Modelling and control of the offshore process

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I hereby declare that this task is performed independently and according to the architect/ chemical engineer graduate regulations.

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Acknowledgements

Abstract

The purpose of this master degree is to make a simple model for a separator/off-shore process, which can be used in control purposes. A dynamic model is implemented in HYSYS to study the off-shore process in more details.

The model was implemented with the PI-control for gas, oil and water level. The tuning parameters were determined by Skogestad's rule. Once the controllers were tuned, the system was tested by making ±20% steps in disturbances (the feed flow rate of water, oil and gas), and ±5% steps in manipulated variables (pressure, oil level and water setpoints). The step responses seem to correspond with physical common sense.

From step responses, analysis and studies have been done to explore the effect of manipulated variables and disturbances in various measurement respectively in the standard basic control which is to control the pressure, oil and water level.

If the assumption about equilibrium theory holds in the separator, there is no problem for the composition of water-in-oil and oil-in-water, as long the pressure, oil, and water are correctly controlled. But if the assumption is not the case, the HYSYS-model is not suitable or acceptable.

Manipulated variables and disturbances has a small effect on the composition of oil (water in oil) and composition of water (oil in water) when the pressure, oil level and water level are controlled.

Without any control, disturbances in the feed can move the operation outside the process constraints. For example, the water level increases too much and water goes out through the oil valve. The gas, oil, and water valves opening have a large effect on outputs, especially pressure, oil and water level.

The main conclusion is that it is possible to control the pressure, oil level and water level to keep the operation inside the constraints. If assumptions connected to the phase equilibrium and no mixing of the phases are acceptable, there is no problem connected to composition constraints (water in oil and oil in water) as long as the pressure, oil level and water level are controlled inside constraints. If these assumptions are not fulfilled, a model based on other principles need to be explored.

CONTENTS

1　Introduction

This master thesis was carried out at The Department of Chemical Engineering, Faculty of Chemistry and Biology at The Norwegian University of Science and Technology (NTNU) in Trondheim during the period of 07.mars-24 august 2001. This task was performed under the leadership of the subject teacher Professor Sigurd Skogestad and by the supervising of Ph.D-student Marius Støre Govatsmark.

1.1　Background

From an oil well a three phase mixture of gas, oil and water is pumped to the oil platform. Gas, oil and water are separated in the separator train on the platform. The gas is carried to a compressor train where the pressure is increased before sending it to the continent through pipes. The oil is sent to a storage tank. The water is sent to a water treatment plant.

We want to evaluate if it is needed or wanted to control the composition (water in oil and oil in water). Heum (2000) implemented composition control by using a model predictive controller which manipulated the setpoints to the water and oil level controllers. We here make a dynamic model of a three-phase separator and a whole off-shore process in Hysys.Plant, the model is based on rigourous thermodynamic. The effect of disturbances in composition, pressure and oil/water levels are evaluated.

In this case the separation takes place in two steps, with one three-phase separator in each step. Water and oil are removed through withdrawal at the bottom, while the gas goes over the top to the compressor train. The compression takes place in two steps with one compressor in each step.

It is standard basic control to control water level in the separator with water out-flow, control the oil level with oil out-flow and the pressure with the compressor.

The work was based on a model where the compositions was correlated with the holdup time in the separator. Heum proposed to evaluate and improve the composition.

The purpose for this project is to make a symplified and dynamic model for an off-shore process in HYSYS.PLANT and a possible control system of the model has to be carefully tested for the composition (water in oil, and oil in water) on an off-shore process.

The two main parts of the project are:

A. Modelling :

1. Make a stationary model of the current off shore process in HYSYS.

2. Make a dynamic model based on the previous stationary model-process.

3. Verify and test the model in MATLAB, by making a matrix process and doing some physical interpretation to the reality (a real behaviour).

B. Control /operation

4. Implement and connect the model by Visual Basic (Microsoft Excel) in one separator.

- by generating and testing the model by making various step responses, without control system called "open loop"

- test again with a control system "closed-loop" with PI-controller and more steps in disturbance

5. Simple and Sequences of steps by increasing/decreasing disturbances(feed flow)

- the effect analysis of controlled variables on the water/oil composition.

6. Finally testing the models ability

- compare the HYSYS-model to the gPROMS-model.

2   Process description

2.1   The process

From an oil well, a mixture of gas, oil and water enters the separator. The flowrate and the composition vary by time. It is desired to separate gas, oil and water.

2.1.1   Separator

Figure 3-1 shows a process flow diagram of a three-phase separator. Here, the mixture from the oil well is separated into gas, oil and water.
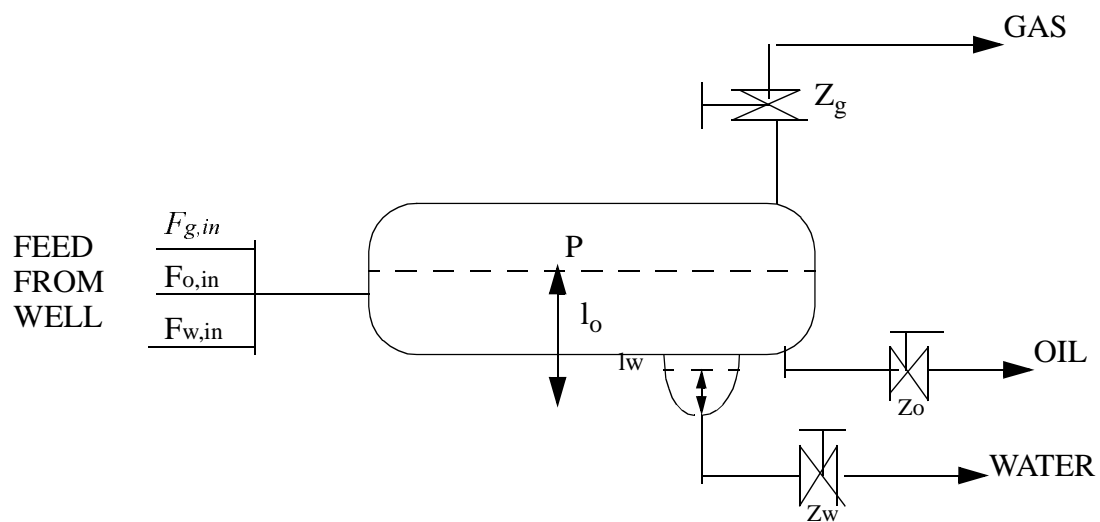
Figure 2–1: A process flow diagram of a three-phase separator.

The Hysys process flowscheme with control of pressure, oil and water levels is shown in appendix A.

2.1.2 Platform process/off-shore process

The mass flow which is pumped up from an oil well consists of gas, oil and water. The size and composition of feed flow vary by time. It is desired to separate gas, oil and water in the separator train. The mixture of gas, oil and water is separated in the current process shown in figure 2-2. This is similar to the process at Valhall.
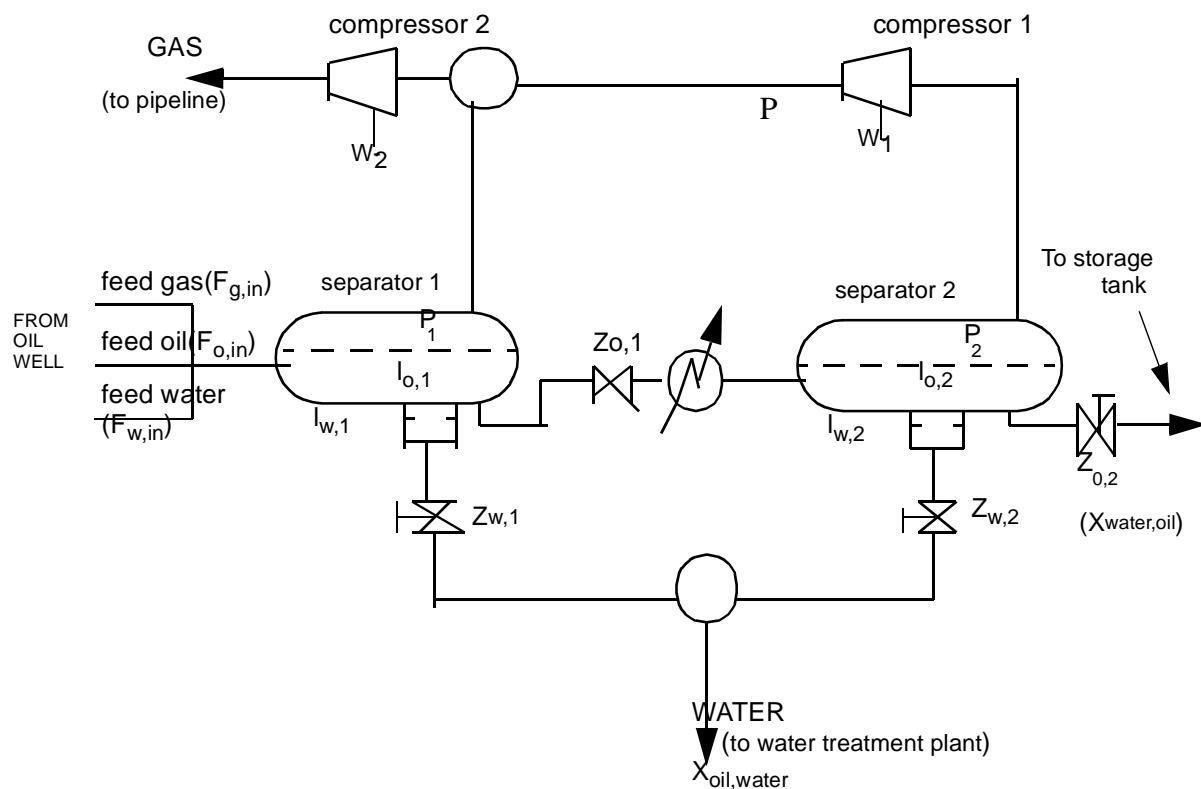
Figure 2–2: A process flow scheme of off-shore process

The separation takes place in a separator train, which separates into gas, oil and water. All water in the outlet drain, is collected and sent to the water treatment plant .

The main part of the separation takes place in the first separator. The oil from the first separator stage enters the second separator where a minor fraction of the water and gas is removed. In the second stage, the pressure is reduced and the oil is preheated to some extent gas. The oil from the second separator is pumped to a storage tank.

The gas from the second separator is compressed in the first compressor before it is mixed with gas from the first separator. It is further compressed in the second compressor before it enters the pipeline.

2.2   Control objectives

The main purpose of the process is to separate gas, oil and water.

2.2.1 Separator

- The primary control objective is to keep the operation inside design constraints.

There are constraints on the pressure and levels due to the process design :

  - 6 bar ≤ P ≤10 bar

  - 3.0 m ≤ l_o ≤ 6.2 m

  - 0 m ≤ l_w ≤ 3.0 m

There are constraints on the product purities, water in oil ($X_{water,oil}$) and oil in water ($X_{oil,water}$)

  - $X_{water,oil} \leq X_{oil,water}$

  - $X_{oil,water} \leq X_{water,oil}$

- The secondary control objectives are to keep the operation closer to economic optimal. This is not considered any further here.

2.2.2 Off-shore process : Platform process

The constraints related to the off-shore process are summarized in table 3-1. In addition to the constraints related to the separator, the gas pressure when entering the pipeline must be sufficiently high : $P_{gas,out} \geq P_{pipe}$

Table 2–1: Constraints related to the off-shore process

separator 1	separator 2	separator 1 & 2
6 bar ≤P_1 ≤ 10 bar	2 bar≤ P_2 ≤ 6 bar	-----------------------
3m ≤ $l_{o,1}$ ≤ 6.2 m	2 m≤ $l_{o,2}$ ≤ 4.5 m	$X_{water,oil} \leq 10^{-3}$ [mass fraction]
0 m ≤ $l_{w,1}$ ≤ 3 m	0 m ≤ $l_{w,2}$ ≤ 2 m	$X_{oil,water} \leq 10^{-3}$ [mass fraction]

2.3   Controlled variables

2.3.1 Separator

To keep the constraints it may be necessary to control gas pressure, oil level, water level, water-in-oil composition and the oil-in-water composition. Possible controlled variables with normal values and acceptable control errors are given in table 2-2. Usually only the pressure, oil and water levels are controlled.

Table 2–2: Possible controlled variables

Controlled variable(c)	Value	Accept. control error	unit
gas pressure(P)	8	2	bar
oil level (l_o)	4.2	1.2	m
water level (l_w)	2.5	0.5	m
composition water in oil ($X_{water,oil}$)	$1.947*10^{-4}$	$8.053*10^{-4}$	mass fraction
composition oil in water($X_{oil,water}$)	$4.86*10^{-19}$	$1*10^{-3}$	mass fraction

2.3.2 Off-shore process : Platform process

Table 2–3: Possible controlled variables

Controlled variables(c)	Value	Acceptable control error	unit
gas pressure(P_1)	8	2	bar
oil level ($l_{o,1}$)	4.2	1.2	m
water level ($l_{w,1}$)	2.5	1.5	m
gas pressure(P_2)	4	2	bar
oil level ($l_{o,2}$)	2.5	0.5	m
water level ($l_{w,2}$)	0.5	0.5	m

Table 2–4: supervisor controlled variables

Controlled variables(c)	Value	acceptable control error	Unit
composition water in oil ($X_{water,oil}$)	$1.867*10^{-4}$	$8.14*10^{-4}$	mass fraction
composition oil in water($X_{oil,water}$)	$4.86*10^{-19}$	$1*10^{-3}$	mass fraction

2.4   Manipulated variables

2.4.1 Separator

The basic manipulated variables for the three phase separator are gas, oil and water valve openings, see tabell 2-5.

Table 2–5: Basic manipulated variables with nominal values.

Manipulated variables (u)	Nominal values	Unit
Gas valve opening (z_g)	18.41	%
Oil valve opening (z_o)	21.23	%
Water valve opening (z_w)	11.4	%

For possible supervisor control layer the setpoints to the lower layer controlled variables may be used as manipulated variables.

2.4.2 Off-shore process : Platform process

The basic manipulated variables for the offshore process are given in table 2-6

Table 2–6: basic controlled variables

Manipulated variable (u)	Nominal Values	unit
Compressor Speed (w_1)	600	rpm
oil valve opening ($Z_{0,1}$)	12.44	%
Water valve opening ($Z_{w,1}$)	11.37	%
Compressor Speed (W_2)	600	rpm
Oil valve opening ($Z_{o,2}$)	15.63	%
Water valve opening ($Z_{w,2}$)	2.88	%
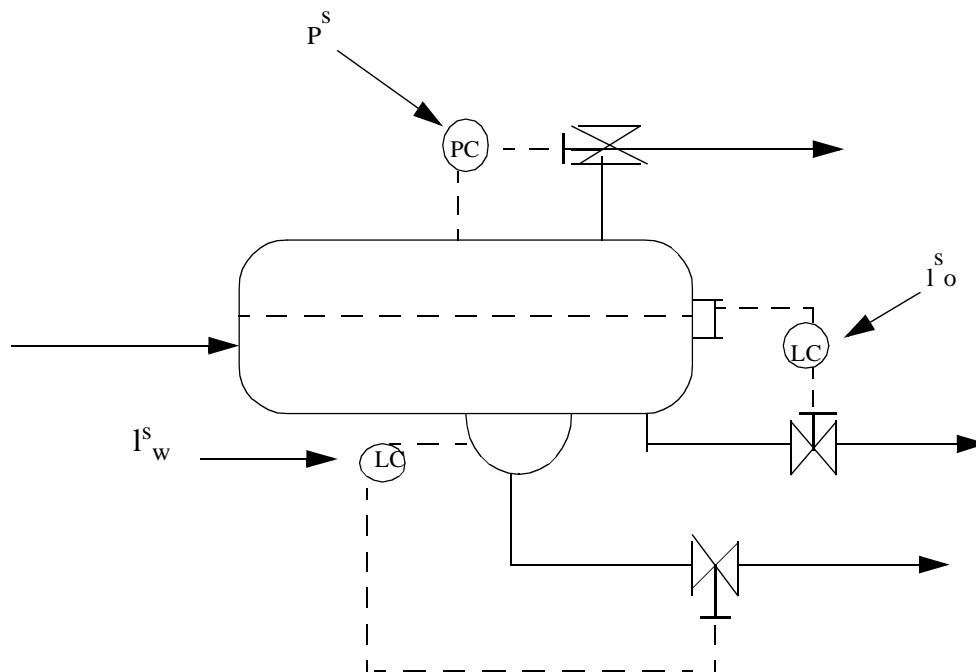
Figure 2–3: Scheme of a closed loop with manipulated variable as setpoint

LC : level control

PC : pressure contol

P^s : pressure setpoint

l^s_o : oil level setpoint

l^s_w : water level setpoint

2.5   Disturbances

The most important disturbances are expected to be the feed composition and the feed flow rate. We consider disturbances in the feed gas flow rate, the feed oil flow rate and feed water flow rate. The disturbances with nominal values and expected variation (+20%) for the separator and the offshore process are shown in table 3-7.

Table 2–7: Disturbances with expected variation.

Disturbance (d)	Nominal Values	Expected variation	Unit
Gas feed flow rate ($F_{g,in}$)	$1.815*10^5$	36300	kg/h
Oil feed flow rate ($F_{o,in}$)	$4.612*10^5$	92240	kg/h
Water feed flow rate ($F_{w,in}$)	$4.1869*10^4$	8373.8	kg/h

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3   Theory

This is a short introduction to the process. It refers to the model composition because of its central role in this task. This chapter will present some theories about tank mass balance

3.1   Separator model

In this section, a simple model of a three-phase separator is described. This consists of a set of quantitative and qualitative relations. We assume ideal gas and isotherm behaviour. We do not consider any specific geometry. This will later be used to evaluate The HYSYS-model. Figure 4-1 shows a three-phase separator
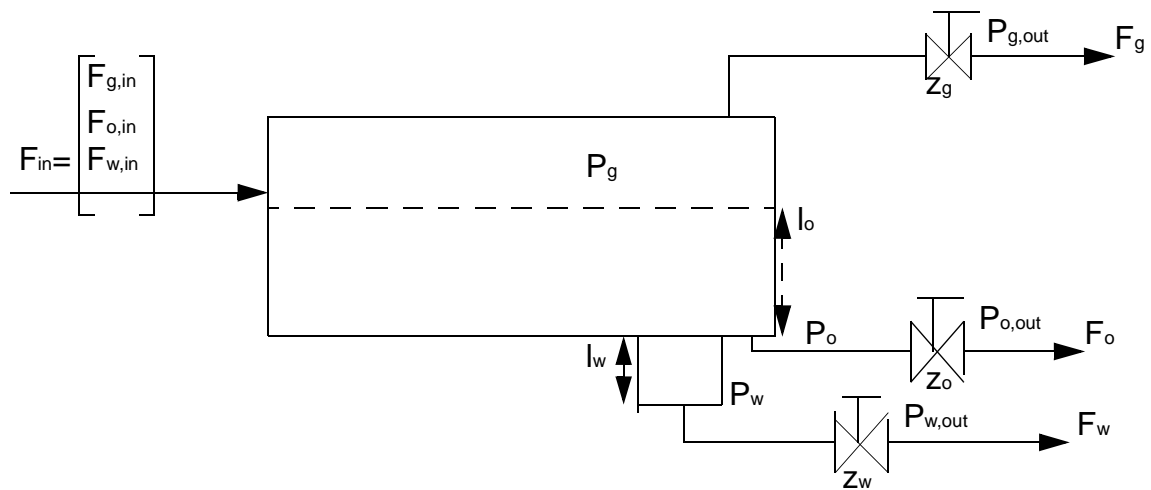
Figure 3–1: Three-phase separator

Explanation of the notation is given below:

Fg,in: gas feed flow rate

Fo,in: oil feed flow rate

Fw,in: water feed flow rate

F_g: gas flow outlet

F_o: oil flow outlet

F_w: water flow outlet

l_o: oil level

l_w: water level

P_g: gas pressure

P_o: oil pressure

P_w: water pressure

3.1.1   Mass balance equations

Mass balance for gas in the separator:

$$\frac{dM_g}{dt} = F_{g,\,in} - F_g \qquad\qquad [3.1]$$

Mass balance for oil in the separator

$$\frac{dM_o}{dt} = F_{o,\,in} - F_o \qquad\qquad [3.2]$$

Mass balance for water in the separator:

$$\frac{dM_w}{dt} = F_{w,\,in} - F_w$$

[3.3]

3.1.2 Flow rate equations for the feed gas:

Gas outlet flow rate:

$$F_g = k_g \cdot z_g \cdot \sqrt{P_g^{\,2} - P_{g,\,out}^{\,2}}$$ [3.4]

k_g is the gas valve constant.

Oil outlet flow rate:

$$F_o = k_o \cdot z_o \cdot \sqrt{P_o - P_{o,\,out}}$$ [3.5]

The oil pressure (Po) depends on the gas pressure (P_g) and oil hold-up (Mo).

k_o is the oil valve constant.

$$Po = Pg + fw(M_o)$$ [3.6]

An increase in the oil hold-up increases the oil pressure.

Water outlet flow rate:

$$F_w = k_w \cdot z_w \cdot \sqrt{P_w - P_{w,\,out}}$$ [3.7]

The water pressure (Pw) depends on the gas pressure (Pg), oil hold-up (Mg) and water hold-up (Mw).

k_w is the water valve constant.

$$Pw = Pg + fw(M_w, M_o)$$ [3.8]

Both an increase in the water hold-up and the oil hold-up (Mo) give an increase in the water pressure (Pw).

3.1.3 Ideal gas law

$$Pg = \frac{M_g \cdot R \cdot T}{V_g(M_w, M_o)}$$ [3.9]

Gas volume (V_g) depends on water hold-up (M_w) and oil hold-up (M_o). Increased water or oil hold-up reduce the gas volume.

3.1.4 Composition equation

We consider three Pseudo-components "gas", "oil", and "water". It seems reasonable that the fraction of water in oil ($X_{water,oil}$) and fraction of oil in water depend on the respective hold-up times:

$$X_{water, oil} = f_{wo}(\tau_{oil}) = f_{wo}(N_o/F_o)$$ [3.10]

$$X_{oil, water} = f_{ow}(\tau_{water}) = f_{ow}(N_w/F_w)$$ [3.11]

An increase in the hold-up time of oil (τ_{oil}) decreases the fraction of water in oil. An increase in the hold-up time of water (τ_{water}) decreases the fraction of oil in water.

In the model used by Heum (2000) the component mass fraction **i** in outlet flow **j** is described by:

$$x_{m, i, j} = \frac{M_i \cdot e^{-\frac{\tau_{m, j}}{\tau_{(ref, j)}}}}{\sum\limits_{k = 1}^{3} M_k}$$ [3.12]

M_i indicates the hold-up for component i in the separator, $\tau_{m,j}$ the detention period (time), which provides the time delay between the change in composition before and during the operating condition. If $\tau_{m,j}$ exceeds the given constraint, limit values is used to avoid numerical problems for the large and clean phase. $\tau_{ref,j}$ is an adjusted tuning parameter for the operation.

3.1.5 Control equations

Gas pressure controller:

$$Z_g = Z_{g, b} + K_p(P_{g, s} - P_g)$$ [3.13]

Oil hold-up controller:

$$Z_o = Z_{o, b} + K_p(M_{o, s} - M_o)$$ [3.14]

Water hold-up controller:

$$Z_w = Z_{w, b} + K_p(M_{w, s} - M_w)$$ [3.15]

K_p is the proportional constant for the controller (controller gain)

3.1.6 Expected initial and steady state gains

Table 4-1 summarizes the expected initial and steady state gain without control. The inputs consist of manipulated variables and disturbances. The outputs consist of possible controlled variables. The positive sign (+) indicates that an increase in the input gives an increase in the output. The negative sign (-) indicates that an increase in the input gives a decrease in the output and number 0 indicates that the input has no effect on the output. The first sign indicates the steady state and the second indicates the initial gain.

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Table 3–1: Expected initial and steady-state effects without control

	$F_{g,in}$	$F_{o,in}$	$F_{w,in}$	Z_g	Z_o	Z_w
M_g	+,+	-,-	0,-	-,-	+,+	0,+
M_o	-,-	+,+	-,-	+,+	-,-	+,+
M_w	-,-	-,-	+,+	+,+	+,+	-,-
P_g	+,+	0,+	0,+	-,-	0,-	0,-
P_o	0,+	+,+	0,+	0,-	-,-	0,-

Table 3–1: Expected initial and steady-state effects without control

	$F_{g,in}$	$F_{o,in}$	$F_{w,in}$	Z_g	Z_o	Z_w
P_w	0,+	0,+	+,+	0,-	0,-	-,-
F_g	+,+	0,+	0,+	0,+	0,-	0,-
F_o	0,+	+,+	0,+	0,-	0,+	0,-
F_w	0,+	0,+	+,+	0,-	0,-	0,+
τ_{oil}	0	+	+	+	-	+
τ_{water}	0	-	+	+	+	-
$X_{water,oil}$	0	-	+	-	+	-
$X_{oil,water}$	0	+	-	-	-	+

The table 4-2 summarizes the expected effects when the pressure, oil and water hold-up are controlled. The inputs consist of disturbances and setpoints to the controllers

Table 3–2: Expected initial and steady-state gains when the pressure, oil/water hold-up are control-

Input	$F_{g,in}$	$F_{o,in}$	$F_{w,in}$	$P_g^{\ s}$	$M_o^{\ s}$	$M_w^{\ s}$
M_g	0,+	0,-	0,-	+,-	-,+	-,+
M_o	0,-	0,+	0,-	0,+	+,-	0,+
M_w	0,-	0,-	0,+	0,+	0,+	+,-

Input	$F_{g,in}$	$F_{o,in}$	$F_{w,in}$	P_g^s	M_o^s	M_w^s
P_g	0,+	0,+	0,+	+,-	0,-	0,-
P_o	0,+	0,+	0,+	0,-	0,-	0,-
P_w	0,+	0,+	0,+	0,-	0,-	0,-
F_g	0,+	0,+	0,+	0,+	0,-	0,-
F_o	0,+	+,+	0,+	0,-	0,+	0,-
F_w	0,+	0,+	0,+	0,-	0,-	0,+
τ_{oil}	0	-	0	0	+	0
τ_{water}	0	-	+	+	+	+
$X_{water,oil}$	0	+	0	0	+	0
$X_{oil,water}$	0	0	+	0	0	-

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3.2   Control

3.2.1   The PI-control

Let u be the manipulated input, y the controlled output, y_s the setpoint (reference) for the controlled output, and y-y_s the control error (offset).

The PI-controller is the most commonly used controller in the process industry. The PI-control algorithm is:

$$u(t) \; = \; u_o - K_c \left(e(t) + \frac{1}{\tau_I} \cdot \int_{t_o}^{t} e(t) \right) dt \qquad\qquad [3.16]$$

where $t = t_o$ is the time when the controller was turned on, time t is the current time, and $u_o =$ $u(t_o)$ is the bias for the input. Note that the convention of feedback is used. In this case the sign of the controller gain should be the same as the plant gain k. Usually, the sign of the variables (u and y) is defined such that k (and K_c) are positive. With negative feedback an undesired increase in the output y will be counteracted by a decrease in the manipulated input u. See supplement to the subject SIK 2050 (Sigurd Skogestad).

The value of the bias u_o is important during start-up. Otherwise, it is important only for the case with pure proportional control (P-controller), because the integral action "resets" the bias. This is seen by rewriting the PI algorithm as:

$$u(t) = u(t_1) - K_c\left(e(t) + \frac{1}{\tau_I} \cdot \int_{t_o}^{t} e(t)dt\right)$$

[3.17]

where $u(t_1) = u_o + \frac{1}{\tau_I}\int_{to}^{t1} e(t)dt$ is the new ("reset") bias at time t_1. Because of this property, integral action is often called reset action and the parameter $1/\tau_I$ is called the reset rate. The integral action will keep resetting the bias until the steady-state is reached, where the offset is zero, i.e. $e(t = \text{infinity}) = 0$.

[3.18]

3.2.2 Controller tuning

The controller tunings are based on the Skogestad's tuning rule for a first-order process plus delay model with the following model information:

- Plant gain, k

- Dominant time constant, τ_1

- Effective time delay, θ

The model for the first-order system is given by:

$$G(s) = k\frac{e^{-\theta s}}{(\tau_1 s + 1)}$$

[3.19]

The following adjustments are recommended:

1. The gain:

$$k_c = \frac{1}{k} \cdot \frac{\tau_1}{\tau_c + \theta}$$ with a tuning parameter τ_c, as response time for the "closed loop". [3.20]

The delay θ is approximately the time it takes for the output to start clearly moving in the "right" direction (towards its new steady-state). For the first-order process, we obtain τ_1 as the additional time until the output has moved 63% of the way to its new steady state.

2. Integral time.

With a process [4.19], we get a reasonably fast response with moderate input usage and good robustness margins by choosing an integral time (τ_I), see supplement to the subject SIK 2050:

$$\tau_I = min\left(\tau_1, \frac{4}{k_c k}\tau_1\right)$$ [3.21]

3.Integrated process with time delay.

$$G(s) = k\frac{e^{-\theta s}}{s}$$ [3.22]

With k'= k / τ_1, when k and τ_1 go to infinity. Note that a pure P-controller is unacceptable for this process, because even with maximum gain (at the limit to instability) the steady-state offset is 0.5 (50%). Thus, integral action will be need.

The P-controller works by changing setpoints, but disturbances in output will start to integrate and counter-action is needed, see supplement to the subject SIK 2050. We obtain parameters from the experimental step response by using following rules:

$$K_c = \frac{1}{k(\tau_c + \theta)}$$ [3.23]

and the integral time

$$\tau_I \geq \frac{4}{K_c k}$$ [3.24]

3.2.3 Control structure design

The issue of selecting controlled variables is the first task in the plantwide control. The control structure design problems are:

1. Selection of controlled variables c.

2. Selection of manipulated variables m

3. Selection of measurements v (for control purposes including stabilization).

4. Selection of control configuration (structure of the controller that interconnects measurements/setpoints and manipulated variables).

5. Selection of controller type (control law specification, e.g. PID, decoupler, LQG,etc.).

Notation. The notation is summarized in the symbol list.

4 Results and Evaluations

4.1 Modeling

The following section in this chapter is a basis for the presented work. This includes the part of the process model in Hysys together with the used software. Visual Basic is the link between Hysys.Plant and MATLAB.

Practicallly all of the water is separated in the first separator. It was therefore necessary to add an extra water feed to the second separator in order to avoid numerical problems in the simulation of the off-shore process.

Data was transfered from Hysys to MATLAB using Excel. The interface was programmed in Visual Basic. The sampling time was 10 seconds.

A dynamic model of a three phase separator and an offshore process are made in Hysys.Plant, (See Hysys reference volume 1.) Hysys flowsheets of the separator and of the offshore process are shown in appendix A [Hysys flowsheet of the off-shore process]

Some comments to the modelling work:

- Peng-Robinson is used as state equation.

- Design and operating conditions are chosen such that it is reasonable from a practical point of view:

    – Valves are sized such that the valve is about 20% open at the normal condition.

    – Separator geometry is shown in appendix E [Separator geometry]

    – Operating condition is shown in the process description.

- The selected feed consists of 24 components, see appendix B4[Feed composition]. The components are placed in three pseudocomponents:

    – "Gas" consists of component 1-8

    – "Oil" consists of component 9-22

    – "water" consists of component 23-24

- The controller is tuned by using trial-and-error.

4.2   Step responses for a three-phase separator

4.2.1   A separator without control (open loop)

Responses for different steps in different disturbances and manipulated variables are done for the separator without control. Steps have been performed by increasing/reducing manipulated variables (u) by 5% or disturbances (d) by 20%.

Figure 4-1 shows dynamic responses for a 20% increase in the oil feed flowrate. An increase in the oil feed flowrate increases the oil level (l_o) and decreases the water level (l_w). The pressure (P) is almost unaffected. The fraction of oil in water is very small and in practice equal to zero. The fraction of water in oil is small and weakly increasing. As long as the level is kept inside its constraints, there is no problem with respect to water in oil and oil in water.

Without any control, the water level is reduced to zero or the oil level increases so the separator is filled up. This results in large amounts of oil in the water or gas outlet flows.
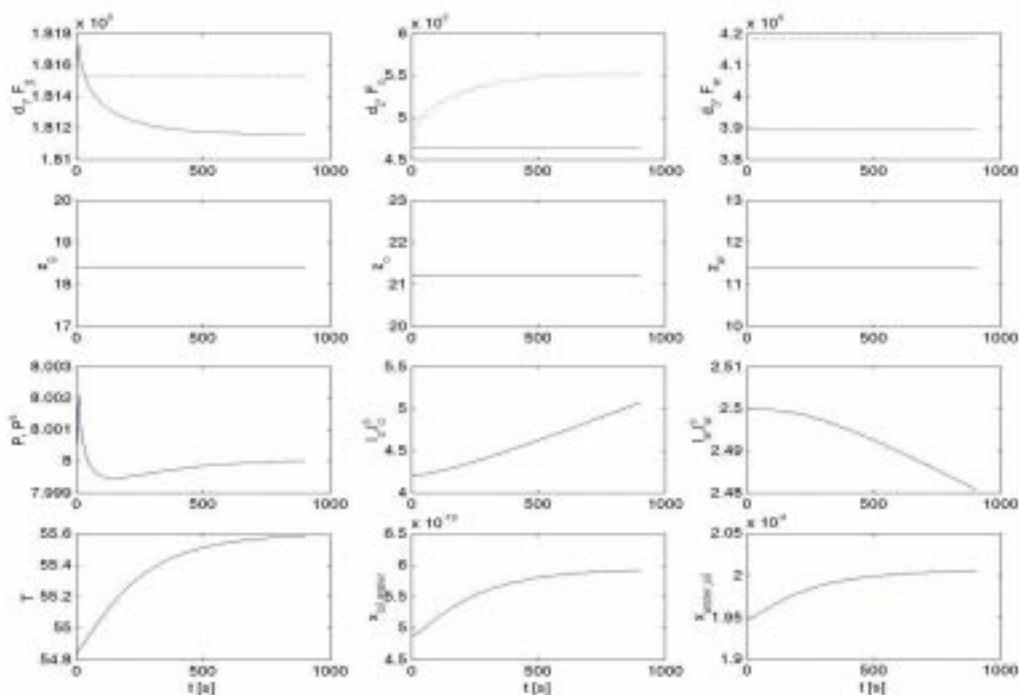

Figure 4–1: Step responses when increasing the oil feed flowrate by 20%.

Table 4-1 summarizes the effect of the responses for different steps in manipulated variables and disturbances. Water level, oil level and pressure need to be controlled and to avoid violations in the constraints.

Table 4–1: steady-state gain between compositions, manipulated variables and distur-
bances.

	Δ P	Δ l$_o$	Δ l$_w$
Z_g	- 0.008	1.6999	0.3900
Z_o	- 0.0049	-1.0469	0.3018
Z_w	- $1.035*10^{-4}$	-0.1139	-2.1908
F_g	0.4852	-1.0540	-2.1965
F_o	0.2286	1.6999	-2.1931
F_w	0.0017	0.9023	0.3889

4.2.2 Selection of control structure

Responses from steps in disturbances shows that pressure, oil level and water level need to be controlled to avoid violating the constraints.

The manipulated variables for the PI-controller could be determined, see Seeborg and SIK2050 Skogestad, by the following criteria :

• The manipulated variable must have a considerable effect on output. That is, the actual element in the matrix step response has to be relatively large.

• The manipulated variable and the output should be physically situated near each other to achieve a quick control system.

A step in the water valve opening has a large and fast effect on the water level, see figure 4-2
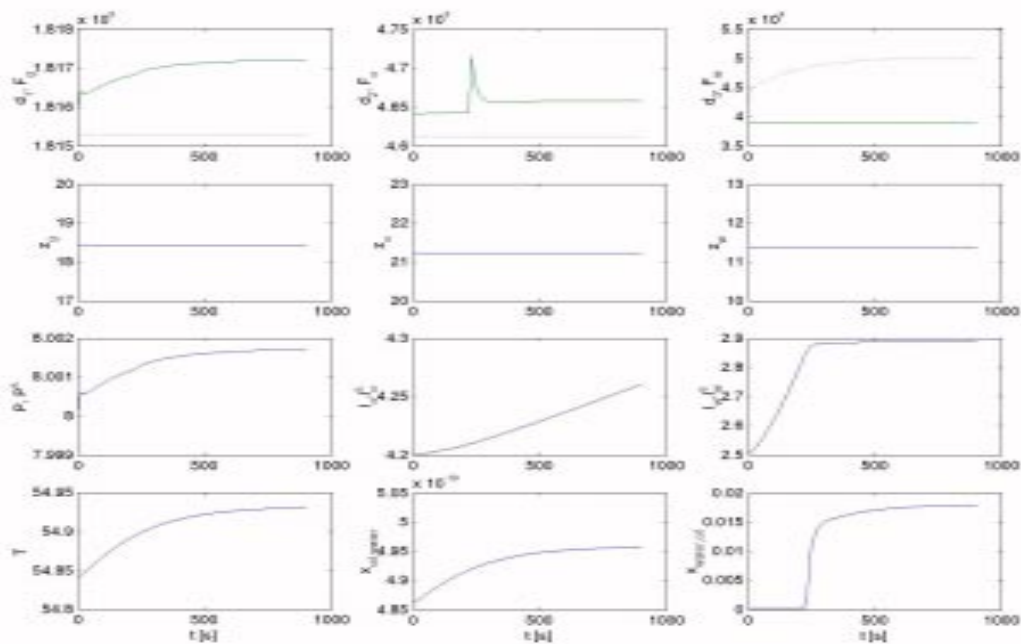

Figure 4–2: Step responses for a separator without control of pressure, oil and water for a 5% increase in water feed flow rate.

A step in the oil valve opening has a large and fast effect on the oil level, see figure 4-3.
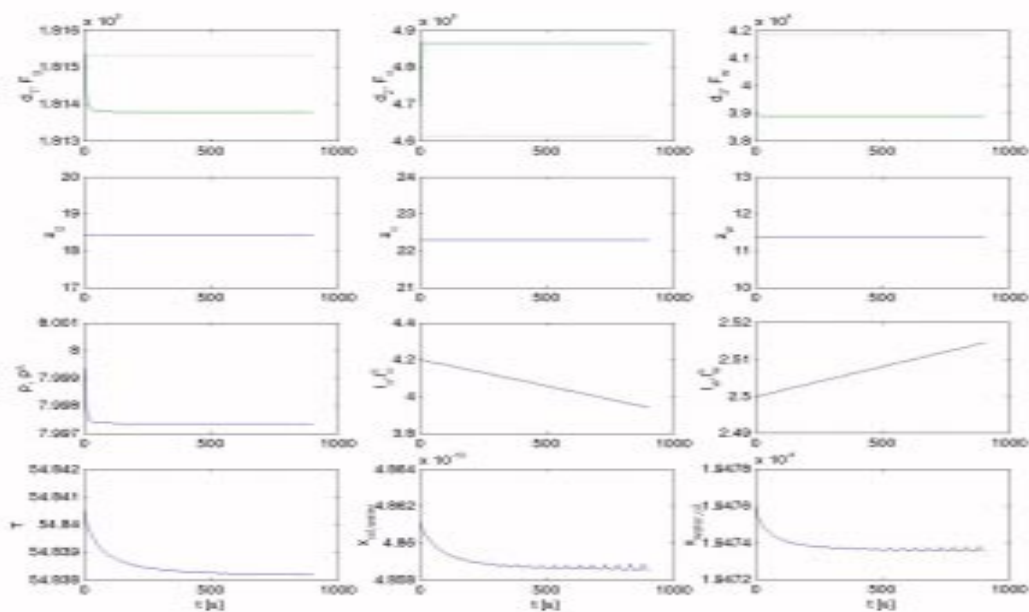

Figure 4–3: Step responses for a separator without control of pressure, oil and water for a 5% increase in oil feed flow rate.

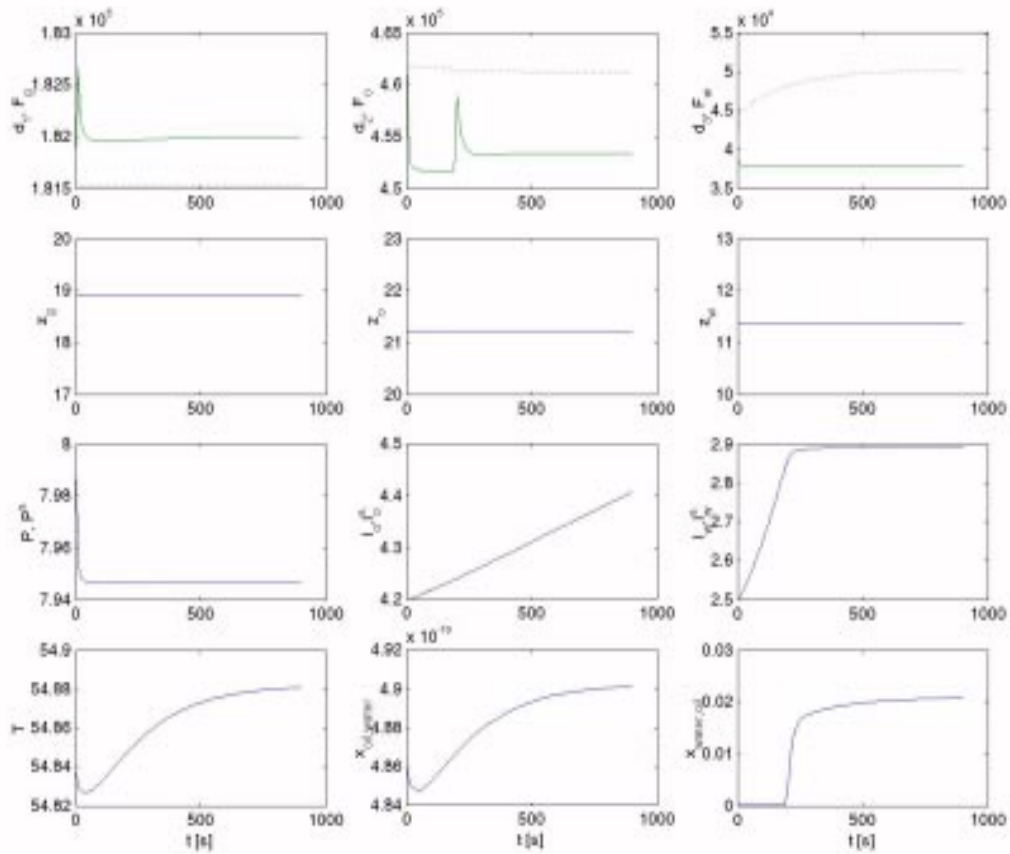A step in the gas valve opening has a large and fast effect on the pressure, see figure 4-4

Figure 4–4: Step responses for a separator without control of pressure, oil and water for a 5% increase in gas feed flow rate.

4.2.3 A separator with level and pressure control (closed loop)

There have been performed steps for all manipulated variables and setpoints with disturbances. The disturbances were increased by 20% and the setpoints were increased by 5%. Water level, oil level and pressure are included and are tuned by Skogestad's rules, see chapter 4.2.2 .

Table 4–2: Tunings parameters

	Kc	Time const.[sec]
PC302	0.21	2.66
PC3115	10.81	40
PC3101	0.89	40
PC304	0.038	40
PC3315	2.48	40
PC3301	384.6	40

Figure 4-5 shows dynamic responses for a 20% increase in the oil feed flowrate. There is no problem controlling the water, oil level and pressure.
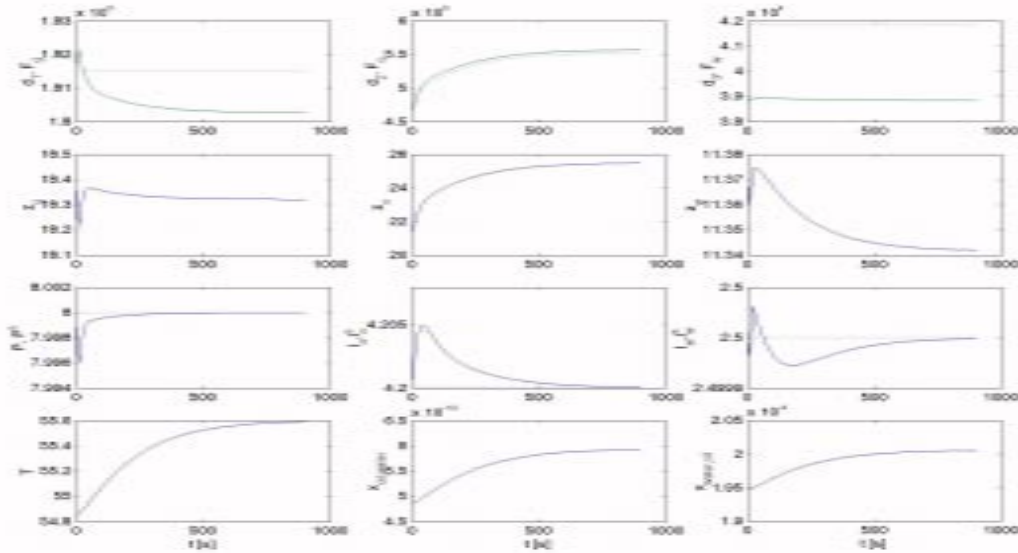

Figure 4–5: Responses for a +20% increase in the oil feed flowrate.

Figure 4-6 shows responses for a 5% increase in the oil level setpoint and shows negligible effect on the fraction of oil in water ($X_{oil,water}$) and fraction of water in oil ($X_{water,oil}$).
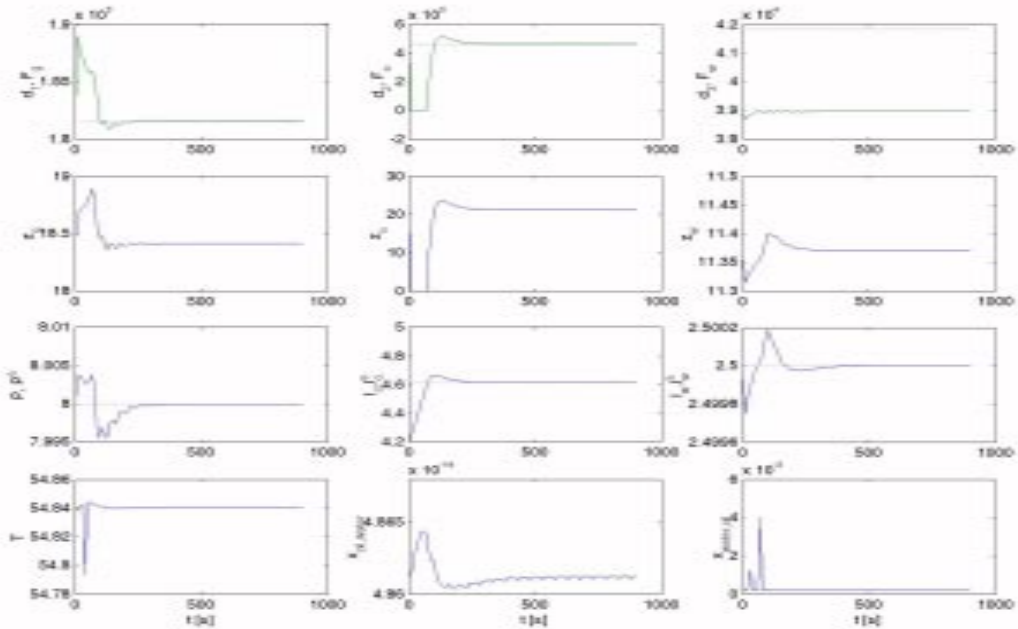

Figure 4–6: Composition responses for 5% steps in the oil level setpoint.

4.3   Step responses for the offshore process

Responses for different disturbances and setpoints are done for the off-shore process with control of pressure, oil level and water level. Controller tuning is done by Skogestad's rules, see chapter 4.2.2

The sampling time is usually 10 seconds, and the system is simulated until all the outputs reach steady state. The coefficient matrix was generated by scaling step response to step unit. The coefficients showed the change in outputs when there was a changed unit in disturbance or setpoint. After tuning, the gain and time constant were calculated, then scaled .

The values are shown in table 4-3 and have been carefully chosen after 200 time steps, this means 200*10s = 0.5556 h (33 minutes). At that time, all values were approximately stationary.

20% steps were performed in all disturbances and 5% steps in manipulated variables. Responses for 20% increase in the oil feed flow are shown in figure 4-1

Table 4–3: Steady-state gain between compositions and manipulated variables/disturbances

output(y) input(e_s,d)	ΔX water,oil	ΔX oil,water
P^s_1	$2.58*10^{-20}$	$4.11*10^{-20}$
$I^s_{o,1}$	$5.05*10^{-11}$	$5.66*10^{-20}$
$I^s_{w,1}$	$-1.24*10^{-11}$	$-1.50*10^{-25}$
P^s_2	$6.80*10^{-7}$	$-8.20*10^{-25}$
$I^s_{o,2}$	$9.54*10^{-21}$	$6.36*10^{-7}$
$I^s_{w,2}$	$-1.02*10^{-6}$	$-4.67*10^{-27}$
$F_{g,in}$	$-6.44*10^{-6}$	$-1.00*10^{-21}$
$F_{o,in}$	$5.77*10^{-6}$	$1.08*10^{-19}$
$F_{w,in}$	$6.36*10^{-7}$	$9.54*10^{-21}$

Figure 4-7 shows the composition responses for 5% steps in different the setpoint.
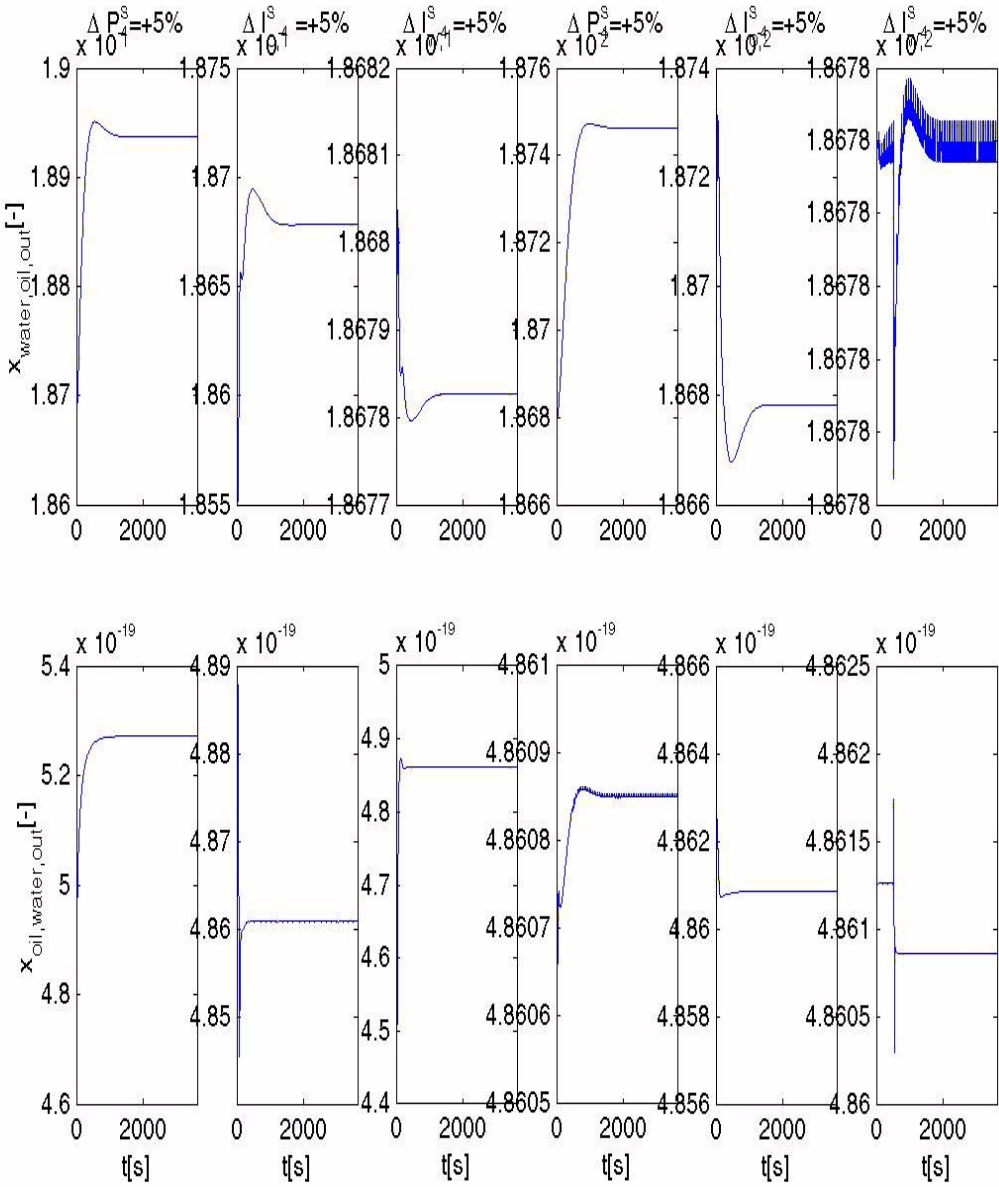

Figure 4–7: Composition responses for a separator with control for 5% steps in different setpoints.

Figure 4-8 shows composition responses for +20% steps for different disturbances. There are only minor changes. The oil in water fraction and the water in oil fraction are still small and the control of compositions are not needed.
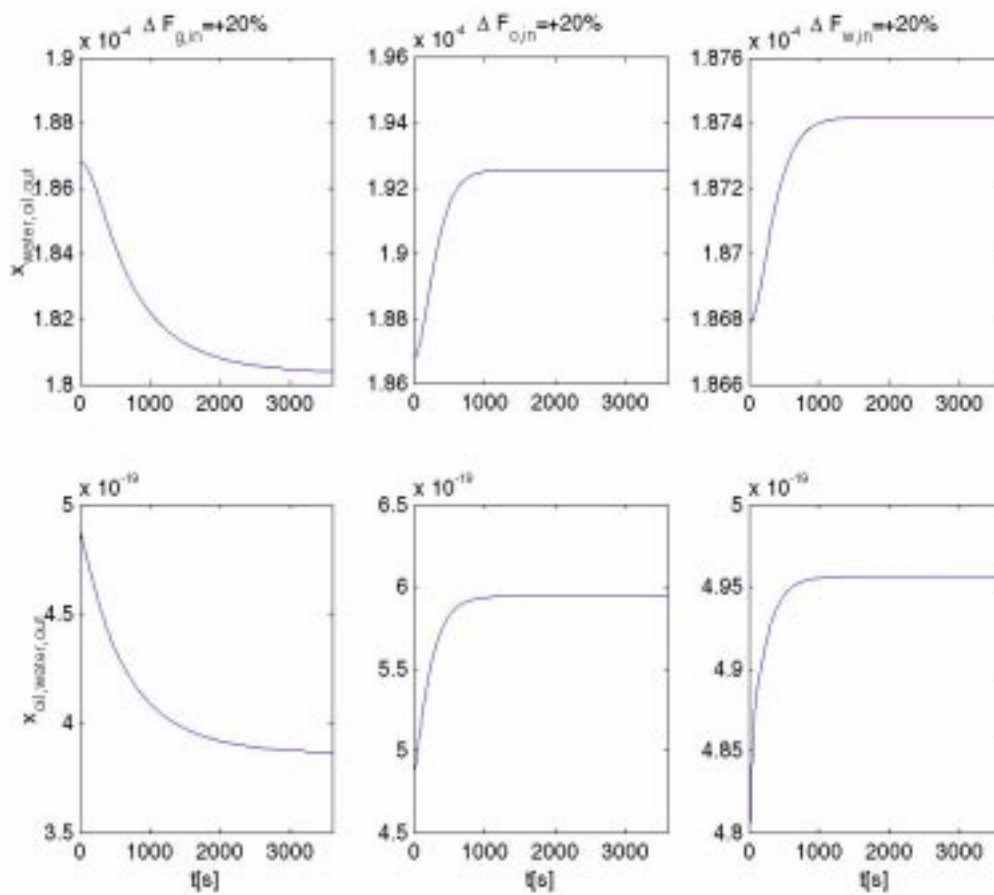

Figure 4–8: Compositions responses for +20% step in disturbances.

5   Discussion

5.1   Dynamic modelling and simulation in Hysys.Plant.

Dynamic modelling and simulation have taken a lot of time. Hysys.Plant is well arranged and it should be simple to develop a dynamic model, but there are some problems.

In many cases, it was necessary to switch between dynamic and steady state for the process. This created difficulties or complications in Hysys. Information related to for example hold-up in separators is lost when switching from dynamic mode to steady-state mode. Pure dynamic information disappears, when switching back to dynamic mode. This(pure dynamic information) needs to be reinitialized. Hysys does not tolerate zero flow rate, and is sensitive to start values. Hysys does not save("remember") or generate information on old and new values together. This may happen for the flow between separators when the oil level in a separator is aggressively controlled.

Some simplification in modeling of the separator was done and this resulted in a small effect in the dynamic model . Realistic start values are needed to achieve convergence in the simulation. If changes are made and the simulation does not converge, it may be necessary to start from an old version. To avoid negative flows, significant pressure loss across the valve is needed.

The proportional gain (K_c) found from Skogestad's rule needs to be scaled with respect to an upper and lower output value specified in Hysys before the calulated can be implemented.

$$\hat{K}_c = K_c \cdot \frac{Y_{MAX} - Y_{MIN}}{100}$$

5.2   Composition responses

The responses show that the concentration of water in oil outlet and oil in water outlet are small and the disturbances have a minor effect on the composition, see figure 4-8. If assumptions connected to the phase equilibrium and no mixing of the phases are acceptable, there is no problem connected to composition constraints (water in oil and oil in water) as long as the pressure, oil level and water level are controlled inside constraints. If these assumptions are not acceptable, a model is needed which includes mixing of phases and no phase equilibrium. This requires another modelling environment other than HYSYS.

5.3   Tuning of the model

A systematical tuning was correctly done. The scaled value of K_c was used in the tuning. The model was implemented with the PI-control for gas, oil and water level. The tuning parameters determined by the Skogestad's rule, gave satisfactory results . The control/ operation using controlled variables and manipulated variables was fully satisfactory. The model was tested by making ±20% steps in disturbances (the feed flow rate), and ±5% steps in manipulated variables (the feed composition and the pressure setpoints). Step responses showed satifisfactory results and the tuning of parameters helped to stabilize the model process/off-shore process.

Analyses and studies could be done from step responses to explore the effect of manipulated variables and disturbances in various measurements respectively in the standard basic control, which is to control the pressure, oil and water level.

5.4   HYSYS-model VS gPROMS-model

There was little time for an analysis of gPROMS, but it seemed like the gPROMS-model is based on the model of a tank.

5.4.1 Compared with a simplified model.

Heum (2000) used a simplified model to describe the off-shore process, where the oil-in-water and water-in-oil fractions depended on the hold-up time in the separators. The oil-in-water and water-in-oil fractions are affected by changes in disturbances or setpoints.

For the model developed in Hysys, the compositions were calculated from phase-equilibrium. The oil-in-water and water-in-oil fractions are very small and show only minor changes when disturbances happen or setpoints change. We did not compare these two models in more details.

5.4.2 Literature

There was little relevant literature related to the project. Some journals came from the library and internet. Most theoretical support for this work came from discussions with faculty at the department and the literature found was more a support reference.

5.4.3 Further work

Evaluation of the phase-equilibrium is needed first. If it is not acceptable, a new model based on the equations presented in theory must be developed. This model should be used in control and to study different types of composition control.

6 Conclusion

A dynamic model was made of a three-phase separator and off-shore process in HYSYS.PLANT. The step responses were done to study the effect of manipulated variables and disturbances on various measurements respectively the standard basic control, which is to control the pressure, oil and water level.

For a three-phase separator without control, the operation will violate the constraints for rather small disturbances. The gas, oil , and water valve openings have, as expected, large effect on the pressure, oil level , and water level respectively.

For a three-phase separator with control of pressure, oil level and water level the setpoints and disturbances have negligible effect on the composition (oil-in-water and water-in-oil). For the offshore process where the pressure, oil level , and water level are well controlled, there are no problems with respect to the compositions.

If the assumption about phase-equilibrium holds, there is no problem for the composition of water-in-oil and oil-in-water, when the pressure, oil , and water are well controlled. If the phase-equilibrium assumption is not acceptable, the Hysys model is not appropriate.

7   List of symbols

Symbol	Description
$d1$	Disturbance in gas feed flow
$d2$	Disturbance in oil feed flow
$d3$	Disturbance in water feed flow
z_g	Valve opening for gas
z_o	Valve opening for oil
z_w	Valve opening for water
M_g	Mass of gas component
M_o	Mass of oil component
M_w	Mass of water component
$F_{g,in}$	Gas feed flow in
$F_{o,in}$	Oil feed flow in
$F_{w,in}$	Water feed flow in
P^s	Pressure setpoint
l_o^s	Oil setpoint
l_w^s	Water setpoint
M_i	Hold -up of phase i in the separator
M_k	Hold -up of phase i in the separator in time k
$\tau_{m,i}$	Time constant for the phase i
$\tau_{ref,j}$	Reference time constant for the phase i
$x_{m,i,j}$	Mass fraction of phase i in the mixture j
k_g	Gas constant for manipulated variables
k_o	Oil constant for manipulated variables

Symbol	Description
k_W	Water constant for manipulated variables
k'	Ratio between a process gain(k) and time constant(τ)
k_C	Controller gain
m	Manipulated variables
c	Contolled variables
v	Selection of measurement
τ_c	Response time for the "Closed Loop"
τ_I	*I*ntegral time

Literature

1. Hansen J.E. : Plant-wide Dynamic Simulation and Control of Chemical Processes, PhD Thesis, Dept. of Chemical Engineering, Danmark Technical University, 1998

2. Heum H A : MPC-regulering av offshore prosess, Hoved Oppgave, Institut For Kjemisk Prosessteknologi, Norges Teknisk Naturvitenskaplige Universitet, December 2000

3. Hysys, version 2.1 : Reference volume 1, Hyprotech, Alberta, Canada, 1996

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7. Skogestad S : Prosessteknikk, Masse-og Energibalanser, s.214-223,Tapir, Norges Teknisk Naturvitenskapelige Universitet, 2000

8. Skogestad S : Compendium , Supplement to the subject SIK2050 Process Control, p 6-13, Dept of Chemical Engineering, Norwegian University of Science and Technology, 2000

Appendix A
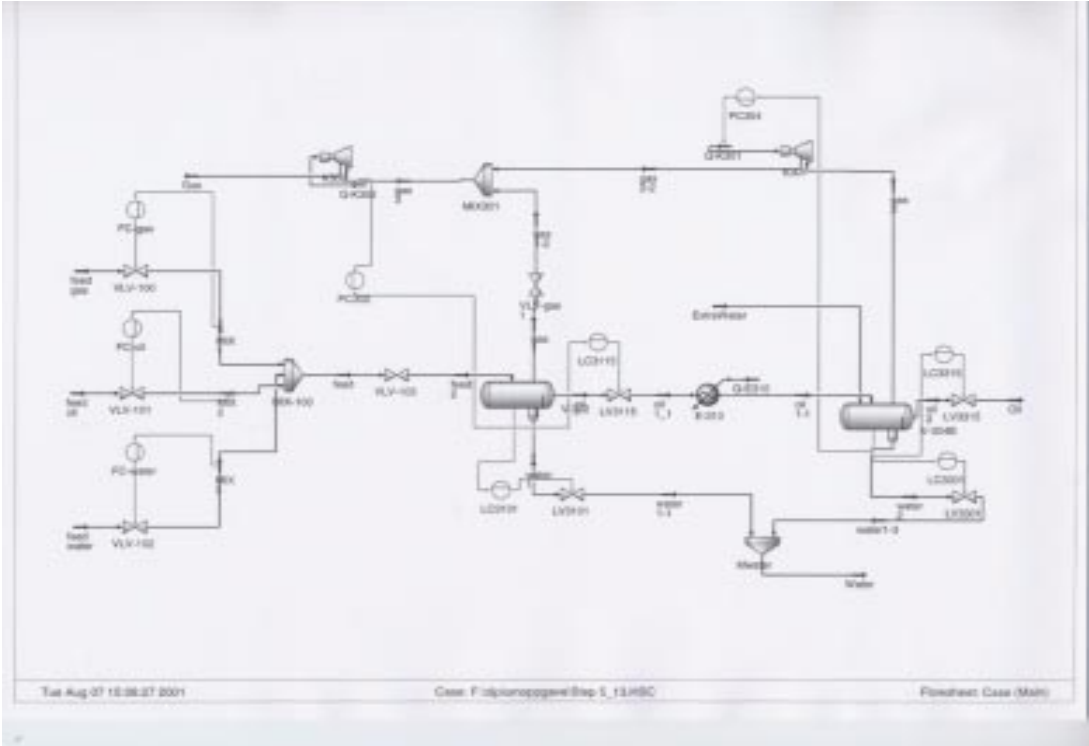
The flowsheet of the off-shore process.

Figure 7–1: Hysys flowsheet of the off-shore process.

Appendix B1

Table 7–1: Start values for a separatorl

	Value	Unit
GAS FEED	181530.00	kg/h
OIL FEED	461200.00	
WATER FEED	41869.00	
GAS VALVE OPENING	18.41	[%]
OIL VALVE OPENING	21.23	
WATER VALVE OPENING	11.37	
PRESSURE	800	kPa
OIL LEVEL	4.2	m
WATER LEVEL	2.5	m
TEMPERATURE	54.8407	C
OIL IN WATER		
WATER IN OIL		

Appendix C

Flowrate equations

$$F_g = Z_g \times K_g \times \sqrt{P_g - P_{out}} \tag{7.1}$$

$$F_o = Z_o \times K_o \times \sqrt{P_g + \rho g l_o - l_w} \tag{7.2}$$

$$F_w = Z_w \times K_w \times \sqrt{P_w + \rho g l_o + \rho g l_w - l_w} \tag{7.3}$$

F(g,o,w) : gas , oil , and-water flow out ; Z(g,o,w) : gas, oil and water valve opening ; K(g,o,w) : gas , oil , and water valve constant ; P(g,o,w) : pressure out for gas, oil, and water l(g,o,w) : level for all three components.

Mass balance: Flow(in) = Flow(out) , and

$$F_{out} = K\sqrt{\Delta P}$$

ΔP is the pressure difference over the valve, which is the difference between the inlet pressure (P_{in}) and the outlet pressure (P_{out})

Appendix B2

Table 7–2: "OPEN-loop" effect for a separator

	d1	d2	d3	y1	y2	y3
GAS FEED	+	-	+	+	+	-
OIL	-	+	-	+	-	-
WATER	+	-	-	+	-	+
GAS VALVE OPENING	+	-	+	+	-	+
OIL V.OP	-	+	-	+	+	-
WATER V.OP	+	-	-	+	+	-
PRESSURE	+	+	+	-	-	+
OIL LEVEL	-	-	+	+	+	-
WATER LEV.	-	+	+	+	+	-
TEMPERAT.	-	-	-	-	-	+
OIL,WATER	+	+	-	-	-	+
WATER,OIL	+	+	+	-	-	+

Table 7–3: "CLOSED-loop" effect for a separator

	d1	d2	d3	y1	y2	y3
GAS FEED	+	-	-	-	-	-
OIL FEED	-	+	-	-	-	-
WATER FEED	-	-	-	-	-	-
GAS VALVE OPENING	+	-	-	-	-	-
OIL VALVE OPENING	-	+	-	-	-	-
WATER VALVE OPENING	-	-	-	-	-	-
PRESSURE	-	-	-	-	-	-
OIL LEVEL	-	-	-	-	-	-
WATER LEVEL	-	-	-	-	-	-
TEMPERATURE	-	-	-	-	-	-
OIL-IN-WATER	-	+	-	-	-	-
WATER-IN-OILL	-	+	-	-	-	-

Minus sign (-) stands for minor or no effect and plus sign (+) stands for large effect.

APPENDIX B3

Data used for the process simulation.

Table 7−4: Feed composition in off-shore process

Components	Feed composition[mass fraction]
Nitrogen	0.004453*
CO_2	0.006768*
Methane	0.4325*
Ethane	0.06171*
Propane	0.04922*
i-Butane	0.008106*
n-Butane	0.02123*
i-Pentane	0.006714*
n-Pentane	0.01347*
n-Hexane	0.01749*
n-Heptane	0.02323*
n-Octane	0.02315*
n-Nonane	0.01370*
n-Decane	0.01544*
C11H*	0.01104*
C12H*	0.01136*
C13H*	0.01040*
C14H*	0.008383*
C15H*	0.009103
C16H*	0.006907*
C17H*	0.006239*
C18H*	0.01091
C20+	0.04905
H20	0.1794
EGlycol	0.0000
Total	1.0000

Appendix D1

"CLOSED LOOP" step responses for a separator.
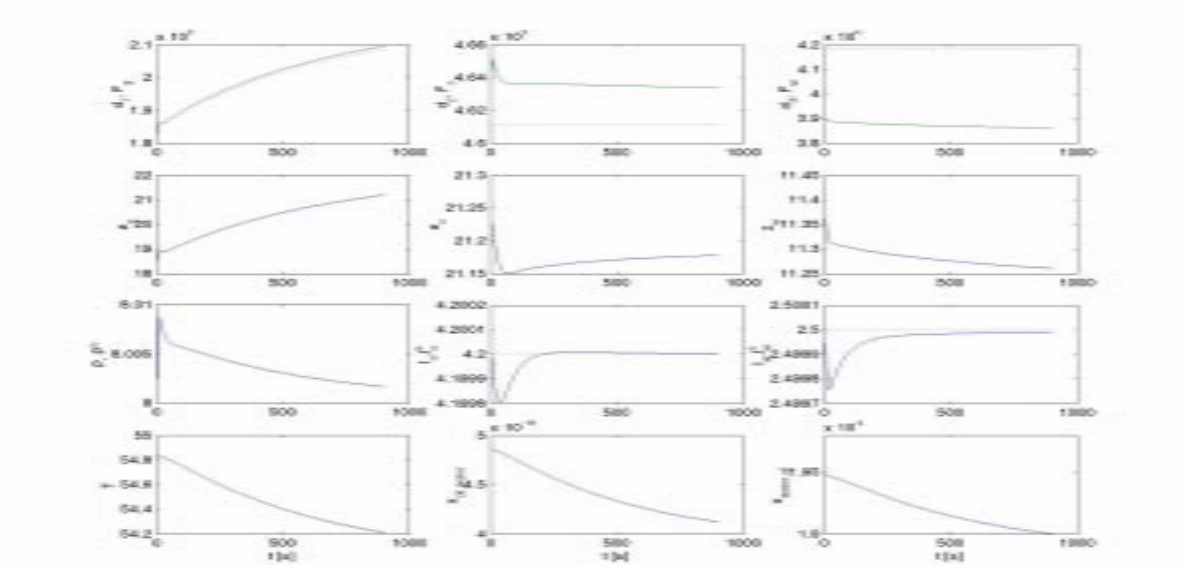
Figure 7−2: Step responses for a separator with control of pressure, oil and water level for a 20% increase in gas feed flow rate.
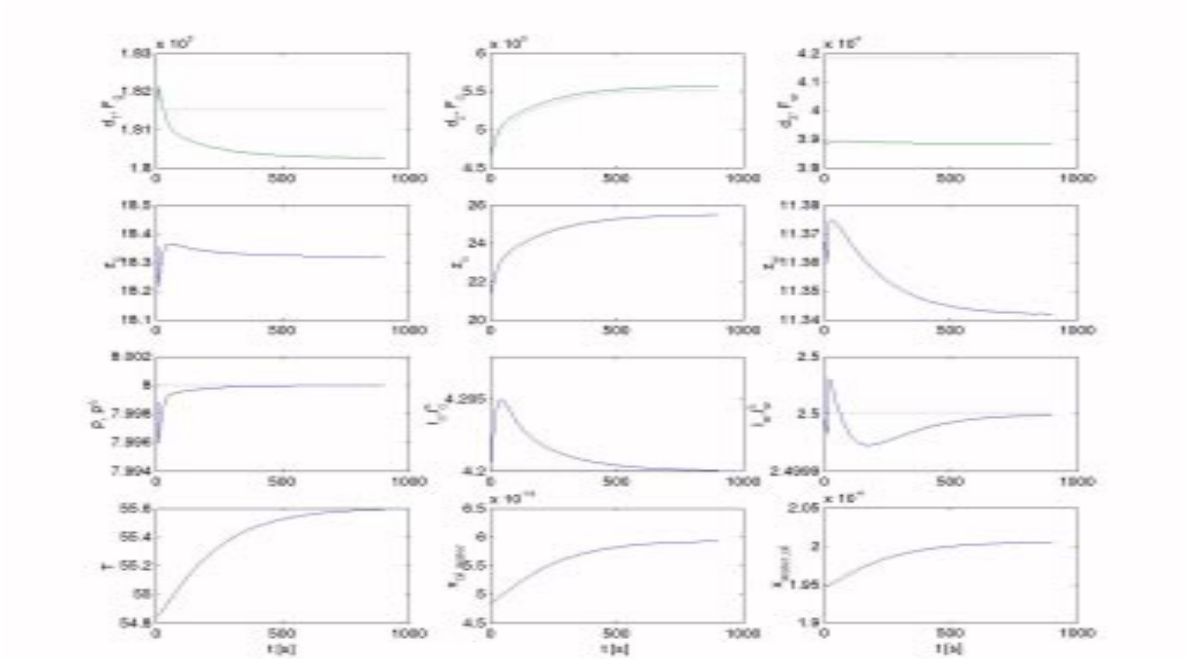
Figure 7−3: Step responses for a separator with control of pressure, oil and water level for a 20% increase in oil feed flow rate.

Appendix D2

"Closed Loop" responses for a separator
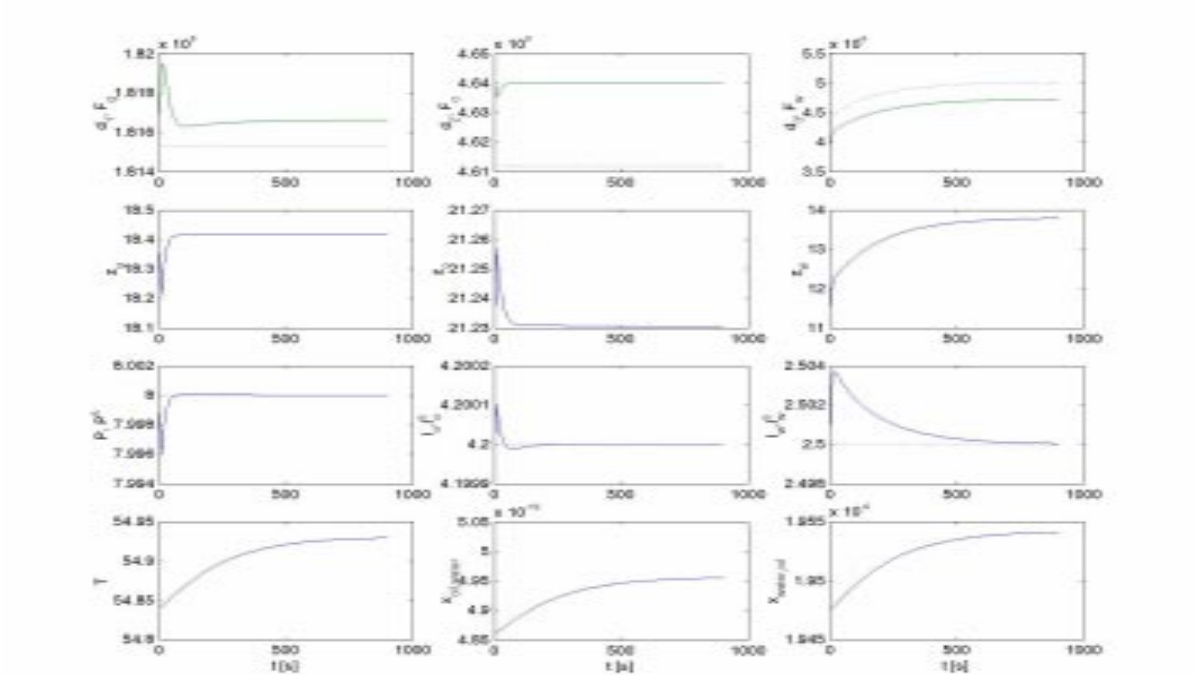
Figure 7−4: Step responses for a separator with control of pressure, oil and water level for a 20% increase in water feed flow rate.
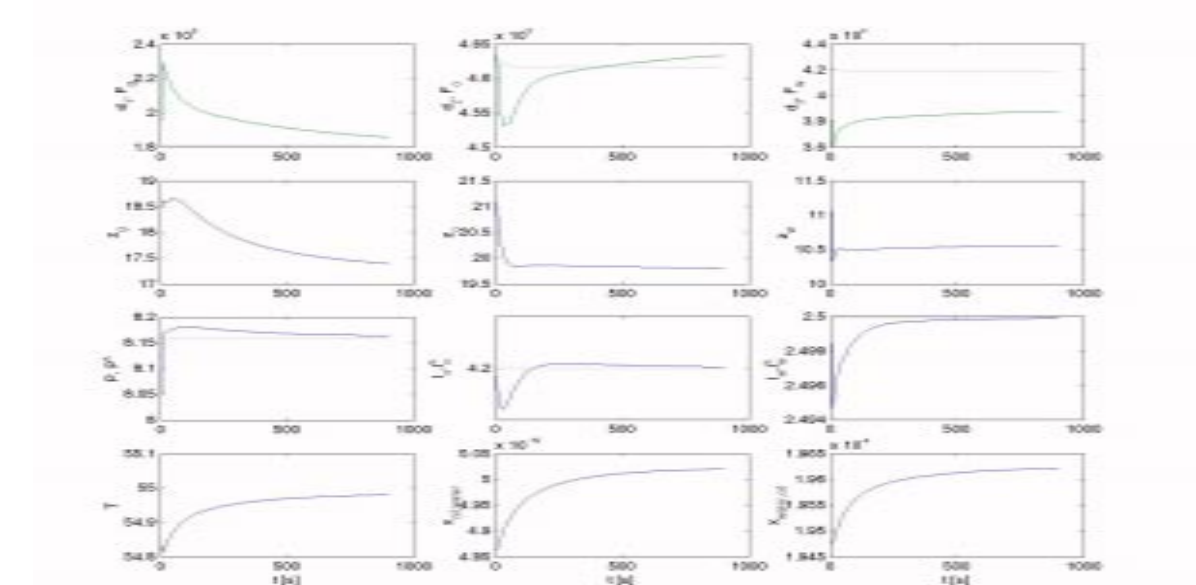
Figure 7−5: Step responses for an 5% increase in pressure setpoint for a separator

Appendix D3

"Closed Loop" step responses for a separator
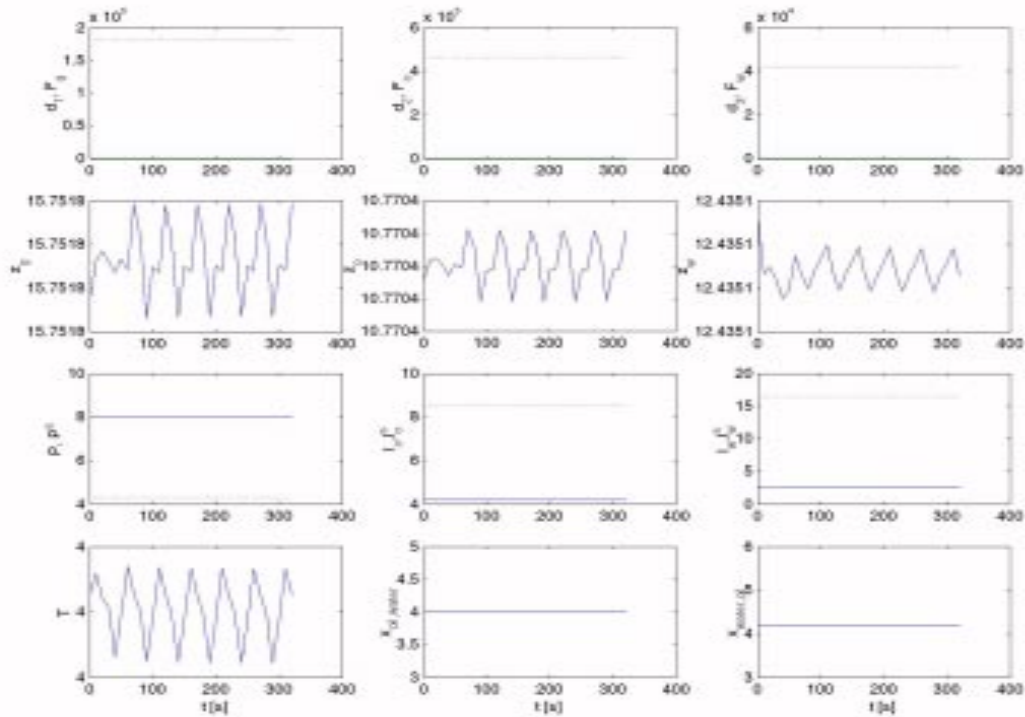
Figure 7−6: Step responses for an 5% increase in water setpoint for a separator

Appendix D4

"Closed loop" responses for the offshore process
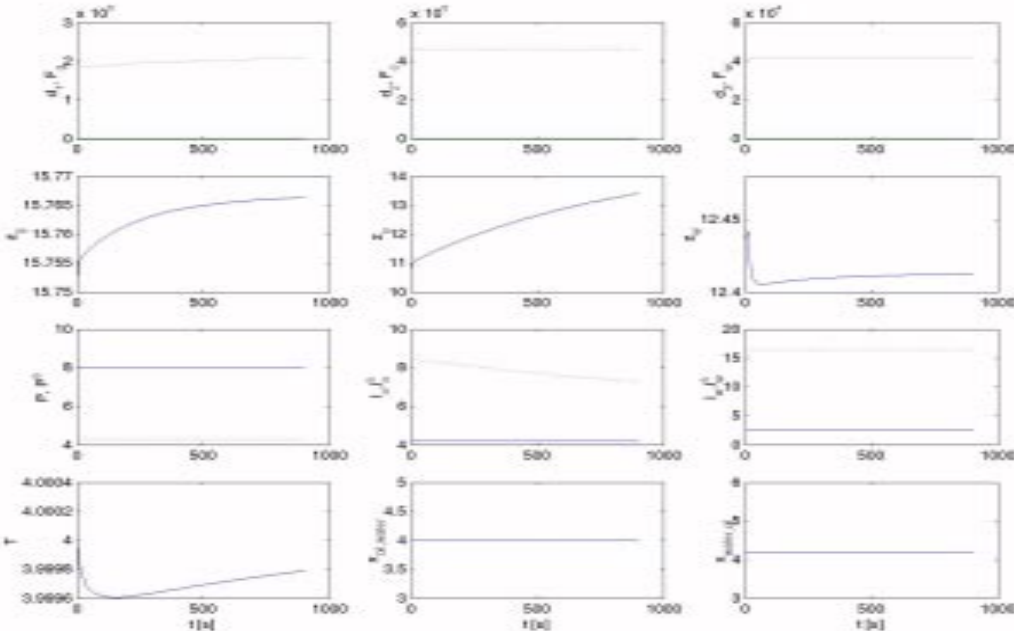
Figure 7–7: Step responses for a 20% increase in gas feed flow rate.
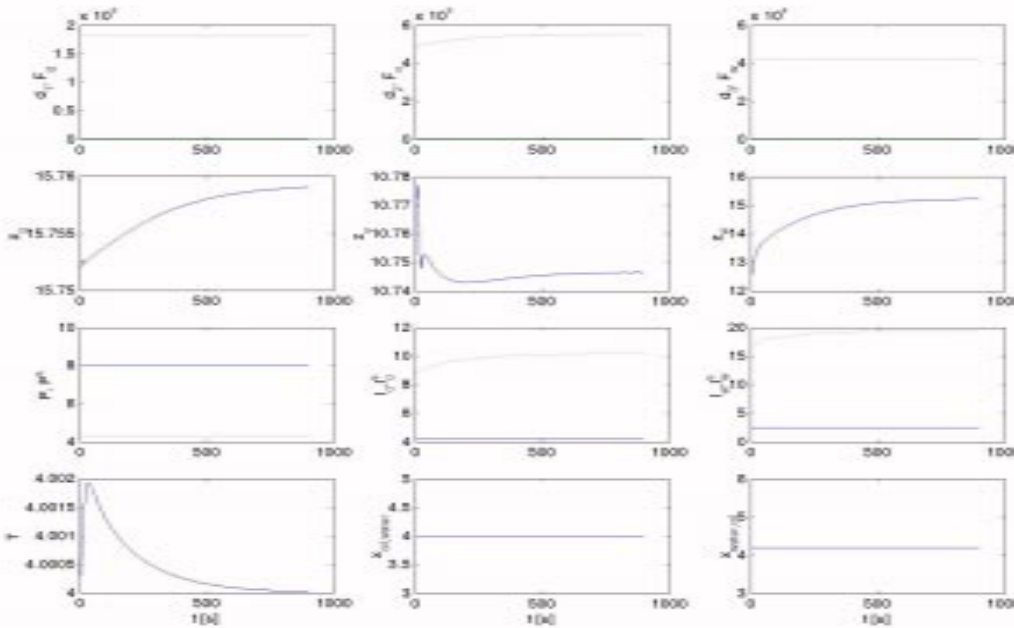
Figure 7–8: Step responses for a 20% increase in oil feed flow rate.

Appendix D5

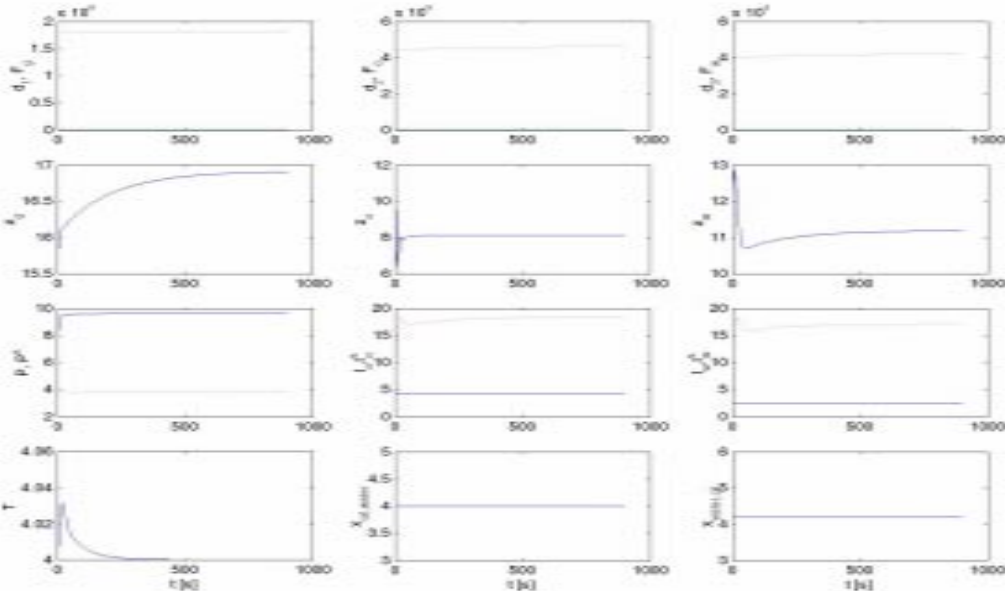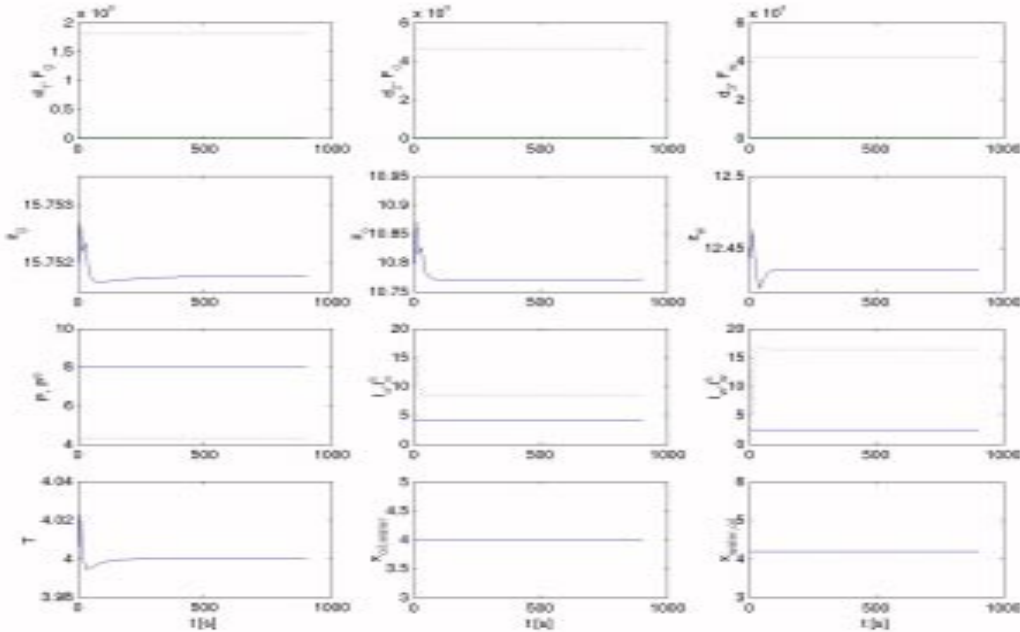## "Closed Loop" step responses for the offshore process

Figure 7−9: Step responses for 20% increase in water feed flow rate.

Figure 7−10: Step response with control for an 5% increase in oil level setpoint .

Appendix D6

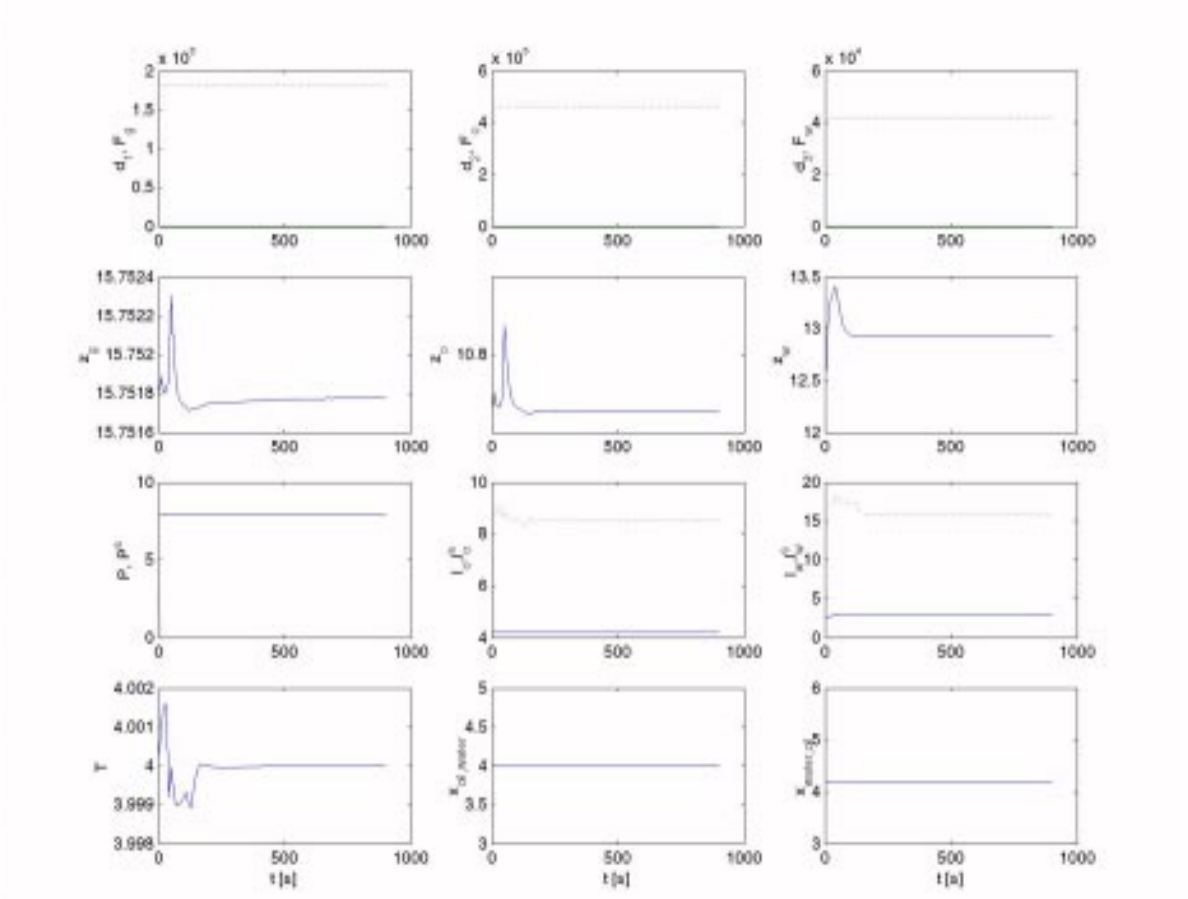## "Closed Loop" step responses for the offshore process.

Figure 7–11: Step response for the offshore process with control of pressure, oil and water level for an 5% increase in water level set point

Appendix D7
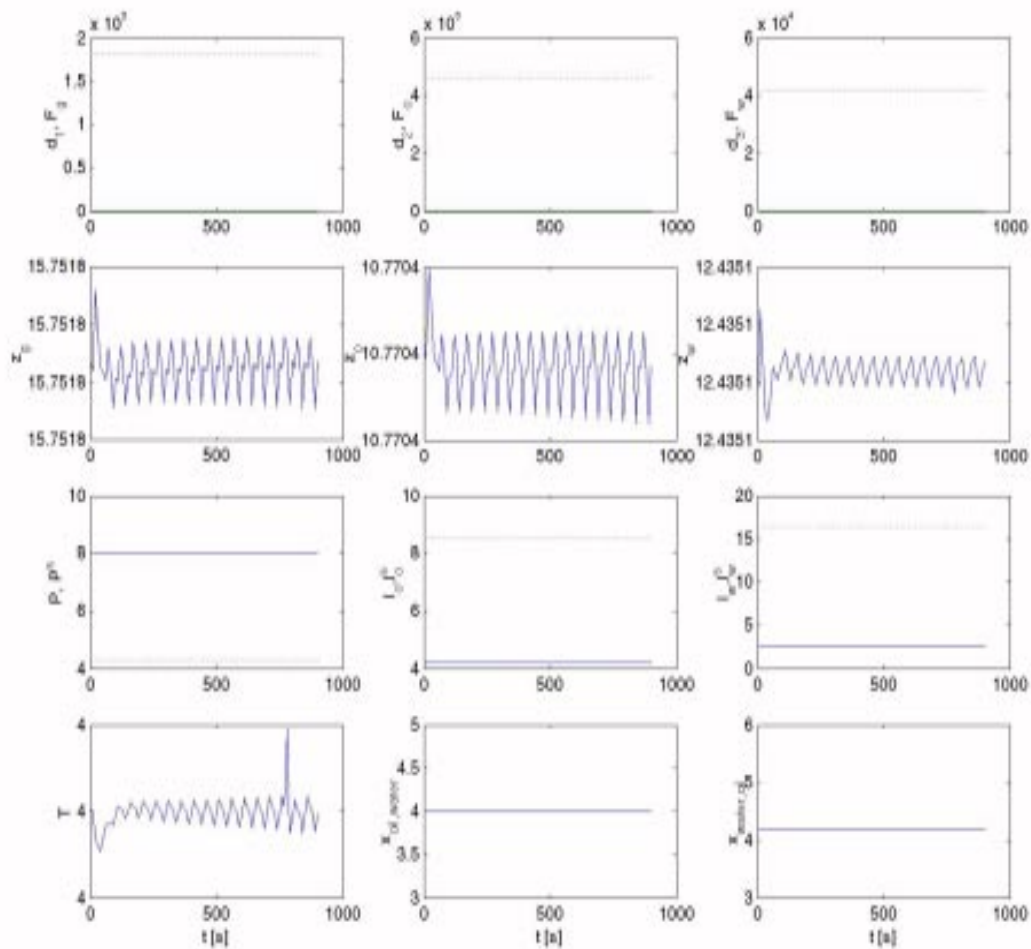
"Closed Loop" responses for the offshore process.

Figure 7–12: Step response for the offshore process with control of pressure, oil and water level for an 5% increase in water level setpoint in the second separator.
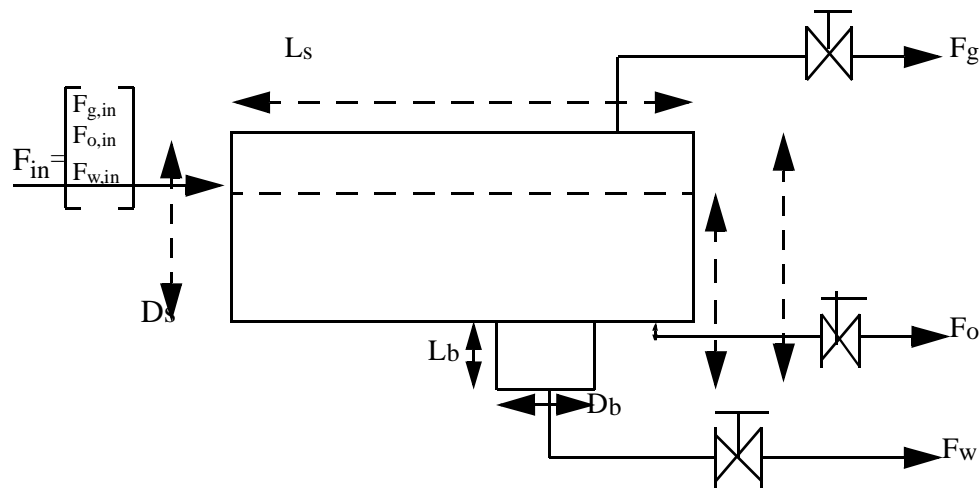
Appendix E

Separator geometry

Figure 7−13: Three-phase separator.

Explanation of the notation is given below:

- Ls : vessel length

- Ds : vessel diameter

- Db : boot diameter

- Lb : boot length

- F_{in} : feed flow rate for gas, oil and water enter in a separator

- Fg : gas flow outlet

- Fo : oil flow outlet

- Fw : water flow outlet