching annular flow.

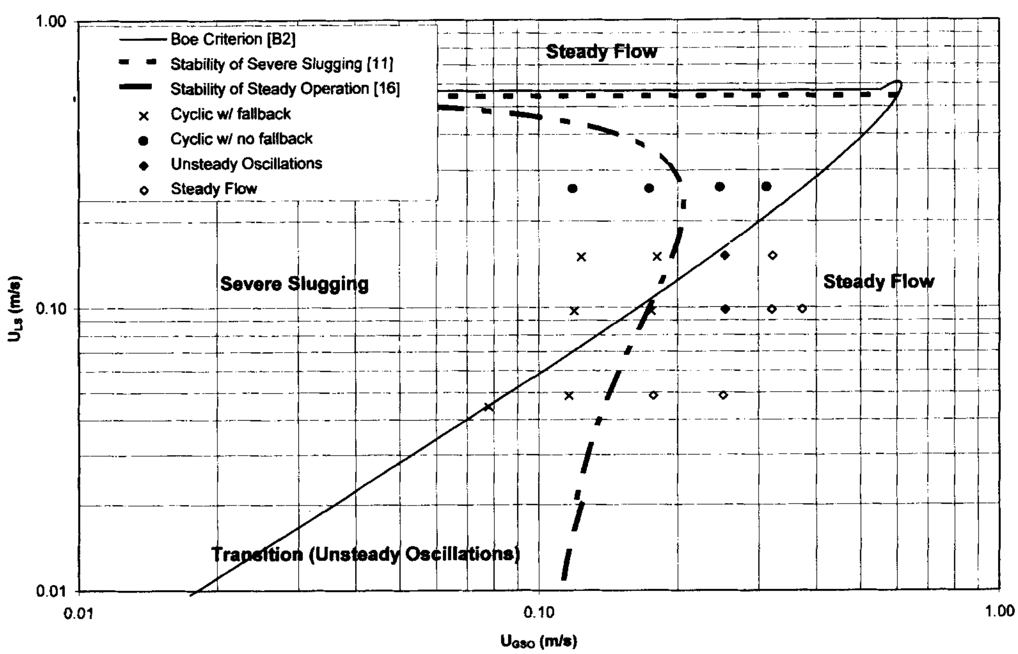

Figure 11. Flow pattern map—gas lift ($U_{GSGL} = 0.178$ m/s).

Table 2. Comparison between experimental and theoretical data

		Experimental				Theoretical		Error	
ULS (m/s)	UGSO (m/s)	Flow type	SL_{max} (m)	t (sec)	Flow type	SL_{max} (m)	t (sec)	SL_{max} (%)	t (%)
0.2528	0.0808	Cycl + fall back	4.78	21.5	23	4.93	29.1	3	26
0.2549	0.1153	Cycl + fall back	4.63	18.9	3	4.63	21.8	0	13
0.2571	0.1702	Cycl + fall back	4.07	14.9	3	4.26	16.1	4	7
0.2582	0.2515	Cycl + fall back	3.66	13.4	3	3.67	11.6	0	−16
0.152	0.0791	Cycl + fall back	4.02	24.1	3	4.34	33.8	7	29
0.152	0.1147	Cycl + fall back	3.69	20.5	3	3.95	24.4	7	16
0.152	0.1714	Cycl + fall back	3.51	16.9	3	3.46	17.4	−1	3
0.1542	0.2499	Cycl + fall back	*	14.2	4	<3	0		
0.1542	0.3125	Cycl + fall back	*	10.8	4	<3	0		
0.1013	0.1695	Cycl + fall back	*	16.8	4	<3	0		
0.0949	0.248	Cycl + fall back	*	13.2	4	<3	0		
0.0487	0.1129	Cycl + fall back	*	27	4	<3	0		
0.0476	0.1737	Cycl + fall back	*	18.8	4	<3	0		
0.0916	0.3215	Unst. oscill	<3	9.5	4	<3	0		
0.0465	0.2489	Unst. oscill	<3	14	4	<3	0		
0.1552	0.366	Steady	0	0	4	0	0		
0.1552	0.4115	Steady	0	0	4	0	0		
0.0981	0.369	Steady	0	0	4	0	0		
0.0444	0.3141	Steady	0	0	4	0	0		

*SL_{max} < 3.5 m could not be measured.
Gas injection into riser base, Constant injection rate, UGSOGL = 0.091 m/s.

From the transient data, one may observe that gas injection affects both the riser bottom pressure and reduces the cycle times. A plot of the cyclic flow cycle is shown in figure 12. From this figure the reduction in the hydrostatic head and cycle times can be observed.

Based on the experimental results, very little improvement in the stability was achieved before large volumes of gas were injected. It is indicated that the riser flow needs to approach annular flow before a steady riser flow is achieved. This lack of stability is shown as unstable flow in the direction of increasing liquid velocity and only small stability increases in the direction of increased gas velocity. Gas injection mainly causes a velocity increase in the riser, where the gas flow will

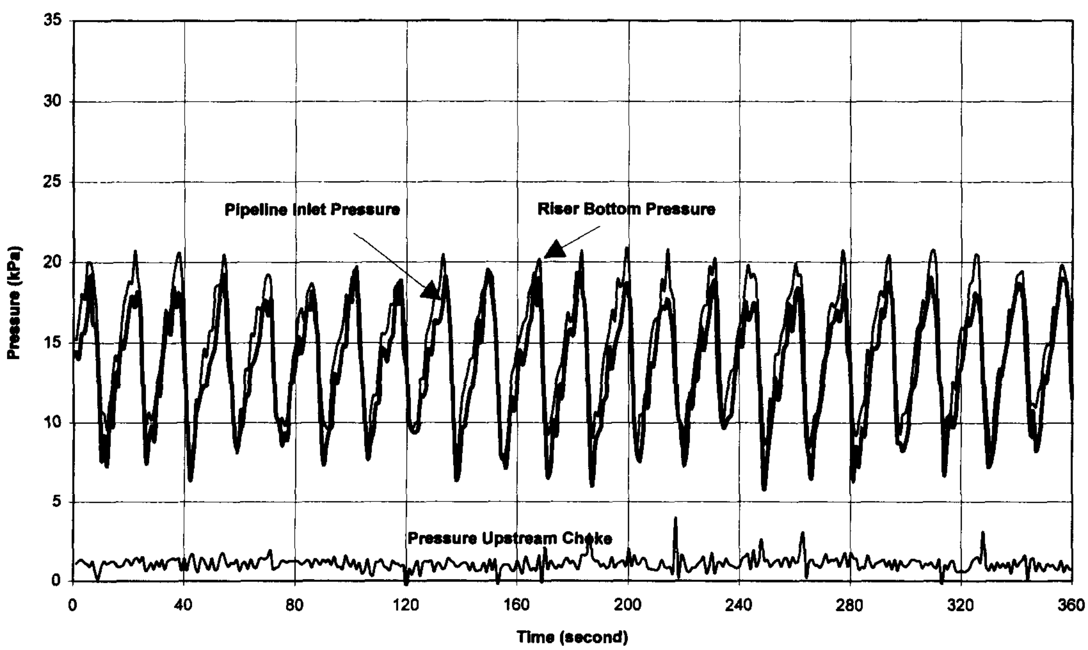

Figure 12. Transient pressure performance for gas lift.

have to be increased until it completely dominates the riser flow before complete stability is achieved.

The main benefits of the gas injection were found to be a decrease in system pressure and the cycle time. Thus, a more continuous liquid production and a reduction of any possible production losses due to a high hydrostatic head results.

5. SUMMARY AND CONCLUSIONS

Two separate models have been developed for the analysis of severe slugging elimination, namely, the stability model and the quasi-equilibrium model. Both models can be used for choking, gas lift or any combination of these elimination methods at any back pressure. The region between the line given by the Bøe criterion and the line given by the steady operation stability criterion (outside the Bøe region) is a transition region between steady flow and severe slugging. This region was termed the unsteady oscillation region. Slug flow occurring in this region is of a height less than one riser height.

Choking eliminates severe slugging by increasing the back pressure and acting as a flow resistance proportionally to the velocity of the liquid slug in the riser. Based on the low pressure air/water experimental data, the pressure drop across the choke is found to be mainly due to the liquid flow. The transient pressure drop is a function of both the liquid holdup and the mixture velocity at the choke. The time averaged pressure drop, however, is mainly a function of the superficial liquid velocity. Choking stabilizes the flow in the direction of the liquid superficial velocity. Careful choking can stabilize the flow with a minimal back pressure increase.

Gas lift eliminates severe slugging by increasing the velocity and reducing the liquid holdup in the riser. Large amounts of injected gas are needed to stabilize the flow. Gas lift will reduce the system pressure and stabilize the flow in the direction of the gas superficial velocity. Both the stability model and the quasi-equilibrium model give good agreement with the experimental results.

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APPENDIX A

Choke Performance

For the evaluation of choking as a method of elimination, it is important to be able to determine the performance of the choke. The choke used in this experiment is a ball valve. The treatment of the choke might not be completely representative of most chokes used in the field, since the theory is validated through low pressure air–water experiments.

To determine the choke performance for riser top choking, both single-phase and two-phase flow experiments were performed with a wide variety of choke sizes. During the experiments the inlet flow rates and the pressure drop across the choke were measured.

It was initially assumed that the performance of the choke at subcritical conditions follows the general homogeneous choking relationship:

$$\Delta P_C = CU_S^2, \tag{A1}$$

where C is a constant choke coefficient representing the choke setting.

The experimental tests showed that the single-phase liquid choking relationship follows this assumption. However, single-phase gas and two-phase gas/liquid mixtures did not follow this ideal relationship. It was found that the pressure drop caused by the single-phase gas was not high enough to be accurately measured and no conclusion could be made from these tests. For the two-phase pressure drop, it was found that the time averaged pressure drop across the choke seems to be mainly a function of the liquid phase and the superficial liquid velocity. The time dependent pressure drop, on the other hand, is a function of both the local liquid holdup and the mixture velocity at the choke.

Based on the experimental results, the time averaged pressure drop for two-phase flow can be approximated by the single-phase liquid flow as follows:

$$\Delta P = CU_{LS}^2. \tag{A2}$$

The time dependent pressure drop can be approximated by:

$$\Delta P_C = C'U_S^2. \tag{A3}$$

The adjusted choke coefficient C' is given by:

$$C' = C\lambda, \tag{A4}$$

where C is the single-phase choke coefficient and λ is a liquid holdup factor for the riser top flow conditions:

$$\lambda = \left(\frac{U_{LS}}{U_S}\right)_{top}. \tag{A5}$$

APPENDIX B

The Bøe Criterion

The Bøe criterion (1981) is a simple mathematical expression which gives the necessary conditions for the occurrence of severe slugging. This criterion, given by the following equations:

$$U_{LS} \geqslant \frac{P_P}{\rho_L g \alpha L} U_{GS} \quad [B1]$$

or

$$U_{LS} \geqslant \frac{\rho_{GO} RT}{\rho_L g \alpha L} U_{GSO}, \quad [B2]$$

is a force balance applied to the liquid slug blocking the entrance into the riser. These forces are the gas pressure that builds in the pipeline and the hydrostatic head of the liquid in the riser. When this equation is satisfied then severe slugging is assumed to occur. The above equation is valid only when no elimination methods are applied. The Bøe criterion is used in this study only for comparison purposes.