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SPECIALIZATION PROJECT 2015

TKP 4550

PROJECTTITLE:
COMPACT SUBSEA SEPARATOR MODULES OF OIL-WATER

By

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Date: **January 08, 2015**

Preface

I like to specially thank my supervisor, prof Sigurd for his support and input. My appreciation also goes to Tamal Das, Adriana and Mohammad for their useful contributions. I acknowledge friends and colleague for their encouragements.

Declaration of Compliance:

I, Rotimi Famisa, hereby declare that this is an independent work according to the exam regulations of the Norwegian University of Science and

Technology (NTNU).

Place and date:

Trondheim, Norway; January 08, 2015

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4.0 RESULTS AND DISCUSSION OF RESULTS

Lists of Symbols

Symbol	Description	Unit
A	Cross section area	m^2
A_d	Reference area of droplet	m^2
a_c	Centrifugal acceleration	$ms–^2$
α	Oil volume fraction / Oil cut	–
C	Concentration	$molm^{-3}$
D	Diffusion coefficient	m
D_d	Diameter of droplet	m2 s−1
F_d	Drag force	N
F_g	Gravitational force	N
FS	Flow split	–
g	Gravitational acceleration (≈ 9.81)	$ms–^2$
h	Vertical distance traveled by droplet	m
H_w	Height of weir	m
L	Length of separator	m
n_{dil}	Dilute efficiency	–
n_{dis}	Dispersed efficiency	–
p	Pressure	Pa
P	Density	kg/m^3
q	Volumetric flow rate	$m^3\ s–^1$
R	Radius of separator	m
r_d	Characteristic droplet radius	-
t	Time	s
μ	Viscosity	Pas
V	Volume	m^3
v_X	Horizontal velocity	ms^{-1}
v_y	Vertical velocity	ms^{-1}

List of Subscripts/Superscripts

Acronyms	Description
b	Bottom product of gravity separator
C	Continuous phase
d	Droplet/dispersed phase
HPO	Heavy phase outlet
in	Feed/inlet stream to separator
max	Maximum
t	Top product of gravity separator
x	horizontal stream
y	Vertical stream

ABSTRACT

Compact subsea separators are useful in the treatment of the different subsea production streams This separation system is becoming increasingly employed in subsea productions and operation because of the economics of cost and its compactness. This project aims at the design and development of a compact steady state model for the bulk separation of oil-water, using the modeling tool of HYSYS. The developed model is comparatively studied with a similar work by Preben: The Modeling and Optimization of a Subsea Oil-Water Separation System. The idea also was to investigate the modeling tool of HYSYS for its robustness in this project type. And hopefully, in fall 2016, this will be subsequently followed through for further optimization and control of the separation system. A re-entraiment unit was integrated into the steady state model of the horizontal gravity separator in order to avoid over simplification. Some of the oil was re-entrained into the water and conversely the water droplets into the oil. This was done within the limits of the regulatory requirements. The steady state model was investigated. Some of the result showed a close correlation with Preben work. Experimental data is needed in order to fit the (input) parameters accordingly as well as validate the accuracy of the model. There is also need to improve on the model to be able to capture more accurately the dynamics of an industrial subsea separator module.

1.0 Introduction

Subsea processing has been around for some time now, but the recent growing confidence in the subsea separation has engendered huge research and investment with the objective of optimizing production and profit ultimately [31]. The immense advantages of the subsea production and processing has enabled viability from initially challenging reservoirs, which in consequence has enhanced oil production and recovery. Prolong the life of production field economically. Because of the capacity of the separator to handle sand and water at the seabed, the potential cost likely to be incurred from topside facility is avoided. This also minimizes environmental impacts and ensures a safer environmental process as against a topside operations.

Subsea processing offers a flexible solution flexible with a broad operating envelope for a wide range of gas-liquid fraction operating conditions. It debottleneck risers, flowlines and topsides. It provides an effective and suitable resolution for flow assurance challenges, disbandment of facilities at topsides with limited production life (thereby foreclosing issues with operation cost and potential integrity) as well as transporting the fluids to other facilities with longer remaining life [10].

1.1 Objective

This project aims at modelling the compact subsea separator module of oil-water with focus on the hrizontal gravity separator. The idea at the end is to optimize and design a control by using HYSYS and/or MATLAB. Summarily the project will be undertaken under the sub endings

i. Industrial use of the subsea separation
ii. Steady state models in HYSYS
iii. Comparatively analysis against Preben Thesis
iv. Research challenges.

1.2 Previous Work

This specialization project is in furtherance to previous Master`s thesis 2014 on the modelling and optimization of subsea separators with MATLAB. The idea is to develop a model in HYSYS and simulate same in contrast to results and observations obtained from Preben Thesis. The horizontal compact gravity separator model for oil-water (liquid-liquid) separation was studied.

2.0 LITERATURE REVIEW

2.1 Subsea Separation

Subsea processing involves the active treatment and handling of streams or fluids produced below or at the seabed [11]. The processes primarily include:

- Pumping
- Gas/liquid separation
- Gas treatment as well as compression
- Water removal and disposal or reinjection
- Sand and solid separation

[11].

The decreasing of the bottom hole pressure by way of decrease on the wellhead backpressure, is considered as one of the principal driving forces in the application of subsea processing and production. This helps to boost the production rate as well as increase the ultimate recovery [8]. Originally, the subsea processing was meant to alleviate the challenges during deep water production. But recently it is becoming extensively used for fields with damaging conditions to process equipment at water surface. In addition, situating the subsea equipment on the seafloor instead of topside provides a relatively less expensive solutions to offshore developments [11].

Subsea processing has several advantages of:

- Reduction in development costs
- Enriched recovery of hydrocarbon resources
- Improved flow rates
- Reduction of or Alternative to chemical injection
- Reduced occurrences of spills and leaks due to environmental damages

- Lessen personnel risks

2.2 Liquid-liquid Separation

Liquid-liquid separation involves the process of separating water and oil, and/or occasionally gas at the seabed. The technology was designed to extend the production life of mature fields by way of high water cuts. But the use has become extensive in finding solution to developments with environmental and economic challenges. Removal of water from produced stream has the additional benefit of limiting the number and size of production pipes required for production, as such, safeguarding the equipment from the environment [23]. Reservoirs with much more water production require a greater force to push the production stream upward to the surface because water is denser than oil, and with time depreciates the reservoir pressure. Contrary, production streams having less oil and increasing water cuts result in a less economic development [23]. Alternatively, with the natural force no longer sufficient to lift the produced water and oil, the production stops if there is no intervention. In Subsea liquid-liquid separation, there are three choices one can employ for the produced water [34]:

- Pumped in separate flowlines to the surface
- Re-injection into the Reservoir or an adequate subsurface layer
- Disposed into the sea

There are, currently, only three installed subsea separation systems. One in Brazil, operated by Petrobras and two, operated by Statoil, in the North Sea. With all having a water re-injection system into the sea

2.3 Reinjection of Subsea Water

Sea water reinjection, has by far, been widely used for support of reservoir pressure. In order for us to achieve this result the produced water must be treated to the right quality before reinjection into the reservoir. Normally, the produced reservoir water is brought to the surface for treatment and thereafter disposed to sea. Treated water usually contains traces of pollution from the residual oil as well as the production chemicals [5]. But the reinjection of produced water forecloses sea water pollution. Treated seawater is primarily reinjected to support the reservoir pressure and secondarily to enhance recovery. The requirements necessary for water injection is complex due to the popularity of the technique. The regulations established by the Petroleum Safety Authority Norway [23], requires the oil content in the water produced for discharge to be smaller than $30 mgL^{-1}$ (i.e 30ppm). The suspended solids in addition to the oil content in the reinjected water is a major concern. Likewise, the produced water is at a higher temperature can reduce the effect of thermos elastic fracturing. Recently hydraulic fracturing is now adopted because it allows the surface area reinjected with produced water to be continually renewed, thereby letting reinjection of water treated by acceptable technology on topside [1].

2.4 Gains of Liquid-Liquid Separation

The goal of oil companies is to optimally produce hydrocarbons in the fastest, most economical and less costly way. There are several benefits ensuing from subsea separation. Among these are the economical, operational as well as the environmental gains. The platform systems for fluid handling are usually limited, and this limited capacity can pose a problem for production because of the increasing water cuts resulting from an older field. This problem from capacity also surfaces when building tie-ins of satellite fields for existing platforms as well as infrastructure or of new wells. The addition of a subsea separation unit to the field forecloses the need for the upgrade of the topside facility that handles new and several operating conditions within the lifespan of the field, in addition to closing out production shot down earlier than necessary since it is cost ineffective. The separation of water produced in cases with limited riser capacity results in increased hydrocarbon transportation. This will require fitting new transport pipes to the topside, the upgrade to the topside facility as well as flowlines are cost intensive and even impossible sometimes because ofspace limitations; subsea separation offers the most feaisble and economical solution for prolonging the life of a field [11]. Subsea separation provides the advantage of compacting process facilities on topside. The removal of water from the production stream results in reduction of the backpressure on the wells which in turn decreases the wellhead pressure. This wellhead pressure reduction increases the production rate from the well, as well as enhance the reservoir total recovery [24].

The removal of subsea water can be achieved together with water reinjection as a means of enhanced recovery method. The water injected water acts as pressure support to the production reservoir by avoiding pressure drop in the reservoir. This in turn sustains a high reservoir pressure necessary for enhanced production and total recovery. Reinjection of the produced water saves energy and expenses required to transport water to the surface. With subsea separation, fields that were typically inaccessible due to their location at the deep sea and the presence of heavy hydrocarbons, are now accessible. The effect of reduced backpressure is increasing with length of the riser, and hence the water dept. The need for powerful pumps can thereby be reduced by water removal on the seafloor. For production of heavy hydrocarbons the benefits will be the same. Heavy oils are thicker and more viscous than oil consisting of lighter hydrocarbon components, the density is also higher, and the reduced pressure drop by not producing the water together with the hydrocarbons will increase the production capacity. In addition, heavy oil fields are often characterized by high water cuts in the production stream, which is rapidly increasing with time, so the effect of separated water will be important early in the fields life. Additionally, water reinjection to the producing well can help increase the well pressure. Subsea separation lessen the incidence of pollution from the platforms. Water reinjection discontinues the discharge of water containing residual oil into sea [24]. The quantity of chemicals applied in the prevention of flow assurance complications are reduced, thereby reducing operational costs and environmental effect[16].

2.5 Problems in Liquid-Liquid Separation

Separation system located at the seabed has limitation of accessibility and the components very prone to failure should be easy to retrieve with an alternate means of production [5]. The separator vessel is largely dominated with high pressure operating conditions at subsea, this is considered in the design of the device. At great sea depths, the normal gravity separator design is usually too big and weighty because of the shell thickness required to safe guard the device from the enormous hydrostatic pressure. The development of novel separator technology is now employed for this reason, typical examples are the pipe separator employed on Marlim and the semi-compact gravity separator assembled on Tordis [16]. A major issue in the development of separation solutions is on the provision of enhanced system efficiency with maintainability as well as ensuring it compactness [32]. The gravity separator is desired to work reliably and ensure optimal separation at sea depth of 3000 m at much higher process fluid pressures and temperatures than on the surface. The device is expected to perform acceptably over the entire life span of the production field because of its inaccessible location. As such, it is designed to withstand the enormous operational conditions faced during the production life time [34]. Important to note also, is the need to design the separator to handle extreme petroleum and water flow rates if it is to be assembled before production. The effective separation of water from oil at the conditions of the separator need to be assessed before the equipment is installed. For a poor crude/water separability, the use of subsea water separation is not considered a feasible alternative [8]. There is serious need to investigate the reservoir fluid as well as the expected production in order to solve these problems.Other challenges of the liquid-liquid separation in subsea, besides the separator, are regarding:

- Water handling and disposal
- Control of process system
- Sand handling method
- Sand and water quality measurement
- Flow assurance

Subsea separation of water comes with challenge of the disposal of the water. The existing options of injection into a disposal well, or into the production reservoir and disposal into the sea, all have limitations regarding the water quality. Therefore an appropriate water processing unit need to be developed. In reinjection, the acceptable water quality is characterized by appraising the concentration, particulate sizes of oil droplets and particles in the water in which the limiting factors are the reservoir characteristics. Plugging and formation of filter cake can result from oil droplets and solid particles which accordingly weakens the reinjection process. [34]. The discharge to the surrounding seawater is considered the simplest solution to the water separated saved for the tough environmental and legal regulations regarding the solids content residual oil and [32]. The handling of produced sand is equally important concern in subsea production and processing, as sand is capable of clogging the separator unit. Although the production of sand might be small in many cases during routine production, this sometimes become significant during start up and testing operations. An important concern also is where and how to get rid of the sand, should it be reinjected into the wastewater, transported along with oil and gas to the topside, or find alternative solution. The simplest is to inject the sand jointly with the wastewater, but this can demage the reservoir as sand particles is being injected with the residual oil content into the water. Another challenge is the amount of sand that can be reinjected into the reservoir. Furthermore, sand is very demaging to injection pumps during the injection process. Sand handling is an important parameter in the design of subsea separation system in order to carter for the uncertainty of the impact of sand on the long term performance of the processing equipment.A subsea separator that has its produced water removed from the production streams may not have sufficient liquid to transport the sand in long pipes downstream the device to the topside facility. An understanding of the behaviour of sand in multiphase flow pipelines is required for handling of the produced sand [32]. For the successful injection or discharge of water and sand, there is need for a system of quality control to monitor this. It is important to note that neither the Tordis SSBI nor the Troll Pilot have installed online continuous water quality measurement system. A major challenge in subsea control system is in the transfer of data from instrument in subsea to the control system topside. Any unnecessary delay in the control system of the separator can heighten the liquid level as well as the pressure in the device. New solutions are being developed for complicated subsea processing equipment, these includefiber optics, which provides fast transfer rates for data as well as transfer high data volume across long distances without the use of an amplifier. [32].

Flow assurance problems like the formation of hydrate and the precipitation of wax are largely dependent on composition of fluid, pressure, water cut and temperature. Subsea separation of water helps to prevent hydrates formation but conversely it can promote both hydrates and wax formation. The separation of water can lead to a sharp temperature drop in the flowline following from the relative lower heat capacity of the oil compared to water, in addition to the lower volumetric flowrate in the flowline.

2.6 Theory of Separations

2.6.1 Sedimentation

Sedimentation employs gravity in separating a liquid dispersed in the continuous phase of another liquid by using the difference in their densities. Consider a droplet having volume $V_d$and density ρ_d in a medium with density ρ, it will experience gravitational buoyancy force as in [20]:

$$F_g = V_d(\rho_d - \rho)g \qquad (2.1)$$

Where g is the gravitational acceleration, and can be substituted if the driving force is another factor other than gravity (e.g. centrifugal force). An object moving through a fluid experiences a frictional force, F_d as given by [15]:

$$F_d = -\frac{1}{2}C_D A_d \rho |v| v \qquad (2.2)$$

Where Ad is the reference area of the object, CD is the drag coefficient, and v is the relative velocity of the object with respect to the surrounding fluid. The drag coefficient is dependent on the relative velocity of the object to the surrounding fluid. Following from Stokes` law for laminar flow ($Re \ll$1) the drag coefficient is given by [20]:

$$C_D = \frac{24}{Re_d} \qquad (2.3)$$

The droplet Reynolds number for a spherical droplet, Re_d, is given as;

$$Re_d = \frac{\rho v D_d}{\mu} \qquad (2.4)$$

Where μ is the viscosity of the fluidand D_d is the droplet diameter and. The drag coefficient deviates from Stokes' law for an increasing droplet velocity within a flow regime of the transition region laminar and turbulent flow. A more appropriate expression for the drag coefficient in this region is given by equation 2.5 [15]. This precludes the linear relationship between the drag force and the droplet velocity.

$$C_D = \frac{24}{Re_d}\left[1 + 0.1 Re_d^{0.75}\right] \qquad (2.5)$$

Conversely, for a valid Stokes' law (laminar flow around the particle), equations 2.1, 2.2, 2.3 and 2.4 are combined to give an explicit relationship for the terminal velocity of the droplet:

$$v = \frac{2r_d^2(\rho_d - \rho)g}{9\mu} \qquad (2.6)$$

2.6.2 Viscosity of Emulsions

The relationship between the terminal velocity of a droplet in a gravity separator and the viscosity of the mixture is that of inversely proportionality (eq. 2.6). The viscosity of an oil-water emulsion is dependent, among other things, on the oil-water ratio and the droplet size of the dispersed phase [3, 33]. The viscosity reaches maximum at the point of phase inversion as shown in Figure 2.1.

Since the objective of the oil-water separator is to migrate the droplets from a continuous phase to another, they will have to move through the bulk interface. The composition closer to the bulk interphase will be close to the phase inversion composition (the mixture viscosity is high) and this in turn will reduce the separation rate.

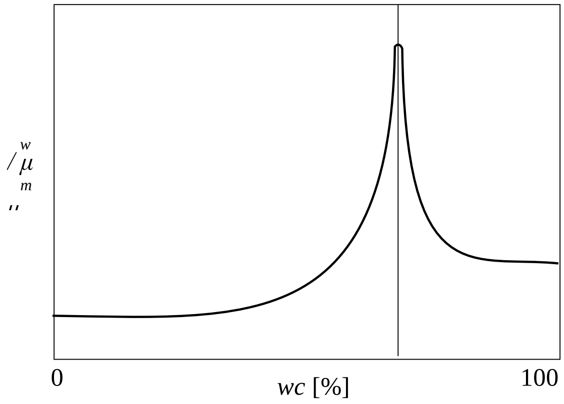


Figure 2.1: Qualitative illustration of the relative viscosity of an oil-water emulsion as a function of the water cut, *wc*. The relative viscosity is given by the ratio between the mixture viscosity, μ_m, and the viscosity of pure water, μ_w. The vertical-dashed-line is the phase inversion point. For a detailed and explicit illustration see Arirachakaran et al. [3].

The viscosity of mixture is dependent on the tightness of the emulsion. The tightness of an emulsion describes qualitative the droplet sizes, with a tighter emulsion having smaller droplets than a loose one. The viscosity increases with the tightness of the emulsion and this in turn increases as the oil-water draws near the point of phase inversion [33]. This effect is described qualitatively for a water-in-oil emulsion in Figure 2.2. The tightness (droplet sizes) of the emulsion entering a separator is, on the other hand, dependent on crude oil characteristics and the degree of turbulence it experienced upstream of the separator. The turbulence effect impact the tightness, and thus the viscosity, which may trigger change in the emulsion as a function of the process variables (flow rates) in the separation system. This results in complications in predicting the separation rate.

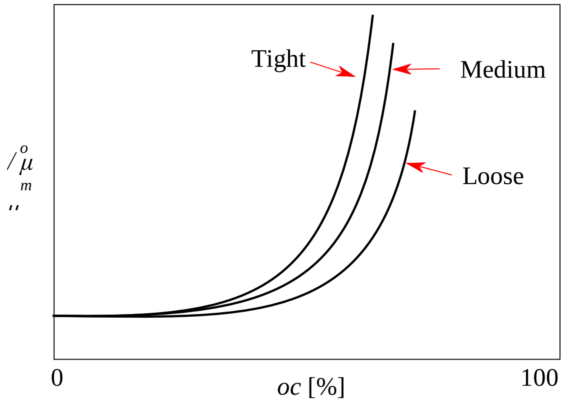


Figure 2.2: Qualitative illustration of the relative viscosity in a water-in-oil emulsion as a function of the oil cut, *oc*, for three emulsions with different tightness. See Woelflin [33], for detailed illustration.

Woelflin [33], concludes that the effect of the oil-water ratio on the mixture viscosity is large relative to the effect of the tightness. He also claims that, even with the several formulas for predicting the viscosity of emulsions, none of these is applicable over the wide range of the conditions in oil fields. If the effect of the emulsion tightness is neglected, equation 2.7 [25] can be used to define the mixture viscosity, μ_m, by fitting the coefficients of *a*, *b* and *c* to known data for a specified emulsion.

$$\mu_m = \mu_c \; 1 + a\varphi + b\varphi^2 + c\varphi^3) \qquad (2.7)$$

Where ϕ is the dispersed phase volume fraction and μ_c is the viscosity of the continuous phase.

2.7 Diffusion

The gravitational sedimentation forces trigger the separation process in the separator, and as a result there is concentration gradients in the direction of separation. This also will lead to diffusion by Brownian motions, with an opposing effect on the separation. The diffusion in an emulsion having a concentration gradient in the x-direction is defined by Fick's 2. law [20];

$$\frac{dC(t,x)}{dt} = D\frac{\partial^2 C(t,x)}{\partial x^2} \qquad (2.8)$$

Where $C(t,x)$ is the concentration of the dispersed phase and D is the diffusion constant for the given system

2.8 Coalescence

Coalescence occurs when two droplets fused together into one in a separator as seen inFigure 2.3a, and also when droplets fuse with the continuous phase via the bulk interface, see Figure 2.3b. The first phenomenon results from the different velocities of the droplets caused by their velocities of sedimentation, turbulence, diffusion and the rest. This intensify collisions thereby causing the droplets to coalesce as a function of the attractive and repulsive forces between the droplet as well as their kinetic energies. Coalescence speeds up separation following from the growth of the droplets engendered by sedimentation.Droplets coalescence through bulk interface is essential in separation theory for separation of droplets from the surrounding phase. In instances of high interfacial tension, this process becoms rate determining while the droplets accumulate closely to the bulk interface.

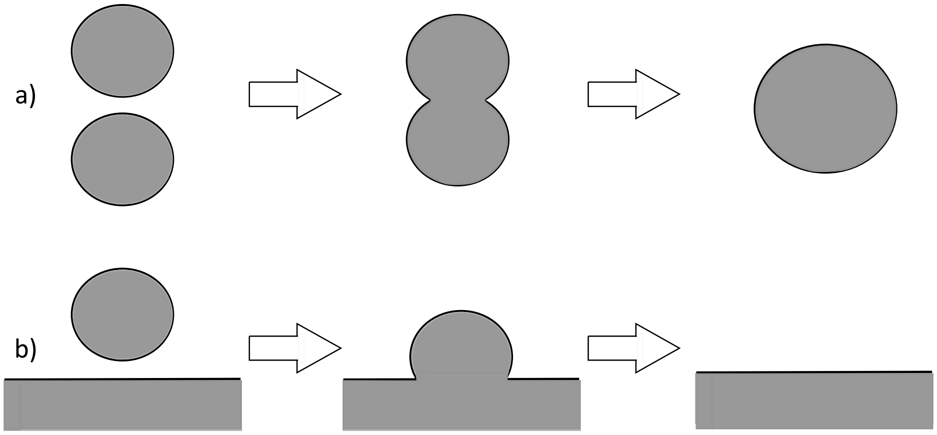


Figure 2.3: a) Two droplets coalesce to form one bigger droplet.

b) A droplet coalesce with the bulk phase.

2.9 Separation Efficiency

In order to appraise the performance of the separator, there is great need to define the measures of the separation efficiency. The dilute and dispersed efficiencies were employed in this project. For a separator having an inlet (feed) stream, a light phase outlet (LPO) and a heavy phase outlet (HPO). The dilute efficiency, η_{dil}, is defined as the fraction of oil that is in the LPO, (eq. 2.10) and this is also termed as the recovery of oil. The dilute efficiency is one if there is no oil in the HPO. It is zero if there is no oil in the LPO, which signifies that all the product would have been separated out from the HPO. It is also important to consider the dilute efficiency if the goal is to minimize the oil loss.

$$\eta_{dil} = \frac{\alpha_{LPO}\ q_{LPO}}{\alpha_{in}\ q_{in}} \qquad (2.10)$$

Where q_i and α_i are the volumetric flow rate and oil volume fraction in stream *i*, respectively.

The dispersed efficiency, η_{dis}, measures the amount of the liquid that exits through the desired outlet, eq. 2.11. The dispersed efficiency is *one* for a HPO stream that is pure water and the LPO stream is pure oil, which of course is the primary objective of the design of any separator.

$$\eta_{dis} = 1 - \frac{(1-\alpha_{LPO})\ q_{LPO} + \alpha_{HPO}\ q_{HPO}}{q_{in}} \qquad (2.11)$$

3.0 Model Description

The model consists of two streams of oil and water. The composition of the emulsion stream in Table 3.4 was adopted closely from Gjengedal Project which was sourced from the industry. The project also serves as a guide in the operational input parameters in Tables 3.1 to 3,4. The model in Figure 3.1 was then investigated. The model in Figure 3.1 was at the input parameter in Table. The fluid package for the model is Kabadi Danner, which is recommended for hydrocarbons with water solubility. A re-entrainment unit was developed in the model to introduce fractions of the oil and water in the different streams conversely. The flash tank and compressor units are to flash the notable amount of gas in the water stream and compress the flashed gas respectively.

The gravity separator has been discussed in earlier chapters. The steady-state model developed is quit simple and is expected to generate rough estimates of the outlet streams composition when fed with set of inlet parameters. These parameters include the dimension of the separator in addition to the properties of the emulsion. The sets of the inputs are presented used to analyze the behavior of the model are presented Tables 3.1 to 3.4

Table 3.1: HYSYS Parameters for the Separator streams

Streams	Well Oil	Well water	Water	Oil	Gas
Temp. °C	60	60	57.17	57.17	57.1
Press. Bar	200	200	140	140	139.7
Molar Flow kgmole/h	275	138	137.8	139	136.4

Table 3.2: HYSYS parameters for the Separator streams

Stream/Unit	Vapor	Flashed water	Oil produced	Water produced	Gas out
Temp. °C	60.93	60.93	26.58	60.93	58.03
Press. Bar	2	2	2	2	139.7
Molar Flow kgmole/h	0.2841	137.5	139	137.5	136.7

Table 3.3: HYSYS parameters for the Separator Units

Streams/Unit	Mixer-101	Subsea Separator	Flashed Tank	Mixer-100	Mixer-102	Mixer-103
Temp. °C	59.44	57.17	60.93	26.58	60.93	58.03
Press. Bar	200	140	200	2	2	139.7
Molar Flow kgmole/h	413.2			139	137	136.7

Table 3.4: Reservoir composition of oil and water

Component	Oil Composition [Mol]	Water Composition [Mol %]
H20	0.004	0.999
N2	0.016	0.000
CO2	0.022	0.001
C1	0.604	0.000
C2	0.076	0.000
C3	0.048	0.000
i-C4	0.021	0.000
n-C4	0.021	0.000
i-C5	0.015	0.000
n-C5	0.015	0.000
C6	0.020	0.000
C7	0.024	0.000
C8	0.023	0.000
C9	0.016	0.000
C10	0.014	0.000
C11	0.010	0.000
C12+	0.051	0.000

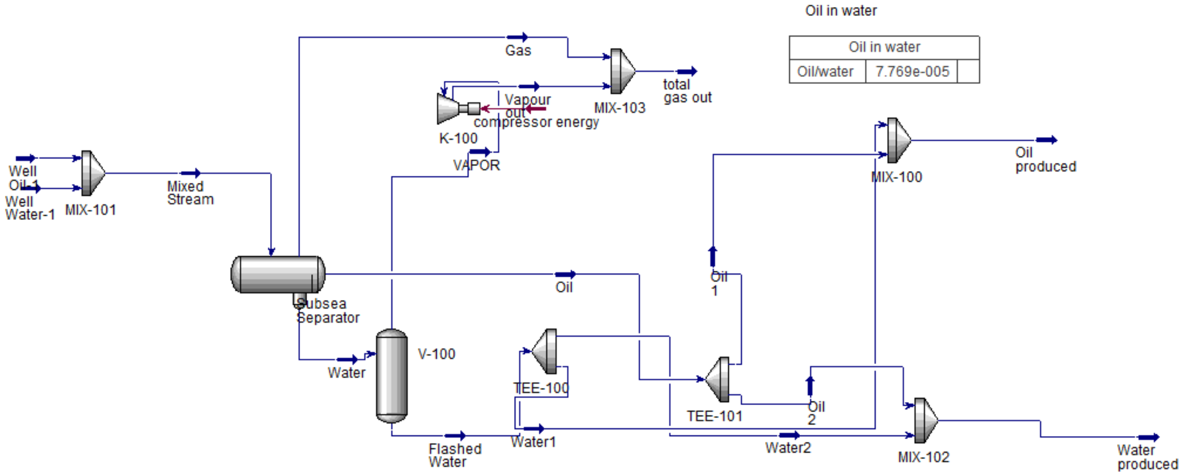


Figure 3.1: HYSYS model of the compact separator module

3.3 Horizontal Gravity Separator

The horizontal gravity separator was developed as a steady-state model in HYSYS with the re-re-entrainment of oil and water in the product streams of water and oil respectively. The gravity separator can take the form of a horizontal or cylindrical tank with two outlets as in Figure 3.8. The feed enters the separator as an emulsion of oil-in-water and the gravitational buoyancy forces push the dispersed oil droplets upward and the continuous water phase downward. This result in the continuous oil phase being formed at the top of the separator and a pure water phase settles at the bottom.A vertical weir at the end of the separator separates the flow into two streams of top (q_t) and bottom (q_b) products. The top product, q_t is collected behind the weir while the bottom product, q_b exits below the weir. The top location of the separator behind the weir, allows for an additional gas outlet from the tank. But, the focus of this project is on oil-water separator so a gas phase was included accordingly.

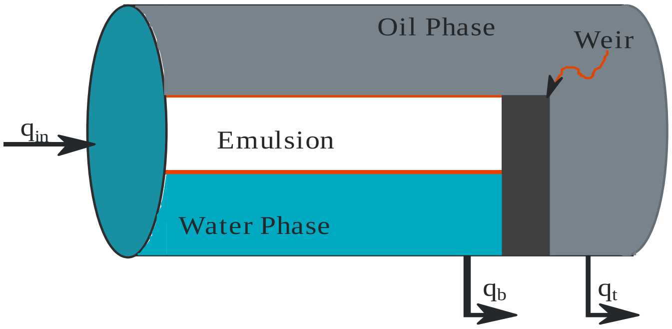
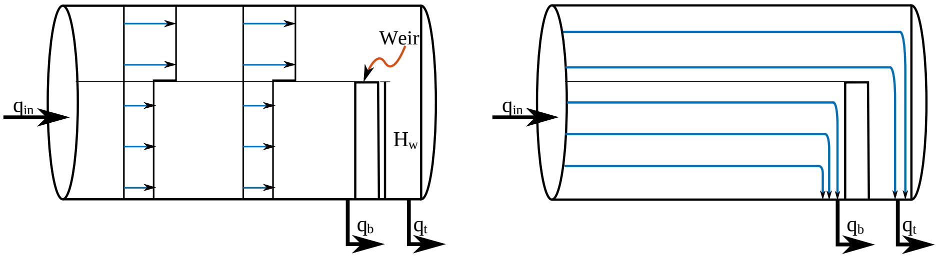


Figure 3.8: Horizontal gravity separator. The liquid is fed into the separator as an oil-in-water emulsion. As the gravitational buoyancy forces push the oil droplets upward, a continuous oil phase is formed in the top of the separator and a pure water phase settles at the bottom.

The following sections describe the model for the horizontal gravity separator and the main assumptions made in this context. This includes the horizontal and vertical velocities, the droplet sizes and the viscosity in the separator. A summary of the model is presented in Chapter 3.3.6.

3.3.1 Horizontal Velocity

The flow through the separator is modeled as two separate plug flows separated by the height of the weir (H_w), see Figure 3.9. It is assumed that there is no net mass transfer between the plug flows, but oil droplets will rise from the bottom part to the upper part with equal volumes of water moving in the opposite direction. The liquid hitting the weir at the end of the separator is supposed to exit through the bottom outlet, while the liquid above H_w is assumed to flow over the weir and exit through the top outlet.



(a) Horizontal velocity profile. (b) Stream lines.

Figure 3.9: The horizontal flow model in the gravity separator is divided into two regions. The liquid under the weir is assumed to have a constant horizontal velocity until it hits the weir and exits through the bottom outlet (q_b). The liquid over the weir also has a constant velocity, flows over the weir and exits through the top outlet (q_t).

The valves on either of the outlet streams are used to manipulate the flow rates of the two plug flows, by adjusting the horizontal velocity, v_x, of the droplet moving through the separator under H_w . And it is assumed to be equal to that of the continuous phase which is given by;

$$v_x = \frac{q_b}{A_b} \tag{3.26}$$

where A_b is the cross section area of the circular segment limited by H_w (lower part of the separator) and q_b is the volumetric flow rate of the bottom outlet product. The cross section area is derived from simple trigonometry as;

$$A_b = \frac{R^2}{2}\left[2\cos^{-1}\left(\frac{R-H_w}{R}\right) - \sin\left(2\cos^{-1}\left(\frac{R-H_w}{R}\right)\right)\right] \tag{3.27}$$

where R is the radius of the separator.

3.3.2 Vertical Velocity

The vertical velocities of the droplets are triggered by the gravitational buoyancy forces and they are given byequation 2.6 with the assumptions discussed in Chapter 2.1. Equation 2.6 is restated below.

$$v_y = \frac{2r_d^2(\rho_d - \rho)g}{9\mu(\alpha)} \tag{3.28}$$

Where ρ and ρ_d are the densities of the continuous phase and droplet respectively, r_d is the droplet radius; and g is the acceleration due to gravity. The viscosity of the emulsion, μ (α), is a function of the oil cut, α

As mentioned inChapter 2.1, v_y is the droplet velocity relative to the continuous phase. However, if the vertical movement of the continuous phase is neglected, then it can be used as an approximation to the absolute velocity. This assumption also entails neglecting all turbulence in the vertical direction.

3.3.3 Droplet Size

The knowledge of the average droplet size is sufficient to evaluate the gravity separator performance. The average droplet size is assumed independent of the flow rate. This is based on the assumption that the droplet break-up effect is insignificant in the device because of the small velocities. Therefore, the assumption of a constant droplet size suffices. In addition, the droplets come under enormous stress during transport in pipes as well as valves upstream of the gravity separator, this in itself is capable of droplet break-up. Experiment is required to validate or improve on this.

3.3.4 Viscosity and Concentration

The gravity separator is divided into three different phases having uniform concentration profiles. The emulsion phase is supposed to have an oil volume fraction equivalent to that of the incoming fluid, $\alpha = \alpha_{in}$. The separation process cause a pure oil phase to be formed in the top and a pure water phase at the bottom of the tank. As the liquid moves downstream in the gravity separator, the emulsion phase decreases while the two pure phases grow. This assumption is shown in Figure 3.10.

The concentration profile of the model is based on the assumption that all the droplets are moving with the same vertical velocity. The accuracy of this assumption reduces with increasing standard deviation in the droplet size distribution, because the buoyancy force is proportional to the droplet volume. This signifies that there is no oil droplets accumulation underneath the oil-emulsion bulk interface. Meaning that the coalescence process is relatively faster than the sedimentation process for the oil droplets and the continuous oil phase (shown in Chapter 2.3). Note that this based on the assumption that the sedimentation rate is relatively low ($g \approx 9.8\,\mathrm{m\,s^{-2}} \ll a_c$), withthe droplets having to penetrate a relatively large bulk interface. The viscosity of the emulsion is considered to be dependent on the properties of the two liquids as well as the oil volume fraction.

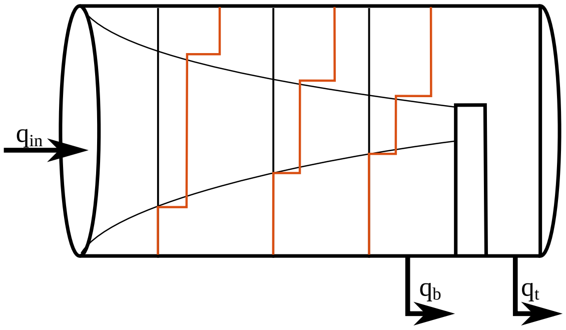


Figure 3.10: The concentration profile in the gravity separator model. The red line signifies the oil volume fraction, α. The liquid is divided into three phases of:

1. The oil phase at the top with $\alpha = 1$
2. The emulsion phase in the middle with $\alpha = \alpha_{in}$.
3. The water phase on the bottom with $\alpha = 0$.

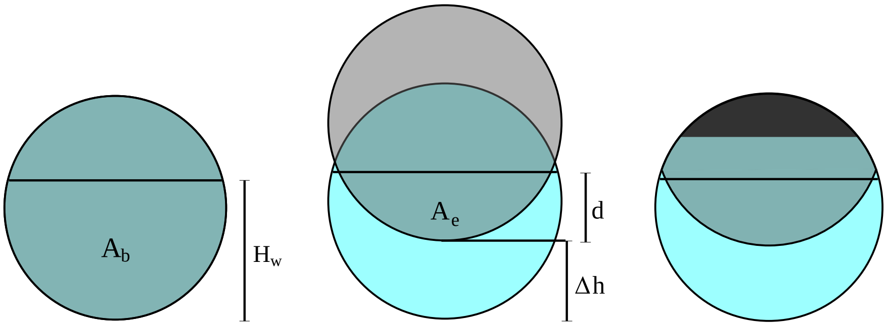
3.3.5 Oil Cut in the Product Streams

The estimation of the oil volume fractions of the product streams are done by finding the vertical distance, Δh, that a droplet inflowing the separator at the bottom travels during its residence time in the separator. A droplet at the lower part of the separator (below H_w) travels the vertical distance of;

$$\nabla h = \frac{v_x}{v_y} L \tag{3.29}$$

where v_x (eq. 3.28) and v_y (eq. 3.26) are the horizontal and vertical velocities of the droplet respectively, L is the horizontal distance between the inlet and the weir.

The situation shown in Figure 3.11 will arise if all the droplets travel with the same vertical velocity. Figure 3.11a illustrates the cross section of the separator at the inlet, where the whole liquid is assumed as an oil-in-water emulsion. In Figure 3.11b, typifies the end of the separator for all droplets moving with the same vertical distance, Δh. In practice, the droplets colliding with the ceiling accumulate and form a continuous stream of oil phase at the top as in Figure 3.11c. It is important to note that the liquid above H_w might have a different horizontal velocity from the liquid below H_w, since the illustration is not an exact representation.The droplets crossing the horizontal plane at the height H_w have different residence times and consequently transit different vertical distances.Nevertheless, the relevant information required to estimate the outlet composition is the aggregate of oil droplets that cross the horizontal plane.



(a) At beginning of separator. (b) At the end separator (c) At the end of separator.

Hypothetical case. ”Actual case”.

Figure 3.11: Cross section of the gravity separator at the beginning and end of the vessel. The emulsion (grey) travels vertically at a distance Δh during its residence time in the device. The pure oil phase (black) forms at the top while the pure water phase (light blue) forms at the bottom of the vessel.

The volume of the of oil residue remaining at the bottom-end of the separator is defined by the limited circular segment of $d = H_w - \Delta h$, see Figure 3.11b. The area of the circular segment is given as:

$$A_e = \frac{R^2}{2}\left[2\cos^{-1}\left(\frac{R-d}{R}\right) - \sin\left(2\cos^{-1}\left(\frac{R-d}{R}\right)\right)\right] \qquad (3.30)$$

The oil volume fraction for the bottom outlet, α_b, is therefore given as;

$$\alpha_b = \alpha_{in}\frac{A_e}{A_b} \qquad (3.31)$$

where α_{in} is the oil volume fraction of the stream at the inlet and A_b is the cross section area of the lower part of the gravity separator given byeqn 3.27. The oil volume fraction of the top outlet is gotten from component-mass balance as:

$$\alpha_t = \frac{1}{q_t}\left[\alpha_{in}\ q_{in} - \alpha_b\ q_b\right] \qquad (3.32)$$

Where q_{in},q_b andq_t are the volumetric flow rates of the inlet, bottom and top outlets respectively.

3.3.6 Summary of Gravity Separator Model

Given the flow rate, the inlet composition and the flow split of the gravity separator model, the oil volume fractions of the outlet can be estimated using the equations 3.31 and 3.32. A prerequisite is that the physical dimensions of the separator and the properties of the emulsion are known. The latter includes the densities of the pure phases, the average droplet size and a correlation between the viscosity and oil content of the emulsion.

The separator is modeled as a two independent plug flows flowing through the vessel and exiting through the two respective outlets. The gravitational buoyancy forces push the oil droplets upwards and transit from the lower plug flow to the upper plug flow with equal volume of water moving in the opposite direction. The droplets are assumed to travel with uniform droplet size distribution (vertical velocity) and as such, the vertical movement of the droplets can be estimated accordingly.

3.4 Model Input

For the successful simulation of the model for output or result, there is need to input parameters of the fluid properties, empirical variables, operational conditions and the physical dimensions for the model. There are no available experimental data for the horizontal gravity separator. Hence, the physical dimension were adopted from Preben Thesis [24]. and the operational variables from source. Then, the behavior of the hypothetical separator was investigated.Theflow rate, oil volume fraction of the feed emulsion as well as the seperator flow split were taken as inputs to the model. The model was simulated for several ranges of these values.

3.4.1 Fluid Properties

The input parameters of the fluid properties as well as its composition are hypothetical and chosen as a close approximate to the Thesis of Gjengedal C[11,.

3.4.4 Horizontal Gravity Separator

The inputs to the horizontal gravity separator model entail the physical dimensions of the device. The inputs, which are hypothetical, were adopted from Preben Thesis. The horizontal gravity separator model is developed for oil-in-water emulsions. It is important to note that the emulsion in this project same adopted by Preben thesis with a phase inversion point at $\alpha = 0.66$, It is therefore expected that the separation unit will perform less optimally for feed oil cut lower than 0.66.

Table 3.6: Physical dmensions of the horizontal gravity separator.

Length L [m]	Outer pipe R [m]	Weir height H_w[m]
7	1.7	2.55

3.5 HYSYS DESCRIPTION

The essence of utilizing HYSYS simulation is to get a broad understanding of the process. In addition to enabling one know how changes influences the process variables like product composition, temperatures and pressures [13]. The steady state as well as the dynamic modeling tools are important in the design and optimization of a chemical process. Steady state model is employed when we intend to maintain the material and energy balances while evaluating varying plant scenarios.It is often used in optimizing the process through cost reduction and maximizing production. The dynamic model is used to confirm if the desired results are being produced as well as the safety and ease of operation of the production. This is usually used in the optimization of controller design and get information regarding the conditions of startup and shutdown. Balances derived from the dynamic model are similar to that of steady state, save for the inclusion accumulation term. The accumulation term specifies the changes in the output variables with time [2].. Typical devices used in the industry have material inventory (holdup). In such instances, the dynamic modeling tool is helpful.

HYSYS is used, as a learning and an engineering simulation tool in institutions, universities, and particularly in chemical engineering. The software is also widely employed in the industry, researches, modeling, development, and design [12]. HYSYS provides the platform for the creation of both steady state and dynamic simulations, and evaluate the model from either of the two perspectives. The modeling tool is furnished with various operations plus designs that enables simulations of different processes. HYSYS can also model upstream, gas processing, chemical and refining processes from the [13]. During model development in HYSYS, it is essential to use the appropriate fluid package and specific components. The Simulation Basis Manager (SBM) allows for the selection, addition and modifications of fluid packages, reactions and components. The fluid package can be chosen from the Fluid Pkgs drop down among several packages. If one is uncertain regarding the choice of fluid package, useful recommendations can be obtain from the Property Wizard. It is only important to specify two of the parameters of pressure, temperature and and vapor fraction, plus the mass/molar flow rate as well as the composition. HYSYS will automatically generate the remaining parameters for both downstream and upstream.

4.0 RESULTS AND DISCUSSION OF RESULTS

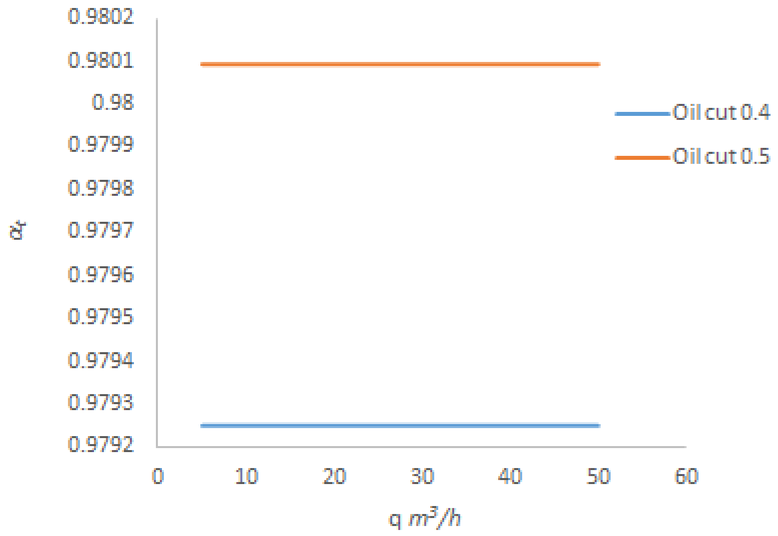


Figure 4.1: Purity of LPO(Oil) versus the flow rates. The oil cut is at 0.4 and 0.5.

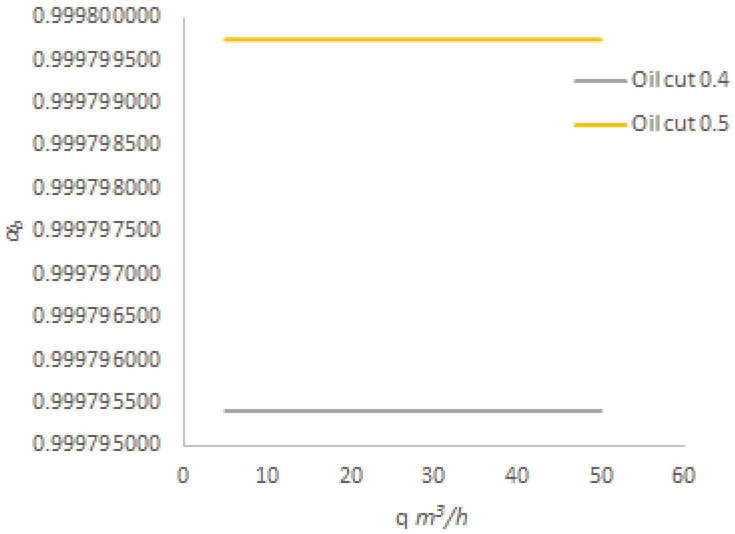


Figure 4.2: Puritty of HPO(water) versus the flow rates. The oil cut is at 0.4 and 0.5.

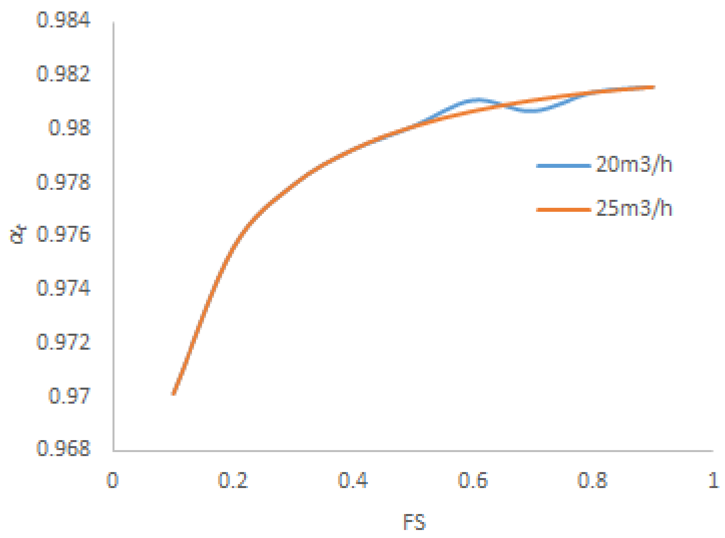


Figure 4.3: Purity of LPO(Oilr) versus the flow splits. The inlet streams are at 20m^3/h and 25m^3/h.. Oil cut in top stream.

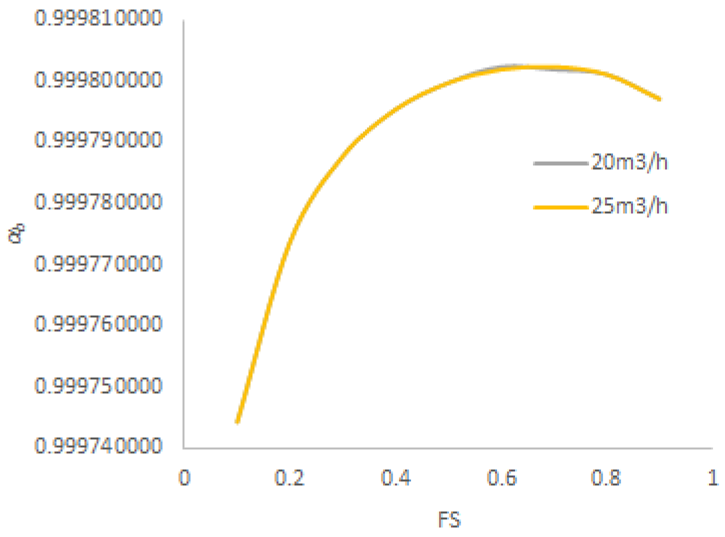


Figure 4.4: Purity of HPO(water) versus the flow splits. The inlet streams are at 20m^3/h and 25m^3/h.. Water cut in bottom stream.

4.1 Gravity Separator

The horizontal gravity separator model was developed and investigated. The separate streams of the oil and water into the mixer in Figure 3.1 is used to manipulate the flow rates, flow splits and oil cuts of the combined emulsion stream. The model is expected to give a close response to a typical industrial subsea separator but some inaccuracies are also expected. This is because the dynamics of an industry subsea separator module is not accurately captured by the HYSYS model. But it is expected that the results should not be too different apart. Experimental data is needed in order to have a valid basis for comparism, fitting the parameters as well as validating the model. A much more complex model might typify the process and dynamics.

4.1.1 Effect of Flow Rates on Purity

The purity of the LPO and the HPO at the oil cut of 0.4 and 0.5 did not show any sign of improvement on the separation efficiency. This might not be unconnected with the VLE equlibrium dynamism of the model and probably on the oversimplification of the model. The higher purity for the product streams is at the higher cut of 0.5. This agrees with the theory that a better performance is attainable for oil between 0.4 to any value below 0.66 which is the point of phase inversion for the oil in water emulsion.

4.1.2 Effect of Flow Splits

The purity and the separation efficiency improves increasingly for an increasing oil cut up until it reaches the oil cut of 0.6 which is the point of optimum separation/purity of the product streams. Values above this result in declining separation effeciecies which is as a result of phase inversion which is at 0.66 for this emulsion type. The better output is for the inlet at 25m3/h. Ultimately, the performance of the separator is acceptable since the impurities did not exceed the regulatory requirement of 30ppm [23]. The results of the purity of the product streams versus the flow rates is at variance with that obtain in Preben Thesis. But that of the purity of the streams against the oilcut is similar to the result of Preben`s work[24].

5.0 Conclusion

The model generally showed an acceptable response to the input parameters. An experimental data would have be important in comparing and validating the results. A much more complex model might help to capture more accurately the dynamics of a subsea separator.

5.1 Further Work

There is the need to build a more complex model that will capture very accurately the dynamics of the separator module. Writing a Subroutine in HYSYS as well as modeling of droplets in the gravity separator will help to improve on the model. It is also important to get experimental data in order to fit the input parameters accordingly as well as validate the accuratecy of the model.

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A. Appendix

A.1: HYSYS simulation results of the purity of oil and water versus oil cut

SN	Oil cut	αt@20m3/h	αt@25m3/h	αb@20m3/h	αb@25m3/h
1	0.1	0.970119316	0.970119316	0.999744315	0.999744315
2	0.2	0.975560229	0.975560229	0.999773681	0.999773681
3	0.3	0.977922294	0.977922294	0.999787704	0.999787704
4	0.4	0.979249267	0.979249267	0.999795406	0.999795406
5	0.5	0.980093095	0.980093095	0.999799741	0.999799741
6	0.6	0.981076944	0.980668778	0.999802362	0.999801903
7	0.7	0.980668778	0.981076944	0.999801903	0.999802362
8	0.8	0.981369599	0.981369599	0.999801110	0.99980111
9	0.9	0.98157408	0.98157408	0.999797117	0.999797117

A.2: HYSYS simulation results of the oil cut versus flowrate

SN	Flowrate	Oil cut 0.4	Oil cut 0.5	Water cut 0.4	Water cut 0.5
1	5	0.979249267	0.980093095	0.999795406	0.999799741
2	10	0.979249267	0.980093095	0.999795406	0.999799741
3	15	0.979249267	0.980093095	0.999795406	0.999799741
4	20	0.979249267	0.980093095	0.999795406	0.999799741
5	25	0.979249267	0.980093095	0.999795406	0.999799741
6	30	0.979249267	0.980093095	0.999795406	0.999799741
7	35	0.979249267	0.980093095	0.999795406	0.999799741
8	40	0.979249267	0.980093095	0.999795406	0.999799741
9	45	0.979249267	0.980093095	0.999795406	0.999799741
10	50	0.979249267	0.980093095	0.999795406	0.999799741