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# Study of Design of a Cost Effective Three-Phase Horizontal Separator for Optimization of Crude Oil Separation

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## ABSTRACT

The design of a three-phase horizontal separator for the separation of crude oil mixed with water into oil, water and gas has been developed. Design is a novel method in engineering, especially in chemical engineering for the sizing of equipment and specification. Here, a cost-effective horizontal separator was designed with parameters, values were obtained from the Tunu flow station SPDC. Design models were developed from first principles using material and energy balance. Also, cost, and mechanical design models were developed. The models for the design were simulated with Micro Soft Excel spreadsheet and results generated. The results for the designed separator indicated that the standard sizes and specifications of the horizontal separator gave sizes of effective length of the liquid capacity, seam-to-seam lengths for the gas and liquid, and slenderness ratio for the half full size respectively 6.63m, 8.46m and 8.84m, and 4.8, compared to values obtained for the size of the separator other than half full which was much higher values for sizes more than 0.5. The design considered the size of 0.8 full separator with results given as 8.29m effective length of liquid capacity, 10.12m and 11.05m seam-to-seam lengths of the gas and liquid capacities and 6.04m slenderness ratio, all at best diameter of the separator of 1828.8mm and at liquid droplet size of 100μm, drag coefficient of 2.1m occurring at Reynolds number 49.71 and terminal velocity of 0.101m/s. The economic evaluation of the plant (separator equipment) gave cost of equipment $10,098; fixed capital cost $5,000- annual operating cost $52,500; total variable cost $21,110; and total fixed cost $15,000. The mechanical design of the horizontal separator gave thickness of cylindrical shell 8.86mm and ellipsoidal heads of 8.81mm. The design results are good, reliable and can be adopted for use as it agrees with the research aim and objectives.

**Key words:** Design, separator, crude oil, study, MATLAB, model

## 1. INTRODUCTION

Phase separation of gas, oil and water is usually performed or carried out in multiple stages of one to four, where pressure is gradually reduced to achieve better separation efficiency as well as the quality of oil [1-2]. The energy industry

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has always been in constant search of many ways to develop smaller and cost-effective production platforms [3]. The desire to achieve a smaller production platform,-which fit the purpose of a typical oil and gas production facilities, necessitates that vessel should be sized in terms of cost and efficiency [4].

The separation efficiency of the liquid-liquid separator is also a good threshold for the inner diameter. The diameter of the droplets was removed with 100% efficiency [5]. Due to the sensitivity of the droplet size to gravity deposition, an inner flask has been developed to ensure the agglomeration of the droplets and reduce entrainment of the liquid entering the separator [6-8].

The residence time required for resolution is also a better criterion for a good separation of the constituent phases [9]. Droplets in the form of mist or haze cannot be separated by gravity and so recombining devices are used to form larger droplets out of these medium and separated easily [10-11].

The field development plan aims to achieve optimal labour and maintenance costs, where the minimum life cycle labor costs are to grow the field economically and profitably [12]. Oil and gas companies have developed smaller production rigs to achieve their desired goals, and separators are the real piece of equipment in the production platform [13]. It is advisable to design the partitions with the appropriate size for the purpose of use. Separator designs are often bulky, cumbersome, and expensive to purchase [14-16]. These limitations will affect the limited space and device load on supported platforms. To optimize the cost and maximize the efficiency of the separator, better separator designs have been proposed. The research hence was suitable for the separation of the oil field products such as crude oil, water and gas using horizontal 3-phase separator [17-20].

The aim of the study is to design a cost effective three-phase horizontal separator for optimal separation performance. The basic steps in design of horizontal separator or sizing are considered the objectives of the research work. The objectives of the horizontal design are to: Develop the three-phase horizontal separator design models for half full and 0.8 full size on the parameters (drag coefficient, Reynolds number, terminal velocity, and effective length, tan-to-tan or (seam-to-seam) length of the separator, and slenderness ratio. Apply the basic steps for the design of horizontal separator for the separation of crude oil into liquid and gas, develop cost and mechanical models for the horizontal design process and simulate the design, cost, and mechanical models with known literature data from Company using MATLAB or micro soft excel spreadsheet.

The research was carried out to develop a three-phase separator design to fit the purpose of separation production of oil field, which separates the crude oil, gas, and water within a reasonable cost and efficiency variables [21-25]. The proposed design will be able to design a cost-effective separator that will reduce space and save cost for offshore/onshore platform. This can reduce overall field development costs and increase project profitability [26-28]. The development of the design models will be simulated for values for the design parameters of the three-phase separator. Design considerations will be used for mechanical design and design cost evaluations [29-31].

## 2. MATERIALS AND METHOD

### Materials

The materials considered for this research work are horizontal separator, crude oil mixed with water, thermodynamics data, material and energy balance, input data from Tunu flow station plant, SPDC and design models for three-phase horizontal separator.

### Method

Three-phase separator and free-water knockout Pressure vessels are designed to separate and remove free water from a mixture of crude oil and water. Flow normally enters these vessels either directly from the inlet manifold or production well or through another separator operating at a higher pressure, the vessel shall be designed to separate the escaping gas from the liquid as well, such as oil and water separation.

Three-phase separator such as horizontal will be used for the separation of crude oil mixed with water into three phases, gas, oil, and water. The basic design aspects of three-phase separation are identical to those discussed for two-phase separation.

### Design Selection and Consideration

Gravity separation is considered for the design of three-phase horizontal separation; the settling velocity and flow velocity are perpendicular. There are greater interface areas which enhance phase equilibrium. Horizontal separators are good for liquid-liquid phase and liquid-gas phase separations. Plane area with large capacity is required and substantial increase in volume is needed with larger diameter up to 1.8m is good Horizontal separators are the most economical for regular oil-$H_2O$ separations and can cause problems with emulsions, foams, or high gas-liquid ratios.

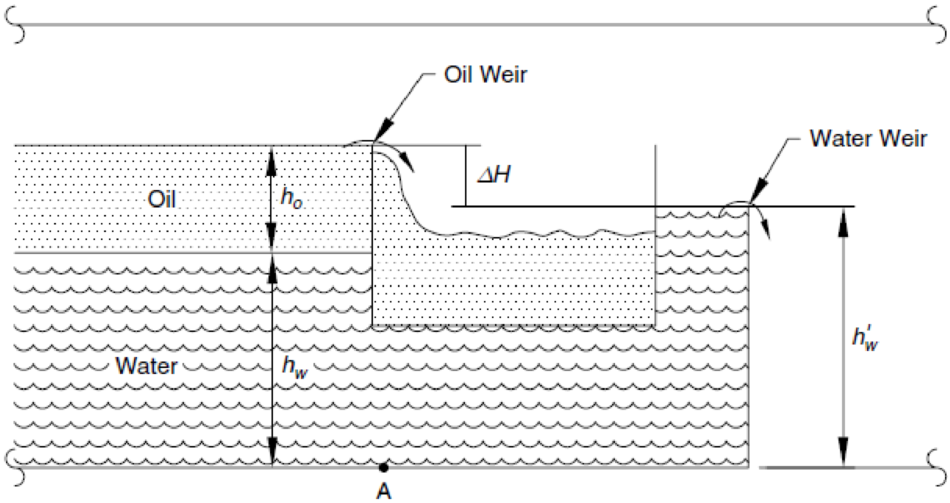


**Fig. 1:** Oil Pad Height Determination [8]

The desired oil pad height is designed in such a way as equating the static heads as shown in Figure 1 as well as the equation (1),

$$\Delta h = h_o[1 - {}^{\rho_o}/_{\rho_w}] \quad (1)$$

Where, $\Delta h$ = distance below the oil weir, mm, $h_o$ = desired oil pad height, mm, $\rho_o$ = oil density (kg/m$^3$), and $\rho_w$ = water density (kg/m$^3$)

From Figure (1) material balance at point A result to:

$$\rho_o h_o + \rho_w h_w = \rho_w h'_w$$

$$h_w = \frac{\rho_w h'_w - \rho_o h_o}{\rho_w} = h'_w - {}^{\rho_o}/_{\rho_w}\, h_o \quad (2)$$

$$\Delta h = h_o + h_w - h'_w$$

$$\Delta h = h_o - \frac{h_o \rho_o}{\rho_w} = h_o\left(1 - {}^{\rho_o}/_{\rho_w}\right) \quad (3)$$

Three-phase separators are useful for bucket and weir designs with high oil flow and / or small density differences.

**Oil-Water Settling Design**

Oil droplets in water or water droplets in oil are laminar flows, and Stokes' law governs this design model. The settling velocity according to Stokes' law is:

$$V_t = \frac{5.56\ x\ 10^{-7} d_m^2 (\Delta SG)}{\mu} \quad (4)$$

Where, $V_t$ = terminal settling velocity; (m/s), $\Delta SG$ = difference in specific gravity relative to water between oil and water phases, $d_m$ = Drop size, $\mu_m$ and $\mu$ = Viscosity of continuous phase, Cp

Because it is difficult to predict the size of the water droplets that must settle from the oil phase that matches the free oil. Values range up to 500 μm, and large settlements with 5% to less than 10% water are selected. Heavy oil system, 1000 μm water droplet size is used for the design of the three-phase horizontal separator, in which the emulsion contains 20%-30% water.



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**Oil Droplet Size in Water**

Oil droplet separation from water is easier than that of water droplets from oil due to variation of viscosity. The three-phase separator prepares the oil for further treating. The retention time for the oil depends on API gravity as shown in Table 1.

**Table 1: The retention time for the oil depending on API gravity [26]**

| S/N | API Gravity | Oil Retention Time (min) |
|---|---|---|
| 1 | Condensate | 2 – 5 |
| 2 | Light crude oil | 5-7.5 |
| 3 | Intermediate crude oil (20°-30°) | 7.5 – 10 |
| 4 | Heavy crude oil (< 20°) | 10⁺ |

With emulsion existing in the inlet stream, the retention time should be increased by a factor of 2 to 4.

**Separator Design for Horizontal Three-Phase**

Design of a three-phase horizontal separator for separating oil mixed with water to adjust vessel diameter, seam to seam vessel length etc. The gas capacity and residence time take into account the established acceptable combination of diameter and length and the need to deposit 500 μm and 200 μm water droplets from the oil. The vessel effective length gives a relationship as:

$$dL_{eff} = 34.5\left[\frac{T_2 Q_g}{P}\right]\left[\left(\frac{\rho_g}{\rho_L - \rho_g}\right) {}^{C_d}\!/_{d_m}\right]^{1/2} \quad (5)$$

Where, d =Vessel inside diameter, mm, $L_{eff}$ = Vessel effective length, m., T - Operating temperature (°K), Z = Gas compressibility, $Q_g$ = Gas flow rate, (SCM/m), P = Operating Pressure ($kP_a$), $\rho_g$ = Density of gas (kg/m³), $\rho_L$ = Density of liquid (kg/m³), $C_d$ = Drag coefficient and $d_m$ = Liquid drop to be separated, $\mu_m$

The liquid retention time limits can also be used to develop the following models:

$$d^2{}_{L_{eff}} = 4.2 \; x \; 10^4\{Q_w(t_r)_w + (Q_o)(t_r)_o\} \quad (6)$$

Where, $Q_w$ = Water flow rate m³/hr, $(t_r)_w$ = Water retention time, min, $Q_o$ = Oil flow rate, m³/hr and $(t_r)_o$ = Oil retention time, min

Equation (6) can be verified using first principle

Thus:

$$t = {}^{Vol}\!/_{Q} \quad (7)$$

$$Vol = \frac{1}{2}\left(\frac{\pi D^2 L_{eff}}{4}\right) = \frac{\pi D^2 L_{eff}}{8(1000^2)}$$

$$Vol = 3.927 \; x \; 10^{-7} d^2 L_{eff} \quad (8)$$

$$(Vol)_o = 3.927 \; x \; 10^{-7} d^2 L_{eff}\left({}^{A_o}\!/_{A_L}\right) \quad (9)$$

$$(Vol)_w = 3.927 \; x \; 10^{-7} d^2 L_{eff}\left(\frac{A_w}{A_L}\right) \quad (10)$$

$Q_o$ and $Q_w$ are in m³/hr

For oil:

$$Q = \frac{Q_o}{3600}$$

$$to = \frac{(Vol)_o}{Q_o} = 0.0014 \; \frac{d^2 L_{eff}}{Q_o}\left(\frac{A_w}{A_L}\right) \quad (11)$$

For water

$$Q = \frac{Q_o}{3600}$$

$$t_w = \frac{(Vol)_w}{Q_w} = 0.0014\frac{d^2L_{eff}}{Q_w}\left(\frac{A_w}{A_L}\right) \quad (12)$$

Where, $A_o$, $A_w$, and $A_l$ are the cross-sectional areas of oil, water, and liquid, respectively.

Re-arranging the equations for $t_o$ and $t_w$

$$0.0014\left(\frac{A_o}{A_l}\right) = \frac{t_oQ_o}{d^2Leff}, 0.0014\left(\frac{A_w}{A_l}\right) = \frac{t_wQ_w}{d^2Leff}$$

$(t_r)_o$ *and* $(t_r)_w$ are in minutes

$$2.356 \text{ x } 10^{-5}\left(\frac{A_o}{A_l}\right) = \frac{(t_r)_oQ_o}{d^2Leff}, 2.356 \; x \; 10^{-5}\left(\frac{A_w}{A_l}\right) = \frac{(t_r)_wQ_w}{d^2Leff}$$

$$2.356 \text{ x } 10^{-5}\left(\frac{A_o + A_w}{A_l}\right) = \frac{(t_r)_oQ_o + (t_r)_wQ_w}{d^2Leff},$$

Where, $A_o + A_w = A_l$

$d^2L_{eff} = 4.2 \; x \; 10^4[(t_r)_oQ_o + (t_r)_wQ_w]$ Seen in equation (6)

**Sedimentation of water droplets from the oil phase**

The rate at which water droplets settle on oil can be calculated using Stokes' law. This settling distance defines the maximum thickness of the oil cushion.

d_m = 500 μm, the maximum thickness of the oil cushion that allows water droplets to settle in time (t_r) o, then;

$$t_w = \frac{\frac{h_o}{1000}}{V_t}$$

But $V_t = \frac{5.556 \; x \; 10^{-7}(\Delta SG)d_m^2}{\mu}$

$$\therefore t_w = 1800\,\frac{\mu h_o}{(\Delta SG)d_m^2}, min \quad (13)$$

$$t_o = 60\;(t_r) \quad (14)$$

Since $t_w = t_o$ (15)

$$\therefore 60(t_r)_o = \frac{1800(\mu h_o)}{(\Delta SG)d_m^2}$$

$$\therefore h_o = \frac{0.033(t_r)_o(\Delta SG)d_m^2}{\mu} \quad (16)$$

$$(h_o)_{max} = \frac{8250(t_r)_o(\Delta SG)}{\mu} \quad (17)$$

Where $d_m = 500\mu m$

For a given settling time [(t_r) o] and a given $H_2O$ settling time (t_r) w, the oil pad maximum thickness limit defines the maximum diameter according to the method.

- Compute $(h_o)_{max}$, with $d_m = 500\;\mu m$
- Calculate the fraction of the vessel cross-sectional area occupied by $H_2O$ phase as:



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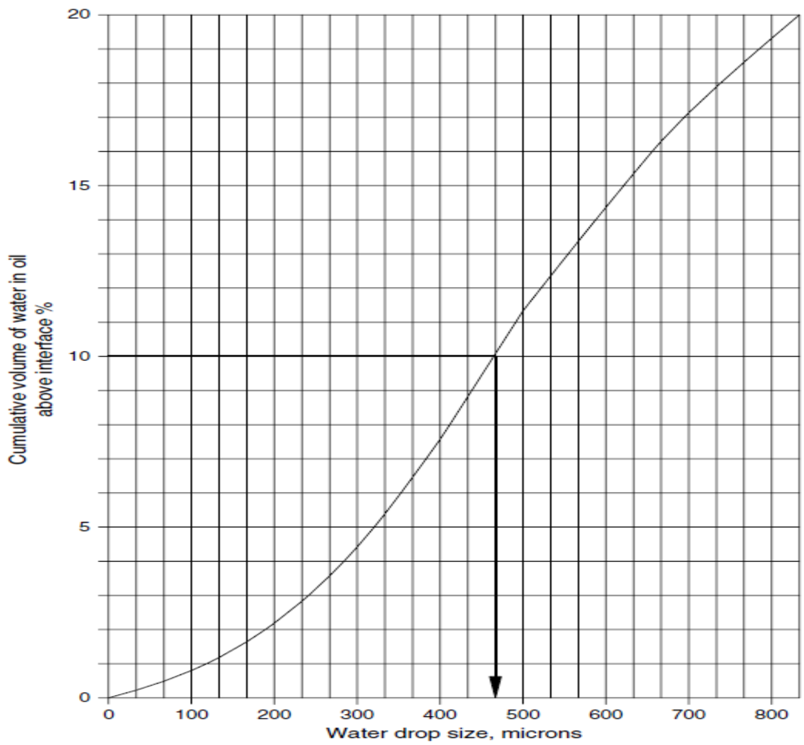


**Fig. 2: Water Droplet Size Distribution Varying for Size Distribution with different Process Conditions and Crude and Water Properties**

$$\frac{A_w}{A} = 0.5 = \frac{Q_w(t_r)_w}{(t_r)_o Q_o + (t_r)_w Q_w} \quad (18)$$

- From figure (3) determine β and hence calculate $d_{max}$ from

$$d_{max} = \frac{(h_o)_{max}}{\beta} \quad (19)$$

Where, $\beta = {}^{h_o}/_{d}$ and combination of d and $L_{eff}$ that satisfies all the models will meet the necessary criteria.

Equation (18) is explained and derived as thus:



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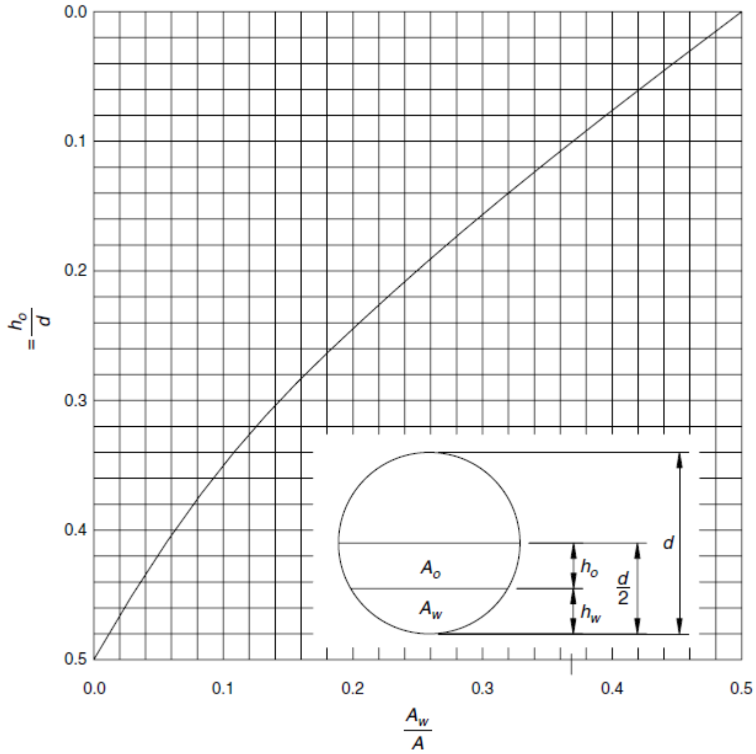


**Fig. 3: Variation of Fraction of Thickness with Fraction of Cross-Sectional Area**

$$A = \frac{Qt}{L_{eff}} \tag{20a}$$

$$Q = \frac{Q_o}{3600}, Q = \frac{Q_w}{3600}$$

$$t_o = 60\,(t_r)_o; t_w = 60(t_r)_w \tag{20b}$$

$$A_o = 0.0167\frac{Q_o(t_r)_o}{L_{eff}}, A_w = 0.0167\frac{Q_w(t_r)_w}{L_{eff}}$$

$$A = 2(A_o + A_w) \tag{20c}$$

$$\therefore \frac{A_w}{A} = 0.5\frac{Q_w(t_r)_w}{(t_r)_0 Q_o + (t_r)_w} \tag{20d}$$

Separation of oil droplets from $H_2O$-phase

**The governing models for this are stokes law and occurs when $d_m$ = 200**

$$(h_w)_{max} = \frac{1520(t_r)_w(\Delta SG)}{\mu_w} \tag{21}$$

$the\ maximum\ diamater\ is:$

$$d_{max} = \frac{(h_w)_{max}}{\beta} \tag{22}$$

$seam - to - seam\ length\ (Lss)$

$$L_{ss} = \frac{4}{3}L_{eff} \tag{23}$$

$$L_{ss_{(g)}} = L_{eff} + \frac{d}{1000} \tag{24}$$

$for\ a\ vessel\ sized\ on\ a\ liquid\ capacity\ basis, the$

$$L_{ss_{(L)}} = \frac{4}{3}L_{eff} \tag{25}$$

Slender ness ratio (SR)

$$S_R = \frac{L_{ss}}{d_o} = 3\ to\ 5$$



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**Sizing procedure for three-phase horizontal separator for half full**

Step 1: Establish the design basis

Step 2: Select a $(t_r)_o$ and $(t_r)_w$

Step 3: Calculate$(h_o)_{max}$, using $d_m = 500\ \mu_w$ see equation (17)

Step 4: Calculate $^{A_w}/_{A}$ see equation (18)

Step 5: Determine $\beta\ \left(^{h_o}/_{d}\right)$see equation (20)

Step 6: Calculate $d_{max}$: see equation (19)

$d_{max}$ depends on $Q_o$, $Q_w$, $(t_r)_o$, $(t_r)_w$

Step 7: Find a combination of d, dLss Leff, dmax that meets the gas capacity constraints. If no information is provided, use d = 100μ_w. See equation (5) for limits

Step 8: Calculate combinations of d, $L_{eff}$ for $dL_{ss}$ than $d_{max}$ that satisfy the oil and water retention time constraints, see equation (6).

Step 9: Estimate $L_{ss}$: see equations (24) and (25) for and liquid constraint, respectively.

Step 10: select a reasonable diameter and length slenderness ratios ($12L_{ss}d$) on the order of 3-5

Step 11: Making final decision, it is always economical to select a standard vessel API size for small separators can be searched.

**Sizing Horizontal Separators other than Half-Full**

For non-50% liquid three-phase separators, the equation can be derived in a comparable way using real oil and body of water.

**Gas capacity constraint**

$$dL_{eff} = 34.5\left(\frac{1-\beta}{1-\alpha}\right)\left[\frac{TzQ_g}{P}\right]\left[\left(\frac{\rho_g}{\rho_l-\rho_g}\right)\frac{C_d}{d_m}\right]^{1/2} \qquad (26)$$

Where: $\frac{1-\beta}{1-\alpha}$ = design constant, shown its variation with fractional liquid light in separation (see Figure 4)



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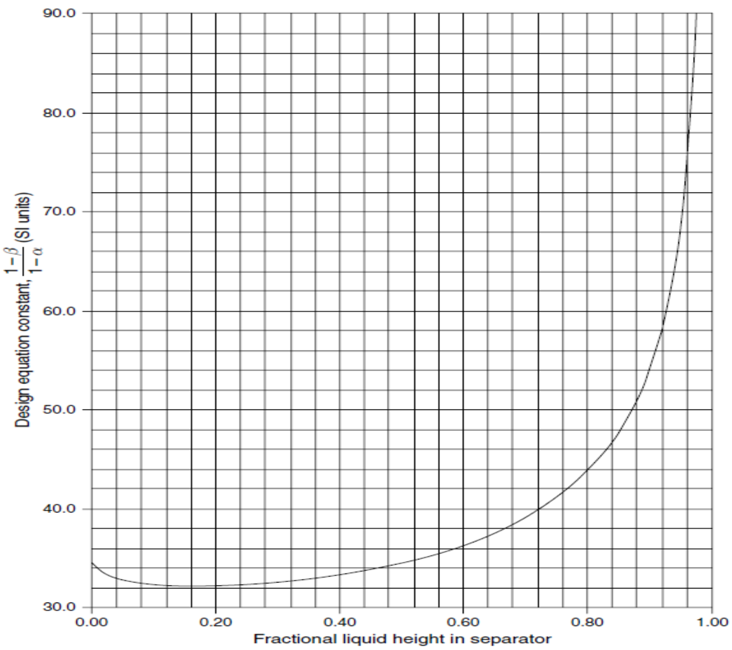


**Fig. 4: Gas Capacity Design Constant versus Liquid Height of a Cylinder for a Horizontal Separator other than 0.5 Full of Liquid in S.I. Unit**

**Retention Time Constraint**

$$d^2 L_{eff} = \frac{21000((t_r)_o Q_o + (t_r)_w Q_w)}{\propto} \quad (27)$$

Where, $\propto = design\ constant$ (See Figure 5)

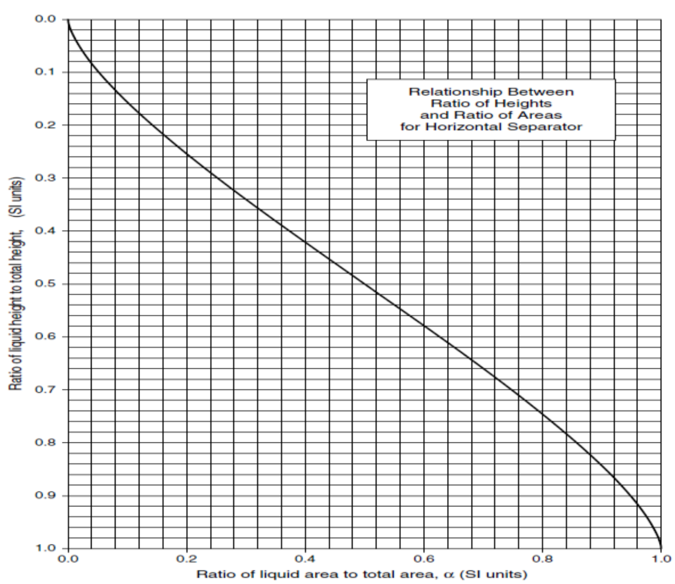


**Fig. 5: Retention Time Constraint Design Constant- Ratio of Areas versus Ratio of Heights for Horizontal Separator other than 0.5 Full of Liquid in S.I. Unit**



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**Settling Equation Constraint**

For the maximum oil pad thickness, liquid flow rate, and retention times, a maximum vessel diameter will be determined. The fractional cross-sectional areas of the vessel required for water retention may be determined as follows:

$$\propto_w = \frac{\propto_l Q_w (t_r)_w}{Q_o (t_r)_o + Q_w (t_r)_w} \quad (28)$$

Where, $\propto_l$ = Partial area of liquids, and $\propto_w$ = Partial area of water

The ratio of the height of the container required for water can be obtained by solving the following equation through trial and error.

$$\propto_w = \frac{1}{80} Cos^{-1}[1 - 2\beta_w] - \left(\frac{1}{\pi}\right)(1 - 2\beta_w) \quad (29)$$

Where, $\beta_w$ = The partial height of water

From the partial heights of all liquids and water, the maximum container diameter can be determined as follows:

$$d_{max} = \frac{(h_o)_{max}}{\beta_l - \beta_w} \quad (30)$$

Where, $d_{max}$ = The maximum vessel internal diameter, mm

Vessel diameter smaller than the maximum can be used to obtain the specified droplet size for a specified oil retention time.

The terminal velocity, Reynolds number and drag coefficient are related to as thus:

$$V_t = 0.0036 \left[\left(\frac{\rho_l - \rho_g}{\rho_g}\right) \frac{d_m}{C_D}\right]^{1/2} \quad (31)$$

$$Re = \frac{\rho_g d_m V_t}{\mu} \quad (32)$$

$$C_D = \frac{24}{Re} + \frac{3}{Re^{1/2}} + 0.34 \quad (33)$$

**Input Parameters**

**Table 2: Input Parameters for Simulation from Tunu flow station, SPDC**

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Oil volumetric flow rate | $Q_o$ | 33 | $m^3$/hr |
| Volumetric flow rate of water | $Q_w$ | 19.8 | $m^3$/hr |
| Gas volumetric flow rate | $Q_g$ | 5902 | $Sm^3$./hr |
| Design Pressure | P | 690 | kPa |
| Design Temperature | T | 32.20 | $^oC$ |
| API gravity | Oil | 30 | API |
| Specific gravity of Water | $(SG)_w$ | 1.07 | - |
| Specific gravity | SG | 0.6 | - |
| Retention time for oxygen | $(t_r)_o = (t_r)_w$ | 10 | Min |
| Viscosity of the oil | $\mu_o$ | 10 | Cp |
| Viscosity of the water | $\mu_w$ | 1 | Cp |
| Droplet removal | $(d)_l$ | 100 | $\mu m$ |
| Droplet size for water | $d_w$ | 500 | $\mu m$ |
| Droplet size for the Oil | $d_o$ | 200 | $\mu m$ |
| Gas density | $\rho_g$ | 49 | $kg/m^3$ |
| Liquid Density | $\rho_l$ | 866 | $kg/m^3$ |
| Drag coefficient | $C_D$ | 2.01 | - |



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## 3. RESULTS AND DISCUSSION

The result presented in Table 3 shows the results of two cases, half-filled and partially filled vessel. The applicable formulas were applied to both, and results were generated as shown below. The varying results will aid in determination of the cost, space, and capital expenditure of the vessel for separation of gas, oil, and water.

**Table 3: Design Result Summary for Three-Phase Horizontal Separator (See Appendix i)**

| Parameter | Half Full | 0.8 Full | Unit |
|---|---|---|---|
| $d^2L_{eff}$ | 22176000 | 27720000 | Mm |
| $L_{eff}$ | 6.63 | 8.288 | M |
| $L_{ss,g}$ | 8.46 | 10.12 | M |
| $L_{ss,l}$ | 8.44 | 11.05 | M |
| $S_R$ | 4.83 | 6.04 | - |
| $d_m$ | 1828.8 | 1828.8 | Mm |
| $C_D$ | 2.01 | 2.01 | - |
| $V_t$ | 0.1014 | 0.1014 | m/s |
| Re | 49.71 | 49.71 | - |

Table 3 indicates the results of the design of the three-phase horizontal separator for the separation of crude oil of API $30^0$mixed with water into oil, water, and gas. The input parameters were obtained from Tunu flow station, SPDC (see Table 2) and imputed to the models for simulation using MATLAB and M.S Excel spread sheet plots and generation of Tables and Figures. The generated result from the spreadsheet was chosen in the design result for the horizontal three-phase separator, obtained based on the standard design specifications of equipment. This thus displayed the actual design of the separator, shown in Table 3.

The effective length of the half full vessel is clearly less in length the partially filled vessel which signals excessive cost of material and more space requirement. The same can be applied to the seam-to-seam ratio or equally referred to as the Tan-Tan ratio which is simply the end-to-end part of the vessel excluding the dish ends.

The slenderness ratio of the partially filled vessel is higher than the standard reference of 3-5 signaling possible gas blowby or liquid carry over during operation of the vessel. This slenderness ratio is a major determining factor for selection of vessel for effective operation and the half-filled vessel met this criterion.

**Table 4: Cost Results obtained from Manual Calculation**

| Parameter | Value ($) | Value (#) at N381 per $ |
|---|---|---|
| Physical plant cost (PPC) | 34334.5 | 13.081 million |
| Cost of equipment (CE) | 10098.40 | 3.85 million |
| Fixed capital cost FCC | 49785 | 18.97 million |
| Total investment cost (TIC) | 52500 | 20 million |
| Total variable cost (TVC) | 21109.26 | 8.04 million |
| Total fixed cost (TFC) | 15000 | 5.72 million |
| Annual operating cost, (AOC) | 36,000 | 13.72 million |

Table 4 depicts the economic analysis of the three-phase horizontal separator for the separation of crude oil mixed with water to oil, water, and gas. These models were solved manually to obtain Table 4. The results indicate the feasibility of the building and functionality of the plant. Let us consider the revenue accruable from only oil which has the following additive value.

Oil Flowrate: 33m$^3$/hr. Converting to barrels per day 33m$^3$/hr = 207.564 barrels/hr. With respect to residence time in the vessel we may not achieve 24hrs in a day, for a more conservative approach 20 hrs. = 1day. Therefore, total residence time in a day amount to 4hrs. Oil flowrate in a day = 207.564 x 20 = 4151.28 barrels/day. In a year, the operational time, besides the maintenance and shut down period = 300days. Therefore; 4151.28barrels/day x 300 days = 1,245,384 barrels of oil per annum. A barrel of oil sells at $60 = 1,245,384 x $60 = $74,723,040



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The result shown proved that the plant is feasible and can be operated with high aim of maximizing profit.

**Table 5: Mechanical Design Result for the Determination of Thickness of the Designed Separator**

| Parameter | Value | Unit |
|---|---|---|
| Cylindrical shell | 8.86 | mm |
| Ellipsoidal ends | 8.81 | mm |

Table 5 depicts the design result for the mechanical design of the three-phase horizontal separation. The design is carefully chosen with the least thickness selected from the different shells and doomed heads. The economically preferred shell and doomed-type ends was cylindrical and ellipsoidal-ends. This is so because they gave smallest thickness and relatively same for the body of the separator and the ends of the separator.

This is economically profitable since the more the thickness, the more the cost of the separator and vice versa. It should be noted that the design models were adopted from volume 6, Chemical Engineering Design Textbook. The models were solved manually.

The design of the three-phase horizontal separator of crude oil mixed with water into liquid, water and gas was carried out with known data from the Tunu flow station plant, SPDC, MATLAB programming software was used for the simulations of the designed models. The results were exported to M.S Excel for evaluation and analysis in graphical as shown below:

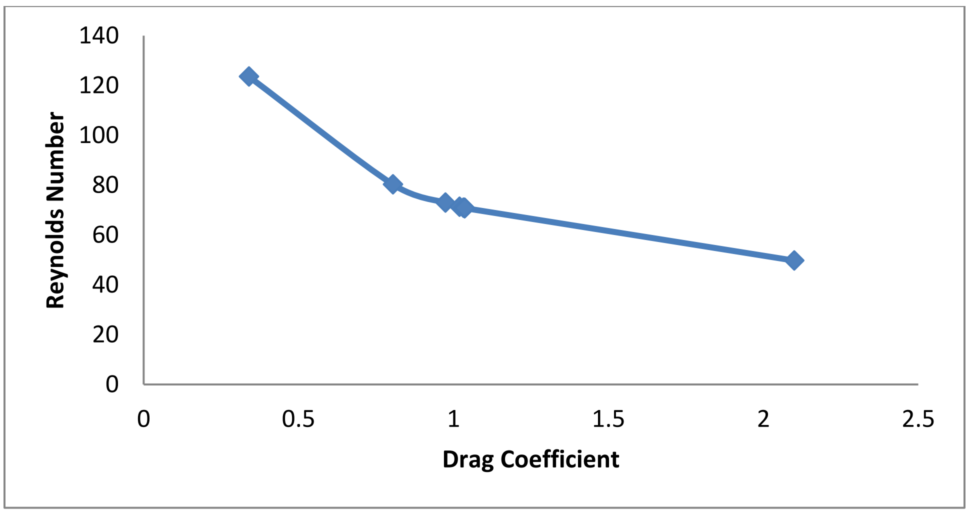


**Fig. 6: Plot of Reynolds Number varying with Drag Coefficient**

Figure 6 depicts the relationship of Reynolds number with drag coefficient. Drag coefficient ($C_D$) variation with Reynolds number is exponentially related. Higher Reynolds number leads to lower drag coefficient.

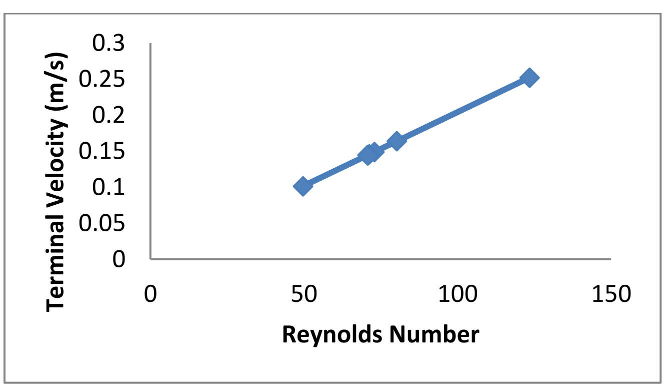


**Fig. 7: Graph of Terminal Velocity versus Reynolds Number**

The profile of Terminal velocity with Reynolds number is shown in Figure 7. This relationship is proportional. The proportionality is directly but studies shown that such variation is direct increase, that in higher values of terminal velocity leads to



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direct increase in Reynolds number. This may be like the present study because the relationship is directly (See Figure 7). This may be due to model error but however, the design models are good prediction of this relationship.

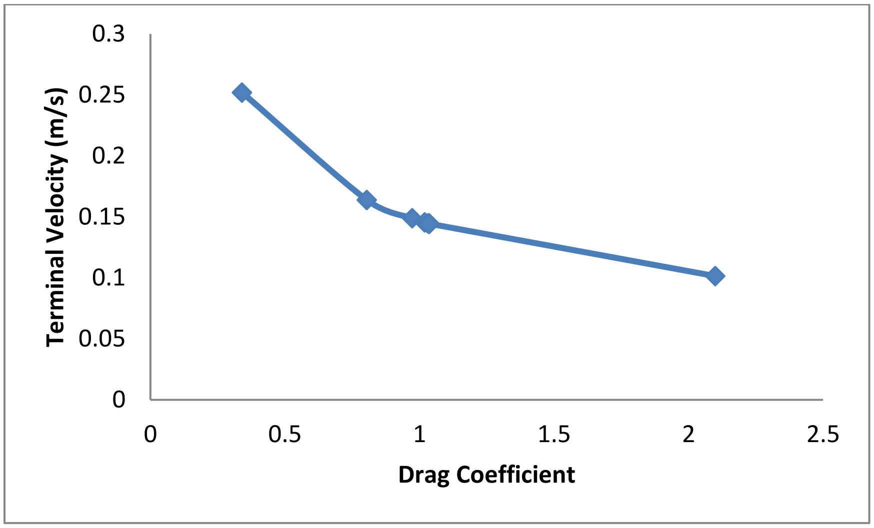


**Fig. 8: Profile of Terminal Velocity versus Drag Coefficient**

Variation of terminal velocity ($V_t$) and Drag coefficient is depicted in Figure 8 and this is exponentially related. The variation of $V_t$ decreases exponentially with $C_D$. The velocity of the fluid is related to the drag coefficient, in such that there is an inverse relation. The velocity of the fluid decreases exponentially as increase of drag coefficient. Higher values of $C_D$ lead to exponential decrease of velocity of the fluid. Studies have shown that there is an inverse exponential decrease of velocity of the fluid with high drag coefficient. Higher terminal velocities occur at lower drag coefficient and vice versa. From the Figure 4.3, as drag coefficient increases from 0.3- 2.1, terminal velocity decreases from 0.26m/s-0.12m/s and the decreases are exponentially.

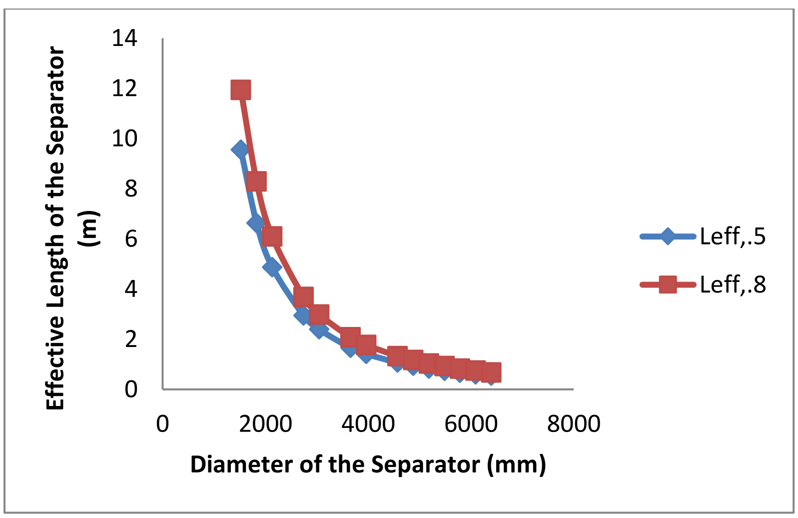


**Fig. 9: Profile of Effective Liquid versus Size of Liquid Droplet for Half Full and 0.8 Full**

Figure 9 demonstrates the relationship among the design parameter of effective length for the half full and other than half full size of horizontal three-phase separator with size of the liquid droplet. The design parameter such as effective length is a function of the size of liquid droplet. The effective length is exponentially related to the size of the liquid droplet as shown in Figure 9. The length is far exponentially decreases with increase in the size of liquid droplet. This relation proved true as provided in an exponential relationship of effective length with size of the liquid droplet in their studies comparable with the present study.

Similarly, the experimental work on the design of horizontal separator reveals that slenderness ratio, seam-to-seam length, and effective liquid droplet. The effective length for sizes other than half full say 0.8 as adopted in this research work is higher than that



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of half full design; this is shown in Figure 9. This is due to those higher sizes have bigger effective length of the separator so that it can accommodate for more of the materials into the separator.

This agrees with the current research work for the design of horizontal three- phase separator is exponentially related to the size of the liquid droplet to be separated. Higher sizes give lower values of these parameters and vice versa.

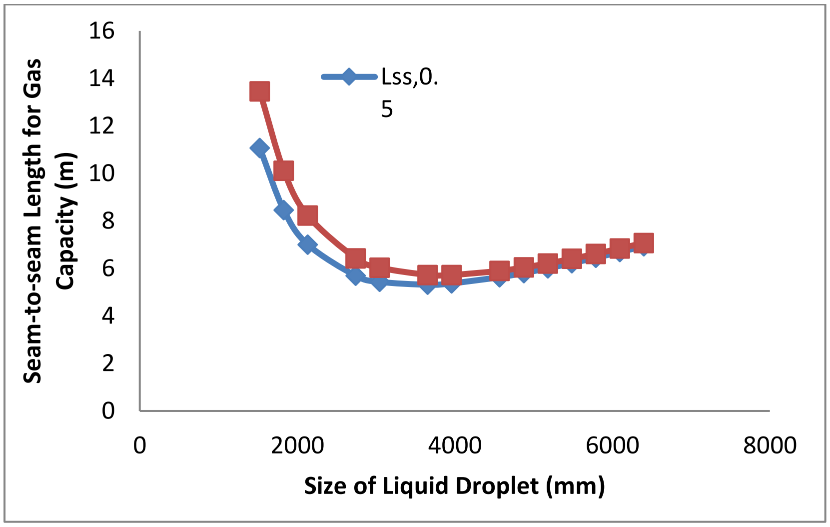


**Fig. 10: Profile of Seam-to-Seam Length versus Size of Liquid Droplet for Gas Capacity**

Figure 10 depicts the relationship between seam-to-seam lengths for the sizing of half full and other than half full of size of liquid droplet for the gas capacity. The relationship as shown is exponentially and decreases as the size of liquid droplet increases from 1524mm to 6400.8mm, the seam-to-seam length for half full drops more exponentially from 11.07m to 6.94m, than 0.8 full decreasing from 13.46m to 7.080m. The seam-to-seam length for the sizing of half full and other than half full of size of liquid droplet for the gas capacity length decreases as size of liquid droplet increases. This agrees with the present studies and indicates that the design is dependable and design models adopted are good with good validation.

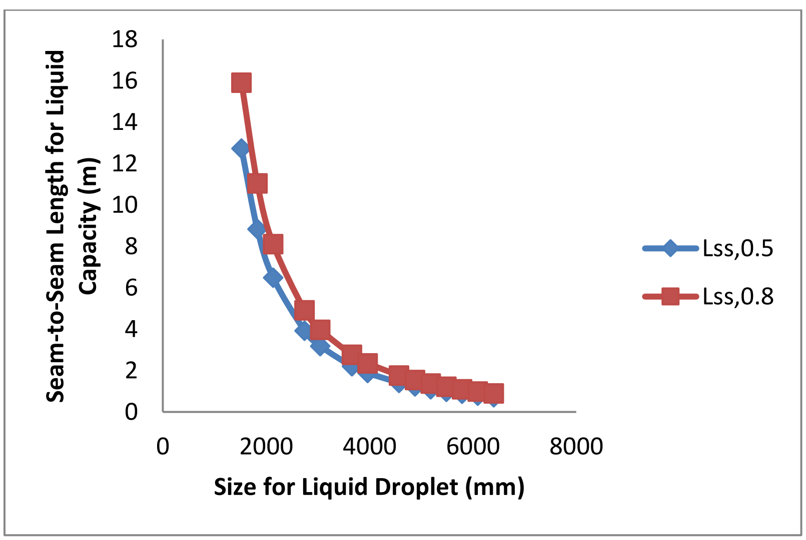


**Fig. 11: Profile of Seam-to-Seam Length versus Size of Liquid Droplet for Liquid Capacity**

Figure 11 depicts the relationship between seam-to-seam lengths for the sizing of half full and other than half full of size of liquid droplet for the liquid capacity length with size of liquid droplet. The relationship as shown is exponentially and decreases as the size of liquid droplet increases from 1524mm to 6400.8mm, the seam-to-seam length for half full drops more exponentially from 12.73m to 0.72m, than 0.8 full decreasing from 15.91m to 0.902m. The seam-to-seam length for half full and 0.8 full decreases as size of liquid droplet increases. This agrees with the present studies and indicates that the design is dependable and design models adopted are good with good validation. The three-phase horizontal separator sizing other than half full is higher in the seam-to-seam length than sizing for half full horizontal separator seam-to-seam length.

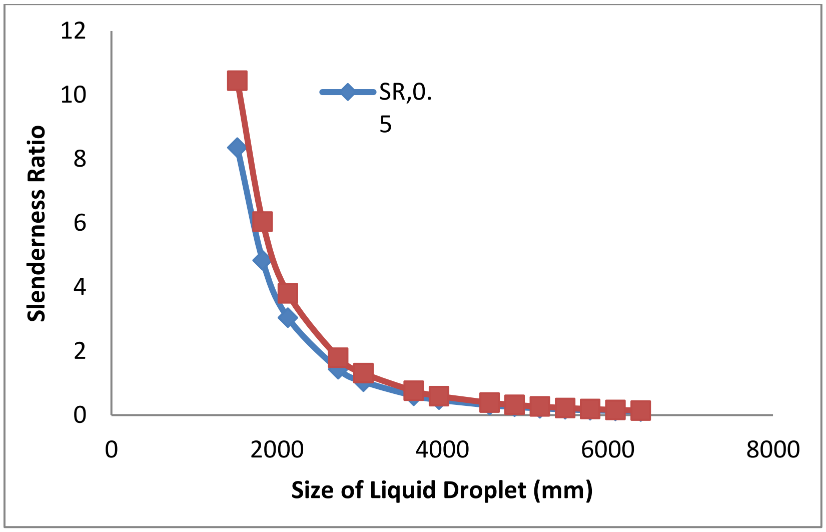


**Fig. 12: Profile of Slenderness Ratio versus Size of Liquid Droplet**

Figure 12 depicts the relationship between the slenderness ratios because of the seam-to-seam length for the liquid capacity with size of liquid droplet. The relationship as shown is exponentially and decreases as the size of liquid droplet increases from 1524mm to 6400.8mm, the slenderness ratios for the half full horizontal size drops more exponentially from 8.35 to 0.11 than 0.8 full size which decreases from 10.44 to 0.14. The slenderness ratio of the seam-to-seam length of the liquid decreases as the size of liquid droplet increases in their own work studied. This agrees with the present studies and indicates that the design is dependable and design models adopted are good with good validation.

## 4. CONCLUSION

The design of a three-phase horizontal separator for the separation of crude oil mixed with water into gas, oil and water has been carried out. The design considers the fundamentals of separation of oil and gas industry with greater emphasis on academics for better understanding of the basic design of equipment and specification of such equipment (separator). The academic theories of separation of liquid-liquid-gas into liquid and gas was studied and separator design models were all developed, paying attention to the three-phase horizontal separator design for sizes of half full and other than half full say 0.8. Field data from the Tunu flow station plant SPDC, was used for the simulation of the design models using MATLAB software.

Various plots of graphs were generated to study the relationship between the following variables and their interactions. Terminal velocity vs Drag coefficient, effective length of separator vs diameter of the separator, seam to seam length for gas capacity vs size of liquid droplet, seam to seam length for liquid capacity vs size of liquid droplet and slenderness ratio vs size of liquid droplet. With the above relationship, a better understanding of the variables' relationship and =d the effect on the horizontal vessel was well established.

Cost models developed from Chemical Engineering Design textbook and mechanical design of the separator was studied. Results were generated including the design parameters such as effective length of the gas and liquid after separation, seam-to-seam lengths for the gas and liquid, slenderness ratio, and others. The cost results and mechanical design results were all obtained and tabulated after manual computation was carried out. The design results follow literature trends and prove that the design models are dependable for used.

**Contribution to Knowledge**

The work contributed by giving a soft landing to complex models used in sizing/design of three phase separator by outlining the basic steps needed. Besides that, the model was developed from first principles and incorporated into a robust model. Additionally, the simplification of input into the design calculation were made possible by creating a system in MATLAB that only accepts input



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of variables and outputs the result for analysis, thereby solving the hassle of calculating from first principle which eliminates errors drastically.

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**Conflicts of interests**

The authors declare that there are no conflicts of interests.

**Data and materials availability**

All data associated with this study are present in the paper.

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