THE PREDICTION OF FLOWS IN PRODUCTION RISERS - TRUTH & MYTH?

P.F. Pickering[1], G.F. Hewitt[2], M.J. Watson[1] and C.P. Hale[2]

[1] *FEESA Ltd, 10 Grayswood Drive, Camberley, Surrey, GU16 6AR.*
E-mail: info@feesa.net

[2] *Department of Chemical Engineering & Chemical Technology,*
Imperial College of Science, Technology & Medicine,
Prince Consort Road, South Kensington, London, SW7 2BY.

ABSTRACT

The paper focuses on the modelling of multiphase flows in larger diameter risers of six inches and greater. The general aspects of the modelling of these flows are discussed before reviewing the current commercially available tools. Two examples are presented to illustrate the predictive capabilities of these codes. The central thrust of the paper is to consider the accuracy of the established tools. It is noted that the existing codes are largely based on data gathered in smaller diameters (typically less than 2 inches) but nonetheless the predictions are still used in the design of larger diameter risers systems. Speculation is given to the impact increases in diameter could have on the underlying physical phenomena, especially the transitions between flow regimes. The paper concludes that the extrapolation of the current methods is extremely tenuous and emphasises the need for a new research attack on this problem.

INTRODUCTION

In the early years of offshore oil and gas exploration and production, the largest and most accessible fields were developed first. These fields presented only moderate technical challenges, and with their large reserves bases offered significant economies-of-scale which made them commercially attractive. However, as these fields are being depleted, producers are being forced to look further afield for replacement reserves. This then has led to increased interest in deeper waters, and harsher and more remote environments, most notably in the Gulf of Mexico, offshore Brazil, West Africa and West of Shetlands. As a result, there have now been a number of developments in deep waters in excess of 500m water depth and a number that exceed 1km (e.g. Elf's Girassol at 1300m or Petrobras' Roncador at 1500-2000m). For these developments the capital investment required in the riser systems represents a significant proportion of the total field development costs and it therefore desirable that the designs are optimal and efficient.

In general, deepwater fields present significant Flow Assurance difficulties which designers need to overcome, not least of which are those associated with the riser systems. In fact, in the area of risers considerable uncertainty exists in the design methods used and therefore in the validity of the designs proposed. The crux of the problem originates from the rather tenuous extrapolation of correlations developed for smaller diameters (typically less than 2 inches) to diameters consistent with deepwater risers (normally greater than 6 inches). This issue is the central thrust of this paper and it is hoped that by publicising it, the authors will draw attention to the serious inadequacies of the established design practices.

The paper begins with a general discussion of Flow Assurance in deepwater systems, highlighting where appropriate issues directly related to riser systems. It then reviews the modelling and prediction techniques for vertical multiphase flows before presenting a review of the current commercial modelling methods. Finally the paper concludes by discussing the accuracy of the established methods, presenting where available, evidence to support the claim that there is grave doubt about the accuracy of the methods and that further research work is needed.

FLOW ASSURANCE IN DEEPWATER FIELDS

'Flow Assurance' is a term that encapsulates a number of fluid flow, heat transfer and production chemistry issues that have important implications for the transportation of hydrocarbons from reservoirs to processing facilities. The term is understood to have been coined initially in Portuguese as 'garantia de fluxo' and translated literally into Flow Assurance.

Deepwater fields present similar Flow Assurance difficulties to those encountered in the traditional shallow water developments, but in many cases the problems are exacerbated by a number of factors particular to the deepwater environment and reservoirs. In addition, the high cost of intervention in deepwater wells and subsea production systems is driving engineers to design inherently reliable and high-availability systems to avoid the need for costly intervention operations.

Many of the problems encountered during the development of reservoirs located in deepwaters, stem from the characters of the reservoirs themselves. They tend to be located in turbidite sandstone formations and ironically while the water depth is large, the depth of the formation below the seabed is often quite small. As a result, the reservoirs tend to be low-energy having relatively low pressures and temperatures compared to other more conventional reservoirs. This has important ramifications where Flow Assurance is concerned because not only is the pressure for driving the flow limited, the low temperatures imply greater difficulties with heat conservation and the avoidance of solids formation, principally hydrates and waxes. To cite two examples of such reservoirs, one need only consider Elf's Girassol and Dalia developments, in deepwater offshore Angola.

The lower pressures available invariably mean that pressure maintenance is required through injection of one sort or another, and artificial lift may also be desirable, perhaps using either gaslift injection, electro-submersible pumps, hydraulic submersible pumps or subsea multiphase booster pumps.

The low characteristic temperatures in the reservoir also imply that the hydrocarbons tend to be heavier containing less gas and more heavy ends. Hence, they often display propensities towards wax deposition or asphaltene flocculation. In addition, oils of this type can also display a tendency towards forming stable emulsions which have viscosities significantly greater than the constituent phases.

On the positive side, since the reservoirs are located at relatively low depths below the seabed, the formations are often loosely consolidated and as a result have excellent permeability characteristics with commensurately low formation pressure drops. However, in common with other loosely consolidated formations, problems associated with sand production also need to be addressed.

For the design of oil and gas production systems, it is commonplace to provide insulation on pipelines and risers in order to conserve heat and prevent the temperature of the production fluids from falling in to either the wax deposition or hydrate formation envelopes. However, for deepwater reservoirs where the initial temperature of the fluids is relatively low (e.g. less than 70°C) and the wax appearance temperature itself can be relatively high (e.g. greater than 40°C), there may not be a great deal of enthalpy to conserve. Moreover, the comparatively large potential energy change from the base of the riser to the production facilities will also cause a reduction in temperature due to the abstraction of internal energy, a point which is illustrated below.

Furthermore, the ambient temperature in deepwater environments also tends to be lower than the temperature encountered in shallower waters, though of course geographical location is also an important factor. Motivated by these difficulties in maintaining temperatures, engineers are often compelled to consider active heating methods, such as bundled pipelines and electrically heated systems, which can provide effective solutions but have an associated cost which will inevitably degrade the economics of the development.

The increase in riser height in deepwater developments also has important implications for system stability. In particular, increases in riser height can be destabilising causing multiphase slugging with serious ramifications for the operation of the reception facilities. Moreover, increasing the riser height also increases the severity of slugging, measured in terms of the magnitude of pressure fluctuations and slug sizes. The subject of stability is considered in more detail later.

Finally, with deepwater risers, engineers need to consider carefully how pipelines will be depressured. The increase in hydrostatic head can mean that for certain pipeline topographies, it may be difficult to reduce the pressure in the pipeline below the hydrate formation pressure at seabed temperatures. This has important implications in respect of unplanned shutdowns.

MODELLING AND PREDICTION OF PRODUCTION FLOWS

The main objectives of modelling flows of production fluids in wells, pipelines and risers are to predict the pressure drop, the phase distributions, the potential for unsteady phase delivery (commonly referred to as slugging) and the thermal characteristics of the system. These objectives arise from the engineer's requirement to design production systems which avoid the Flow Assurance problems discussed in the previous section.

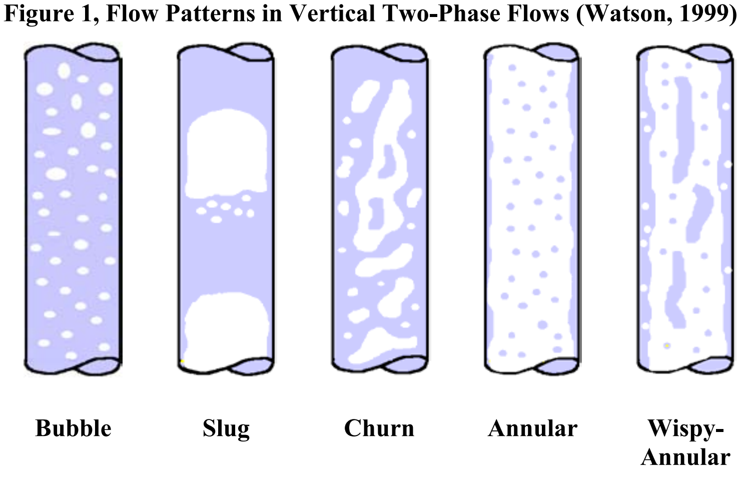
The discussion in this Section focuses on the modelling of multiphase flow and reviews the approaches that have been applied to date. As is well-known, true predictions of fluid flow are only available for single-phase laminar flows and very low Reynolds number flows in simplified geometries; when the Reynolds number increases to values typical of real applications, true predictions are no longer available and the only practical way forward is through empiricism. It should not be surprising therefore, that multiphase flows with deformable interfaces, able to take a virtually infinite number of configurations, present an intractable problem which only in very idealised scenarios, for example laminar flow over an isolated spherical particle, bubble or droplet (Einstein, 1906 and 1911, Taylor, 1932), yield analytical solutions to the conservation equations. This is particularly true given that in the vast majority of cases multiphase flows are turbulent in nature. Thus the analysis and modelling of multiphase flows relies heavily on empiricism and the predictions for the models are only as reliable as the empirical relationships on which they are based.

Faced with the intractable nature of multiphase flow prediction, researchers have sought pragmatic approaches to the problem. Numerous visualisation experiments have been performed over the last fifty years (mainly with the convenient fluids air and water) and researchers have identified that the flows observed can usually be classified into one kind or another. It was natural therefore, for *flow patterns* or *flow regimes* to be defined and for flows to be categorised accordingly.

Hewitt (1999) provides an introductory discussion of flow patterns and states that these can themselves be categorised into three types: *dispersed*, *separated* and *intermittent flows*. Dispersed flows include all flow regimes where one phase is uniformly distributed as roughly spherical elements throughout another continuous phase. Such flows include *bubbly flow* where small gas bubbles are dispersed through a liquid continuous phase or *drop flow* where small droplets of liquid are carried along in a vapour stream. Separated flows are those where the phases are not intimately mixed. These include *stratified flow* in horizontal pipes where the liquid flows at the base of the pipe with a gas stream flowing above, and *annular flow* where the liquid flows around the periphery of the pipe as a thin film with a gas core flowing internally. Finally, intermittent flows include those where the phases are not distributed uniformly along the pipe, for example *slug flow* or *plug flow*.

Figure 1 presents an illustration of the various flow patterns that exist in vertical two-phase flows. At lower gas-liquid ratios, the fluids flow as a bubbly flow with small bubbles of gas distributed throughout the continuous liquid phase (which in oil and gas production is probably itself a water-in-oil dispersion). At higher gas-liquid ratios, the fluids are transported in the annular flow regime. For intermediate gas-oil ratios the slug (sometimes known as "plug") and churn flow regimes occur and, at high flow rates of both liquid and gas, the *wispy annular flow* regime occurs.

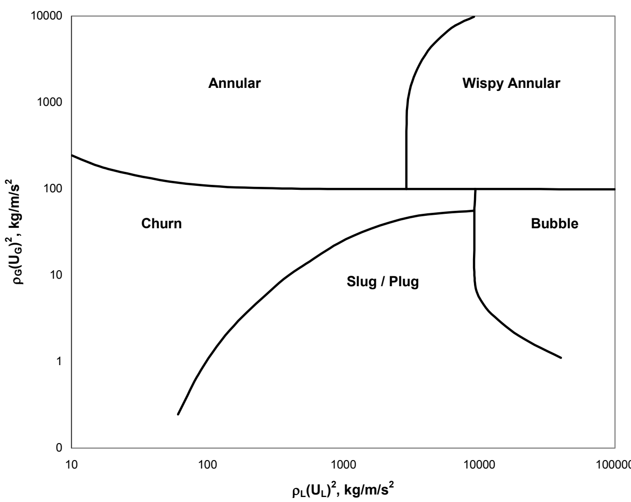
Figure 1, Flow Patterns in Vertical Two-Phase Flows (Watson, 1999)



The identification and classification of flows into flow patterns, while subjective, has presented a useful approach for the modelling of multiphase flows. In particular, the pressure drop and phase holdups differ significantly from one pattern to another and hence the prediction of multiphase flows benefits from a knowledge of the flow pattern and the subsequent application of appropriate relationships specific to the flow pattern in question.

To predict flow patterns, researchers first sought to define two-dimensional flow pattern maps. For design purposes the procedure was then to locate a system on the map and apply the appropriate correlations for the prevailing flow pattern. Such vertical flow pattern maps are typified by that of Hewitt and Roberts (1969), which is presented in Figure 2 and is for upwards cocurrent flow. The map plots the momentum flux of the gas on the ordinate and the corresponding parameter for the liquid on the abscissa.

Figure 2, Vertical Upwards Flow Map of Hewitt & Roberts, 1969

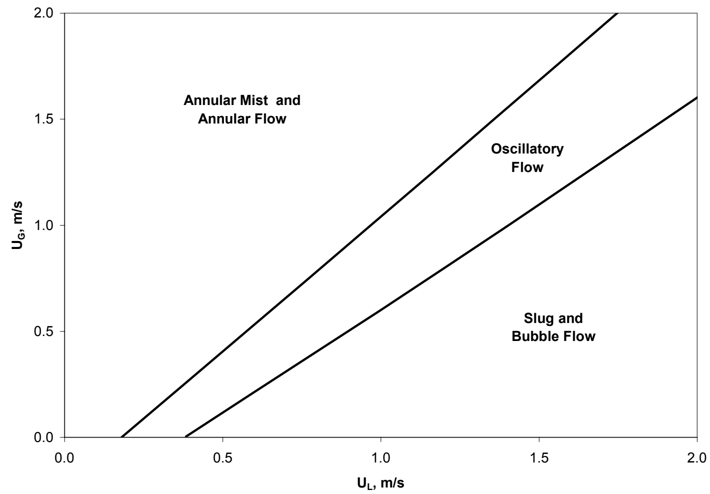


However, this approach, while useful in its time, is of limited applicability. The essential problem is that the transition from one flow regime to another cannot be reduced to just two defining parameters. Even through the application of dimensional analysis, it is still not possible to group parameters into just two groups. Motivated by this limitation, in recent years researchers have attempted to predict transitions from one regime to another by mechanistic means. For example the transition from bubble to slug flow has traditionally been explained through the competing effects of bubble break-up and coalescence using arguments based on surface tension and turbulence forces, proposed earlier by Levich (1962) and more recently developed by Taitel *et al* (1980). Through the application of tested mechanistic relationships for transitions between flow patterns, it is hoped that ultimately, it will be possible to reliably predict the boundaries between flow patterns in a multi-dimensional parameter space and hence more accurately predict the characteristics of multiphase flows. However, it should be stressed that there is no generally accepted mechanistic basis for predicting flow regimes; for example, it is now thought by many workers that a necessary condition for the formation of slug flow is the development of regions of high bubble concentration (“void waves”) within the preceding bubble flow. Thus, it is certainly correct to say that much additional effort is required before a generally accepted, ‘grand-unified theory’ is available.

Finally on the subject of vertical flow pattern maps, it is also noted that the vast majority of data collected for vertical multiphase flows has been confined to upwards cocurrent flow. Until recently this has not presented much of a restriction in the prediction of oil and gas production systems since designers are normally concerned with upwards flows in wells and risers. However, in recent years the emergence of the deepwater development concept utilising a *Dry Completion Unit* (DCU) with full wellstream transfer to a nearby *Floating Production, Storage and Offloading* vessel (FPSO) for processing, has prompted designers to consider the accuracy of prediction methods for downwards multiphase flow. Unfortunately the work in this area is very limited and the question of accuracy of predictions in downwards cocurrent flow remains the subject of considerable speculation.

An example of a flow pattern map for downwards cocurrent two-phase flow is that of Golan and Stenning (1969) (see Figure 3). Comparing the map to the earlier one presented for upwards flow (see Figure 2), there is an apparent increase in the propensity towards annular flow. This has important implications for the design and operation of multiphase transfer lines carrying production fluids from a DCU to an FPSO, for if the downcomer operates in annular flow the system will not benefit to any great extent from pressure recovery due to the gravitational pressure rise. It will not therefore behave anything like a manometric system and care must be taken to ensure that sufficient pressure is available on the DCU to effect the transfer.

Figure 3, Vertical Downwards Flow Map of Golan & Stenning, 1969



Hewitt (1999) provides a brief discussion of modelling approaches for multiphase flows which is applicable to the subject of modelling riser flows. The most straightforward model for multiphase flow is perhaps the one-dimensional homogeneous flow model which assumes that the phases are intimately mixed and travel at identical velocities. The method benefits from requiring only limited empirical information to mathematically *close* the model, this being a suitable formula for predicting the friction term. However, the underlying assumptions of homogeneity mean that the model's applicability is very limited and its accuracy in predicting real multiphase flows is therefore usually poor.

The next approach, which is similar in formulation to the homogeneous model, is the one-dimensional separated flow (drift-flux) model. Here the restriction of identical phase velocities is removed, necessitating an additional empirical relationship to relate the local void fraction to the separate phase flow rates. Examples of such relationships are those presented by Zuber and Findlay (1965) or more recently by Chexal and Lellouche (1986).

Next comes the one-dimensional two-fluid model where separate conservation equations for mass, momentum and energy are proposed for the gas and liquid phases, giving in total six coupled partial differential equations describing the flow. This method benefits from a more sound physical description of the multiphase flow, but as a consequence of the increasing complexity requires additional empirical relationships to close the model. In particular, correlations are required to quantify the interfacial exchange of mass, momentum and energy and the wall shear stresses for the respective phases. Unfortunately, in general, reliable correlations for these terms are not easy to derive either theoretically or experimentally.

The methods that perhaps offer the best chance of predicting multiphase flows accurately are the phenomenological models. These models rely on the identification of flow patterns and the use of separate bespoke models for each regime. For example, in slug flow the traditional Eulerian solution of a two-fluid model which specifies a stationary spatial grid over which the partial differential equations are discretised, presents certain difficulties associated with the unphysical dispersion of discontinuities (i.e. the noses and tails of slugs). These problems can be partly alleviated using complex adaptive-grid techniques which allow the spatial nodes to bunch in order to 'resolve' discontinuities. However, perhaps the only robust solution will come from a Lagrangian phenomenological model where individual slugs are followed throughout the system and appropriate correlations are employed for entrainment of bubbles at the nose and shedding of liquid from the tail.

Finally, the advances in Computational Fluid Dynamics (CFD) and their extension to multiphase flows needs mention since this perhaps offers a long-term solution to multi-dimensional multiphase flows. Various workers have shown how the fundamental equations of fluid mechanics can be averaged and discretised in three-dimensions for multiphase flows and have produced successful solutions to engineering problems. However, as with all of the methods described, the ultimate accuracy depends intrinsically on the empirical relationships that are provided to close the model, and this is where these advanced methods need additional improvement. Furthermore, for the specific problem of multiphase flows in risers which have large L/D ratios, it is difficult to see how the application of CFD could yield practical engineering solutions without very substantial improvements in computing power.

CURRENT COMMERCIAL MODELLING TOOLS

Having now briefly described the methods applied for the solution of multiphase flows in risers, it is appropriate to consider the state-of-the-art in commercially available computer codes. The current commercial methods for modelling multiphase oil and gas production systems (including wells, pipelines and risers) subdivide into the steady-state and the transient codes.

Of the steady-state codes, the three main companies are Baker Jardine with the Pipesim software, Petroleum Experts with Prosper Gap and SimSci with Pipephase. The steady-state codes are predominantly based on the traditional empirical methods developed over the years, although more mechanistic correlations are often provided as well. Popular oil industry flow correlations for vertical flow in wells and risers are listed in Table 1. Although this table excludes the modified correlations offered by the software vendors which are usually only minor variations on the published methods.

Table 1, Popular Oil Industry Flow Correlations

Name	Published	Comments
Ansari	-	Developed as part of the Tulsa University Fluid Flow Projects (TUFFP). A comprehensive mechanistic model designed primarily for well flows.
Aziz, Govier & Fogarasi	1972	A semi-empirical method designed and tested for gas-condensate flows in wells.
Duns & Ros	1963	Developed for vertical flow of gas and liquid mixtures in wells and based on extensive experimental work using air and oil simulants.
Gray	1974	Developed by Shell for modelling vertical flows of gas-condensate mixtures in tubes up to 3.5 inch.
Hagedorn & Brown	1965	Developed using data gathered from a 1500ft experimental well but restricted to tubing diameters of less than 1.5 inch.
OLGA-s	-	Mechanistic model developed using data collected in the 8 inch SINTEF flow loop which includes a 50m riser.
Orkiszewski	1967	Developed for flows in vertical and deviated wells.

From inspection of the table, it is clear that only the OLGA-s correlation can claim to have been developed for flows in risers of larger diameter. The other correlations have been developed for flows in wells which usually have internal diameters of less than 5 inches. Moreover, the correlations are largely empirical and based on interpolation of two-dimensional flow regime maps. It is now generally accepted that methods of this kind have limited future potential.

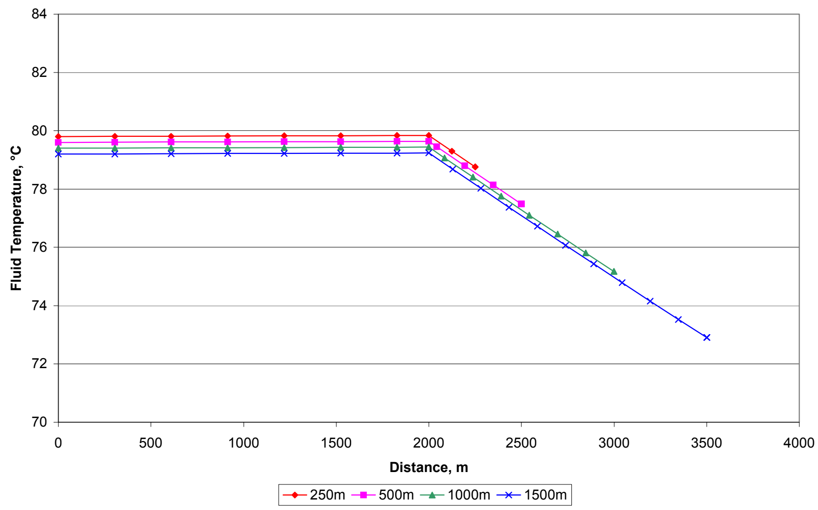
While these traditional correlations remain popular for steady-state parametric studies of oil and gas production systems, they are being progressively displaced by the more advanced mechanistic or phenomenological models that are embodied in the transient multiphase flow codes. Of these codes, the three main commercially available codes are Scandpower's OLGA, AEA Technology's PROFES (formerly known as PLAC) and IFP's TACITE. Both OLGA and PROFES are based on complex one-dimensional multi-fluid representations of the multiphase hydrodynamics, whereas TACITE is based on a drift-flux formulation. These codes are generally superior to the traditional steady-state methods and have been extensively validated against experimental measurements. However, as will be discussed later, in common with all other available techniques a great deal of additional effort is required, particularly in the case of large diameter deepwater risers.

In the remainder of this section, two examples are presented to highlight some of the relevant physical phenomena evident in deepwater riser systems. In the earlier discussion, the problem associated with the abstraction of internal energy into potential energy was mentioned briefly. To illustrate this phenomenon, steady-state simulations were performed with one of the commercially available codes. An 8 inch flowline-riser system was defined with a flowline length of 2 km, fed by a gas-oil mixture at 70 bara and 80°C. The gas-oil mixture had a Gas-Oil-Ratio (GOR) of 90 sm^3/sm^3 and the oil was 35°API.

The simulations were performed for a range of riser heights from 250 to 1500m. To eliminate heat losses from the production fluids a very low overall heat transfer coefficient of 0.006 $W/m^2/K$ was specified.

The predicted temperature profiles are presented in Figure **4**, where to aid clarity the curves have been displaced downwards with increasing riser height by a small temperature offset.

Figure 4, Predicted Temperature Profiles along 8 inch Flowline-Riser System



It is evident that increasing the riser height leads to a greater temperature drop as the fluid flows up the riser. Since the riser is effectively perfectly insulated the explanation for this is not heat losses to the surroundings. In fact, the explanation is the abstraction of internal energy (related to the temperatures of the fluids) in to potential energy and to a lesser extent kinetic energy (since the fluids are travelling faster at the top of the riser). In addition, some internal energy is employed for the expansion of the fluids up the riser and for latent heat of vaporisation.

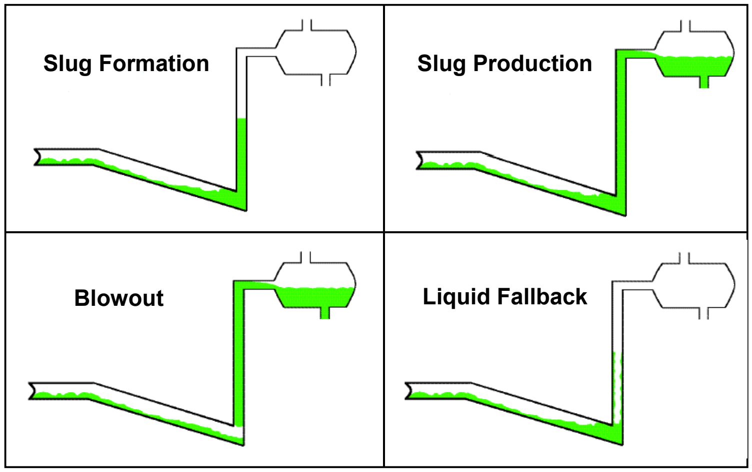
For the 1500m riser case, the temperature drop up the riser is circa 6.5°C compared to about 1°C for the 250m riser case. This phenomenon has important implications for riser design for some of the world's leading deepwater oil and gas developments. For example, some of the high-profile deepwater Angolan developments in water depths of greater than 1200m have very low reservoir temperatures, typically in the range 50-65°C, with relatively high minimum arrival temperatures to avoid wax deposition of around 40°C.

Clearly, after heat losses in the wells and flowlines are accounted for, there is little scope for additional heat loss as the fluids flow up the riser. But as demonstrated here, even perfect insulation would not prevent a temperature drop of in excess of 5°C. In these cases, designers need to consider active heating of production fluids to mitigate wax deposition problems. In addition, since it is commonplace for model developers to neglect kinetic and potential energy terms in the energy equation, it is also paramount that designers confirm that the code they employ has the full formulation.

The second example of model application cited here, is the use of the one-dimensional transient multiphase flow codes to predict slugging behaviour in pipeline-riser systems. For this analysis, we have selected the well-known 'severe slugging' problem which has been discussed in numerous earlier publications, for example Sarica and Tengesdal (2000), Henriot *et al* (1999), Jansen and Shoham (1994), Taitel *et al* (1990) and Fabre *et al* (1987) to name just a few.

The severe slugging phenomenon is illustrated in Figure 5. The phenomenon manifests itself with cyclical production of liquid and gas coupled with cyclical pressure fluctuations in the pipeline. The first phase of the cycle is referred to as 'slug formation'. Here the base of the riser has become blocked with liquid preventing free passage of gas. The pressure in the pipeline then increases as more liquid runs down to the base of the pipeline increasing the size of the liquid slug. The system remains 'stable' until the pressure has built sufficiently to overcome the gravitational head associated with the liquid slug. The system is then hydrodynamically unstable and the liquid slug is discharge rapidly up the riser followed immediately by a gas surge as the pipeline blows down. The pressure in the pipeline then returns to a low value, leading to insufficient gas velocities to carry the liquids up the riser, and the process is repeated.

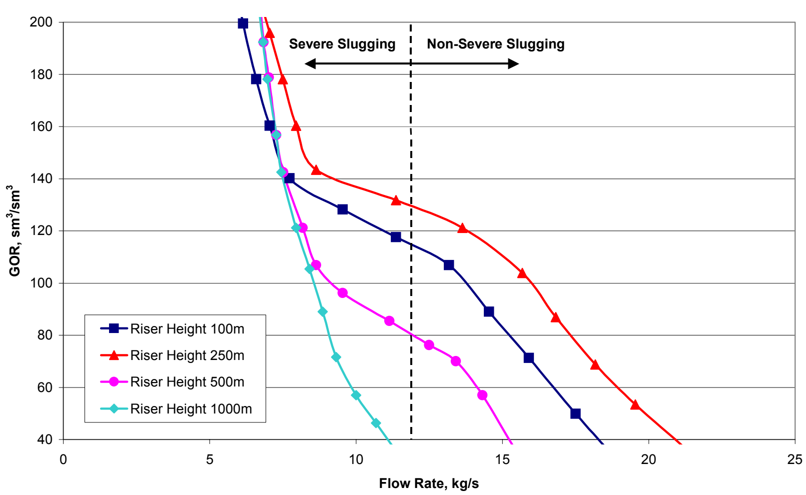
Figure 5, Schematic of Severe Slugging in Flowline Riser Systems



In recent years with the proliferation of deepwater developments, the phenomenon of severe slugging has come to the fore. With the increase in riser heights, it has been proposed (for example recently by Sarica and Tengesdal, 2000) that severe slugging will be exacerbated in deepwater systems. This question has been investigated numerically in this paper using a commercially available transient multiphase flow simulator. Calculations were performed for a range of fixed Gas-Oil-Ratios (GORs) and for various riser heights. The delivery pressure at the topsides slug catcher was fixed at a constant 30 bara (typical first stage separator pressure), and simulations were carried out for a range of flow rates in order to establish the stability boundary. The system simulated included a 1km horizontal flowline followed by a downhill 100m section dropping by 5m. The vertical riser started at the end of the downhill section and was varied from 100 to 1000m in height.

The results of the simulations of slugging potential showed some surprising results. Figure 6 presents a stability map showing boundaries of stability. Conditions to the left of a boundary (i.e. at lower flow rates) are unstable whereas conditions on the other side of the boundary are stable. The map shows that higher GOR oils are stable at lower flow rates than the lower GOR oils which is as expected since the higher gas velocities for a given mass flow rate are more likely to motivate the liquids up the riser.

Figure 6, Stability Map for Flowline-Riser Systems with Increasing Riser Height



However, when examining the position of the stability boundary for various riser heights, it is clear that increasing the riser height can be either stabilising or destabilising. This behaviour is somewhat unexpected and requires explanation. From inspection of the results, it is apparent that there are two competing effects that interact as the riser height increases. First, the increase in the riser height leads to an increase in the gravitational pressure drop up the riser which increases the propensity towards blockage at the base of the riser and is destabilising. However, this is countered by the increase in the pipeline operating pressure with riser height, which reduces the compressibility of this upstream volume and is stabilising.

It is interesting to note that reducing upstream compressibility by elevating the pipeline pressure has been proposed by a number of researchers as a method for mitigating severe slugging. For example, Hollenburg *et al* (1995) and Jansen and Shoham (1994) propose choking back at the top of the riser to increase upstream pressure. While this does present a method of stabilising systems, the increase in back pressure is usually undesirable since it reduces the deliverability of the system and ultimately the amount of hydrocarbons recovered. This is particularly true in the relatively low energy deepwater turbidite reservoirs where initial reservoir pressures are low and designers are keen to reduce system pressure drops as much as possible.

Closer inspection of the predicted flow rates for the various cases examined shows that the character of the instability changes across the stability map. To the left of the dashed line, the stability boundaries delimit stable flow from classical severe slugging with complete intermittent blockage of flow at the riser base. However, to the right of the dashed line, the stability boundary delimits stable from unstable flows where the base of the riser does not become completely blocked with liquid and the liquid flow rate is non-zero at all times.

A typical flow rate trace for the predicted severe slugging cases is given in Figure 7. The accompanying phase portrait of normalised outlet liquid flow rate versus normalised pipeline inlet pressure is shown in Figure 8. A better feel for the instability behaviour can be obtained by plotting a *phase portrait* where state variables are plotted against each other removing time. The character of the time dependency is often reflected in the shape of the trajectory thus improving understanding. This method has proved invaluable in the study of chaotic attractors. The phase portrait corresponding to the results shown in Figure 7, shows points plotted in a Poincaré section (i.e. at regular time intervals) and clearly illustrates the bifurcation to a stable limit-cycle. The shape of the limit-cycle is characteristic of severe slugging, having a flat bottom where the flow rate is zero and the pressure is building continuously until at a critical pipeline pressure the blocked system becomes unstable and a liquid slug is discharged very quickly.

Figure 7, Severe Slugging Liquid Flow Rate Trace – 1000m Riser, GOR 107 sm^3/sm^3

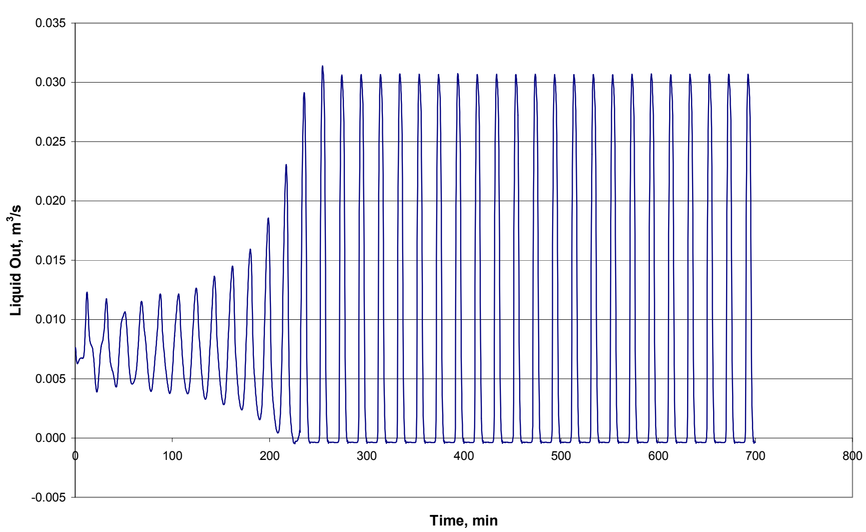
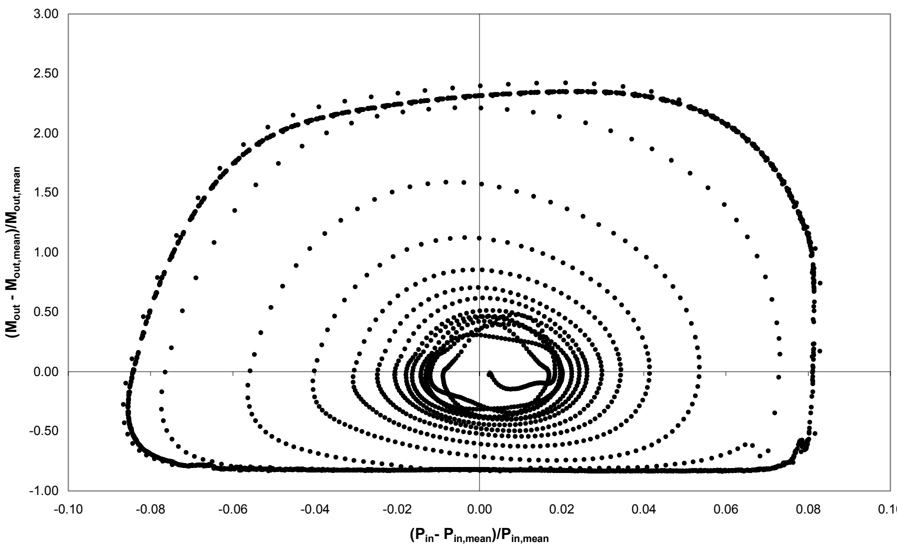


Figure 8, Severe Slugging Phase Portrait – 1000m Riser, GOR 107 sm^3/sm^3



The non-severe slugging behaviour is characteristically different from the severe slugging case. Figure 9 shows an example time trace of predicted liquid outlet flow rate and Figure 10 presents a phase portrait of normalised outlet flow rate versus normalised pipeline inlet pressure. The phase portrait shows that the systems diverges relatively slowly from the initial conditions to a stable limit-cycle. The shape of the limit-cycle is closer to being circular than the one presented earlier for severe slugging which is a reflection of the near-sinusoidal variation of the state variables of outlet flow rate and pipeline inlet pressure.

Figure 9, Non-Severe Slugging Liquid Flow Rate Trace – 250m Riser, GOR 36 sm^3/sm^3

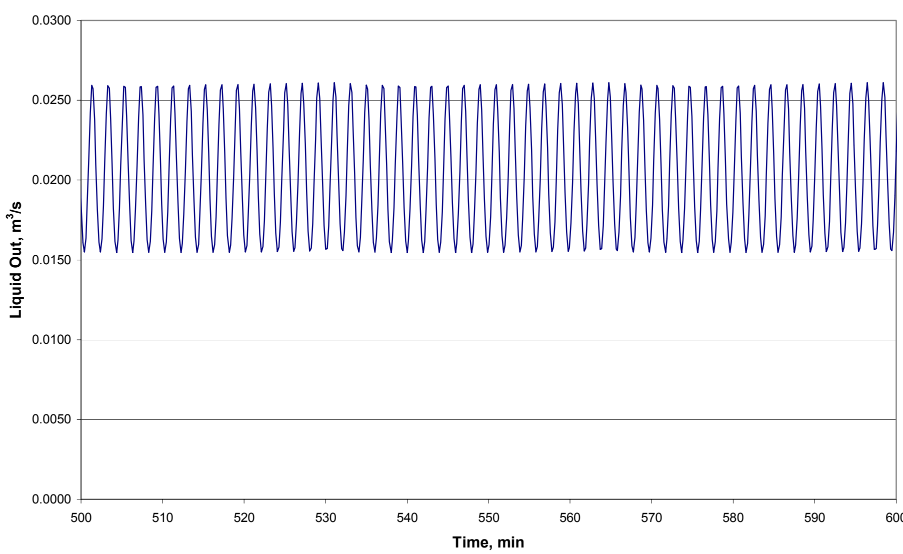
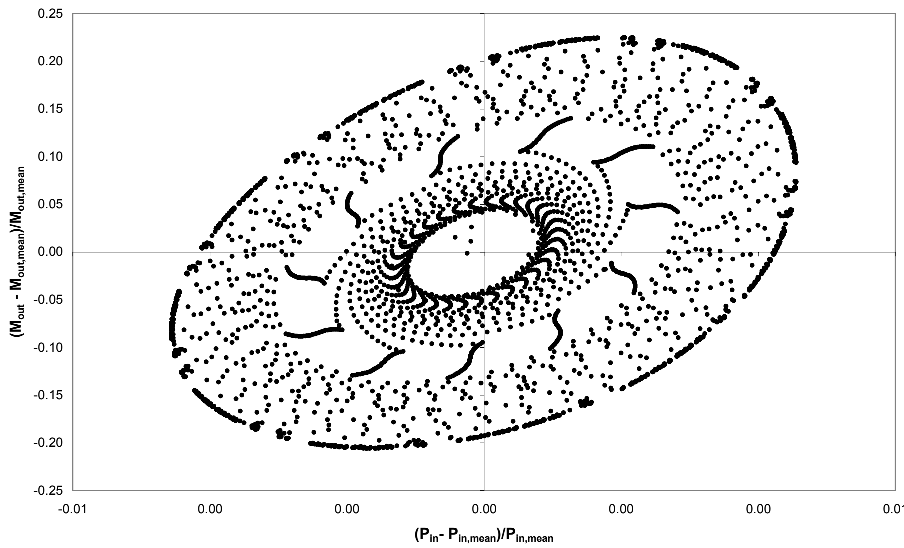


Figure 10, Non-Severe Slugging Phase Portrait – 250m Riser, GOR 36 sm^3/sm^3

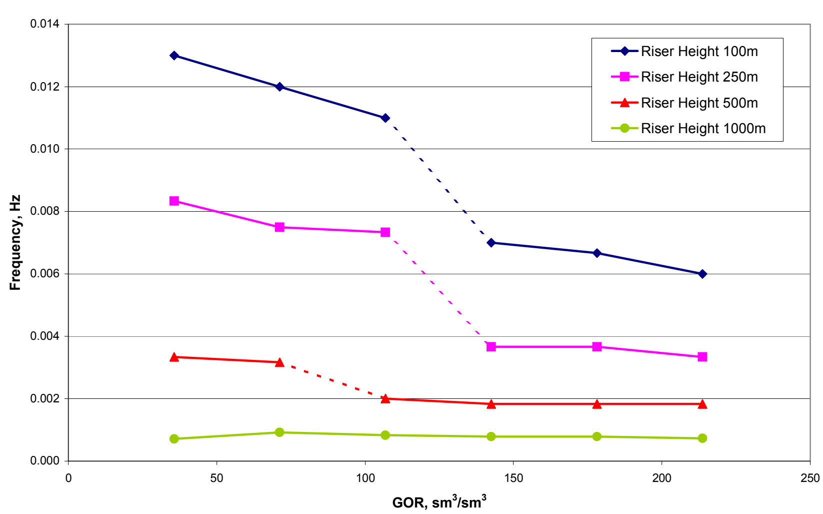


Finally, in this example presentation on slugging analysis of flowline-riser systems, Figure 11 presents the results of predicted slugging frequency for the four riser heights and the range of GORs examined. It is evident from the chart, that the slugging frequency decreases with riser height. For the 100, 250 and 500m risers, the curves are broken by a dashed line. This denotes the transition from the non-severe slugging mode to the severe slugging mode. For the 1000m riser, all cases examined displayed severe slugging behaviour.

At a fixed flow rate the amount of liquid accumulated at the base of the riser increases as the slugging frequency decreases. From the frequency data, it is apparent that when unstable, systems with greater riser heights will produce larger slugs.

The example analysis of slugging in flowline-riser systems of various heights presented here, provides some insight into the behaviour of such systems. From the results it is evident that increases in Gas-Oil-Ratios (GORs) are generally stabilising whereas increases in riser height can be both stabilising and destabilising. However, for unstable systems close to the marginal stability boundary, the results show that increases in riser height will produce larger slugs at lower frequencies leading to increased difficulties with topsides processing facilities.

Figure 11, Predicted Slugging Frequencies for Various Riser Heights and GORs



THE ACCURACY OF THE ESTABLISHED METHODS

Having now discussed the practical difficulties that arise in deepwater flowline-riser systems, the general approaches to modelling of multiphase flows in such systems and the current state of the commercially available modelling tools, what remains is to consider the possible accuracy of the established methods. The results presented in the previous section seemed qualitatively reasonable, displaying explainable physical trends. But how accurate are the predictions and can they be reliably employed for the purposes of design? In this section, we attempt to address this question.

It is perhaps little known in the industry, that nearly all information on multiphase flow in vertical pipes is for diameters less than, say, 2 inches (50 millimetres). In single-phase flows, there is a rational basis for extrapolating from small diameter pipes to larger diameter pipes on the basis of Reynolds number and pipe roughness. However, for multiphase flows, extrapolation from small to large diameters is not at all secure.

As mentioned previously, design work in two-phase flow has traditionally been based on purely empirical correlations (typified by those of Lockhart and Martinelli 1949 and Beggs and Brill 1977). Even for small diameter pipes, extrapolation of such correlations beyond the range of data for which they were developed is of extremely doubtful validity. The tendency in more recent work has been to use *phenomenological models*. Here, the *flow pattern* or *flow regime* is identified by one means or another and models developed which deal with the specific flow pattern (bubble flow, slug flow, annular flow etc). This raises immediately the problem of identifying the flow regime; traditional empirical flow regime maps (for instance that of Baker, 1965) are commonly applied. Alternatively, phenomenological interpretations of flow regime transitions can be hypothesised, an example of this approach being that of Taitel *et al* (1980). The difficulty with this approach is that the suggested transition mechanisms may not be correct, or if they are correct for small diameter tubes, they cannot be applied to larger diameter tubes.

For tubes of diameter less than, say, 50 millimetres, there is evidence to suggest that the regime transitions occur by the following sequence of mechanisms:

1. **Bubble-to-slug.** Here, at void fractions typically above 25-30%, *void waves* are formed which lead to locally very high concentrations of the bubbles. In these regions of high concentration, contact times between the bubbles rise to a sufficiently high value that coalescence can take place (this would not be possible at the *mean* void fraction of 25-30%). Evidence for the void wave mechanism is presented by, for example, Bouré (1997) and Beisheuvel and Gorissen (1989).
2. **Slug-to-churn.** The likely mechanism for this transition is that of flooding within the slug flow bubble (Jayanti and Hewitt, 1992, Watson and Hewitt, 1999).
3. **Churn-to-annular**. This transition is a gradual one. The flooding waves (with intermediate zones of falling films) characteristic of churn flow gradually die out, the liquid films between the waves begin to move upwards and disturbance waves are formed on them which lead to further entrainment (extensive entrainment occurs also from the flooding waves). Annular flow may be defined as occurring when the falling films disappear.
4. **Annular-to-wispy-annular flow.** An important regime at high mass fluxes (where a large fraction of the liquid is entrained) is that of *wispy annular flow*. Here, core structures develop not unlike void waves (except that they are now concentration waves) and these have a very strong influence on the flow behaviour (Hewitt, 1997).

An example of a systematic treatment of two-phase flow by delineation of flow regimes and subsequent modelling of individual regimes is that of Holt *et al* (1999). This study was for small diameter passages and showed that the approach of delineation of flow patterns and subsequent modelling of each individual flow pattern gave much better predictions of pressure drop than did the application of empirical correlations which took no cognisance of the nature of the flow. Thus, the flow pattern based approach offers the best chance of improving prediction. Unfortunately, there are very significant effects of tube diameter on the very nature of the flow patterns and the transitions between them. Specifically, we may note the following:

1. There is a strong possibility that slug flow, as envisaged by the most commonly used flow pattern maps, *does not actually exist in large diameter pipes.* While it is true that large spherical capped bubbles are formed in large diameter pipes, these bubbles become unstable. Waves are formed on their surface which grow and which lead to the shedding of small bubbles at the trailing edge. This means that further growth of the spherical-capped bubbles is not possible. The maximum diameter appears to be around 2-4 inches and the existence of Taylor bubbles (characteristic of slug flow) at diameters greater than this seems unlikely except under transient conditions (e.g. in start-up - Cheng *et al* 1998).

2. As was mentioned above, the process of flooding in counter-current flow is an essential part of the mechanism of breakdown of slug flow into churn flow. It seems unlikely that this mechanism can apply at large diameter since the slug flow bubbles do not exist in the same form as they do for smaller diameter pipes. Furthermore, direct experiments on flooding in large diameter pipes (Watson, 1999) show that the mechanism of flooding in large diameter pipes is quite different. Thus, in small diameter pipes, flooding waves are formed which are coherent around the tube periphery and which can be swept up the tube as a result of forces on them by the gas core. Between these waves, there would be a falling liquid film. However, in flooding experiments in large diameter pipes, the waves are not coherent around the pipe but are localised in short regions around the circumference. These local flooding waves are not swept upwards by the gas phase (the forces on them are insufficient, Jayanti *et al,* 1992). Rather, the non-coherent waves are broken up into droplets which are then levitated by the gas phase, this process continuing until the annular flow region is reached.
3. Within the annular flow region itself, the *disturbance waves* are again not coherent around the periphery. These characteristic waves exist above critical film Reynolds numbers and may be associated with turbulent structures (Hewitt, 1969). However, work on a 5 inch diameter tube (Azzopardi *et al*, 1983) shows that the disturbance waves are not coherent under these circumstances showing distinct and important differences between behaviour in large and smaller diameter pipes.

It will be seen, therefore, that flow regime transitions in large diameter pipes, and the behaviour within given flow regimes within large diameter pipes, may be expected to be quite different to that observed in small diameter pipes. Current computer codes are based empirically and phenomenologically on ideas which have been developed from small diameter pipe data and observations. For instance, the Taitel *et al* (1980) flow pattern map has been applied to large diameter risers; this could not be expected to give good results since the map is not even applicable in the case of small diameter pipes, containing a number of quite incorrect mechanisms. It certainly cannot be applied to large diameter pipes.

For large diameter pipes, the crucial flow pattern changes between bubbly flow and annular flow are quite unknown. Perhaps the sequence might be as follows:

1. Smaller bubbles coalesce (either independently or within void waves) to form spherical cap bubbles which cannot in themselves grow to a large enough size to occupy the full pipe cross section as in the case of small diameter pipes.
2. The spherical cap bubbles formed will themselves rise in concentration and may also form void waves. This will lead to coalescence of these bubbles and the formation of large voids in the centre of the channel.
3. If the flow velocity is high enough, then the voids formed in the channel core may become continuous to form a churn or annular type flow. In the churn flow case, flooding waves will be locally formed which would break up into droplets, the flow falling partially downwards in the associated falling films. At high enough velocities, the flow would become annular with no falling film regions.

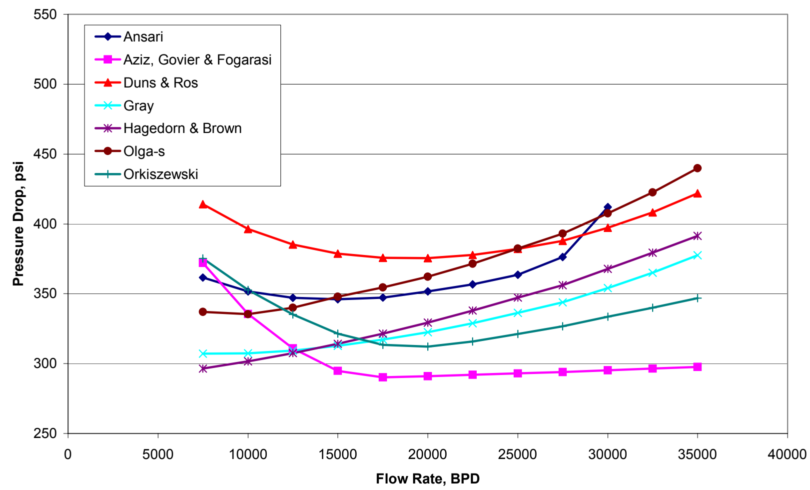
It should be stressed that this interpretation is highly speculative. The nature of these transitions is quite unknown. Another area which may be important is that of the transition from annular to wispy annular flow. The fraction of liquid which is entrained increases with increasing diameter in order to maintain the balance between entrainment and deposition.

It seems clear that concern about the reliability and accuracy of the established methods for larger diameters suitable for deepwater applications is justified. But is there any evidence to suggest that the current methods may not be applicable? Recent comparisons between observations of severe slugging in an experimental facility and the predictions from the leading transient multiphase flow codes, show that none of the codes accurately predict the measured data with the deviations between measurements and predictions lacking any consistent pattern. In addition, the predicted slug frequencies are higher than the measured values indicating that the codes under-predict slug sizes and are therefore non-conservative.

To further support our assertion that the accepted methods give questionable results, calculations were performed to illustrate the variability of predictions from the standard oil industry correlations (see Table 1). An example 8 inch vertical riser, 1000m in height was analysed assuming a 35°API oil with a stock-tank GOR of 89 sm^3/sm^3, fed with oil and gas at a temperature of 50°C.

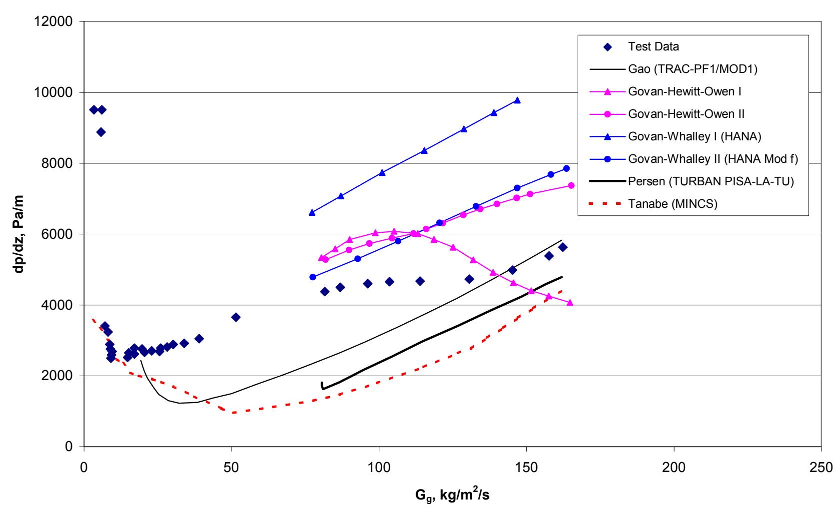
Figure 12 presents the predicted pressure drops up the riser as a function of the oil stock-tank flow rate. Clearly there is considerable variability among the correlations. At a flow rate of 30,000 BPD the variation on the average value is +13% -20%, which from a quantitative perspective could be considered acceptable if it were not for the fact that there are significant variations in parametric trends also! Given that significant under-predictions in pressure drop could lead to substantial losses of production and hence revenues, we suggest that the variations are unacceptable and more work is required to establish a more reliable and accurate method.

Figure 12, Comparison of Flow Correlations for 1000m, 8 inch Vertical Riser



With the results of predictions for deepwater riser now seriously in doubt, it would be instructive to know whether the problem has been solved perhaps in another industrial sector. The sector where multiphase flow has perhaps been studied the most is the nuclear industry, where prompted by safety concerns diabatic multiphase flows have been studied very thoroughly. Figure 13 shows data presented by Hewitt *et al* (1992) during a benchmarking exercise. A test data set of pressure gradient versus gas mass flux was compared to the predictions of a number of the established design codes for vertical multiphase flow developed in the nuclear industry. The figure speaks for itself: none of the methods predict the data!

Figure 13, Comparison of Nuclear Codes with Air-Water Data, (Hewitt *et al*, 1992)



CONCLUSIONS & RECOMMENDATIONS

From this brief assessment of Flow Assurance and multiphase flows in larger diameter deepwater risers, a number of important conclusions are evident:

1. It is clear from the qualitative discussion of Flow Assurance, that deepwater developments are a special case presenting particularly onerous conditions for designers and operators alike. The combination of low-energy / low-temperature reservoirs and large riser heights suggests that these field developments could be susceptible to production losses due to wax, hydrate and asphaltene deposition. Moreover, at low flow rates, riser systems can be expected to experience transients with the potential for large slugs delivered at the reception facilities with all of the attendant ramifications this implies.

2. From the assessment of the established design methods, it is clear that these have developed into complex tools able to qualitatively predict rich and varied physical phenomena such as severe slugging. However, while it is accepted that to a great extent these methods do predict the data on which they were founded, their general accuracy is doubtful, especially given the large variations in hydrocarbon fluids and development scenarios. This assertion is supported by recent experimental work which compared severe slugging data to the predictions of the main transient multiphase flow codes; none of the codes predicted the data particularly well and all over-predicted the slugging frequency which is a non-conservative error.

3. For multiphase flows in risers, it is known that the vast majority of experimental data have been collected in vertical air-water systems with pipes less than 2 inches in diameter, although there are some exceptions. Current design practice for larger diameters (such as those proposed for deepwater risers) relies on the extrapolation of the methods developed from the data gathered in the small diameter tests. The reliability of this extrapolation is extremely doubtful and it is highly likely that the characteristics of multiphase flows are markedly different in larger diameters. In particular, there is evidence that suggests that classical hydrodynamic slugging in larger diameters may not occur due to instabilities in the Taylor bubble. Recent tests by a major oil company in a 12 inch diameter air-water system also support this view.

Motivated by these conclusions, it is recommended that the industry establishes a joint-industry research programme to address these specific issues. Since the fundamental physical phenomena evident in larger diameter risers are in doubt, this programme must include properly controlled laboratory experiments designed to examine the minutiae of multiphase flow. In addition, the methods developed should be benchmarked against field data collected from adequately instrumented systems. Only with the results of such a programme in-place, can engineers be confident in their design methods and their proposed deepwater riser designs.

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