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Investigating the Effect of Changes in Pipeline Declination on Severe Slugging

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Abstract— Severe slugging is an obnoxious multiphase flow regime in offshore oil and gas production systems. Its unstable nature poses problems not just to production/processing systems in form of sudden surges in liquid production that could result in separator overflow and shutdown and fluctuations in gas production that could cause operational /safety issues but also to the life of the well where increase in back – pressure could kill the well. A more grave consequence could be a reduction in the recoverable reserve in an oil and gas field. Hence, pipelines and subsea systems must be designed to assure that the multiphase fluids are transported from the wells to the processing facility safely and economically. In this work severe slugging and other unstable flow regimes in pipeline riser systems have been modelled in LedaFlow Engineering 1D transient multiphase flow simulator. A model was designed for the case (case 1) of pipeline - vertical riser configuration to implement laboratory scale experiments carried out by Fabre, et al. Case 1 presenting a declination angle of 0.57o, and cases 2, 3 & 4 with declination angles of 1.5 o, 3 o and 5 o respectively were simulated to investigate the effect of varying the declination angle of the pipeline on severe slugging. Results analysed were presented in terms of liquid production and pressure cycling characteristics. Hydrostatic pressure of riser at 1.32 bars confirms the occurrence of severe slugging in all cases of varied pipeline declination angles. Simulation results present Slug frequency as 0.006829 Hz, 0.005922 Hz, 0.005574 Hz & 0.00545 Hz and slug size volume as 0.040448 m3, 0.047081m3, 0.050207 m3 &0.051679 m3 for cases 1, 2, 3 and 4 respectively. It was observed that LedaFlow characterises severe slugging in terms of liquid production and pressure cycling to an acceptable level of accuracy as results of riser base pressure indicate the four phases involved in a severe slugging cycle. However, the model significantly under predicts the minimum riser base pressure and exaggerates the severe slugging frequency. LedaFlow simulations reveal that as the declination angle of the pipeline in the pipeline – riser system is increased the frequency of severe slugging occurrence decreases while the slug production increases.

Index Terms— Severe Slugging, LedaFlow Engineering, Pipeline Declination

1 INTRODUCTION

Typically, as oil and gas fields reach the end of their productive life, the natural reservoir pressure of fields decline resulting in low oil and gas flow rates. This makes lifting of hydrocarbons from reservoir to seabed and from seabed to the surface facility difficult. Also, investments on many wet gas or high gas – oil ratio (GOR) fields would not be economically rewarding if they are to be developed with dedicated gas and condensate separation and transportation systems. However, the economics of the field can be improved by considering a field development plan that employs a system which transports the total fluid as multiphase in a single pipeline to shore or to a nearby offshore production facility for processing. [1]

Considering the instances described above, pipelines and subsea systems must be designed to assure that the multiphase fluids are safely and economically transported from the bottom of the wells all the way to the downstream processing plants. Severe slugging is one of many issues encountered in ensuring that fluids are transported safely and economically to their destination.

Severe slugging an offshore oil and gas production flow assurance issue, (also known as Riser base – induced slugging) which occurs in a two phase liquid – gas multiphase flow where a pipeline segment with a downward inclination angle is followed by another segment (the riser) with upward inclination angle.

1.1 Severe slugging Mechanism

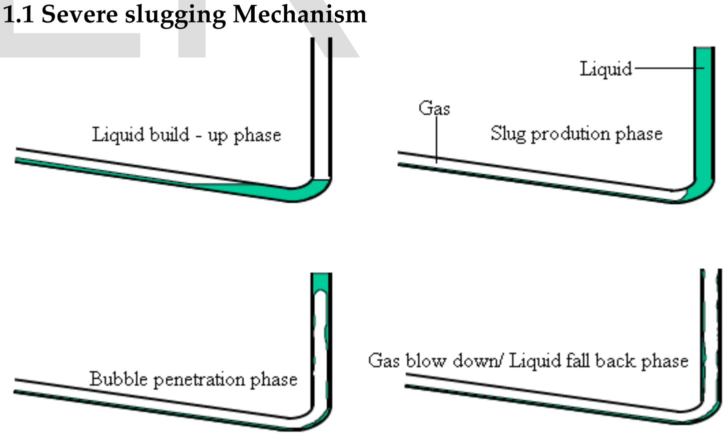

Fig. 1: Schematic of severe slugging mechanism

A severe slugging cycle comprises of four phases: liquid build up phase, slug production phase, bubble penetration phase and gas blow down / liquid fall back phase. During the liquid build up phase, liquids gather at the riser base causing increase in slug length in the pipeline and the riser causing the riser differential pressure (DP) to increase gradually.

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The liquid column builds up to the riser top, causing the riser DP to reach its maximum and then remains almost constant for a period i.e. the slug production phase. During this phase the slug tail in the pipeline moves towards the riser base and the slug front at the riser top moves to the topside separator. The liquid slug becomes longer than the riser length. The gas-blowdown/liquid-fallback phase is initiated as the gas bubbles behind the slug tail moves into the riser. This phase is typically characterised by the gas sweeping the liquid column remaining in the riser and subsequently rushing into the separator at high velocity, the riser DP decreases sharply to its minimum and the cycle continues. [2]

1.2 Criteria for Severe Slugging

[3] reports from the work by [4] that three conditions are to be fulfilled for severe slugging to occur.

1. Pipeline riser system with the pipeline being downwardly inclined upstream of the riser.
2. Liquid and gas flow in the pipeline take a stratified flow fashion
3. The hydrostatic head accumulation at the riser base increases at a rate greater than the upstream pipeline gas pressure.

1.3 Problems associated with Severe Slugging

Severe slugging causes undesirable flow assurance/production problems such as:

- Periods of no liquid and gas production followed by very high liquid and gas production resulting in flow instability (fluctuations) and large pressure variations in the production system.
- Sudden surges in liquid production could result in separator overflow and shutdown, and fluctuations in gas production could cause operational /safety issues as well as flaring.
- High pressure fluctuations could impact negatively on the production performance and eventually lead to a reduction in the recoverable reserve in an oil and gas field
- The increased average pressure experienced by the riser base due to severe slugging reduces the flow from the well. The increase in back – pressure may be sufficient to kill the well.
- Pipework and supports suffer fatigue and reduction in operating life (Mechanical integrity issues) as a result of the fluctuating weight of liquid in the riser as the riser empties and fills. Other causes of increased mechanical wear are the movement of slugs around bends and impact on obstructions [5].

The purpose of this work is to implement a successful run of severe slugging simulation using the LedaFlow Engineering 1D v1.6.246.819 multiphase transient simulator and to evaluate the effect of variations in pipeline declination on severe slugging.

2 METHODOLOGY

The approach involved modelling severe slugging in pipeline - vertical riser configuration system using the multiphase transient simulator LedaFlow Engineering 1D v1.6.246.819. The angle of pipeline declination with respect to the vertical riser was varied in order to describe the effects of changes in pipeline declination on severe slugging.

2.1 Case 1: Pipeline - Vertical Riser

2.1.1 Case 1 Problem Description

The pipeline – vertical riser system modelled in case 1 is the case of Laboratory scale experiments carried out by Fabre and others [6] to comprehend the severe slugging flow regimes.

The laboratory set up consisted of a 53 mm diameter flow loop made of transparent polyvinyl pipes. The test fluid was water and air. The test fluid flowed through a 25 m long pipe inclined to a vertical riser of 13.5 m height (Figure 2). A bend with radius of 0.5m connected the pipeline to vertical riser. The test fluid was introduced to the pipeline in a manner to prevent flow disturbances and to achieve a stratified flow. The riser outlet was connected to gravity separator vessel operating at atmospheric conditions.

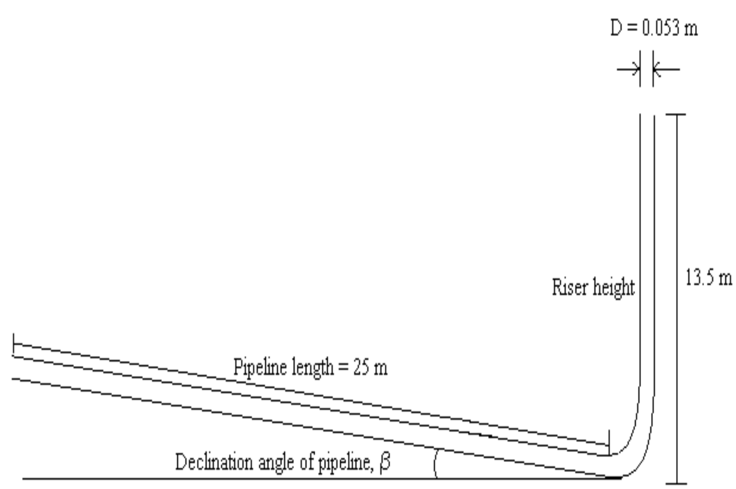

Fig. 2: Pipeline – vertical riser system set – up

The set up for the base case (Case 1.1) to be simulated maintained a pipeline declination angle of 0.57°, superficial

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gas velocity (u_{SG0}) = 0.20 m/s and superficial liquid velocity (u_{SL}) = 0.127 m/s.

2.1.2 LedaFlow Simulation of pipeline - vertical riser

2.1.2.1 PVT option

Fluid properties simulated were defined in the PVT option by clicking on the 'Case Settings' Tab [7]. Air and water were the fluids used for this simulation, with properties assumed to be constant.

Air is treated as compressible fluid and water was modelled as incompressible. Thermodynamic properties of water and air at a reference temperature and pressure of 15.6°C and 1.01325 bar respectively used for the simulation is provided in Table 1. [8]

Table 1: Properties of fluid (air and water) specified in the simulation

	Densities [kg/m3]	Viscosities [Pa.s]	Compressibility [kg/m3/bar]	Conductivities [W/m.K]	Heat capacities [J/kg.K]	Molar mass [g/mol]
Air	1.208	1.8014e-5	1.4	0.0242	1006.4	28.96
Water	1000	0.001	0.0	0.6	4181.8	16

2.1.2.2 *Pipe geometry set up*

Pipe geometry set up involves describing the path profile of the pipeline. This was executed by deriving the X – Z coordinates using Microsoft Excel and importing to geometry (Profile Tab) of the Pipe editor window of LedaFlow engineering 1D. Table 1 in appendix B gives the X- Z coordinates. The pipe roughness was specified as 0.0015.

2.1.2.3 *Boundary conditions*

The following boundary conditions are assigned to the system.

2.1.2.3.1 Pipeline Inlet

The pipeline inlet mass fraction was specified as the inlet boundary condition. Values for total mass flow and equivalent mass fractions of the gas and liquid (Table 2) were obtained from the set up superficial gas velocity of 0.20 m/s and liquid superficial velocity 0.127m/s were used for the simulation.

Table 2: Pipeline inlet boundary condition

Parameter	Value
Time [s]	0
Flow rate [kg/s]	0.2807
Gas mass fraction [-]	0.0019
Liquid mass fraction [-]	0.9981
Temperature [°C]	20

2.1.2.3.2 Riser top (Outlet)

The riser top pressure is set as the outlet boundary condition and is specified in the Table 3 below.

Table 3: Riser top boundary condition

Parameter	value
Time [s]	0
Pressure [bar]	1
Gas volume fraction [-]	1
Liquid volume fraction [-]	0
Temperature [°C]	20

2.1.2.4 *Set numerical parameters/ run case*

The numerical parameters are set as follows:

Table 4: Numerical settings for pipeline – vertical riser simulation

Parameter	value
Maximum time step size	0.05
CFL	0.80
Simulation time	1000

Thereafter the simulation is run.

2.2 Variations in Pipeline Declination Angle

After the successful run of the base case (case 1), the angle of declination of the pipeline was varied on three occasions to investigate its effect on severe slugging. The three cases (Cases 2, 3 and 4) were simulated similar to case 1 in respect to the following: Mesh configuration, pipe wall properties, PVT Option, Thermal Option, Simulation parameters, inlet (pipeline inlet) and outlet (riser top) boundary conditions, while pipeline angle declines at 1.5°, 3° and 5° for Cases 2, 3 and 4 respectively. The derived X – Z coordinates for the pipeline profile are provided in Appendix A.

2.2.1 Case 2: Pipeline declined at 1.5°, with Superficial gas velocity (u_{SG0}) = 0.20 m/s and superficial liquid velocity (u_{SL}) = 0.127 m/s

The derived X –Z coordinates for the pipeline geometry for case 2 is given in Appendix A.

2.2.2 Case 3: Pipeline declined at 3.0°, with Superficial gas velocity (u_{SG0}) = 0.20 m/s and superficial liquid velocity (u_{SL}) = 0.127 m/s

The derived X –Z coordinates for the pipeline geometry for case 3 is given in Appendix A.

2.2.3 Case 4: Pipeline declined at 5.0°, with Superficial gas velocity (u_{SG0}) = 0.20 m/s and superficial liquid velocity (u_{SL}) = 0.127 m/s

The derived X –Z coordinates for the pipeline geometry for case 4 is given in Appendix A

The cases were designed accordingly and simulation was run for the cases.

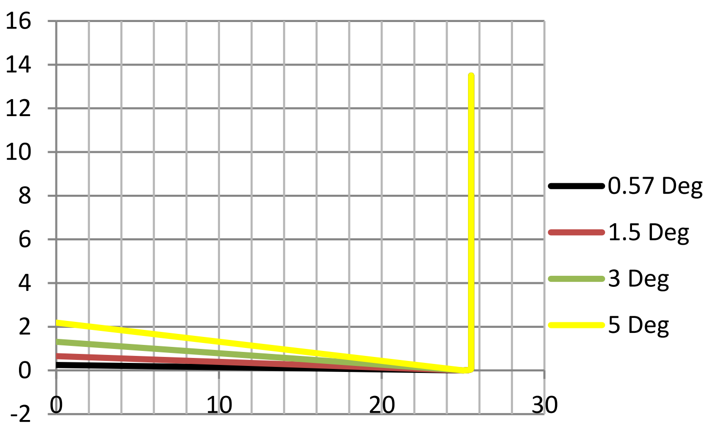


Fig. 2: Pipeline – vertical riser profile for the Cases 1, 2, 3, 4

2.3 Post Processing

Results of the simulation were set to save at every second. Results of interest such as pressures at the riser base and riser top as well as results of liquid rate at the riser top were exported from Leda flow Engineering 1D v1.6.246.819 into Excel spread sheet for analysis to characterize severe slugging.

3 RESULTS ANALYSIS

3.1 Severe Slugging Analysis Medium

The plot in Figure 4 gives results for the base case i.e. case 1, and the plot represents a typical severe slugging analysis medium. It is a plot of the riser base differential pressure (DP in bars) and riser top or outlet liquid rate (in m^3) against flow time (in seconds). From the plot important parameters selected and analysed to characterize the flow as severe slugging include; Riser base DP amplitude per cycle, Severe Slugging period/frequency, Duration of slug production phase per cycle, Slug size per cycle.

3.1.1 Riser base DP amplitude per cycle

Values of riser base DP amplitude confirm the occurrence of severe slugging if they equate the evaluated riser base hydrostatic head.

3.1.2 Slugging Period/Frequency

Slugging period/frequency evaluates the time it takes for a cycle of severe slugging to occur. It is estimated from points of one peak to another.

3.1.3Duration of slug production

The duration of the slug production gives an indication of period for liquid slug production. Hence, the time left from the severe slugging period is the time taken for the other three phases of the severe slugging cycle (liquid build up, bubble penetration and gas blow out/ liquid fall back) to occur.

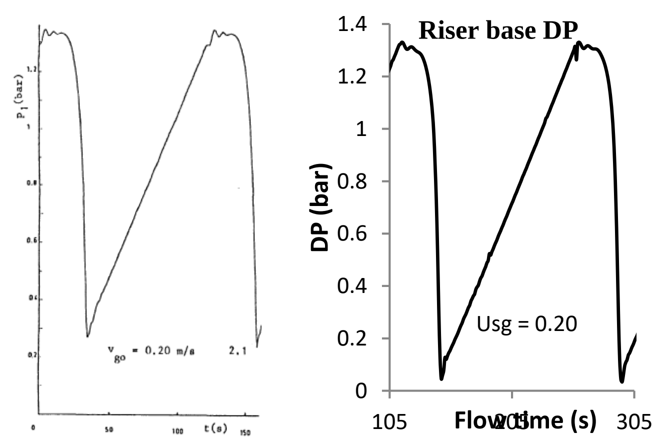
From Figure 4, it is also important to observe that the initial time for the steady peak riser DP coincides with the initial time of a non – zero outlet liquid rate. Likewise, the time of minimum riser DP relates to the end of the liquid production phase. This relationship ascertains that a steady peak riser DP corresponds to a continuous liquid production at the riser top during severe slugging.

3.1.4 Slug size

This estimates the quantity of liquid slug produced in a severe slugging cycle.

3.2 Validation of Simulation Results

Results of the simulation for case 1 were validated by comparison with results obtained from the experiment conducted by Fabre and others described in case 1above. Results show that there is good correspondence in the results of maximum riser DP between the experiment and the LedaFlow Engineering simulation as reported by [9]. However, the model significantly under-predicts the minimum riser DP when compared to the experimental campaign as seen in Figure 4. [10]



(a) Experimental riser base DP plot. Courtesy: [6]
(b) Simulation riser base DP Plot

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Fig. 4: Comparison of riser base DP trend

3.3. Case 1: Pipeline declined at 0.57°, with Superficial gas velocity (U_{SG0}) = 0.20 m/s and superficial liquid velocity (U_{SL}) = 0.127 m/s

For case 1 (Figure 5), a flow time of 1000 seconds, produces six complete severe slugging cycles

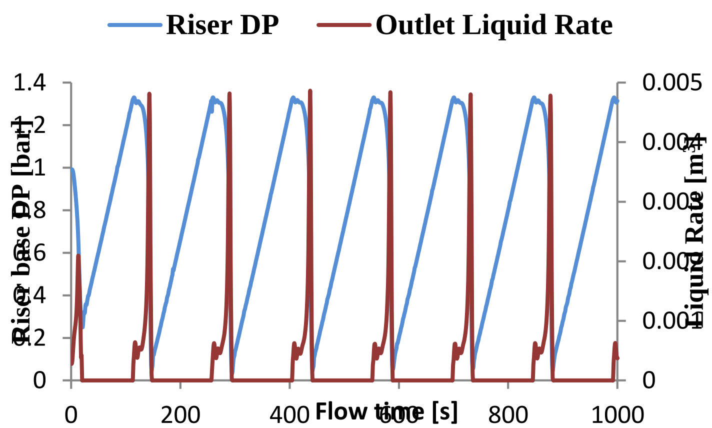


Fig. 5: Riser base DP and outlet liquid rate cycle trend for case 1

3.4 Variations in Pipeline Declination Angle

Plots for analyses of severe slugging when the pipeline declination angle is varied at 1.5°, 3.0° and 5.0° are presented in Appendix B (B-1, B -2, & B – 3 respectively). Results obtained are also compared with results of case 1 in Table 5.

Table 5: Results for variations in pipeline declination angle for pipeline – vertical riser system

Case	Declination Angle [°]	Pressure DP [bar]	Slug frequency [Hz]	Slug production Duration [s]	Slug size volume [m³]
1	0.57	1.3305	0.006829	36.67	0.040448
2	1.5	1.329636	0.005922	49.4	0.047081
3	3.0	1.329636	0.005574	66.2	0.050207
4	5.0	1.328746	0.00545	60.2	0.051679

Results in Table 5 show the riser base DP amplitude of the system is greater than the hydrostatic pressure of the riser of 1.32 bars for all the varied pipeline declination angles, this confirms the occurrence of severe slugging in the system. Results show a continuous decrease in severe slugging frequency as the pipeline declination increases while slug production duration increases when the pipeline declines from 0.57° to 1.5° and further to 3.0°. There is a drop in slug duration time when the pipeline is further declined to an angle of 5.0° and the slug size is largest.

4. CONCLUSION

Results of simulations show that increases in pipeline declination decrease the frequency of severe slugging and increases the amount of liquid slug per cycle. This surge poses serious issues for the topside equipment. It is important to carryout sensitivity analysis on offshore production systems during the design stage using capable multiphase transient simulators for the purpose of investigating possible severe slugging occurrence. This will give a clue towards the implementation of suitable mitigation or control strategies

APPENDICES

APPENDIX A: X –Z COORDINATES FOR PIPELINE PROFILE

The table in this Appendix provides the derived X –Z coordinates for the pipeline profile for **p**ipelines declined at 0.57°, 1.5°, 3.0° and 5.0°, with Superficial gas velocity (u_{SG0}) = 0.20 m/s and superficial liquid velocity (u_{SL}) = 0.127 m/s.

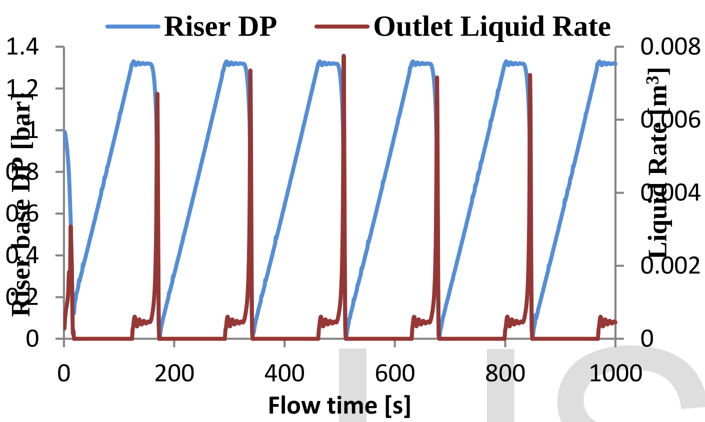
X	Z [0.57°]	Z [1.5°]	Z [3.0°]	Z [5.0°]
0	0.25	0.654648	1.310194	2.18721
5	0.2	0.523718	1.048156	1.74977
10	0.15	0.392789	0.786117	1.31233
15	0.1	0.261859	0.524078	0.87488
20	0.05	0.13093	0.262039	0.43744
22	0.03	0.078558	0.157223	0.26246
24.1	0.009	0.023567	0.047167	0.07874
24.3	0.007	0.01833	0.036685	0.06124
24.5	0.005	0.013093	0.026204	0.04374
24.7	0.003	0.007856	0.015722	0.02624
25	0	0	0	0
25.1	0.005	0.005	0.005	0.005
25.2	0.009	0.009	0.009	0.009
25.3	0.015	0.015	0.015	0.015
25.35	0.02	0.02	0.02	0.02
25.4	0.03	0.03	0.03	0.03
25.45	0.04	0.04	0.04	0.04

25.48	0.048	0.048	0.048	0.048
25.49	0.06	0.06	0.06	0.06
25.5	0.08	0.08	0.08	0.08
25.5	7	7	7	7
25.5	13.5	13.5	13.5	13.5

APPENDIX B

APPENDIX B -1

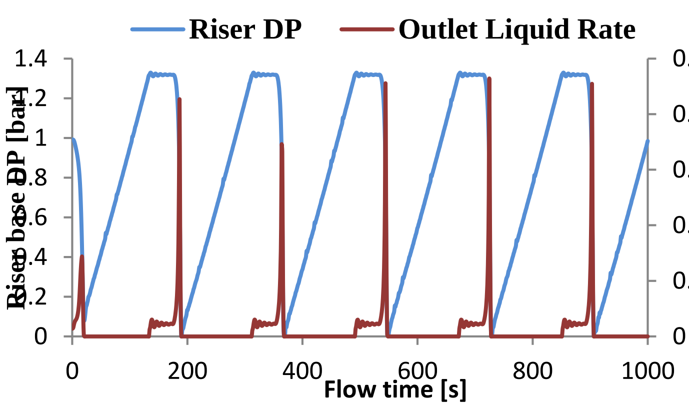
Case 2: Vertical riser with pipeline declined at 1.5°



Riser base DP and outlet liquid rate cycle trend for case 2

APPENDIX B – 2

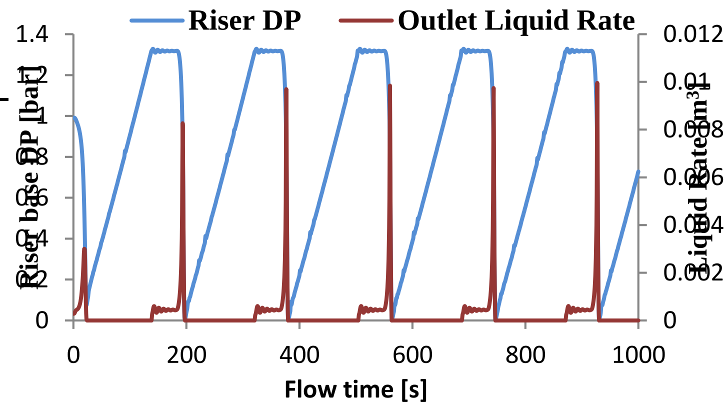
Case 3: Vertical riser with pipeline declined at 3.0°



Riser base DP and outlet liquid rate cycle trend for case 3

APPENDIX B – 3

Case 4: Vertical riser with pipeline declined at 5.0°



Riser base DP and outlet liquid rate cycle trend for case 4

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