



Novel design methods for conventional oil-water separators

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ABSTRACT

The regulatory effluent oil limit which is the allowable quantity of hydrocarbons in industrial and stormwater effluents varies from one country to another. Several authors have suggested the need to improve the design methods of conventional oil-water separators because current design methods do not address the quality of effluents produced despite the fact that the conventional oil-water separator is the predominant wastewater treatment facility in developing countries. Regulatory effluent oil limit and oil separation efficiency are not design parameters of the current standard design methods for conventional oil-water separators but there is pressure from environmental regulatory agencies on companies over compliance with regulatory effluent oil limit for industrial wastewaters. This research work conducted a survey on the oil content of the wastewater effluents of some functional conventional oil-water separators in the Niger Delta, Nigeria. Sequel to the outcome of the survey, this work invented novel design methods for conventional oil-water separators titled: novel design approach, innovative design approach and alternative design approach through mathematical modeling. The novel design methods apply the concept of design volume, novel sizing data and novel mathematical models to design conventional oil-water separators that conform to American Petroleum Institute (API) design criteria for conventional oil-water separators; taking into account oil separation efficiency and the regulatory effluent oil limit of a country to establish the technical basis for the periodic evaluation of separator performance and evaluation of compliance with the environmental regulation. The conventional oil-water separators designed with the novel design methods conformed to API design criteria and their dimensions are similar to dimensions of separators designed with the City of Tacoma design approach (a certified design approach), thus validating the novel design methods for the design of conventional oil-water separators. The novel design methods have global applicability. They can be applied in every country.

1. Introduction

Environmental regulations of oil-in-wastewater disposal are becoming more stringent. Oil-water separators are used to separate petroleum and its products from water in the petroleum, chemical and other industries (Ashraf et al., 2015). Conventional oil-water separators have been widely used not only in petroleum industry but also in electrical utilities (Wang, 2013). Significant efforts have been made to regulate pollution in most industrialized countries and the stringency of pollution regulations has continued to increase worldwide (Managi et al., 2015). Mohr and Veenstra (2000) stated that Governments around the world have been working towards protecting the environment by enacting and enforcing laws regarding hydrocarbon discharges.

Oil in wastewater is dangerous to aquatic life and it hinders self-purification processes of receiving water bodies. Treatment of the wastewater within the premises should be the aim of each industry

(Domkundwar, 2014). Oil-water separation is critical to addressing the challenges of industrial, municipal and domestic wastewaters (Gupta et al., 2017). Oil-water separators remove oil and other water-insoluble hydrocarbons and settleable solids from wastewater and stormwater runoff (City of Tacoma Stormwater Management Manual, 2016). Conventional oil-water separators are gravity oil-water separators which rely on differences in specific gravity to separate oil and suspended solids from a wastewater stream (US Environmental Protection Agency, 2005). Conventional oil-water separators are rectangular devices in which wastewater flows lengthwise at a horizontal velocity, v_H . The API oil-water separator is a standard example of baffle-type conventional oil-water separators; designed in accordance with API design criteria. The baffle-type separator consists of three chambers; forebay, separation section and the afterbay (See Fig. 1). The forebay traps, collects floatables, sediments, reduces turbulence and distributes the wastewater to the separation section. The separation section (also called the separator,

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Fig. 1. Conventional oil-water separator.

separation chamber or separator chamber/channel or oil separation/collection cell) is the actual chamber which provides quiescent conditions for oil separation, traps and holds oil as it rises through the water column. The afterbay is the chamber where relatively oil-free wastewater (effluent) from the separation chamber collects and flows out through the outlet to the sewer or downstream treatment system. Another type of gravity oil-water separator is the parallel-plate oil-water separator which consists of series of parallel inclined plates. Parallel-plate oil-water separators have been reported to be more efficient than conventional oil-water separators (API, 1990).

API (1990) stated that conventional oil-water separators are designed based on the design criteria summarized as follows:

- i) Horizontal velocity of wastewater through the oil-water separator should be less than or equal to 0.9144 metre/minute (3 feet per minute) or 15 times the rise rate (v_r) of the oil globules ($15v_r$) whichever is smaller
- ii) Depth of oil-water separator ranges from 0.9144 metre (3 feet) to 2.4384 metre (8 feet)
- iii) The range of depth-to-width ratio for oil-water separator is 0.3–0.5
- iv) The width of oil-water separator ranges from 1.8288 metre (6 feet) to 6.096 metre (20 feet)
- v) Minimum length-to-width ratio for oil-water separator is 5 to 1

2. Background

The performance of gravity oil-water separators is a function of design, operating conditions and characteristics of the oil and wastewater (Arthur et al., 2005). Wastewater releases to receiving water bodies are subject to regulation by responsible governmental agencies (Fair et al., 1981). Several authors have suggested the need to improve the design methods of conventional oil-water separators because current design methods do not address the quality of effluents produced. The conventional oil-water separator is a more accessible technology where limited financial resources play a major role as commonplace in developing countries (Lopez-Vazquez and Fall, 2004). There is pressure from environmental regulatory agencies on companies over compliance with regulatory effluent oil limit for industrial wastewaters.

This research work conducted a survey on the oil content of the

wastewater effluents of some functional conventional oil-water separators in the Niger Delta, Nigeria. The results are presented in Table 1. Sequel to the outcome of the survey, this work invented novel design methods for conventional oil-water separators titled novel design approach, innovative design approach and alternative design approach for conventional oil-water separators through mathematical modelling taking into account oil separation efficiency and the regulatory effluent oil limit of a country to establish the technical basis for the periodic evaluation of separator performance and compliance with the regulatory effluent oil limit of same country. The technical reasoning for this innovation is that when a piece of equipment is not designed to conform to a standard there is no strong technical basis to expect its performance to conform to that standard. Regulatory effluent oil limit and oil separation efficiency are not design parameters of any of the current standard design methods for conventional oil-water separators. The novel design methods being introduced in this work apply novel sizing data for conventional oil-water separators presented in Table 2, the concept of design volume and novel mathematical models to design conventional oil-water separators that conform to API design criteria. The novel design methods can be applied in every country. They have global applicability.

The design volume is calculated from the design flow rate or expected peak wastewater flow rate. (API, 1990) stated that the design flow rate for conventional oil-water separators is based on the expected wastewater flow rate and the safety factor required for accommodating flow variations. Unless flow equalization is provided upstream the separator the design flow rate should be based on the maximum flow rate expected from present and future oil-contaminated wastewaters and storm-water runoff.

3. Study area

The Niger Delta is the delta of the River Niger situated on the Gulf of Guinea on the Atlantic Ocean in Nigeria. It is located within nine coastal southern states of Nigeria including Delta State, Rivers State, Bayelsa State, Edo State, Akwa Ibom State, Cross River State, Imo State, Abia State and Ondo State. The Niger Delta extends over about 70000 km² and makes up 7.5% of Nigeria's land mass. It is very densely populated. The area was the British Oil Rivers Protectorate from 1885 until 1893 when it was expanded and became the Niger Coast Protectorate. The Niger Delta is a petroleum-rich region (Wikimedia Inc. 2016).

Table 1
Effluent oil contents of some conventional oil-water separators.

Separator	Week 1 effluent	Week 2 effluent	Week 3 effluent	Week 4 effluent	Average oil content	Maintenance schedule
A	120.7 mg/l	175.3 mg/l	96.8 mg/l	101.5 mg/l	123.6 mg/l	Monthly
B	162.9 mg/l	253.6 mg/l	170.5 mg/l	227.2 mg/l	203.6 mg/l	Quarterly
C	90.4 mg/l	103.6 mg/l	75.7 mg/l	118.5 mg/l	97.1 mg/l	Monthly
D	156.8 mg/l	189.7 mg/l	135.6 mg/l	110.3 mg/l	148.1 mg/l	Monthly
E	220.3 mg/l	180.8 mg/l	164.9 mg/l	298.2 mg/l	216.1 mg/l	Quarterly
F	102.6 mg/l	95.2 mg/l	87.9 mg/l	93.5 mg/l	94.8 mg/l	Monthly
G	265.1 mg/l	228.5 mg/l	188.7 mg/l	237.6 mg/l	230 mg/l	Quarterly
H	137.5 mg/l	113.0 mg/l	205.6 mg/l	155.4 mg/l	152.9 mg/l	Monthly
I	133.5 mg/l	110.7 mg/l	126.2 mg/l	95.0 mg/l	116.4 mg/l	Monthly
J	256.2 mg/l	280.4 mg/l	293.6 mg/l	271.3 mg/l	275.4 mg/l	Quarterly

Table 2
Novel sizing data for conventional oil-water separators.

Aspect ratio, R	Length, L (m)	Width, W (m)	Depth, D (m)	Volume, V (m ³)
5	9.144 (30 ft)	1.8288 (6 ft)	0.9144 (3 ft)	15.29118 (540 ft ³)
6	12.8016 (42 ft)	2.1336 (7 ft)	1.2192 (4 ft)	33.30079 (1,176 ft ³)
7	17.0688 (56 ft)	2.4384 (8 ft)	1.524 (5 ft)	63.43008 (2,240 ft ³)
8	21.9456 (72 ft)	2.7432 (9 ft)	1.8288 (6 ft)	110.0965 (3,888 ft ³)
9	27.432 (90 ft)	3.048 (10 ft)	2.1336 (7 ft)	178.3971 (6,300 ft ³)
10	33.528 (110 ft)	3.3528 (11 ft)	2.4384 (8 ft)	274.1086 (9,680 ft ³)
11	40.2336 (132 ft)	3.6576 (12 ft)	2.4384 (8 ft)	358.833 (12,672 ft ³)
12	47.5488 (156 ft)	3.9624 (13 ft)	2.4384 (8 ft)	459.415 (16,224 ft ³)
13	55.4736 (182 ft)	4.2672 (14 ft)	2.4384 (8 ft)	577.2137 (20,384 ft ³)
14	64.008 (210 ft)	4.572 (15 ft)	2.4384 (8 ft)	713.5884 (25,200 ft ³)
15	73.152 (240 ft)	4.8768 (16 ft)	2.4384 (8 ft)	869.8982 (30,720 ft ³)
16	82.9056 (272 ft)	5.1816 (17 ft)	2.4384 (8 ft)	1,047.502 (36,992 ft ³)
17	93.2688 (306 ft)	5.4864 (18 ft)	2.4384 (8 ft)	1,247.76 (44,064 ft ³)
18	104.2416 (342 ft)	5.7912 (19 ft)	2.4384 (8 ft)	1,472.031 (51,984 ft ³)
19	115.824 (380 ft)	6.096 (20 ft)	2.4384 (8 ft)	1,721.674 (60,800 ft ³)

Note: R = Aspect ratio (L/W), L = length, W = width, D = depth and V = volume of separator.

4. Materials & methods

Sampling, laboratory analysis and mathematical modelling were the methods adopted. Materials used include wastewater effluents and sample containers. Wastewater effluents were collected from ten functional conventional oil-water separators in the Niger Delta, Nigeria and analyzed for oil content in the laboratory. Mathematical models titled aspect ratio model, length model, efficiency-time model, volume-aspect ratio model and aspect ratio-length model were developed for conventional oil-water separators. The novel design approach, innovative design approach and alternative design approach for conventional oil-water separators were invented; each based on different mathematical models. Novel sizing data for conventional oil-water separators were generated from API design criteria. The new design methods were demonstrated with a design example. The same design example was also demonstrated with the City of Tacoma design approach for conventional oil-water separators to enable comparison. The City of Tacoma design approach is a certified design approach for conventional oil-water separators.

4.1. Wastewater effluents – oil content analysis

Samples of the wastewater effluents of ten functional conventional oil-water separators in the Niger Delta were collected and analyzed for oil content in the Laboratory. Wastewater samples were collected on Wednesday of each week for a period of four weeks. The results are presented in Table 1.

4.2. Novel sizing data for conventional oil-water separators

The novel sizing data for conventional oil-water separators presented in Table 2 were generated from the aforesaid API design criteria ii, iv and v for conventional oil-water separators.

4.3. Model

4.3.1. Efficiency-time model, length model and aspect ratio model for conventional oil-water separators

Ultraspin Inc. (2015) stated that the oil separation (removal) efficiency (E) of oil-water separators can be expressed as in Eq. (1):

$$E = \frac{C_i - C_o}{C_i} \times 100 \quad (1)$$

Based on mass balance equation where the accumulation term is non-zero for conventional oil-water separators, separation efficiency, E can be defined in fractional form, in terms of influent and effluent mass rates of

oil as in Eqs. (2) and (3) (Metcalf and Eddy Inc, 2004):

$$E = \frac{M_i - M_o}{M_i} \quad (2)$$

$$E = \frac{C_i Q_i - C_o Q_o}{C_i Q_i} \quad (3)$$

Practically, the flow rate of wastewater in every standard conventional oil-water separator decreases as it flows from the inlet to the outlet due to the presence of laminar flow promoting devices such as flow distributor, grit chamber, baffles and velocity-head diffusion devices. This implies that outflow rate, Q_o is less than inflow rate Q_i .

The volume of the separator can be calculated from Eq. (4) (City of Tacoma Stormwater Management Manual, 2016):

$$V = Q_i t \quad (4)$$

Applying Eq. (4) in Eq. (3) results in Eq. (5):

$$E = 1 - \frac{C_o Q_o t}{C_i V} \quad (5)$$

Eq. (5) is the “Efficiency-time model for conventional oil-water separators”.

The volume of the separator can also be calculated from Eq. (6) (City of Tacoma Stormwater Management Manual, 2016):

$$V = LWD \quad (6)$$

Using Eq. (6) in Eq. (4) leads to Eq. (7):

$$t = \frac{LWD}{Q_i} \quad (7)$$

Applying Eq. (7) in Eq. (5) results in Eq. (8):

$$L = \frac{VQ_i C_i (1 - E)}{Q_o C_o WD} \quad (8)$$

Eq. (8) is the “Length model for conventional oil-water separators”.

The aspect ratio of the separator is given by Eq. (9) (Agunwamba, 2000):

$$R = \frac{L}{W} \quad (9)$$

Using Eq. (8) in Eq. (9) produces Eq. (10):

$$R = \frac{VQ_i C_i (1 - E)}{Q_o C_o W^2 D} \quad (10)$$

Eq. (10) is the “Aspect ratio model for conventional oil-water

separators”.

Where,

- V = volume of separator (separation section) in cubic metre (m³)
- t = residence (retention) time in the separator in minutes (min)
- Q_i = flow rate (inflow) of wastewater into the separator in m³/min
- Q_o = outflow (effluent) rate of wastewater from the separator in m³/min
- L = length of separator in metre (m)
- W = width of separator in metre (m)
- D = depth of separator in metre (m)
- R = aspect ratio of separator (dimensionless)
- M_i = C_iQ_i = influent mass rate of oil in kg/min
- M_o = C_oQ_o = effluent mass rate of oil in kg/min
- E = oil separation efficiency (separator performance) in % or fraction of mass flow rates or fraction of oil concentrations
- C_i = concentration of oil in the influent wastewater, kg/m³
- C_o = concentration of oil in the effluent wastewater, kg/m³

4.3.2. Volume-aspect ratio model for conventional oil-water separators

The volume-aspect ratio model was developed from the data in the aspect ratio, depth (m) and volume (m³) columns of Table 2 by applying multiple linear regression analysis to obtain a power equation model as in Eq. (11):

$$V = a_1R^{a_2}D^{a_3} \tag{11}$$

Transposing the power equation results in Eq. (12):

$$\log V = a_1 + a_2 \log R + a_3 \log D \tag{12}$$

Eq. (12) will result in a 3 × 3 matrix with three unknowns. Eq. (12) in matrix form produces Eq. (13):

$$\begin{bmatrix} n & \sum \log R & \sum \log D \\ \sum \log R & \sum (\log R)^2 & \sum \log R \log D \\ \sum \log D & \sum \log R \log D & \sum (\log D)^2 \end{bmatrix} \begin{Bmatrix} a_1 \\ a_2 \\ a_3 \end{Bmatrix} = \begin{bmatrix} \sum \log V \\ \sum \log R \log V \\ \sum \log D \log V \end{bmatrix} \tag{13}$$

Obtaining the log of the data in the aspect ratio, depth (m) and volume (m³) columns of Table 2, putting them and the other elements in the matrix and computing constant coefficients for Eq. (12) using MATLAB:

$$a_1 = -0.7870, a_2 = 2.8684 \text{ and } a_3 = 0.9143$$

Substituting values of a₁, a₂, a₃ into Eq. (12) leads to Eq. (14):

$$\log V = -0.7870 + 2.8684 \log R + 0.9143 \log D \tag{14}$$

Solving for volume, V produces Eq. (15):

$$V = 0.163305194R^{2.8684}D^{0.9143} \tag{15}$$

Eq. (15) is the volume-aspect ratio model for conventional oil-water separators, where; volume (V) is in cubic metre (m³) and depth (D) is in metre. (Similarly, with depth, D in feet and volume, V in cubic feet as in Table 2, the equation, V = 1.9458081R^{2.8683}D^{0.9144} emerges as the imperial unit version of the volume-aspect ratio model). The model was validated by using it to predict the values (volume, actual) in the volume column of Table 2 by imputing the values of the corresponding depths and aspect ratios and comparing the predicted values (volume, model) with the actual values. Statistical analysis gave the following results:

Standard deviation, S_y = 552.667

Standard error of estimate, S_{est} = 1.60590

Coefficient of determination, r² = 0.99999 = 99.999%

Correlation coefficient, r = 0.999995 = 99.9995%

The results indicate that 99.999 % of the original uncertainty has been explained by the model. Therefore, the results show that we can be 99.999 % confident in making predictions with the model. The model makes an excellent fit for the data as evidenced by Fig. 2.

4.3.3. Aspect ratio-length model for conventional oil-water separators

The aspect ratio-length model was developed from the data in the aspect ratio, length (m) and depth (m) columns of Table 2 by applying multiple linear regressions analysis to obtain a power equation model as presented by Eq. (16):

$$R = a_1L^{a_2}D^{a_3} \tag{16}$$

Transposing the power equation leads to Eq. (17):

$$\log R = a_1 + a_2 \log L + a_3 \log D \tag{17}$$

Eq. (17) will result in a 3 × 3 matrix with three unknowns. Writing Eq.

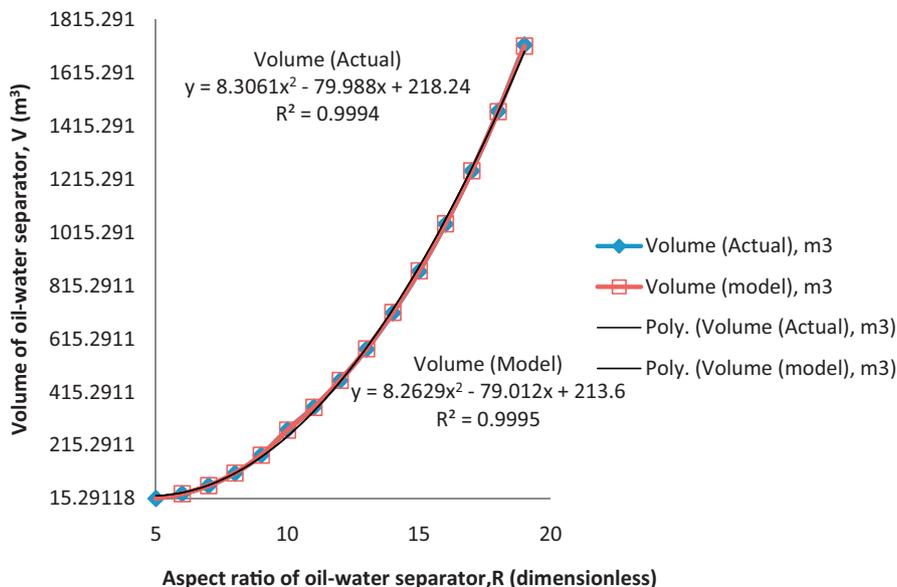


Fig. 2. Volume of oil-water separator versus aspect ratio.

(17) in matrix form produces Eq. (18):

$$\begin{bmatrix} n & \sum \log L & \sum \log D \\ \sum \log L & \sum (\log L)^2 & \sum \log L \log D \\ \sum \log D & \sum \log L \log D & \sum (\log D)^2 \end{bmatrix} \begin{Bmatrix} a_1 \\ a_2 \\ a_3 \end{Bmatrix} = \begin{bmatrix} \sum \log R \\ \sum \log L \log R \\ \sum \log D \log R \end{bmatrix} \quad (18)$$

Obtaining the log of the data in the aspect ratio, length (m) and depth (m) columns of Table 2, putting them and the other elements in the matrix and calculating constant coefficients for Eq. (17) using MATLAB:

$$a_1 = 0.2035, \quad a_2 = 0.5170, \quad \text{and} \quad a_3 = 0.0222$$

Substituting values of a_1, a_2, a_3 into Eq. (17) leads to Eq. (19):

$$\log R = 0.2035 + 0.5170 \log L + 0.0222 \log D \quad (19)$$

Solving for aspect ratio, R leads to Eq. (20):

$$R = 1.597717529L^{0.5170}D^{0.0222} \quad (20)$$

Eq. (20) is the aspect ratio-length model for conventional oil-water separators, where length (L) and depth (D) are in metre, m. (Similarly, with the length, L in feet and depth, D in feet as in Table 2, the equation, $R = 0.84197656L^{0.5170}D^{0.0222}$ emerges as the imperial unit version of the aspect ratio-length model). The model was validated by using it to predict the aspect ratio values (aspect ratio, R actual) in the aspect ratio column of Table 2 by imputing the corresponding values of lengths and depths and comparing the predicted values (aspect ratio, R model) with the actual values. Statistical analysis gave the following results:

Standard deviation, $S_y = 4.47214$

Standard error of estimate, $S_{est} = 0.0081725$

Coefficient of determination, $r^2 = 0.99999 = 99.999\%$

Correlation coefficient, $r = 0.999995 = 99.9995\%$

These results indicate that 99.999 % of the original uncertainty has

been explained by the model. Therefore, the results show that we can be 99.999 % confident in making predictions with the model. The model makes an excellent fit for the data as evidenced by Fig. 3.

5. Theory/calculation

5.1. The novel design approach for conventional oil-water separators

The application of the aspect ratio model and the novel sizing data in Table 2 in the design of conventional oil-water separators is hereby defined as the novel design approach for conventional oil-water separators. During design of conventional oil-water separators, the novel design approach assumes desired depth within the API range, calculates the design volume before calculating the corresponding width of the separator from Table 2 by interpolation. The length of the separator is calculated from the aspect ratio model. Application of the novel design approach involves the following design steps:

- 1.) Calculate oil droplet rise rate, v_t using Eq. (21) (API, 1990):

$$v_t = \frac{g(\rho_w - \rho_o)d^2}{18\mu_w} \quad (21)$$

Where, oil droplet rise rate, v_t is in m/s . Multiply by 60 to get the value in m/min ; g = acceleration due to gravity in m/s^2 ($9.8 m/s^2$); ρ_w = density of wastewater at the design temperature in kg/m^3 ; ρ_o = density of oil at the design temperature in kg/m^3 ; d = oil droplet diameter in metre (m); μ_w = absolute viscosity of the wastewater in Pa.s.

- 2.) Calculate residence (retention) time, t : Assume desired depth, D of separator (within the API range) and calculate residence (retention) time from Eq. (22) (City of Tacoma Stormwater Management Manual, 2016):

$$t = \frac{D}{v_t} \quad (22)$$

Note: Separator depth: $0.9144m \leq D \leq 2.4384m$ (API standard).

- 3.) Calculate the design volume, V of the separator using Eq. (4):

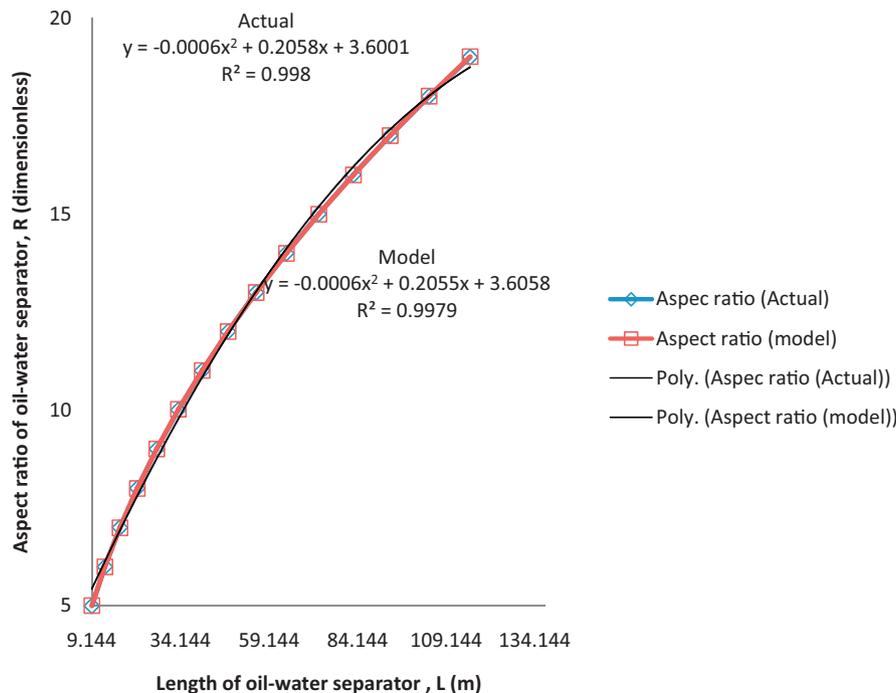


Fig. 3. Aspect ratio versus length of oil-water separator.

$$V = Q_i t$$

Where, V = volume of the separator in m³; Q_i = expected maximum wastewater flow rate into the separator or design flow rate in m³/min; and t = residence (retention) time in minutes.

4.) Calculate oil separation efficiency required by law using Eq. (3):

$$E = \frac{C_i Q_i - C_o Q_o}{C_i Q_i}$$

Note: Assume 5% reduction in flow rate as the wastewater flows through the separator to calculate the outflow (effluent) rate, Q_o as in Eq. (23):

$$Q_o = Q_i - 0.05(Q_i) \tag{23}$$

Where, E = Oil separation efficiency in fraction. Multiply by 100 to convert to percentage (if need be); Q_i = Expected maximum wastewater flow rate into the separator or design flow rate in m³/min; Q_o = outflow (effluent) rate in m³/min; C_i = oil concentration in the wastewater in kg/m³ and C_o = regulatory effluent oil limit of a country or desired effluent oil concentration in kg/m³.

5.) Calculate the width, W of the separator: Refer to Table 2 with the design volume calculated in step 3 and calculate the corresponding width from Table 2 by interpolation. **Note:** Separator width: 1.8288m ≤ W ≤ 6.096m (API standard)

Separator depth-to-width ratio: 0.3 to 0.5 (API standard).

6.) Calculate horizontal velocity, v_H using Eq. (24) (City of Tacoma Stormwater Management Manual, 2016):

$$v_H = \frac{Q_i}{DW} \tag{24}$$

Where, v_H = horizontal velocity of wastewater through the separator in m/min, D = depth of separator in metre (m) and W = width of separator in metre (m).

The calculated horizontal velocity, v_H should be less than or equal to API maximum horizontal velocity of 0.9144 m/min (API standard).

7.) Calculate the aspect ratio, R of the separator from the aspect ratio model, Eq. (10):

$$R = \frac{V Q_i C_i (1 - E)}{Q_o C_o W^2 D}$$

Where, R = aspect ratio of separator (dimensionless).

8.) Calculate the initial length of the separator from Eq. (9):

$$R = \frac{L}{W}$$

Where, L = length of separator in metre (m).

Solving for length leads to Eq. (25):

$$L = RW \tag{25}$$

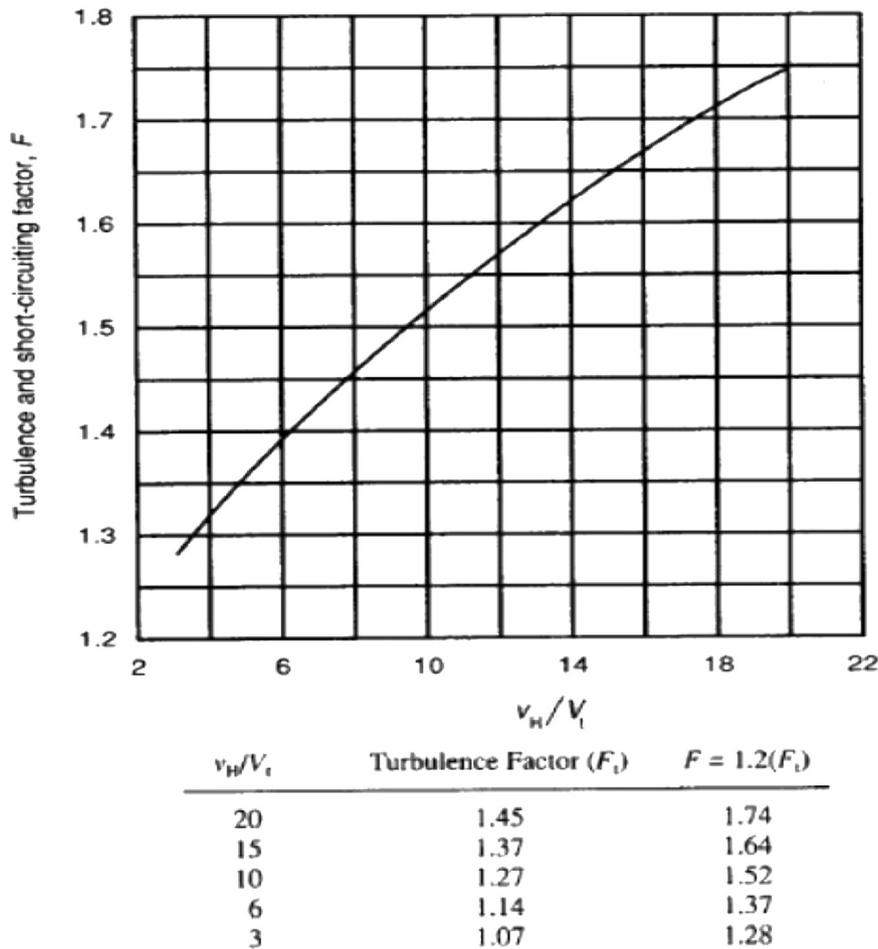


Fig. 4. Recommended values of F for various values of v_H/v_t (API, 1990).

- 9.) Calculate the design length of the separator (compensating for turbulence and short-circuiting) as follows: Calculate the value of the ratio v_H/v_t from the value of v_H calculated in step 6 and the value of v_t calculated in step 1. Use the calculated value of the ratio v_H/v_t to calculate the turbulence and short-circuiting factor, F from the API turbulence and short-circuiting factor versus v_H/v_t graph in Fig. 4. Calculate the design length of the separator from Eq. (26) (API, 1990):

$$\text{Design length of the separator} = \text{initial length} \times F \quad (26)$$

Note: Length-to-width ratio (aspect ratio) should be equal to or greater than 5 (API standard).

5.2. The innovative design approach for conventional oil-water separators

The application of the “length model for conventional oil-water separators” and the novel sizing data in Table 2 in the design of conventional oil-water separators is hereby defined as the innovative design approach for conventional oil-water separators. During design of conventional oil-water separators, the innovative design approach assumes desired depth within the API range; calculates the design volume and calculates the corresponding width of the separator by interpolation from Table 2 before calculating the length of the separator using the “length model for conventional oil-water separators”. The length model allows the direct calculation or prediction of the initial length of separator corresponding to any wastewater stream without going through aspect ratio calculation. Application of the innovative design approach involves the following design steps:

- 1.) Calculate oil droplet rise rate, v_t from Eq. (21):

$$v_t = \frac{g(\rho_w - \rho_o)d^2}{18\mu_w}$$

Where v_t is in m/s. Multiply by 60 to get the value in m/min.

- 2.) Calculate residence (retention) time, t. Assume desired depth, D of separator (within the API range) and calculate residence (retention) time, t from Eq. (22):

$$t = \frac{D}{v_t}$$

Note: Separator depth: $0.9144m \leq D \leq 2.4384m$ (API standard).

- 3.) Calculate the design volume, V of the separator from Eq. (4):

$$V = Q_i t$$

Where, Q_i = expected maximum wastewater flow rate into the separator or design flow rate in m^3/min ; and t = residence (retention) time in minutes.

- 4.) Calculate oil separation efficiency required by law from Eq. (3):

$$E = \frac{C_i Q_i - C_o Q_o}{C_i Q_i}$$

Note: Assume 5 % reduction in flow rate as the wastewater flows through the separator to calculate the outflow (effluent) rate using Eq. (23):

$$Q_o = Q_i - 0.05(Q_i)$$

- 5.) Calculate the width, W of the separator: Refer to Table 2 with the design volume calculated in step 3 and calculate the corresponding width from Table 2 by interpolation.

Note: Separator width: $1.8288m \leq W \leq 6.096m$ (API standard).
Separator depth-to-width ratio: 0.3 to 0.5 (API standard).

- 6.) Calculate horizontal velocity, v_H from Eq. (24):

$$v_H = \frac{Q_i}{DW}$$

Note: The calculated horizontal velocity, v_H should be less than or equal to API maximum horizontal velocity of 0.9144 m/min (API standard).

- 7.) Calculate the initial length of the separator using the Length model, Eq. (8):

$$L = \frac{VQ_i C_i (1 - E)}{Q_o C_o W D}$$

- 8.) Calculate the design length of the separator (compensating for turbulence and short-circuiting) as follows: Calculate the value of the ratio v_H/v_t from the value of v_H calculated in step 6 and the value of v_t calculated in step 1. Use the calculated value of the ratio v_H/v_t to calculate the turbulence and short-circuiting factor, F from the API turbulence and short-circuiting factor versus v_H/v_t graph in Fig. 4. Calculate the design length of the separator from Eq. (26):

Design length of the separator = initial length \times F

Note: Length-to-width ratio should be equal to or greater than 5 (API standard).

5.3. The alternative design approach for conventional oil-water separators

The application of the efficiency-time model, volume-aspect ratio model and the aspect ratio-length model in the design of conventional oil-water separators is hereby defined as the alternative design approach for conventional oil-water separators. During design of conventional oil-water separators, the alternative design approach assumes desired depth within the API range; calculates the design volume and calculates the corresponding aspect ratio of the separator from the volume-aspect ratio model before calculating the length of the separator using the aspect ratio-length model. The alternative design approach can be applied with or without reference to Table 2. Application of the alternative design approach involves the following design steps:

- 1.) Calculate oil droplet rise rate, v_t from Eq. (21):

$$v_t = \frac{g(\rho_w - \rho_o)d^2}{18\mu_w}$$

v_t is in m/s. Multiply by 60 to get the value in m/min.

- 2.) Calculate residence (retention) time, t. Assume desired depth, D of separator (within the API range) and calculate residence time from Eq. (22):

$$t = \frac{D}{v_t}$$

Note: Separator depth: $0.9144m \leq D \leq 2.4384m$ (API standard).

- 3.) Calculate the design volume, V of the separator from Eq. (4):

$$V = Q_i t$$

Where, Q_i = Expected maximum wastewater flow rate into the separator or design flow rate in m^3/min ; and t = residence (retention) time in minutes.

- 4.) Calculate oil separation efficiency, E required by law using the Efficiency–time model, Eq. (5):

$$E = 1 - \frac{C_o Q_o t}{C_i V}$$

Note: Assume 5 % reduction in flow rate as the wastewater flows through the separator to calculate the outflow (effluent) rate, Q_o from Eq. (23):

$$Q_o = Q_i - 0.05(Q_i)$$

- 5.) Calculate the aspect ratio, R of the separator from the volume–aspect ratio model, Eq. (15):

$$V = 0.163305194R^{2.8684}D^{0.9143}$$

Solving for aspect ratio, R leads to Eq. (27):

$$R = \sqrt[2.8684]{\frac{V}{0.163305194 \times D^{0.9143}}} \quad (27)$$

- 6.) Calculate the initial length of the separator from the aspect ratio–length model, Eq. (20):

$$R = 1.597717529L^{0.5170}D^{0.0222}$$

Solving for length leads to Eq. (28):

$$L = \sqrt[0.5170]{\frac{R}{1.597717529 \times D^{0.0222}}} \quad (28)$$

- 7.) Calculate the width of the separator, W from Eq. (9):

$$R = \frac{L}{W}$$

Solving for width, W leads to Eq. (29):

$$W = \frac{L}{R} \quad (29)$$

Note: Separator width: $1.8288m \leq W \leq 6.096m$ (API standard).
Separator depth-to-width ratio: 0.3 to 0.5 (API standard).

- 8.) Calculate horizontal velocity, v_H using Eq. (24):

$$v_H = \frac{Q_i}{DW}$$

The horizontal velocity, v_H should be less than or equal to API maximum horizontal velocity of 0.9144 m/min (API standard).

- 9.) Calculate the design length of the separator (compensating for turbulence and short circuiting) as follows: Calculate the value of the ratio v_H/v_t from the value of v_H calculated in step 8 and the value of v_t calculated in step 1. Use the calculated value of the ratio v_H/v_t to calculate the turbulence and short-circuiting factor, F from the API turbulence and short-circuiting factor versus v_H/v_t graph in Fig. 4. Calculate the design length of the separator from Eq. (26):

Design length of the separator = initial length \times F

Note: Length-to-width ratio should be equal to or greater than 5 (API standard).

5.4. The City of Tacoma design approach for conventional oil-water separators

The design guide for conventional oil-water separators (separation sec-

tion) written in the [City of Tacoma Stormwater Management Manual \(2016\)](#) is hereby defined as the City of Tacoma design approach for conventional oil-water separators. The City of Tacoma design approach is a certified design guide for conventional oil-water separators. The [City of Tacoma Stormwater Management Manual \(2016\)](#) stated the following guide for the design of conventional oil-water separators (Separation section):

- 1.) Calculate oil droplet rise rate, v_t using Eq. (21):

$$v_t = \frac{g(\rho_w - \rho_o)d^2}{18\mu_w}$$

- 2.) Select depth and width based on the following”

Separator depth: $0.9144m \leq W \leq 2.4383m$

Separator width: $1.8288m \leq W \leq 6.096m$

Depth-to-width ratio of 0.3–0.5.

- 3.) Calculate the residence time using Eq. (22):

$$t = \frac{D}{v_t}$$

- 4.) Calculate horizontal velocity, v_H using Eq. (24):

$$v_H = \frac{Q_i}{DW}$$

- 5.) Calculate the length of the separator (separation section) using Eq. (30):

$$L = F \frac{Q_i t}{WD} \quad (30)$$

6. Design

The application of the novel design methods (novel design approach, innovative design approach & alternative design approach) to design conventional oil-water separators in conformity with API design criteria was demonstrated with the following design example. The City of Tacoma design approach was also demonstrated with the same design example to enable comparison and validation of the novel design methods. The City of Tacoma design approach is a certified design approach for conventional oil-water separators. The design example shows the calculation of the fundamental separator dimensions (separation section) required for detailed unit design. The specific gravity of diesel fuel oil ranges from 0.81 to 0.96 ([Engineering Toolbox, 2017](#)). It is the oil referred to in the design example.

6.1. Example

Design an oil-water separator to treat a wastewater with 220 mg/l of oil and peak flow rate of 1.5 m³/min. SG of wastewater = 0.992, SG of oil = 0.92, viscosity of wastewater = 0.00065 Pa.s, diameter of oil droplet = 150 microns.

6.2. Solution

Applying the design steps stated for each of the novel design methods and the City of Tacoma design approach, the dimensions and other parameters of the designed separator are as presented in [Table 3](#).

7. Results & discussion

The conventional oil-water separator designed with each of the novel

Table 3

Design example: novel design approach, innovative design approach, alternative design approach & City of Tacoma design approach comparison.

Type	Length (m)	Width (m)	Depth (m)	Volume (m ³)	Aspect ratio (length-to-width ratio)	Horizontal velocity (m/min)	Depth-to-width ratio	Design oil separation efficiency
Novel Design Approach	15.29	1.855	0.9144	25.94	8.24	0.8843	0.493	95.68%
Innovative Design Approach	15.29	1.855	0.9144	25.94	8.24	0.8843	0.493	95.68%
Alternative design approach	15	1.8861	0.9144	25.87	7.95	0.86974	0.485	95.68%
City of Tacoma design approach	15.29	1.855	0.9144	25.94	8.24	0.8843	0.493	

Note: See supplementary content for design calculations.

design methods (novel design approach, innovative design approach and alternative design approach) satisfied API design criteria. Similarly, the conventional oil-water separator designed with the City of Tacoma design approach satisfied API design criteria. Table 3 presents the conventional oil-water separator designed with each of the novel design methods and the City of Tacoma design approach for comparison. It is evident from Table 3 that the dimensions and other API-parameters of the conventional oil-water separator designed with the novel design approach; innovative design approach, alternative design approach and the City of Tacoma design approach are similar. In Table 3, the dimensions and the other API-parameters are same for the novel design approach, innovative design approach and the City of Tacoma design approach.

However, there is a negligible difference of 0.29 m (1.9%) between the length of separator designed with the alternative design approach and the length of separator designed with the City of Tacoma design approach. There are also negligible differences of 0.008 (1.62%) between the depth-to-width ratios, 0.01456 m³/min (1.65%) between the horizontal velocity values, 0.29 (3.52%) between the aspect ratio (length-to-width ratio) values and 0.0311 m (1.68%) between the values of the widths of the separator designed with the alternative design approach and the separator designed with the City of Tacoma design approach.

The novel design approach and the innovative design approach can be applied only when Table 2 is handy or available because they depend on Table 2 for interpolation when calculating the width of the separator. Uniquely, the alternative design approach can be applied with or without reference to Table 2. Thus, the alternative design approach can be applied when Table 2 is not handy or not available. The aspect ratio model in the novel design approach enables prediction or calculation of the initial aspect ratio of separator corresponding to any wastewater stream prior to calculating the initial length. The volume–aspect ratio model in the alternative design approach also enables prediction or calculation of the initial aspect ratio of separator corresponding to any wastewater stream prior to calculating the initial length. Uniquely, the length model in the innovative design approach enables direct prediction or calculation of the initial length of separator corresponding to any wastewater stream. Chapara and Canale (2012) stated that mathematical models describe a natural process or system in mathematical terms, yield reproducible results and they can be used for predictive purposes.

Nigeria's regulatory effluent oil limit is 10 mg/l (Federal Environmental Protection Agency, 1991). The oil contents of the wastewater effluents of the conventional oil-water separators presented in Table 1 are above the regulatory effluent oil limit. Mohr and Veenstra (2000) stated that the regulatory effluent oil limit is the allowable quantity of hydrocarbons in industrial and stormwater effluents and it varies from one country to another; some countries specifying only “no sheen” and others stipulating a specific allowable concentration.

The effluent oil contents in Table 1 will be offensive, if the wastewater effluents are discharged directly into receiving water bodies without further treatment. Domkundwar (2014) stated that oil in wastewater is dangerous to aquatic life. Metcalf & Eddy Inc. (2004) stated that wastewater treatment objectives must go hand in hand with the water quality objectives or standards established by environmental regulatory agencies and effective industrial pretreatment is an essential part of an

overall water quality management programme. Fair et al. (1981) stated that wastewater discharges to receiving water bodies are subject to regulation by responsible governmental agencies.

Therefore, it is imperative to account for oil separation efficiency and regulatory effluent oil limit of a country in the design of conventional oil-water separators. Regulatory effluent oil limit and oil separation efficiency are not design parameters of any of the current standard design methods (traditional design methods) for conventional oil-water separators. López-Vazquez and Fall (2004) wrote that current design methods of conventional oil-water separators do not address the quality of effluents produced.

Therefore, there is no strong technical basis to evaluate the performance of the ten conventional oil-water separators against the regulatory effluent oil limit of 10 mg/l. The supportive technical reason is that when a piece of equipment is not designed to conform to a standard, there is no strong technical basis to expect its performance to conform to that standard. Yu et al. (2014) stated that quality is built into a product at the design stage and that majority of quality crises or problems are a function of design. Appendix F of the Oregon (DOT) Hydraulics Manual (2014) stated that conventional oil-water separators can be designed to achieve performance goal of 10–15 mg/l in treated effluent.

This implies that when future designs of conventional oil-water separators are based on a design oil separation efficiency corresponding to the regulatory effluent oil limit of a country such separators can be evaluated against the regulatory effluent oil limit. This prompted the initiative for the novel design methods. The design of conventional oil-water separators based on the oil separation efficiency corresponding to the regulatory effluent oil limit of a country as innovated by the novel design methods (novel design approach, innovative design approach and the alternative design approach) establishes the technical basis for the periodic evaluation of separator performance and compliance with the regulatory effluent oil limit of same country. Subsequently, informed decision can be reached on the need or relevance of further treatment and executed as appropriate.

It is also evident from Table 1 that the average effluent oil contents of the separators operated under monthly maintenance schedule are lower than the average effluent oil contents of separators operated under quarterly maintenance schedule. Therefore, frequent maintenance is hereby recommended.

The novel sizing data for conventional oil-water separators presented in Table 2 make separator design easier and faster. Table 2 is a useful design tool. It is very informative and technical. It will be a valuable asset to engineers, polytechnics, universities, other educational institutions, Government, petroleum industry, wastewater treatment industry, companies, professional bodies and environmental regulatory agencies worldwide.

Advantages of conventional oil-water separators designed with the novel design methods include:

- i) Design oil separation efficiency: The separators designed with the novel design methods have design oil separation efficiency which serves as reference for periodic performance evaluation. Conventional oil-water separators designed with the current design methods (traditional design methods) have no design oil

Table 4

What has been and what is new?

S/N	What has been?	What is new?
1	Current standard design methods (Traditional design methods) for conventional oil-water separators do not consider oil separation efficiency, so existing separators have no design oil separation efficiency.	The novel design methods (novel design approach, innovative design approach & alternative design approach) for conventional oil-water separators take into account oil separation efficiency in the design of conventional oil-water separators. The design oil separation efficiency serves as the reference for periodic performance evaluation.
2	Traditional design methods for conventional oil-water separators do not consider the regulatory effluent oil limit of a country in the design of conventional oil-water separators.	The novel design methods for conventional oil-water separators take into account the regulatory effluent oil limit of a country in the design of conventional oil-water separators, establishing the technical basis for evaluating separator compliance against the regulatory effluent oil limit of a country.
3	Table 2 is not part of traditional design methods for conventional oil-water separators	The novel sizing data presented in Table 2 make separator design easier and faster. Table 2 is a valuable design tool.
4	Not same with traditional design methods for conventional oil-water separators	With the aspect ratio model of the novel design approach and the aspect ratio-length model of the alternative design approach, the aspect ratio of oil-water separator corresponding to any wastewater stream can be calculated directly, thus making separator design easier and faster

separation efficiency. Oil separation efficiency is not a design parameter of the traditional design methods for conventional oil-water separators.

- ii) Compliance with the regulatory effluent oil limit of a country: The separators designed with the novel design methods are designed based on the oil separation efficiency corresponding to the regulatory effluent oil limit of a country. This implies that given appropriate operating conditions; the separators should operate at the design oil separation efficiency and the effluent oil content should conform to the regulatory effluent oil limit of the country of interest. This provides the technical basis for periodic evaluation of compliance with the regulation. Regulatory effluent oil limit of a country is not a design parameter of the traditional design methods for conventional oil-water separators.
- iii) Decision on further treatment: With the design efficiency, use of separators designed with the novel design methods will enable quicker informed decision on further treatment because of the culture of periodic performance & compliance evaluation being prompted by the novel design methods. For example; consistent separator performance below the design oil separation efficiency (or consistent non-compliance with the regulatory effluent oil limit of a country) would be suggestive of the need for further treatment which should be confirmed through comprehensive troubleshooting. *API (1990)* stated that the performance of conventional oil-water separators varies with changes in the characteristics of the oil and wastewater and that conventional oil-water separators can only remove free oil from wastewater but emulsified oil and dissolved oil require further treatment.

Limitations encountered during this research are funding and equipment. **Table 4** highlights the novelty inherent in the novel design methods.

8. Conclusion

The dimensions and other API-parameters of the conventional oil-water separator designed with the novel design methods (novel design approach, innovative design approach & alternative design approach) and the City of Tacoma design approach are similar as evidenced by **Table 3**, thus validating the novel design methods for the design of conventional oil-water separators. The City of Tacoma design approach is a certified design approach for conventional oil-water separators.

Application of any of the novel design methods for future designs of conventional oil-water separators, with frequent maintenance, periodic evaluation of separator performance alongside evaluation of compliance

with the regulatory effluent oil limit and further treatment (as required) will promote environmental protection in the Niger Delta, Nigeria and other developing countries where the conventional oil-water separator is used standalone as wastewater treatment facility.

The novel design methods have global applicability. They can be applied in every country by imputing the regulatory effluent oil limit of the country in the relevant equations.

Declarations

Author contribution statement

William E. Odiete: Conceived, designed and performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools and data; Conceived the novel design methods; Wrote the paper.

Jonah C. Agunwamba: Contributed reagents, materials and analysis tools.

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