NUMERICAL SIMULATION OF AN OIL AND GAS SUBSEA SEPARATION AND PUMPING SYSTEM FOR OFFSHORE PETROLEUM PRODUCTION USING THE METHOD OF CHARACTERISTICS

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Abstract. *This work addresses numerical simulations of oil and gas subsea separator and pumping systems. This system is also composed of two risers that transport separately liquid and gas from Subsea Separator to the Platform. The main objective of these simulations is study the dynamic performance of the control of the pumping system to maintain an accepted range of liquid level in the separator considering the transient flow in the risers. This development has been carried out using the Method of Characteristics to solve the transient of the flow inside the risers. The subsea separator is solved using the conservation of mass equation and the pumping system is modeled using second order polynomial pumping equation. The system was coupled and the analysis of the overall system was possible. The main results obtained from these simulations are the variation of pumping frequency and head; pressure, flow and liquid level in the separator; and the variation of pressure and flow in the liquid and gas risers. These results could demonstrate the robustness of the pumping control for this application.*

Keywords*: Subsea Separation, Numerical Simulation, Method of Characteristics*

1. INTRODUCTION

Nowadays the discoveries of the petroleum reservoirs in deepwater fields, like the Tupi field in Santos Basin, Brazil, are driven the search for new technologies that make possible the exploration and production of oil and gas in greater water depths.

In this scenario, an innovative system to perform the multi-phase separation and pumping from the seabed are being developed. The system is a two-phase separation process that separates the liquid and gas phases from the well production. After the gas/liquid mixture is separated, the liquid phase is pumped to the platform by the Electric Submersible Pump (ESP) and the gas is vented to the platform. This system, called in many references as Vertical Annular Separation and Pumping System (VASPS), has proven to be a feasible solution to increase subsea production from marginal and mature fields (Caetano et al. 2005).

The main advantages of use this system are listed as follow.

1) This solution can substitute the heavy separator equipment generally installed on the production platform, reducing considerably the weight, which will allow the use of a smaller and cheaper platform;
2) This system can increase the reservoir recovery as the pressure at the wellhead is lowered, since a pump will be installed near the well or manifold (do Vale, 2002);
3) The flow inside the risers cannot present slug flow, since the multiphase flow of the well will be separated and transported to the platform by two different risers, one for liquid and other for gas;

The separation comprises three stages that will be briefly described from up to down. In the higher part of the separator, an expansion chamber is used to expand the gas upwards, which will be vent to the platform, whereas the liquid flows down. Then, almost all of the remaining gas is separated by centrifugal forces in conducting helix installed in the middle of the separator. A reservoir in the bottom of the separator is used to separate the gas provided by small bubbles that will lift by gravity and from where the liquid should be drawn by pumping.

The liquid level inside the separator vessel must be controlled because if the liquid level surpasses a maximum level limit, the efficiency of the separation process is decreased, since the useful area in the conducting helix is reduced. On the other hand, if the liquid level becomes lower than the physical height of the intake of the pump, a high quantity of gas will flow to the pump affecting the operation and ultimately causing serious damage. There are evidences of difficulties in keeping designed operation levels, given the disturbances caused by the slug inflow in the system. Such disturbances allied to the nonlinearities of the system imply high randomness on the system behavior, making it difficult to predict the necessary control actions and demanding the supervision of an operator (De Mello et al., 2007).

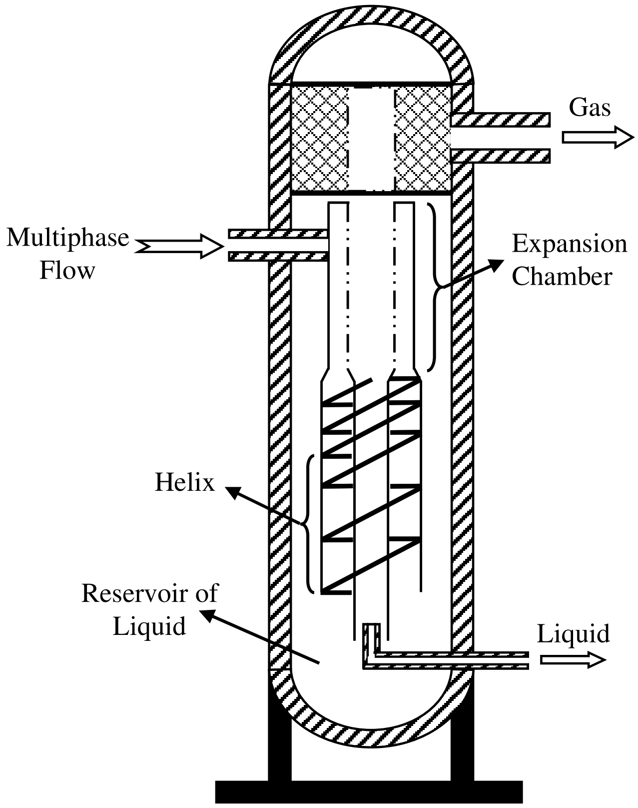

Figure 1. Subsea Separator description.

Such panorama justifies the interest for designing a control system focused on improving the performance of the system. A simplified model was idealized by Teixeira et al. (2004), reflecting the basic dynamics of the system, with the intent of conceiving a controller which allows a steady operation in laboratory, providing refinements of this model, initiation of the computational simulations of the controlled system, evaluation response, stability and disturbances. The level of liquid in the reservoir inside the separator vessel was considered as the controlled variable. The manipulated variable was the frequency rotation of the pump, which is the control signal. The controlled variable must follow a reference signal, which restrains to a closed interval.

Based on Teixeira's works (Teixeira et al., 2004 and 2006), De Mello et al. (2007a,b) developed two approaches. The first one focuses on improvement performance of the system by means of a Fuzzy-PID control for the liquid level variation, minimizing the error against the reference signal. The other focuses on the stabilization of the control signal, minimizing the amount of acceleration and deceleration of ESP activation ramps, which enlarges its lifespan and therefore reduces operational costs, in detriment of the level control, which must oscillate within the stability band, given by the interval allowed to the reference signal.

Pinheiro et al (2009) presented an approach based on stochastic impulse control, which can be transformed in a sequence of iterated optimal stopping problems and expressed equivalently as a sequence of variational inequalities. A numerical solution was proposed, based on the Mean Value Scheme (MVS) method.

In this work the dynamic performance of the control approach presented by Pinheiro et al. (2009) is tested considering the effects of the gas in pressure vessel and the transient flow in the gas and liquid lines (risers). This development has been carried out using the Method of Characteristics to solve the transient of the flow inside the risers. The subsea separator is solved using the conservation of mass equation and the pumping system is modeled using second order polynomial pumping equation. The system was coupled and the analysis of the overall system was possible. The main results obtained from these simulations are the variation of pumping frequency and head; pressure, flow and liquid level in the separator; and the variation of pressure and flow in the liquid and gas risers. It is expected three different scenarios for this system: 1) Slug flow scenario, 2) Constant flow scenario and 3) Production scenario.

In the actual state, the approach adopted to simulate the separator, pump and riser system cannot represent a real case, once some simplifications were adopted in this work. In order to calculate the variation of the liquid level inside the separator, mass balance considering the inlet of the multiphase flow of the petroleum well and the outlet flow that is pumped by an ESP to the platform trough the riser. This model do not accounts for the PVT variation of the oil properties, therefore do not considers the gas dissociation from the oil which could occurs inside the separator and in the oil riser due to variation of pressure and temperature. This phenomenon could affect the pressure drop and the velocity propagation in the liquid riser flow. Otherwise, it is believed that these limitations do not significantly influence the liquid level in the separator, which is the main parameter used in the present system control. The main objective of this work is test the system control for different scenarios as presented before.

2. NUMERICAL MODEL

Gas Pipeline Modeling

The one dimensional mass and momentum equations of the gas flow in pipeline were presented by Wylie and Streeter (1993) as can be seen by the Eq. 1 and 2 respectively,

$$L_1 = \frac{\partial p}{\partial t} + \frac{B^2}{A}\frac{\partial M}{\partial x}dx = 0 \tag{1}$$

$$L_2 = \frac{\partial p}{\partial x} + \frac{fB^2M^2}{2DA^2p} + \frac{\rho_G g}{B^2} sen\theta + \frac{\alpha^2}{A}\frac{\partial M}{\partial t} = 0 \tag{2}$$

The gas pressure and density are represented by p and ρ_G, respectively. M is the mass rate of gas, A is the cross section area of the pipeline, t and x are respectively the time and position in the length of the pipeline, g is the gravity acceleration. α is defined as the inertial multiplier and was introduced by Yow (1971) in order to make the simulation quicker through the possibility of use larger time increments. But in this work α is considered as 1 which means that it has no effect at simulations.

The speed of sound (B) is given by:

$$B = \sqrt{\gamma ZRT} = \sqrt{\gamma \frac{p}{\rho_G}} \tag{3}$$

where γ is the specific heat ratio, Z is the compressibility factor, R is the gas constant and T is the absolute temperature. The wall shear stress is represented by the second term in the right hand side of Eq. 2, which is expressed through the Darcy-Weisbach friction factor, f.

Using Eq. 1 and 2 and applying the Method of Characteristics, one obtains a system of four ordinary differential equations (Eqs. 4 and 5).

$$\frac{1}{A}\frac{dM}{dt} \pm \frac{1}{B}\frac{dp}{dt} + \frac{\rho_G g sen\theta}{B^2} + \frac{f_G B^2 M^2}{2DA^2 p} = 0 \tag{4}$$

$$\frac{dx}{dt} = \pm B \tag{5}$$

Eqs. 4 and 5 is valid only for isothermal flow and constant compressibility. The kinetic energy variation through the length of the pipeline is not considered. Further, for curved pipelines as the case of the Catenary Riser for offshore petroleum production a great discretization is demanded, because each element of the Method of Characteristics will have a constant inclination through time.

The solution could be imagined by xt plane, as can be seen by Fig. 2. The lines (C^+ and C^-) on the xt plane are defined by characteristics lines, represented by Eqs. 5, along which Eqs. 4 are valid. The latter equations are referred as compatibility equation, each one being valid only in the appropriate characteristic line (Wylie and Streeter, 1993). The point P is found by solving this system of four equations.

Liquid Pipeline Modeling

The one dimensional mass and momentum equations for the flow in the pipeline in charge of transport the liquid pumped by the ESP to the platform were presented by Wylie and Streeter (1993) as can be seen by the Eq. 6 and 7 respectively,

$$L_1 = \frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \tag{6}$$

$$L_2 = \frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{f_L Q|Q|}{2DA} = 0 \tag{7}$$

where H and Q are the pressure head and liquid flow, respectively. a is the liquid wave velocity in the pipeline, which could be evaluated as:

$$a = \sqrt{\frac{K/\rho_L}{1+(K/E)(D/e)C}} \tag{8}$$

where K is the bulk modulus of the elasticity of the fluid, E is the Young's modulus of elasticity of the pipeline, e is the pipeline thickness, ρ_L is the liquid density and C is a constant function of the Poisson Module (ν) of the pipe material and of the boundary conditions of the pipe.

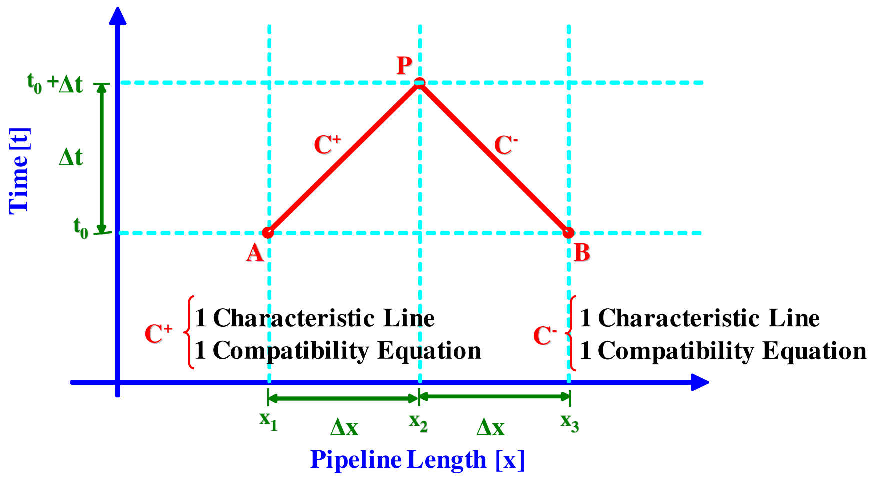

Figure 2. Characteristic lines in the *xt* plane.

The pressure head is defined as:

$$(p - p_{atm}) = \rho_L g(H - z) \tag{9}$$

where z is the elevation of the centreline of the pipe at x position.

Similarly to the development of the gas pipeline equations, the Eqs. 6 and 7 are reduced to a system of four ordinary differential equations applying the Method of the Characteristics. Eqs. 10 represent the compatibility equations for the liquid flow in the pipe and the Eqs. 11 are the characteristic lines.

$$\frac{dQ}{dt} \pm \frac{gA}{a}\frac{dH}{dt} + \frac{f_L Q|Q|}{2DA} = 0 \tag{10}$$

$$\frac{dx}{dt} = \pm a \tag{11}$$

Eqs. 10 and 11 considered an isothermal flow and a constant compressibility fluid. For the same reason of the gas pipeline the discretization should be great to reproduce the catenary riser. Furthermore, as previously discussed, this model do not considers the variation of the PVT properties of the liquid fluid due to the pressure and temperature variation. This limitations could influence in pressure drop of a long the riser and in the velocity of the wave propagation of the liquid, mainly because of a possible gas dissociation of the oil. However, as the main objective of this work is test the control system (Pinheiro *et al*, 2009) for different scenarios, these limitations may not present significant influence for control system response, since its influence in the liquid level of the separator should be small.

Liquid-Gas Separator

The behaviour of the Liquid-Gas Separator was evaluated by the conservation of mass equation considering the equipment as a cylindrical pressure vessel, as could be seen by Fig. 3. A multiphase flow with a mass rate of liquid $\dot{m}_{L1}$ and a mass rate of gas $\dot{m}_{G1}$ feed the separator, which after process will vent the gas to the platform with a $\dot{m}_{G2}$ mass rate due to the difference of pressure inside of the separator (P_G) and the pressure in the Platform (P_{PLAT}) while the liquid will be pumped to the platform with $\dot{m}_{L2}$. The connection between the separator and the ESP are at a distance r from the bottom of the separator. The remaining gas inside of the separator has a volume V_G and a mass m_G, and the remaining liquid has a mass m_L and a volume V_L, which make possible the calculation of the liquid level (l) when considering a constant cross-section area of the pressure vessel.

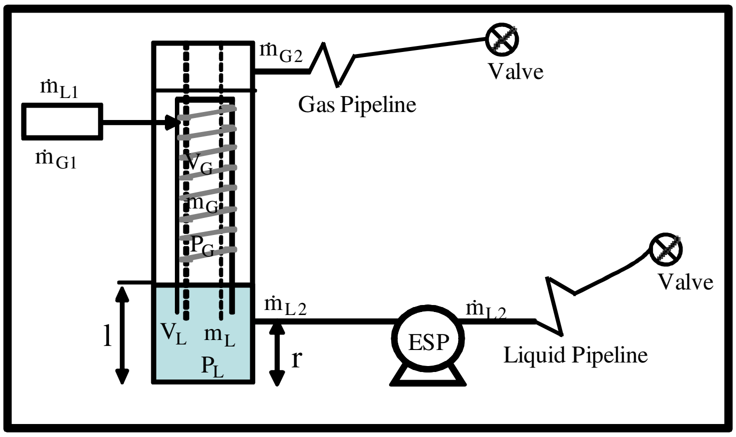

Figure 3. Scheme of the subsea separator and ESP system.

Using the notation of the Fig. 3, the liquid level rate could be calculated by the conservation of mass equation considering an incompressible flow, as could been seen by Eq. 12,

$$\frac{dl}{dt} = \frac{A}{\rho_L}\left(\dot{m}_{L1} - \dot{m}_{L2}\right) \tag{12}$$

The pressure of the liquid inside the vessel is calculated as follow,

$$P_L = P_G + \rho_L g\left(l - r\right) \tag{13}$$

The pressure of the gas inside the vessel is calculated following the constitutive equation of gas,

$$P_G = \frac{Z\, m_G\, RT}{M_G V_G} \tag{14}$$

where V_G is found by subtracting V_L from the total volume of the vessel (V), $V_G = V - V_L$. The mass rate of the gas is found applying the conservation of mass equation,

$$\frac{dm_G}{dt} = \dot{m}_{G1} - \dot{m}_{G2} \tag{15}$$

In numerically modeling the separator, the change of the PVT properties of the oil inside the separator due to the pressure and temperature variation is not accounted and thus do not considered the gas dissociation from the oil, as previously explained. However, the influence of it in the control response is small, since in normal conditions the pressure variation inside the separator have small variation in relation to the initial conditions hence the gas dissociation is small, which not affect considerably the liquid level.

ESP Curve

The ESP was mathematically modelled by a second order polynomial equation, as follows.

$$H_{ESP} = {\alpha_{ESP}}^2 H_0 + \alpha_{ESP} C_1 Q_{ESP} + C_2 Q_{ESP}^2 \tag{16}$$

where $Q_{ESP} = \dot{m}_{L2} / \rho$ is the volumetric flow rate of liquid pumped by the ESP, C_1 and C_2 are constants, H_0 is the maximum head of the pump for a determined value of α_{ESP} which is a dimensionless parameter found by similarity between two different conditions of the pump (e.g. $\alpha_{ESP} = f_{op} / f_{nom}$, $\alpha_{ESP} = Q_{op} / Q_{nom}$). In this case the subscript "op" represents the operation condition while "nom" represents a nominal condition.

The coupling of the Separator, the ESP and the liquid line was obtained through the Eq. 17, which can be seen as follows,

$$H_{ESP} + \frac{P_L}{\rho g} - H_{Riser} = 0 \tag{17}$$

where H_{ESP} and P_L are calculated by Eq. 16 and Eq. 13, respectively. To simplify the evaluation of the H_{Riser}, it was considered that the volumetric flow rate is the same along all length of the riser, yielding to Eq. 18.

$$H_{Riser} = \frac{f L}{2gDA^2} Q_{ESP} \left| Q_{ESP} \right| + \Delta H \tag{18}$$

where ΔH represents the difference of height between the subsea separator and the platform.

The objective of Eqs. 16, 17 and 18 is found Q_{ESP} but as could one observe this is not possible analytically, which demands a numerical solution. In this work a Newton-Raphson method was applied considering as initial value for computation the value found in a time step before.

ESP Control

In this work a stochastic impulse control approach presented by Pinheiro et al (2009) for this specific problem is adopted. The control can be transformed in a sequence of iterated optimal stopping problems and expressed equivalently as a sequence of variational inequalities. As it is usually difficult to obtain analytic solutions, a numerical solution was proposed, based on the Mean Value Scheme (MVS) method. The computations will yield to a Risk Map, as presented by Fig. 4, where the vertical axis represents the liquid level in the vessel (l) and the horizontal axis represents the inflow/outflow balance (δ), where δ is given by Eq. 19. These two variables are the state variables of the proposed model.

$$\delta = \frac{\dot{m}_{L1}}{\rho} - Q_{ESP} \tag{19}$$

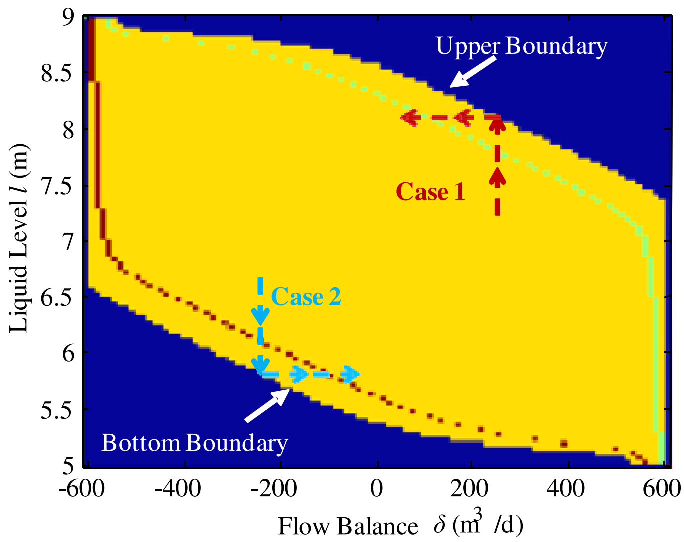

Figure 4. ESP control Risk Map.

This unconventional control system evaluates these two parameters of the system at each time step in the Risk Map and returns a response for intervention or non-intervention. In Fig. 4 the non-intervention region is colored in yellow, while the intervention region is in blue. Therefore for any conditions that one of the boundaries of the non-intervention region is reached the ESP control will require an intervention. This intervention could be of two types, hereafter described as Case 1 and Case 2.

When an intervention occurs, it moves the system state horizontally to another value of flow balance through the variation of the ESP rotation frequency. If the state comes from the right upper boundary (Case 1), the ESP frequency should increase to transfer the state to the indicated value given by the green line. Otherwise, if the state comes from the left bottom boundary (Case 2), then the frequency of the ESP should be decreased to transfer the balance to the value indicated by the red line.

3. RESULTS

In order to analyze the performance of the ESP control in the subsea separator and pump system behavior, numerical simulations were carried out to simulate the flow in the system for different scenarios. Depending on the gas and liquid velocity, the multiphase flow that comes in the separator could be a slug flow, which is one of the most commons for intermediate fluids flow velocities and is represented by the first scenario (Scenario 1) which was found using step signal for the liquid and gas shifted by 180 degrees. When the gas velocity is much higher than the liquid flow velocity an annular pattern could probably happens, in this case the gas and liquid flow will be almost constant (Scenario 2). The third scenario (Scenario 3) represents a sine signal with very low frequencies simulating the variation of the pressure of the reservoir during the production of the field. An outline of this study is presented in Fig. 5. The subsea separator was modeled as a cylinder of almost one meter of diameter and 46 meters length and the acceptable liquid level range was between 5 and 9 meters, an idealized ESP of 10 stages with a maximum head of 2000 meters and maximum flow rate of almost 7200 m^3 per day working at 40 Hz is considered. The lines were modeled as catenary risers for 900 meters waterdepth with 20 degree of inclination at the top. The inner diameters were 0.483 meters and 0.305 meters for the liquid and gas riser respectively. Following the classification presented by Pinheiro et al. (2009), a moderated map risk was used for the ESP control.

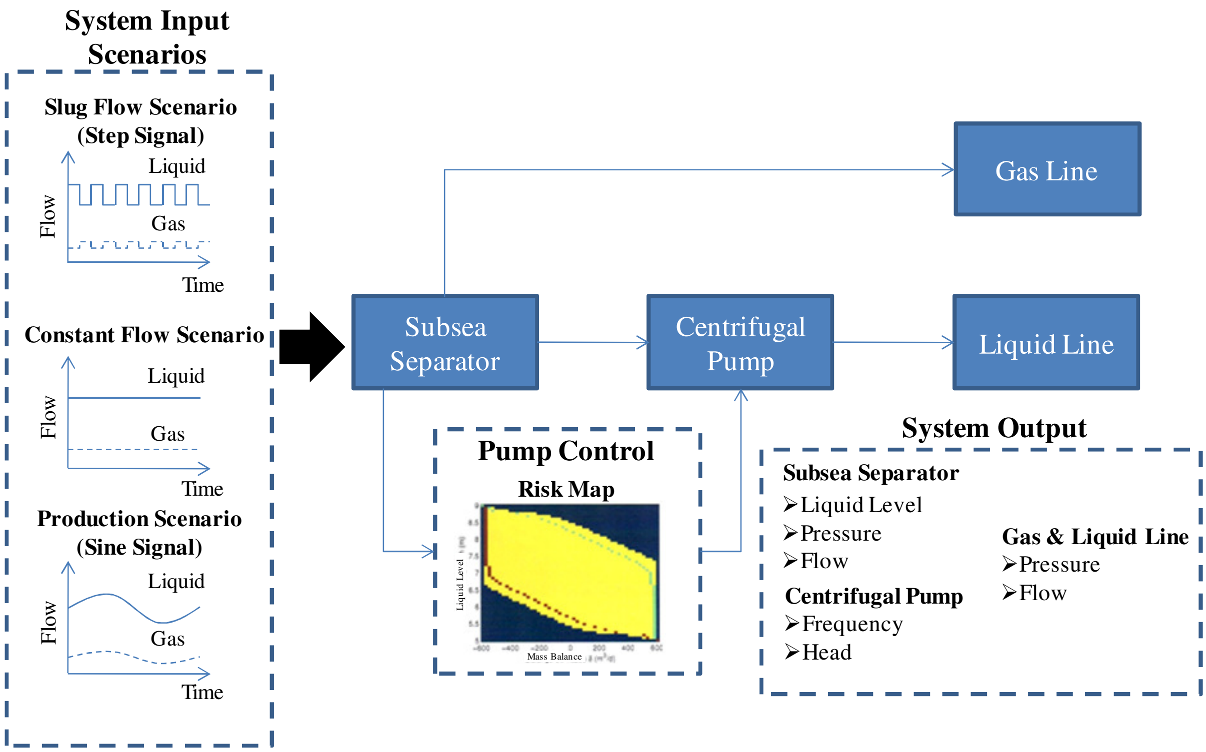

Figure 5. Scheme of the numerical simulation carried out in the study.

Figure 6 presents the results for the slug scenario considering an average mass rate of gas and liquid coming in the separator of 28.6 [kg/s] and 5.6 [kg/s], respectively. In order to simulate the slug flow pattern an amplitude of 6.0 [kg/s] for the liquid and 0.5 [kg/s] for the gas was regarded shifted by opposed phases with a frequency of 0.1 [Hz]. Since the main objective of this work is study the separator and pump system behavior for different types of flow patterns the following results will be presented: 1) Liquid flow entering in the separator; 2) Liquid flow leaving the separator considering the transient behavior of the liquid riser; 3) Liquid level inside the separator; 4) Pressure inside of the separator, which will be dominated by the gas pressure; and, finally 5) ESP frequency. This is only a part of the results obtained by the computations. As could be seen in Fig. 5, others results could make this work much longer, therefore they were not presented in this work.

By the results presented in Fig. 6, it could be observed that the ESP control works well in maintaining the liquid level inside the acceptable range. A few quantities of actuations (increase or decrease of the ESP frequency) were necessary which is good for the ESP service life. As expected, the liquid flow leaving the separator follows the increase and decrease of the ESP frequency. The pressure inside the separator was almost constant and follows the tendency of the liquid level. Another reason for the increase of the pressure in the separator could be associated to the small capacity of the riser to carry the gas due to the slow transient of the gas.

SLUG SCENARIO RESULTS

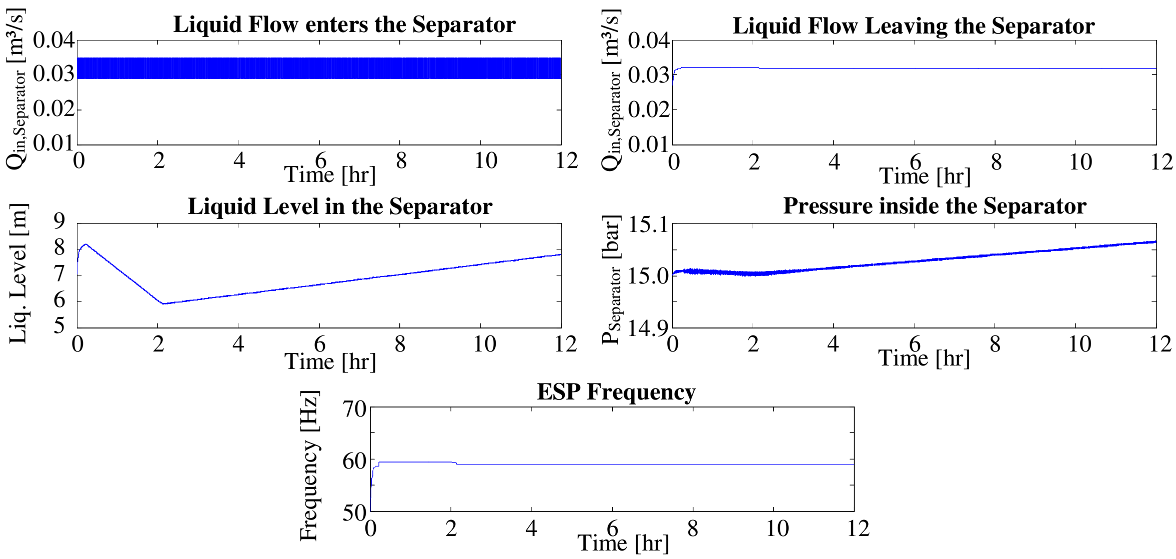

Figure 6. Subsea Separator and Pump system behavior for the Slug Scenario (Scenario 1).

CONSTANT FLOW SCENARIO RESULTS

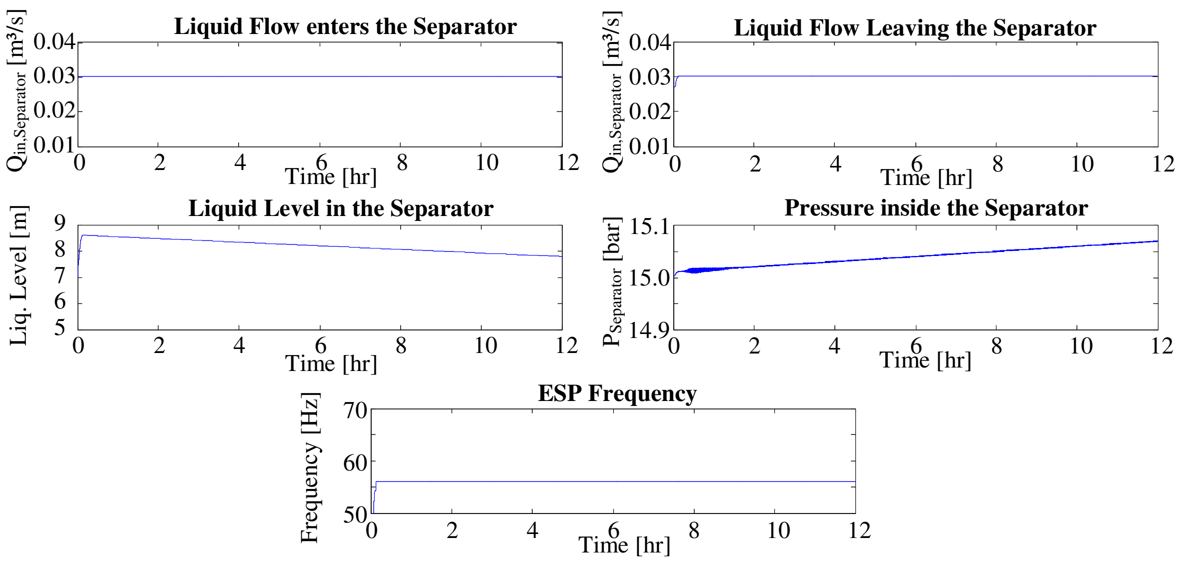

Figure 7. Subsea Separator and Pump system behavior for the Constant Flow Scenario (Scenario 2).

Figure 7 presents the results for the constant flow scenario which could represent the case of annular pattern flow. The gas flow rate was 6.0 [kg/s], while the liquid flow rate was 30.0 [kg/s]. The same type of results presented in Fig. 6 will be presented in Fig. 7 and 8. By the results of Fig. 7 it could be observed that the ESP control requires a small quantity of interventions on the pump frequency to maintain the liquid level in the separator in the acceptable range. In this case even the decrease of the liquid level was not sufficient to decrease the pressure inside the separator. Probably this occurs due to the slow transient of the flow inside the riser of gas and the incapacity of the riser to carry out the same quantity of gas that enters in the separator. But the increase of pressure is small and it could be considered not warning.

Figure 8 presents the results for the production scenario, where a sine signal with an average values of 25.6 [kg/s] and 3.6 [kg/s] were considered to model the liquid and gas flow, respectively. The amplitude of oscillation was 12 [kg/s] for the liquid and 3.5 [kg/s] for the gas. The oscillation in the flow occurs at each 1000 seconds.

The results show that for cases of high amplitude and period of oscillation of the flow the ESP control requires many interventions of the pump frequency. This is not a realistic case. In real conditions, variations of this magnitude in the flow will occur due to the variation of the reservoir pressure and in greater periods of oscillation. However this case was presented as an example of a severe case, which the flow was so high that the ESP frequency almost follows the input signal of the liquid flow entering the separator. As a consequence, the liquid flow leaving the separator, the liquid level inside the separator and the pressure inside the separator follows the same trend. Interventions between small steps of time and with high variations of the pump frequency could cause serious damage for the pump.

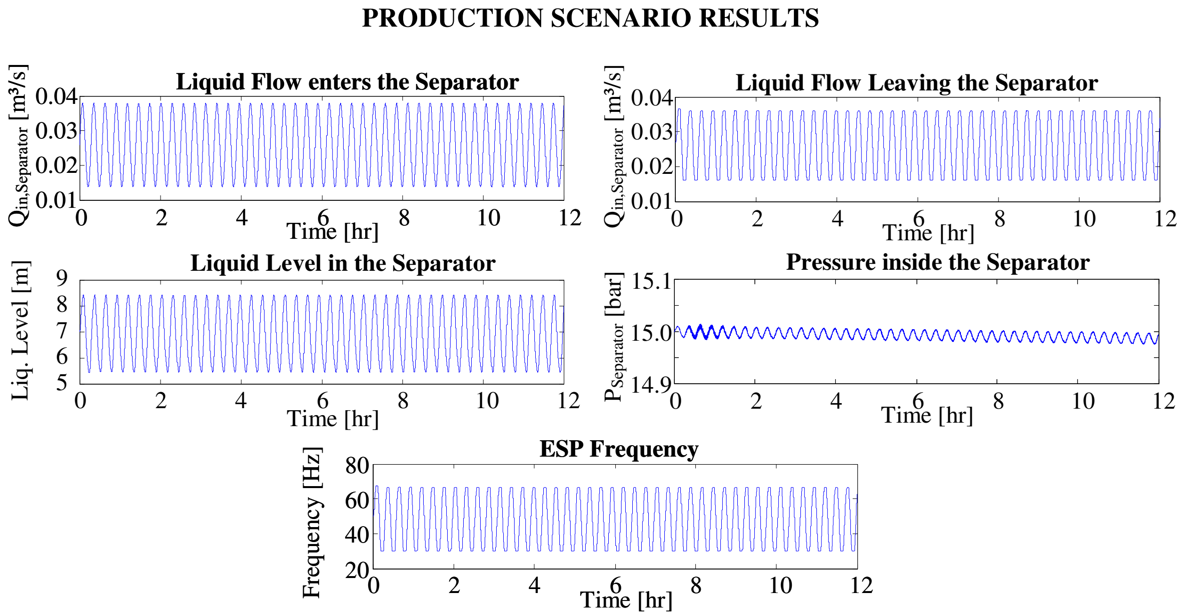

Figure 8. Subsea Separator and Pump system behavior for the Production Scenario (Scenario 3).

4. CONCLUSIONS

This work presents a numerical model to predict the dynamic behaviour of a subsea and pump system considering the transients flow inside the productions risers. The numerical calculation was equated by mass and quantity of moment balance equations solved by the Method of Characteristics, which demonstrated to be an efficient tool for this application. Applying this approach, it was possible to observe that the transient flow in the risers have significant impact on the separator behaviour, mainly the influence of riser's gas flow in the separator pressure.

By the numerical simulations results it could be observed that the ESP control works well in maintaining the liquid level inside the separator in the acceptable range. However, for cases of great variation of the flow a great number of interventions were necessary. Sometimes, the interventions require great variations in the pump frequency, which is not recommended because it could cause damages to the pump.

It is important to mention that this work is still in development and refinements are necessary to reproduce more realistically the behaviour of the separator and pump system. For example, in this work the separator is modelled by a mass balance without considering many parameters of the separation process; also the inertial effect of the pump was not considered, therefore the pump responds instantaneously for the controls commands, and the variation of the PVT properties of the oil is not considered.

5. ACKNOWLEDGEMENTS

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