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Design of Three Phase Separator for 12.5bpd Crude Oil Atmospheric Distillation Unit

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ABSTRACT

Purification of substances by different separation processes is a common phenomenon in the process industry. In crude oil refining, the separation of different liquid fraction is the main activity achieved by distillation process based on boiling point differences of the components. Also, the separation of poorly miscible liquids like oil and water is frequently encountered, thus requiring secondary separation equipment generally referred to as separators. Effective sizing and design of these separators determine to a large extent the efficiency of the process and purity of products and also significantly affect other downstream operational processes. Thus, this research study determined basic design parameters of a three-phase separator such as determination of maximum allowable gas and liquid velocities of the fluids to be separated and three phase separator dimensions that include diameter, length, holdup or surge parameters, heavy and light liquid parameters for the separation of off – gas, naphtha and water from the crude oil distillation column of an atmospheric distillation unit. Computational results of the design analysis were compared with industrial three phase separator parameters with minimal percentage absolute error or deviation value, which fall within tolerable limits or range of the three phase separator design.

1. INTRODUCTION

Separation of mixtures is a fundamental and frequent unit operation in the process industry. It is even more frequently encountered in the chemical and petrochemical industrial subsector, given the very nature of their products, which are often accompanied by both desirable and undesirable by – products that require separation to purify (Wu *et al.*, 2022). In crude petroleum distillation, popularly called refining, separation of different hydrocarbon components by selective vaporization is the main activity, only accompanied in some cases by chemical conversion such as hydrogenation or dehydrogenation, and cracking reactions amongst others (Usman, 2016). The homogenous crude oil mixture results in less miscible products like gases,

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smaller hydrocarbons and water that need simpler separation processes after distillation. The equipment used in the separation of gases from hydrocarbon liquids and water are generally called separators. They are of different types, configurations and it has been established that some of the main factors affecting gas, oil, and water separation include droplet size, physical properties of the fluids and slenderness ratio. A well designed separator should separate the gas, oil, and water streams to ensure feeds to other downstream equipment are within design specifications (Arnold & Stewart, 2008, Ghaffarkhah, 2018, Ahmed *et al.*, 2020). Thus, only the horizontal three phase separator has been widely used in major oilfield situations due to its strong adaptability, and mature design theory and experience (Zhang *et al.*, 2022). Two major classifications of separators are; based on their orientation as *vertical* and *horizontal* separators, and on the number of fluids separated as *Two – phase* and *Three – phase* separators (Nigan, 2015). Different types of surface facilities are used for phase separation in the oil industry (Arnold& Stewart, 2008, Kharoua *et al.*, 2010). Gravity-based facilities include horizontal three-phase separators consisting of large cylindrical vessels designed to provide a sufficient res idence time for gravity -based separation of liquid droplets. The gravity settling approach requires very long cylinders which is not practical and inconsistent with the space restrictions in the oil fields especially offshore. Hence, three-phase separators are equipped with different types of internals to enhance droplet coalescence and optimize their length (Kharoua *et al.*, 2013).

The gravity settling theory of gas – liquid mixtures postulate that dispersed drops/bubbles settle out of the continuous phase when gravity force is greater than the drag force. This is at a velocity determined by equating these forces on the droplets/bubbles caused by its motion relative to the continuous phase (Wu *et al.*, 2022, Campbell, 2014). A typical gas – liquid separator is a hollow vessel, usually with an input device for injection of the fluid, and other internals that are determined by the separator type (see Figure 1). While the liquid settles out of the gas phase to bottom of the separator by gravity, the gas exits from top of the separator.

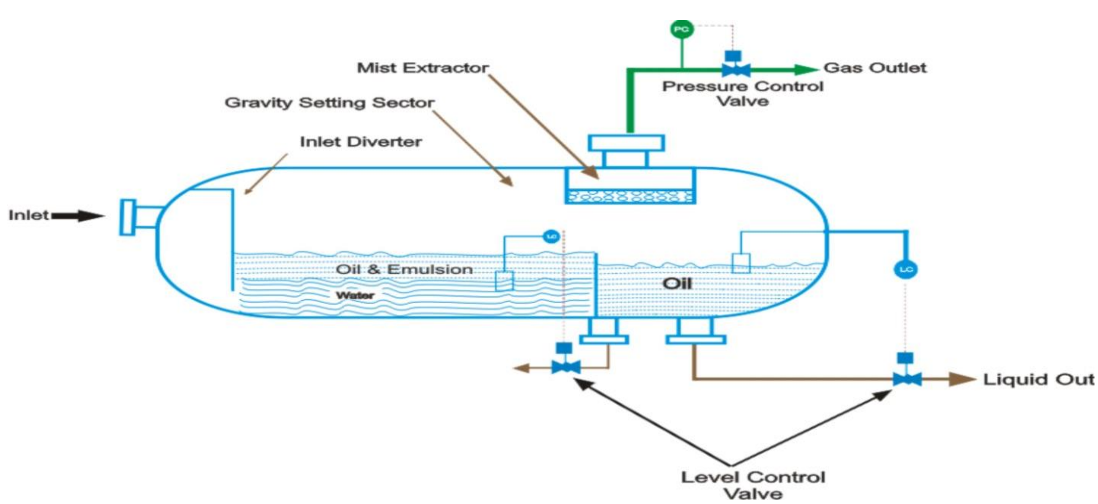

Figure 1: Three Phase Separator

The gravity separation section of a separator (not in all separators) helps to reduce entrained liquid load not removed by the inlet device and improves the gas velocity profile. Mist extractors are sometimes limited in the amount of entrained liquid droplets that can be efficiently removed from the gas upstream of the mist extractor, especially for conventional separators that handle higher liquid loads, whence the gravity separation section. For scrubber and related applications with low liquid loadings, the gravity settling section may not be necessary and K_s – values will be primarily dependent on the mist extractor type. Two methods of sizing gas-liquid separators are the Souders – Brown's Approach (SBA) and the Droplet Settling Theory (DST) method. Souders – Brown's equation which is the earlier of the two is easy to use and gives reasonable results. However, its limitation is in its dependence on the average droplet size (which cannot quantify the volume of liquid droplets exiting the gas) to enable determination of major design parameters like separator diameter and length. On the other hand, the droplet settling theory can more accurately quantify separator performance, but more complex to use (Bothanley, 2013).

Since the three-phase separator was put into use, the control methods have been fixed value controls based on experience, which has great limitations, which include poor self-adaptability when the production medium has physical and chemic al properties and recovery fluid changes causes the production process parameters to deviate from the optimal working conditions, preventing the control target from being automatically corrected, which may cause a certain technical index to fail to meet the standard (Qi, 2021, Bai & Zhang, 2020). The oil–water interface control effect is poor, and failures cannot be found in time, resulting in the subsequent equipment load increases, and low efficiency of the entire oilfield system (Guo *et al.*, 2016). Also, the top product of atmospheric distillation column is a mixture of effluent gases, naphtha and water. The water results from bottom steam used to heat the down coming liquid in the column. Therefore, the top crude distillation unit product requires a three – phase separator to purify before storage. This research study focused on the design of a three – phase separator for rectifying section purification of 12.5 barrel per day atmospheric crude oil distillation unit. Hence, this study applied Souders – Brown's equation constant, K_s (referred to as the sizing parameter) using simple correlations and standard empirical field data to establish elementary design parameters for the separator. The importance of sizing parameter on the performance of a gas-liquid separator cannot be overstated, but identification of appropriate sizing parameter values from correlation data was a major constraint in separator analysis. In addition, the aim of this research study was achieved through the determination of maximum allowable gas and liquid velocities of the fluids to be separated, determination of separator dimensions: diameter, length, heavy and light liquid parameters, holdup/ surge parameters, etc, thereby sizing the separator, and performance evaluation of the separator using standard process simulation software.

2. MATERIALS AND METHODS

This research study applied the stepwise approach outlined by previous study of Monnery and Svrcek (1994) to determine basic separator dimensions and parameters. This approach of separator sizing, applied various empirical correlations such as the Souders – Brown constant, length to diameter ratio, liquid holdup/surge, etc, developed from field data. Therefore, this stepwise procedures are highlighted thus.

2.1 Computational Techniques and Correlations

For a fluid stream under plug flow without eddies and other disturbances, a single droplet of liquid at equilibrium (free fall or terminal velocity) is assumed to be acted upon mainly by two forces in the Souders – Brown (1994) approach. These are the drag and gravity forces, and are equal in opposite directions as shown in Figure 2.

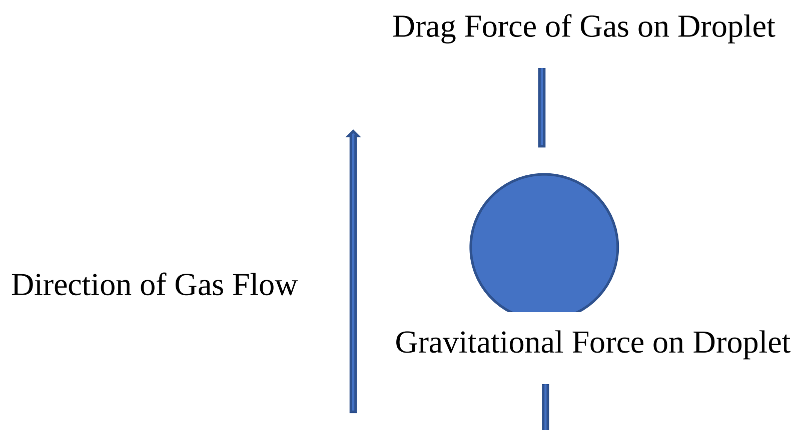

Figure 2: Forces acting on Liquid droplet

Equating these forces, therefore;

$$F_D = F_{Gr} \quad (1)$$

The maximum vapour velocity or terminal velocity, U_T which prevents entrainment of liquid in the vapour was determined from Equation 1. Hence, the stage wise procedures for separator sizing are discussed thus.

2.1.1 Terminal Velocity and Vapour Velocity

The terminal velocity of the separator flowing fluid is evaluated as shown in Equation 2.

$$U_T = K_s \sqrt{\frac{\rho_L - \rho_G}{\rho_G}}$$

The design parameter or Souders – Brown constant K_s, depends on a number of factors that include temperature, pressure, fluid properties that are temperature dependent, separator geometry, vessel length and the liquid level (for horizontal separators), steadiness of flow, inlet device design and performance, relative amounts of gas and liquid, and most importantly – mist extractor type and design (mesh pad, vane pack, multi–cyclone), for separators with mist extractor.

The design parameter has been empirically determined from field data for various processes and operations, and correlated by different methods.

The velocity of gas is related to terminal velocity and expressed as shown in Equation 3.

$$U_G = 0.75 U_T \quad (2)$$

2.1.2 Minimum Separator Diameter

The minimum diameter of separator required for a given separation opearation is deduced via Equation 4

$$D_{min} = \sqrt[3]{\frac{16(V_H + V_S)}{0.6\pi(L/D)}} \quad (4)$$

Since the holdup/surge volumes of the liquid are not known, the two parameters can only be determined when D_{min} and L/D_{min} are as highlighted in Table 2.

For separator operational pressure, $0 < P < 250P$sia, $L/D = 1.5 - 3.0$.

Therefore, taking $D_{min} = 3.281ft\ and\ L/D = 1.6$, $V_H + V_S$ was determined.

2.1.3 Total Cross-sectional Area

The total cross-sectional area of the separator is deduced via Equation 5.

$$A_T = \frac{\pi {D_{min}}^2}{4} \quad (5)$$

2.1.4 Area Occupied by Gas

The cross-sectional area occupied by gas in the separator is evaluated as

$$\frac{A_G}{A_T} = \frac{a + cx + ex^2 + gx^3 + ix^4}{1.0 + bx + dx^2 + fx^3 + ih} \quad (6)$$

where

$$x = \frac{H_G}{D_{min}} \quad (7)$$

Since the diameter of the separator is known, x is only determined by assuming the height of gas. The height of gas for a separator without mist extractor can also be determined, and consequently, the ratio of A_G/A_T and A_G were evaluated. Similarly, the cross sectional areas of the low liquid level (A_{LLL}) and heavy liquids (A_{HL}) were based on the same principle applied for cross-sectional area occupied by gas.

2.1.5 Weir Height

The weir height of the separator is determined as:

$$H_W = D_{min} - H_G \quad (8)$$

2.1.6 Minimum Length for Light Liquid

The minimum length of light liquid required in accommodating holdup or surge in the separator is estimated as

$$L_2 = \frac{V_H + V_S}{A_T - A_G + A_{LLL}} \quad (9)$$

Hence, the length for liquid-liquid separation in the separator is deduced as

$$L_1 = L - L_2 \quad (10)$$

2.1.7 Light and Heavy Liquid Height

The height of light and heavy liquid in the separator is determined based on the assumption that both light and heavy liquid height are the same. Hence,

$$H_{HL} = H_{LL} = H_W/2 \quad (11)$$

2.1.8 Cross-sectional Area of Light Liquid

The cross-sectional area of light liquid is estimated as the difference between the total cross-sectional area and the summation of cross-sectional areas of gas and heavy liquid.

$$A_{LL} = A_T - A_G - A_{HL} \quad (12)$$

2.1.9 Settling Velocities

The settling velocities of heavy liquid out of the light liquid phase and the light liquid out of the heavy liquid phase are determined as expressed thus.

$$U_{HL} = K_s(\frac{\rho_H - \rho_L}{\mu_L}) \quad (13)$$

and

$$U_{LH} = K_s\left(\frac{\rho_H - \rho_L}{\mu_H}\right) \quad (14)$$

2.1.10 Settling Time

The settling times of the heavy liquid component out of the light liquid phase and the light liquid component out of the heavy liquid phase are determined as

$$t_{HL} = 12\ H_{HL}/U_{HL} \quad (15)$$

and

$$t_{LH} = 12\ H_{LL}/U_{LH} \quad (16)$$

2.1.11 Volumetric Flow Rate of Heavy and Light Liquids

The volumetric flow rates of heavy and light liquids are estimated as

$$Q_{HL} = L_1 . A_{HL}/t_{LH} \quad (17)$$

and

$$Q_{LL} = L_1 . A_{LL}/t_{HL} \quad (18)$$

2.1.12 Liquid Droplet Time

The determination of the time it takes the liquid to drop out from the gas is expressed as

$$\varphi = \frac{H_G}{U_G} \quad (19)$$

2.1.13 Actual Gas Velocity

The actual gas velocity in the separator is determined using Equation 12

$$U_{A\,G} = \frac{Q_G}{A_G} \quad (20)$$

2.1.14 Minimum Length for Gas – Liquid Separation

$$L_{min} = U_{AG}\varphi$$

Where $L > L_{min}$, design is acceptable, otherwise parameters such ad the diameter and holdup times are varied, and the process repeated.

2.2 Three Phase Separator Operating Parameters

In designing of engineering units and components such as three phase separator in this research study, there are basic principles that guides the process and one of these principles is the identification of key operating parameters that can be fixed and other parameters that are driven by the process itself. For this research study (three phase separators), while quantities such as density and viscosity are properties of the process fluid and are constant, parameters such as volumetric flowrate, pressure, etc can be controlled and thus fixed. Consequently, diameter of the vessel, length to diameter ratio, height of the gas phase, heights of the light and heavy liquids are all deduced for this study. The separator basic properties applied in this study are based on the result of Aspen Hysys simulation of three phase separator for the rectifying section of crude distillation unit as shown in Table 1, while the design parameter or Souders – Brown constant correlation at different operating pressure and its value for separation of heavy and light hydrocarbons are shown in Tables 2 and 3 respectively.

Table 1: Basic Parameters of Separator

Property	Off – Gas	Naphtha	Water

Mass Density (lb/ft^3)	0.22	44.26	60.63
Vapour	1.00	0.00	0.00
Molar Volume (ft^3/kgmole)	533.18	4.94	0.65
Viscosity (cP)	0.0087	0.33	0.39
Pressure (atm)	1.81	1.81	1.81
Temperature (C)	71.63	71.63	71.63
Watson K	12.62	11.64	18.05
Molar Enthalpy (kJ/ kgmole)	-1.4e - 005	-2.1e – 005	-2.83 – 005
Specific Heat (kJ/kgmole - C)	96.88	212.9	78.25
Liquid Fraction	0.00	1.00	1.00

Table 2: K_s Values for Separator within Fixed Pressure Limits of Hydrocarbon Liquid and Water

Pressure in Psia	
$1 < P < 15$	$K_S = 0.821 + 0.0029P + 0.046lnP$
$15 < P < 40$	$K_s = 0.35$
$40 < P < 5500$	$K_s = 0.43 - 0.023lnP$

Monnery and Svrcek, 1994

Table 3: K_s – Values for Separation of Hydrocarbon Liquid and Water

Light Liquid	Heavy Liquid	Minimum Droplet Diameter (μm)	K_s
Hydrocarbon			
S_G @$60^oF < 0.85$	Water or Caustic	127	0.333
S_G @$60^oF < 0.85$	Water or Caustic	89	0.163
Water	Water	89	0.163
Methylethyl ketone	Water	89	0.163
sec-Butyl alcohol	Water	89	0.163
Methyl isobutyl ketone	Water	89	0.163
Nonyl alcohol	Water	89	0.163

Monnery and Svrcek 1994

3. RESULTS AND DISCUSSION

The results of the design analysis of three phase separator in this study based on the correlation results derived empirically from experimental and field data are highlighted in Table 4. The design parameter or Souders – Brown constant for separation of hydrocarbon liquid and water is 0.0163 as depicted in Table 3, while, the York Demister index that showed separator design parameter as 0.35 for a separator having operating pressure $0 < P < 40$Psia, which was applied in this study as shown in Table 2. Therefore, the design parameters or results for the three phase separator carried out in this research study are highlighted in Table 4.

Furthermore, the deductions or parameters or results of the design analysis of the three phase separator were compared with industrial three phase separator parameters and its deviation determined as depicted in Table 5

Table 4: Three Phase Separator Design Parameters

D_{min}	3.281 (ft)	H_W	2.281 (ft)
L	5.0 (ft)	H_G	1.0 (ft)
L_1	4.0 (ft)	U_{HL}	8.09 (ft/min)
L_2	1.0 (ft)	U_{LH}	6.81 (ft/min)
A_G	0.291 (ft^2)	t_{HL}	3.4 $mins$
A_T	8.45 (ft^2)	t_{LH}	4.0 $mins$
A_{HL}	2.621 (ft^2)	Q_{HL}	2.78 (ft^3/min)
A_{LL}	5.54 (ft^2)	Q_{LL}	6.92 (ft^3/min)
A_{LLL}	1.46 (ft^2)	V_H	4.44 (ft^3)
H_{HL}	1.141 (ft)	V_S	2.22 (ft^3)
H_{LL}	1.141(ft)	t_H	0 mins
H_{LLL}	1.0 (ft)	t_S	0 mins

Table 5: Compatison of Design and Industrial Parameters

Parameter	Design Data	Industrial Data	Deviations (%)
D_{min}	3.281	3.281	0.00
L	5.25	5.25	0.00
L/ D_{min}	1.6	1.6	0.00
H_G / D_{min}	0.31	0.45	0.14
H_{HL}	1.141	0.9	0.24
H_{LL}	1.141	0.9	0.24

Therefore, the percentage absolute error or deviation between the design and industrial data is minimal as shown in Table 5 and within the acceptable range or value, thereby affirming the appropriateness, effectiveness and efficiency of the three phase separator design procedures. Also, the determined three phase separator design parameters fall within the limiting range value (control data) of industrial separator parameters as shown in Table 6.

Table 6: Three Phase Separator Design Parameters Check

Parameter	Control value	Design Value

Weir Hight (H_W)	$H_W > 2$	$H_W = 2.281$
Minimum Length for liquid – liquid Separation (L_1)	$L_1 = Max\ (L_{1,1}, L_{1,2})$	$4.0, 4.0$
Minimum Length for vapour/liquid Separation (L_{min})	$L > L_{min}$	$4.0 > 0.0053$
Length – Diameter ratio (L/D_{min})	$1.5 - 6.0$	1.6

Hence, based on the three phase separator parameters determined above with low value of percentage absolute error or deviation from industrial three phase separator, the designed dimensional three phase separator is shown in Figure 3.

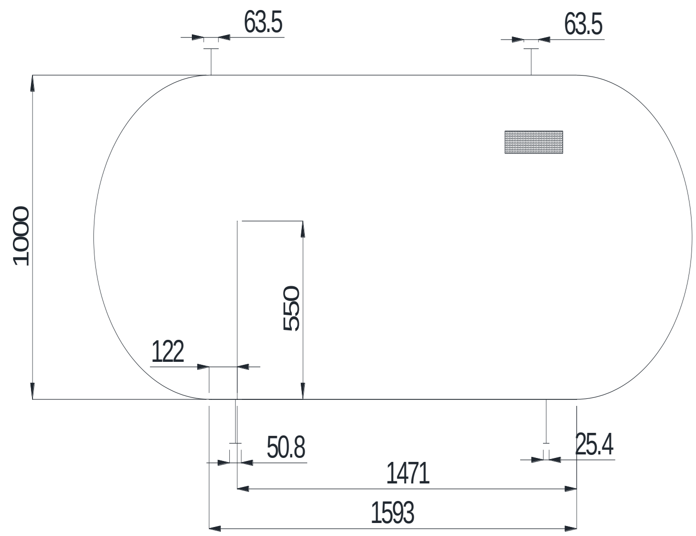

Figure 3: Dimensional Diagram of Three Phase Separator

4. CONCLUSION

The research study focused on the design of a three phase separator for separation of off – gases, naphtha (the top product) and water from bottom steam in the distillation of crude oil. The main objective of this study was to determine basic separator dimensions, and operating parameters for a crude oil distillation unit of 12.5 barrels per day capacity throughput. Also, the results of the design parameters were compared with industrial three phase separator parameters with minimum percentage absolute error values, thereby affirming the efficacy of the design procedures. However, it is further recommended that the design three phase separator should be constructed or built so as to access its suitability and operational performance for the crude distillation unit.

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Appendix

Nomenclature

A_T = Total cross − sectional area

A_G = Cross − sectional area of gas phase

A_{HL} = Cross − sectional area of heavy liquid

A_{LL} = Cross − sectional area of light liquid

A_{LLL} = Cross − sectional area of low liquid leve

D_{min} = Diameter of vessel

F_D = Drag force

F_{Gr} = Gravitational force

H_{HL} = Height of heavy liquid

H_{LL} = Height of light liquid

H_G = Height of gas phase

H_W = Weir Height

L = Length of vessel
L_2 = Length to accommodate holdup/surge
L_1 = Length for liquid − liquid separation
L_{min} = Length for gas − liquid separation
P = Pressure
Q_{HL} = Volumetric flowrate of heavy liquid
Q_{LL} = Volumetric flowrate of light liquid
t_{HL} = Settling time of heay liquid out of light liquid
t_{LH} = Settling time of Light liquid out of heavy liquid
U_T = Terminal velocity of gas
U_G = Maximum velocity of gas
U_{LH} = Superficial velocity of light liquid
U_{HL} = Superficial velocity of heavy liquid
V_H = Holdup volume
V_S = Surge volume
ρ_G = Density of light gas
ρ_L = Density of light liquid
ρ_H = Density of heavy liquid
μ_L = Viscosity of light liquid
μ_H = Viscosity of heavy liquid
φ = Dropout time of liquid from gas