HYDRODYNAMIC BEHAVIOUR IN LARGE DIAMETER VERTICAL RISER: EXPERIMENTAL AND SIMULATION STUDIES

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ABSTRACT

An experimental campaign has been performed to investigate the hydrodynamic behaviour in 12m high and 254mm nominal diameter horizontal flowline-vertical riser setup using air-water as working fluid. The data generated from near riser base and flowline pressure variations were used to characterize the stable and unstable flows encountered during the experiments. A model to study the dynamic behaviour of the large diameter horizontal flowline-vertical riser system is developed using OLGA software (v5.1). Experimental results were compared with simulated model.

The major objective of undertaking this work is to investigate the performance of the well-known code for flows encountered in large diameter horizontal flowline-vertical riser. Additionally based on the results, also identify the areas of the improvement in the simulator.

1. INTRODUCTION

A significant proportion of the available Oil & Gas reserves are in deep offshore waters. Design and operation of the recovery systems in these deep offshore facilities are therefore crucial in terms of CAPEX & OPEX. For such critical application, much optimised designs are needed; therefore use of the transient multiphase flow simulators plays a vital role. These simulators are not only used for the designing of recovery systems and prediction of their expected operational behaviour, they are also used for flow assurance in existing facilities. As the industry seeks to recover above resources from increasing water depths, another challenge that has arisen is the need to transport the fluids to the surface via longer and larger diameter risers. However field data as well as experimental data of such systems are scarce.

In view of the aforementioned, an experimental campaign has been performed in a large diameter horizontal flowline-vertical riser facility at Cranfield University. As no simulation study is so far has been conducted with respect to large diameter vertical riser, in this paper the potential of leading commercial multiphase flow simulator OLGA has been explored. The assessment is important in order to identify the ability of the code to predict the stable and unstable flow characteristics. Additionally based on the results, also identify the areas of the improvement in the simulator that can lead to closer and accurate predictions.

2. OLGA – STATE OF THE ART REVIEW

OLGA (‘OiL’ & ‘GAs’) code is jointly been developed by IFE and SINTEF, Norway. The simulator is widely applied to design and operational problems e.g. start-up & shutdown transients, terrain slugging, variable production rates, pigging, gaslift etc. The code is based on 1D, extended two-fluid model and is available as steady state point model (OLGAS) and as complete transient computational code (OLGA). A mathematical review of the code can be found in Bendiksen *et al.* (1991). Although the use of OLGA since its commercialization in 1983 has been continuously expanding, very limited publications can be found in open access discussing its performance, below is a brief literature review available on code.

Bendiksen *et al.* (1980) benchmarked the code against published data for flow regime and terrain slugging predictions. Bendiksen *et al.* (1983) validated the code with data from the 189mm diameter SINTEF loop. Klemp (1985) presented the simulations using actual field data comparing the steady state vs. dynamic simulations, terrain slugging, shut-in & start-up operations and temperature transients. Bendiksen *et al.* (1986) provided a case study of terrain slugging and its successful elimination by choking at the riser outlet. Bendiksen *et al.* (1991) compared the code with SINTEFF data, Vic Bilh-Lacq field data and Schmidt *et al.* (1980) data. While the former two cases simulations predicted the trends successfully; in the latter an over prediction of flowline and under prediction of riser base pressures was seen in the simulation. Burke *et al*. (1992) compared the field results of a North Sea oil flowline with the OLGA. A good match between the OLGA and the field data was found after fine tuning the fluid and heat transfer properties. Vigneron *et al.* (1995) compared his data with the predictions of the three leading codes OLGA, PLAC and TUFFP. The codes did not yielded satisfactory results indicating that further work was needed to obtain better predictions. Dhulesia & Lopez (1996) critically evaluated five mechanistic models including OLGA. The results indicated that TACITE, another famous drift flux based simulator performed better than OLGA. Burke & Kashou (1996) provided a study of field case with OLGA simulation. However the model was fine tuned to obtain closer match. Kashou (1996) simulated the severe slugging trends in S-shaped and catenary riser. The detailed characteristics of severe slugging in both the risers were not predicted well by code. Xu (1997) demonstrated the successful prevention of severe slugging in Dubar-Alwyn flowline and controlling of hydrodynamic slugging from Hudson field to Tern platform. Lopez & Suchaux (1998) assessed OLGA and TACITE with TUFFP loop data and Bekapai-Senipah pipeline field data. Both the codes successfully simulated the steady state behaviour but the transient behaviour associated with flow rates changes was underestimated by the codes. Yeung and Montgomery (2001) also compared the results from three leading transient multiphase flow codes OLGA, PLAC and TACITE with data obtained from S-shaped riser. The work highlighted many discrepancies between experimental and simulated results. The main findings of Granato *et al.* (2001) study on the Aquila field included the closer prediction of some the main system parameters, numerical instabilities with OLGA 2000, weaknesses in choke and the well module of OLGA ver3.4. Putra (2002) simulated the East Java gas pipeline with OLGA. A fine tuning of pipeline flow parameters was performed in simulation to match the field data. Postvoll *et al*. (2002) simulations on Huldra-Heimdal flowline with OLGA real time analysis predicted the pressure drop within 10% of field data after tuning the pipe roughness but the liquid holdup predictions indicated fairly large inaccuracies. Yeung *et al*. (2003) investigated the causes of the deviation of OLGA simulation from experimental results of Yeung and Montgomery (2001). They verified from the experimental data that code did not predict the details characteristics correctly. Irfansyah *et al.* (2005) compared Bekapai-Senipah field data with OLGA. The result showed the steady state pressure drop within +8% of the measured value with discrepancies in transient simulation. Eidsmoen & Robert (2005) highlighted the modelling aspect of steady state and transient simulation of gas-condensate pipelines. Heskestad (2005) compared the North Sea field results with OLGA; the code highly under estimated the pressure drop and transients cases also did not perform well.

3. EXPERIMENTS CAMPAIGN

The data used for the simulation is taken from the 254mm (nominal) diameter horizontal flowline of 36m and 12.2m vertical riser facility. A detailed description of the facility and the measurement techniques can be found in Ali and Yeung (2008a). A total of 22 cases were carried out to test the capabilities of the simulator with gas and liquid superficial velocities range of 0.18 - 2.14m/s and 0.20 to 0.62m/s respectively. The flow regimes in this range were stratified smooth, wavy, plug and slug flow in flowline with stable bubbly to highly intermittent churn/froth flow in the riser

Many parameters were investigated in the simulations, for the sake of brevity, here only the results of the flow regimes and flowline/riser base pressure cycling characteristics are presented. Above variables have been used in identifying the nature of the flow in different topology pipeline-riser (Schmidt *et al.*, 1980; Fabre *et al.*, 1990; Tin, 1991; Yeung and Montgomery, 2001; Yeung *et al.*, 2003). The methodology used is to test some stable flow cases along with unstable flow cases. Thus if the simulation can reflect the stable flow characteristics, then we can have some confidence on the simulation results for unstable cases. The results of only few cases will be presented, hereafter referred as case A, B, C, D, E and F.

4. MODEL FORMULATION

Before stating the results, assumptions and boundary conditions used are briefly defined. The large diameter facility was modelled as simplified horizontal flowline-vertical riser with short horizontal pipe at the end of the vertical riser. Use of the short horizontal pipe is to avoid numerical instability during simulations. It was further assumed that the diameter of the flowline-riser is constant with standard carbon steel properties. Three grids were implemented, here results of one of the grid is presented; horizontal pipeline of 36m divided into 40 sections (0.9m) with vertical riser modelled as 13 sections (0.9m). The PVTsim fluid property simulator was used for air-water properties with air treated as an ideal gas. Since experiments are conducted at low pressures, no heat and mass transfer between the phases and the environment was assumed. The cases discussed use the steady state pre-processor in the code for generating the initial values for transient simulations.

5. RESULTS

5.1 Flow patterns and Riser base pressure – 1st model results: Table 1 summarizes the results of the simulated cases. In the table, the discrepancies between experiments and simulations are evident. The code predicted cases of the flowline accurately while failed to predict the unstable cases in the riser. The code only recognized the bubbly flow in the riser for cases A and D. It is pointed out that while agitated bubbly, unstable slug and churn/froth flows are not recognized by code due to its strict classification (bubble, slug and annular flow for vertical flows), it interesting to note that code predicted bubbly and agitated bubbly flow as slug flow and churn/froth flow as annular flow. This highlights that the code's flow regime mechanism is not able to distinguish between the bubbly/agitated bubbly & slug flow and

Table 1. Results summary of the flow regimes by first model.

Case Name	**Superficial Air velocity** (m/s)	**Superficial Water velocity** (m/s)	**Experimental Flow regime** (FL/R/E) †	**Simulated Flow regime** (FL/R/E) †
A	0.18	0.20	ST / BU / BU	ST / ST / SL
B	1.22	0.29	ST-SL / AB-SL / AB	ST / ST-SL / ANN
C	2.17	0.32	SL / C / C	SL / ANN / ANN
D	0.18	0.50	PL / BU / BU	ST / ST-BU / BU
E	1.22	0.29	SL / US / US	SL / ST-SL / SL-BU
F	1.86	0.61	SL / C / C	SL / ST-SL / SL-BU-ANN

† FL=Flowline, R=Riser base, E=Riser Exit, ST=Stratified, PL=Plug, SL=Slug, BU=Bubbly, AB=Agitated bubbly, US=Unstable slug, C=Churn and ANN =Annular flow regime

churn/froth & annular flow, thus classifying them as slug and annular flow in case of large diameter. It is emphasised that inability of the code to predict the correct flow regime may be signifying the differences of the database used in developing the flow regime prediction mechanism. It is also pointed out that while the experimental flow regimes of the large diameter horizontal flowline are in reasonable agreement with Taitel & Duckler (1976) flow map, it is in contradiction with typical vertical flow pattern map of Taitel & Duckler (1980).

The experimental result shows the cases A and D to be bubbly flow with stable stratified smooth and wavy flow in flowline respectively, cases B and E to be agitated bubbly flow in riser with initial stratified wavy flow turning into slugging, and cases E and F are unstable churn/froth flow in the riser with large slugs in the flowline. According to the flow regime map (Taitel *et al.*, 1976), no slug should be present under the conditions of the cases B and C; however slugs were already formed at these low liquid velocities. In context of experiments, it is postulated that formation of slugs are due to the downstream topology of the flowline (90º elbow) connecting to the riser. The pressure sensor near the exit and the base indicates almost periodic arrival of slugs (Figure 1b). Similar pressure cycling is also observed in smaller diameter horizontal flowline-vertical riser configuration (Schmidt *et al.*, 1980; Fabre *et al.*, 1990). At higher gas-liquid velocities (case E and F), when the flowline is highly slugging, the hydrodynamic slugging, liquid accumulation along with the uneven gas penetration in the riser base compounded the whole process. Thus the pressure time trace is more irregular and periodicity is less straightforward, see Figure 1d. The figure also shows that the flowline slugs are comparatively larger then the slugs formed due to the liquid fall back. The small slugs are either ejected from the riser base by the gas drive from flowline or commingle with incoming slug to make complete blockage. However, both slugs in later sections dissipated completely or partially, turning to churn/froth flow (Ali & Yeung, 2008a).

The riser base pressure simulated by the first model for cases A, B, C and D under steady state average inputs turned out to be stable, see Figure 1 (case A not given). No tendency of small fluctuations (due to bubbly flow) or oscillations (due to slug flow) are observed. While the cases A and E were indeed stable bubbly flows (Figure 1c) in riser, cases B and C were predicted stable flow due to the incorrect flow regime prediction (annular flow), see Figure 1 (a & b). In the cases E and F, see Figure 1d (case E not given), pressure cycling were partially reproduced. Note that the code did not show any significant variations in case F within first 100s (case E - 50s) and appeared more or less as steady. However later, pressure cycling starts to set in slowly and gradually the amplitude level off, becoming apparently constant after

200s (E-100s). From above behaviour, it is suspected that the code does not distinguish between hydrodynamic slugging and terrain induced slugging.

Based on the above results, it is obvious that while the code did predict the stable flows satisfactorily, it was unable to predict the unstable flow accurately. The code also globally underestimated the steady state liquid inventory (Ali & Yeung, 2008b). Part of the explanation of this discrepancy could be the incorrect flow regime predictions and/or under estimation of the oscillation period. This implies that the code underestimate the size of the slug and over predicts the slugging frequency. This is an offset from designer's point of view as it may result in non conservative error. Underestimation of the liquid inventory by code has also been reported earlier (Straume et al., 1992; Montgomery & Yeung, 2001; Postvoll et al., 2002; Yeung et al., 2003). Thus the major challenge for the code is to be able to capture correctly the flowline and riser base pressure for unstable flows.

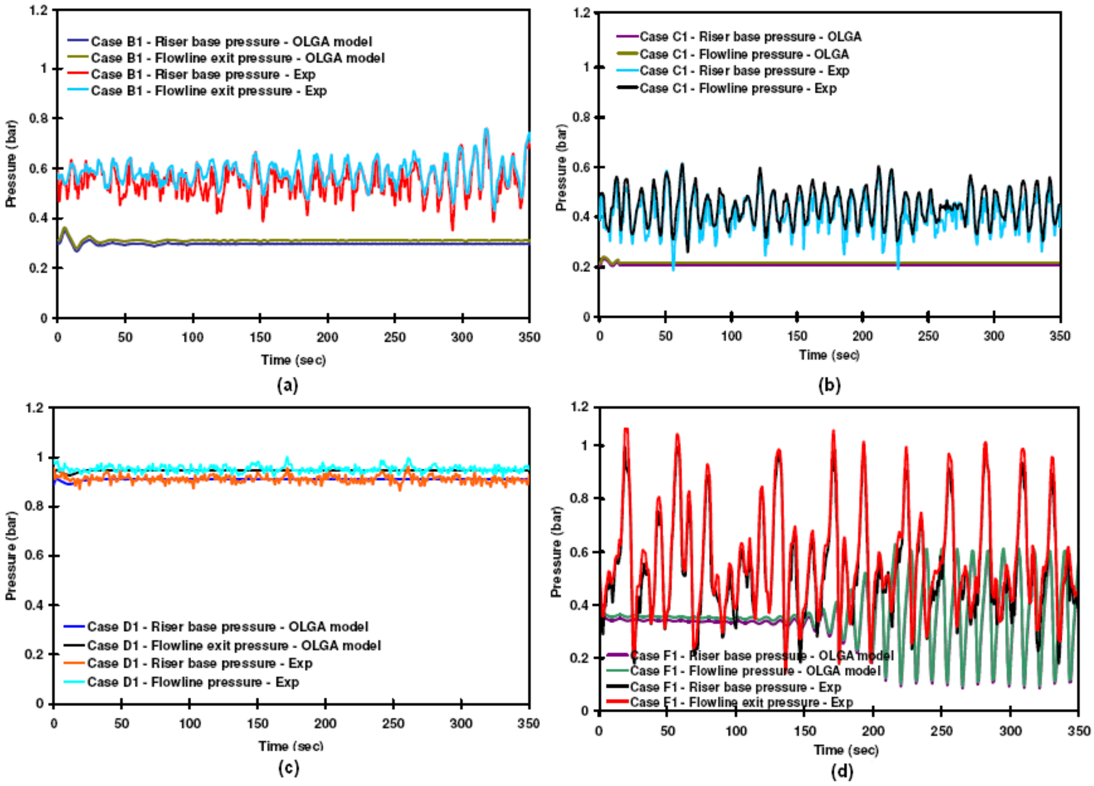

Figure 1. Riser base pressure time series of all cases (1st model results).

5.2 Extended model: Many attempts were made in modifying the first model; however these modifications did not improve the results. Thus it was concluded that the possible alternative was to change the boundary conditions; because during unstable flows the boundaries of the system are most affected. A satisfactory alternative to this was to use the sensor time series as the boundary conditions. Since the upper plenum was open to atmosphere, therefore sensor response near the exit of the riser was used instead, while all other conditions were kept same. Admittedly, this change does bring the mean pressure in the simulation and the riser base slightly close to each other as a consequence of the head imposed (≤0.09bar). However with this change, we will still be able to examine/verify the riser base pressure trends. Thus if positive results are obtained, it at least indicates that the code is capable of capturing the dynamics of typical unstable flow phenomena in large diameter horizontal flowline-vertical riser system.

5.3 Flow patterns & Riser base Pressure – extended model results: The change in the outlet boundary condition did not resulted in any change of the flow regimes predictions. However the code's plot option exhibited a non-physical flow regime flipping between various flow regimes ID in all unstable flow cases indicating the numerical difficulty posed to the code. The most interesting change in the results is the riser base pressure trends (Figure 2). It can be noted that unlike the first model, the unstable flow cases now indicates riser base pressure cycling. Although the riser base pressure amplitude is still under predicted by the code, the application of the pressure time series has now reproduced the overall riser base pressure trends at lest qualitatively. Thus in general this model showed a degree of success in predicting the overall nature of the unstable flow. In fact some of the slugging cycles along with kinks as observed in the experiments are also replicated (Figure 2a). Since these cycles and kinks were not simulated before, they can be attributed to the presence of pressure or void fraction waves due to the newly imposed boundary condition. It is likely that the code tends to smoothen out such perturbations when using steady state average boundary conditions. It is to be noted that in some cases, unlike the experimental results, the pressure cycling was regular with slightly higher frequency and shorter cycle time than in the experiments. In experiments more non-regular complex cycling behaviour was observed (Figure 2c). From above, one can deduce that the code does not predict these pressure surges quantitatively. In fact, code under predicts the pressure fluctuations than the experimental data. Moreover there is also a slight time shift between experiments and simulations in some cases, the reasons for this are unknown. Similar time shift is also seen in Yeung et al. (2003) work. Considering the overall simulated results of unstable flow cases, the enhanced deviation seen in the first model results was reduced by the extended model. This extended model qualitatively improved the unstable flow results; most notably in simulating the pressure trends, however according to the quantitative measures, the values are still lower from those observed in the experiments.

5.5 Grid and time step independency test: Here only the results for cases C and D are presented for the grid and timestep independency as the same conclusions are drawn from all the other cases. Three grid sizes of 0.9m, 1.8m and 3.6m were used (Figure 3a & 3c). It can be noted that varying the grid size does produces a slight effect on the riser base pressure predictions due to the numerical diffusion caused by the staggered grid. Some effects of higher frequency and mean pressure amplitude are also seen with coarsening the grid density. This observation is in corroboration with Montgomery (2002), Bendiksen et al. (1990) and Straume et al. (1992). In time resolution study, trials were performed with various timesteps and finally the initial timestep of 0.001s was manipulated from Δt/10, Δt, 10Δt (Figure 3b & 3d) to reduce global volume error. In time sensitivity study for some unstable flow cases, a slight affect of increase average amplitude was seen with increase in timestep.

6. CONCLUSION

Below are some of the findings based on the numerical simulation of large diameter horizontal flowline-vertical riser along with a literature survey on the code.

1. The survey indicates that in many field cases, the code has produced the desired results only after available parameters in the code were calibrated to match the results.

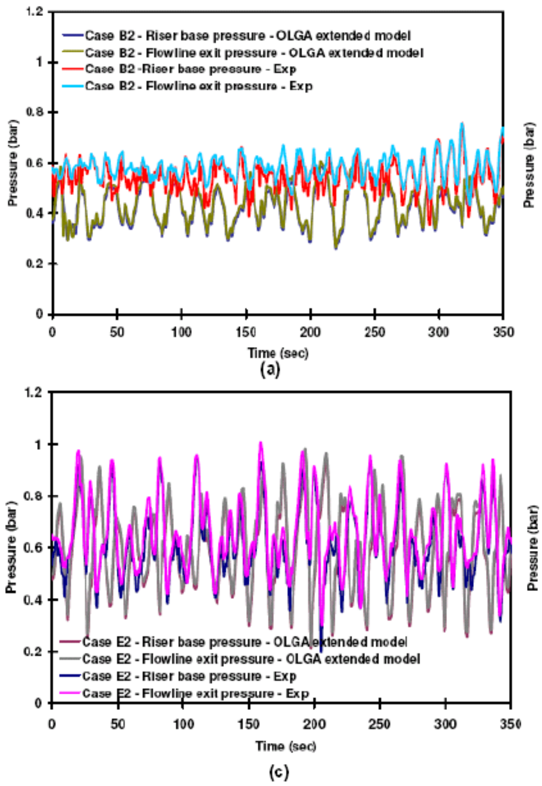

Figure 2 Riser base pressure time series for the cases B, C, E and F (Extended model results).

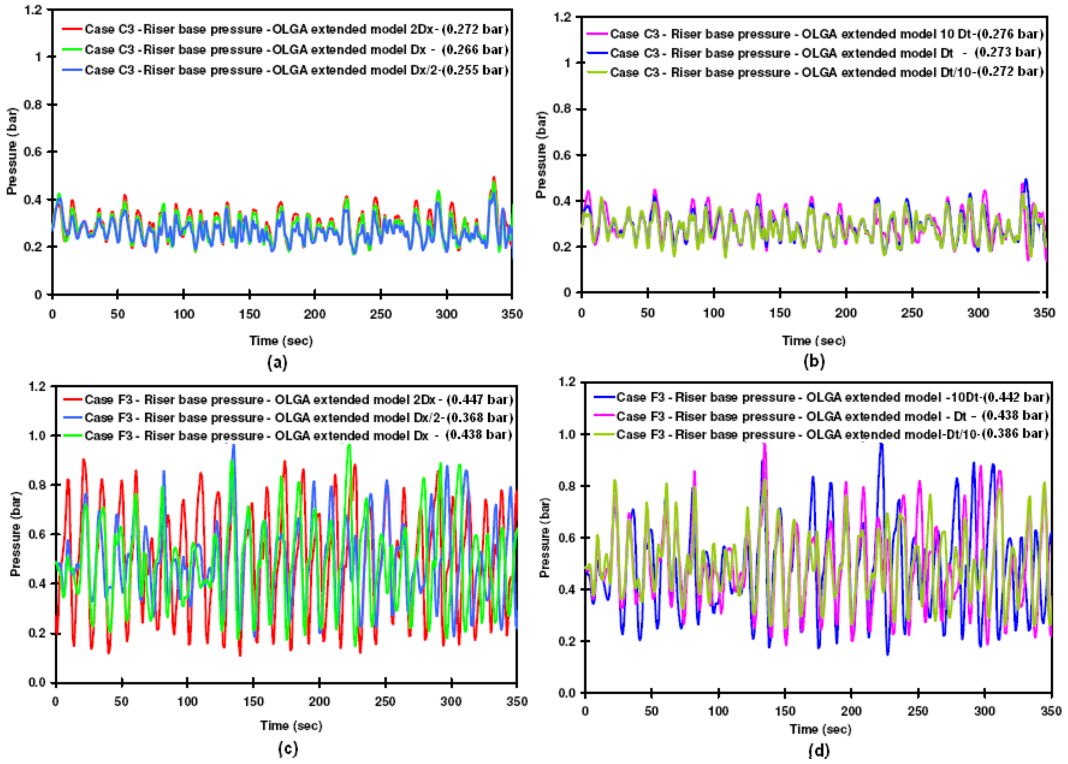

Figure3. Effect of grid density and time step changes for the cases C & F (Extended model results).

2. The study also shows that very limited work is done with regard to code's application

in the experimental loops (Schmidt *et al.*, 1980; Kashou, 1996; Yeung & Montgomery, 2001 and Yeung *et al.*, 2003). It further indicates that apart from the SINTEFF, on which the OLGA validation is based on, the code was unable to demonstrate satisfactory performance.

3. It is quite clear that the effects of boundary conditions on simulations are indeed substantial. Whilst stable flows have been satisfactorily modelled with steady state average boundary conditions, this practice was insufficient for determining the real behaviour in unstable flows in large diameter horizontal flowline-vertical riser.

4. Although this work has shown that inconsistencies were found in the prediction of flow regimes and liquid holdup along with the under prediction of the riser base pressure, still unstable flows in large diameter horizontal flowline-vertical riser were qualitatively reproduced with OLGA real time application to some extent. However, in order to perform a quantitative comparison, the code needs improvements in:

(a) Flow regime identification mechanism - as incorrect flow regime prediction can result in the use of incorrect closure relations.

(b) Gas-liquid interface modelling – as considerable errors can be made in predicting the liquid holdup and the pressure drop if gas-liquid interface is assumed flat.

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