

# Modified Design Approach for Conventional Oil Water Separator

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## Abstract:

Designing the conventional oil-water separator with the City of Tacoma design approach and the Modified design method approach all satisfied the API design criterion. The City of Tacoma design approach is a standard method and procedure for designing conventional oil-water separators with respect to API criteria. In most design approaches relating to oil-water separators, pressure was invariably not an inclusive criterion, hence the need to incorporate pressure into the design approach named modified design method became an important part of this work. Five physical models were built of varying sizes in terms of length, width and height. It was interesting to note that, the model with the longest hydraulic retention time shows a better separation efficiency. However, the comparative analysis of the two methods shows some similarity considering the various parameters calculated. The results shows that, there was a significant improvement in the design length of the separator using the modified design method as compared to the city of Tacoma design manual. Knowing the initial pressure of the vessel prior to hydro-testing through the modified design approach enhances the proper working of the vessel and also reduces loss time as a result of leak-off test.

**Keywords:** Flow rate, separation efficiency, volume, pressure, aspect ratio

## 1. Introduction

Produced water during oil and gas extraction constitutes a major waste stream as it pollutes both land and the receiving waters. Hence efforts in preserving the natural environment in terms of improving the quality of effluent sent to the environment, and controlling or reduction of wastewater from oil and gas production justify this research. Also considering the amount of money spent in treating oily wastewater effluent including frequent litigations with government agencies and communities in the area of pollution gave credence to this study. Hence the need to continuously improve on the working of the conventional oil-water separation in terms of design becomes a necessity. [5] novel design methods for conventional oil-water separators and [3] did not mention pressure as a variable in their derivation for various parameters aiding the design of separators besides the flow rate, separator length, width, height/depth, residence time, volume etc. However, most times these gravity separators are hydro-tested to determine their minimum and maximum pressures. In the oil and gas industries pressure plays a major role right from the reservoir to the sub-surface and through the surface where it undergoes various transformations and the discharge of by-

products of wastewater called produced water and gas flaring. Apart from the gases released from the valued fluid which exert tremendous pressure on the vessel, relief valves are provided in these vessels to save them from damage, injury to personnel and lost time in operation. Also, the separator must be adequately sized to handle the total flow of gas and liquids that could potentially cause an overpressure situation. The valve relieved the pressure by routing this stream to a safe location where it could be vented to the atmosphere or burned. In other words, these vessels are called pressure vessels. Hence this work intends to incorporate pressure into the equations used in designing these vessels by API extension tagged Modified Design Method. This Modified Design Method will then be used in designing an oil-water separator and compare results with that of the City of Tacoma.

## 2. Methods

The method involved detailing and comparative analysis of the two methodologies of the city of Tacoma design approach and modified design method. Considering the five physical models constructed, the model with the most

appreciable separation efficiency was used for the design in terms parameters obtained.

## 2.1. Modified Design Method for conventional oil-water separator

From the hydrostatic pressure expression,

$$P = h\rho g = h\rho(\rho_w - \rho_{oil}) \quad (1)$$

$$V = LWD; \text{ Where, } h=D$$

$$\text{Hence, } h = \frac{P}{\rho g} \quad (2)$$

Substituting Equation (2) into Equation (3). We had

$$V_H = \frac{Q_i}{DW} \quad (3)$$

$$V_H = \frac{Q_i \rho g}{WP} . \text{ Also, } t = \frac{D}{V_t} = \frac{P}{\rho g V_t}$$

Hence

$$t = \frac{P}{\rho g V_t} \quad (4)$$

$$V = Q_i t \text{ And substituting Equation (4), we have Equation (5)}$$

$$V = \frac{Q_i P}{\rho g V_t} \quad (5)$$

$$\text{But, } L = \frac{V}{WD}, \text{ hence we have Equation (6).}$$

$$L = \frac{Q_i P}{WD \rho g V_t} \quad (6)$$

Separation Efficiency is given by:

$$E = \frac{C_i - C_o}{C_i} * 100$$

Mass Balance Equation in terms of efficiency gives

$$E = \frac{M_i - M_o}{M_i}$$

However,  $M = C * Q$  ; Where  $C$  = concentration (mg/l) and  $Q$  =flow rate,  $M$ = mass. Hence, by common simplification and substitution,

$$E = \frac{C_i Q_i - C_o Q_o}{C_i Q_i} ; E = 1 - \frac{C_o Q_o}{C_i Q_i} \quad (7)$$

But,

$$V = \frac{Q_i P}{\rho g V_t} \text{ and } Q_i = \frac{V \rho g V_t}{P} = V \rho g V_t P^{-1}$$

Hence

$$E = 1 - \frac{C_o Q_o}{C_i V \rho g V_t P^{-1}}$$

$$E = \frac{C_i V \rho g V_t P^{-1} - C_o Q_o}{C_i V \rho g V_t P^{-1}} \quad (8)$$

Hence, the Aspect Ratio of the separator is given by the Equation [1].

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

Applying the equation below, we have

$$R = \frac{Q_i P}{WD \rho g V_t} * \frac{1}{W}$$

$$R = \frac{Q_i P}{W^2 D \rho g V_t} \quad (10)$$

Equation (10) shows the modified Aspect Ratio. However, tables 1 and 2 shows the model geometric and aspect ratio of the wetted perimeter of the models.

**Table 1:** Geometric of models

Model	Length L(m)	Width W(m)	Height H(m)	Volume V(m <sup>3</sup> )
A	2.0	0.28	0.32	0.1792
B	1.8	0.30	0.32	0.1728
C	1.6	0.32	0.32	0.1638
D	1.4	0.34	0.32	0.1523
E	1.2	0.36	0.32	0.1382

**Table 2:** Geometrical factor (Aspect Ratio) of wetted perimeter of models (A, B, C, D, E)

Aspect Ratio (R=L/W)	Length L(m)	Width W(m)	Height H(m)	Volume V(m <sup>3</sup> )
RA	1.90	0.28	0.20	0.1064
RB	1.70	0.30	0.20	0.1020
RC	1.50	0.32	0.20	0.0960
RD	1.30	0.34	0.20	0.0858
RE	1.10	0.36	0.20	0.0792

[2] stated that conventional oil-water separators are designed based on the following criteria:

- Horizontal velocity of produced water/wastewater through the oil-water separator should be less than or equal to 0.9144metres/minute or 15 times the rise rate( $V_t$ ) of the oil globules( $15V_t$ ) whichever is smaller.
- Depth of oil-water separator D, 0.9144 m – 2.4384m.
- Maintain  $\frac{D}{W}$  ratio of 0.3 to 0.5

- d. Adjust the depth and width of the separator until you achieve a horizontal velocity  $\leq 3$ . Ideal horizontal velocity should be in the range  $\leq 2$  at average flow.
- e. The width of oil-water separator ranges from 1.8288m to 6.096m.
- f. Minimum  $\frac{L}{W}$  for oil-water separator is 5 to 1.
- g. An oil droplet size of 150 microns is typically the norm for API separator and the minimum useable value is 60microns.

## 2.2. City of Tacoma design approach of conventional oil-water separator

The various segments and component of this approach were outline.

$$E = \frac{C_i - C_o}{C_i} * 100 \quad (22)$$

Mass Balance Equation in terms of efficiency gives

$$E = \frac{M_i - M_o}{M_i} \quad (11)$$

However,  $M = C * Q$  ; where  $C$  = concentration (mg/l) and  $Q$  = flow rate

$$E = \frac{C_i Q_i - C_o Q_o}{C_i Q_i} \quad (12)$$

According to [3]

$$V = Q * t \quad (13)$$

$$\text{Also } Q_i = \frac{V}{t} \quad \text{and} \quad E = 1 - \frac{C_o Q_o}{C_i V}; \quad (14)$$

$$E = 1 - \frac{C_o Q_o t}{C_i V} \quad (15)$$

Where Equation (15) represent the efficiency time model.

(ii) Volume of separator can be calculated from the Equation

According to [3]

$$V = LWD$$

$$V = Qt$$

$$\text{Hence, } Qt = LWD \quad (17)$$

$$\text{Where, } t = \frac{LWD}{Q}$$

Applying Equation (17) into Equation (16), we have

$$Qt = LWD \quad (18)$$

$$t = \frac{LWD}{Q} \quad (19)$$

Also applying Equation (19) into Equation (14) leads to

$$E = 1 - \frac{C_o Q_o LWD}{C_i Q_i V} \quad (20)$$

After substitution and simplification and making  $L$  the subject matter, we have the expression below representing the Length Model.

$$L = \frac{C_i Q_i V (1-E)}{C_o Q_o WD} \quad (21)$$

According [1] the Aspect Ratio of the separator is given by

$$R = \frac{L}{W} \quad (22)$$

However, by simple substitution we have the expression below.

$$R = \frac{V Q_i C_i (1-E)}{Q_o C_o WD} * \frac{1}{W}$$

$$R = \frac{V Q_i C_i (1-E)}{Q_o C_o W^2 D} \quad (23)$$

Equation (23) is the Aspect ratio model for oil- water separator.

Based on droplet settling theory or retention time for the liquid phase and from stokes equation, the droplet diameter was calculated.

Given as

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

$$\text{And } d^2 = \frac{V_r \times 18\mu}{g(\rho_w - \rho_o)}; V_r = 0.000276 \text{ m/sec}; \mu = 4.55 \times 10^{-6} \text{ m}^2/\text{sec}; g = 9.81 \text{ m/s}^2; \rho_w = 1000 \text{ kg/m}^3; \rho_o = 0.881 \text{ kg/m}^3$$

$$d_m^2 = \frac{0.000276 \times 18 \times 4.55}{9.81(1000 - 0.881)} = \frac{2.2604 \times 10^{-8}}{9801.35} = 2.306 \times 10^{-12}$$

$$d_m = \sqrt{2.306 \times 10^{-12}}$$

$$d_m = 1.519 \times 10^{-6} \text{ m} = 1.519 \mu\text{m}$$

Where

$V$  = volume of separator (separation section) in cubic metre ( $\text{m}^3$ )

$V_r$  = rise velocity in metre per second (m/sec)

$\rho_w$  = Density of water in kilogram per  $\text{m}^3$ .

$\rho_o$  = Density of oil in kilogram per  $\text{m}^3$

$d$  = Diameter of oil droplet in metres (m)

$\mu$  = Viscosity of oil water in metre square per seconds (m<sup>2</sup>/sec)

$g$  = Acceleration due to gravity in metre per second square (m/s<sup>2</sup>)

$Q_i$  = Inlet flow rate oil water (produced water) into the separator in meter cube per min (m<sup>3</sup>/min)

$Q_o$  = Outlet flow rate oil water (produced water) into the separator in meter cube per min (m<sup>3</sup>/min)

$L$  = Length of separator in metre (m).

$W$  = Width of separator in metre (m).

$D$  = Depth of separator in metre (m).

$C_i$  = Inlet concentration of oil in the produced water (kg/m<sup>3</sup>).

$C_o$  = Outlet concentration of oil in the produced water (kg/m<sup>3</sup>).

$M_i = C_i Q_i$  = Inlet mass rate of oil in kg/min;  $M_o = C_o Q_o$  = Outlet mass rate of oil in kg/min.

We choose  $\frac{D}{W} = 0.5000$

But,

$$\frac{0.9144}{W} = 0.5000$$

$$W = \frac{0.9144}{0.5000} = 1.8288m$$

For  $V_H = \frac{Q_i}{DW}$

$$VH = \frac{1.2}{0.9144 \times 1.8288} = 0.7175 m$$

Which satisfied the API standard of  $V_H \leq 0.9144m/min$ .

Also

$$t = \frac{D}{V_t} = \frac{0.9144}{0.1047} = 8.7335 min$$

$$V = Q_i * t = 1.2 * 8.7335 = 10.4802$$

$$L = \frac{V}{WD} = \frac{10.4802}{1.8288 * 0.9144} = 6.2671m$$

$$\frac{L}{W} = 5 - 1 \text{ (API)}$$

Hence,  $\frac{6.2671}{1.8288} = 5 - 1$  satisfying (API standard).

[5] stated that practically the flow rate of waste water/produced water in every standard conventional separator decreases as it flows from the inlet to the outlet due to the presence of laminar flow enhancing devices such as flow distributor, grit chamber, baffles and velocity-head diffusion devices. Additionally same is the case for oil-water concentration in the separator as it flows and gravity separation taking place inside the separator as a result of laminar flow, residence time and densities of the immiscible liquid. However, considering a 6% reduction in the flow rate  $Q$ , through the separator and 95% reduction in the produced water concentration also through the separator.

We have assumed the following:

$$Q_o = Q_i - 0.06(Q_i)$$

$$Q_o = 1.2 - 0.06(1.2) = 1.2 - 0.072 = 1.128 m/min$$

And

$$C_o = C_i - 0.95(C_i)$$

$$C_o = 0.283 - 0.95(0.283) = 0.283 - 0.2688 = 0.0141kg/m^3.$$

Using the equation of separation, according to [4]

$$E = \frac{C_i Q_i - C_o Q_o}{C_i Q_i} = \frac{0.283 * 1.2 - 0.0141 * 1.128}{0.283 * 1.2}$$

$$E = \frac{0.3396 - 0.0159}{0.3396} = \frac{0.3237}{0.3396} = 0.9532 = 95.32\%$$

Aspect ratio derived from [1] stated as follows;  $R = \frac{L}{W}$

Hence,

$$R = \frac{V Q_i C_i (1 - E)}{Q_o C_o W^2 D} = \frac{10.4802 * 1.2 * 0.283 (1 - 0.9532)}{1.128 * 0.0141 * 1.8288^2 * 0.9144}$$

$$R = \frac{0.1665}{0.0486} = 3.4230$$

$$L = F \frac{Q_i * t}{W * D}$$

$$F = 1.2 * (F_t) = 1.2 * 1.14 = 1.368$$

$$\text{Hence, } L = \frac{1.368 * 1.2 * 8.733}{0.9144 * 1.8288} = 8.572 \text{ m}$$

### 3.3. Using Modified Design Method

The new expressions like the efficiency time model, aspect ratio, flow rate, velocity developed by inserting the hydrostatic pressure formed the modified design method. However, [2] stated that conventional oil-water separators are designed based on the following criteria:

- Horizontal velocity of produced water/wastewater through the oil-water separator should be less than or equal to 0.9144 metres/minute or 15 times the rise rate ( $V_t$ ) of the oil globules ( $15V_t$ ) whichever is smaller.
  - Depth of oil-water separator D, 0.9144 m – 2.4384 m.
  - Maintain  $\frac{D}{W}$  ratio of 0.3 to 0.5
  - Adjust the depth and width of separator until you achieve a horizontal velocity  $\leq 3$ . Ideal horizontal velocity should be in the range  $\leq 2$  at average flow.
  - The width of oil-water separator ranges from 1.8288 m to 6.096 m.
  - Minimum  $\frac{L}{W}$  for oil-water separator is 5 to 1.
  - An oil droplet size of 150 microns is typically the norm for API separator and the minimum useable value is 60 microns. Hence,
- $$V_t = \frac{g(\rho_w - \rho_o)d^2}{18\mu} = \frac{9.81(955 - 881)0.00015^2}{18 * 0.00052} = \frac{9.81 * 74 * 2.25^{-8}}{9.36^{-03}} = 0.00174 * 60 = 0.1047 \text{ m/min}$$

Let  $D = 0.9144$  (API standard). Where  $h = D$

$$P = hgp = hg(\rho_w - \rho_{oil}) = 0.9144 * 9.81(955 - 881)$$

$$P = 0.9144 * 9.81 * 74 = 663.7995 \text{ Kg/m}^2$$

$$\text{Let } \frac{D}{W} = 0.500 \quad (\text{API standard})$$

$$\frac{0.9144}{W} = 0.500 \quad ;$$

$$W = \frac{0.8144}{0.5000} = 1.8288$$

$$V_H = \frac{Q_i \rho g}{WP} = \frac{1.2(955 - 881) * 9.81}{1.8288 * 663.7995} = 0.7175$$

$V_H$  – Satisfies API criteria.  $V_H \leq 0.9144$

$$t = \frac{P}{\rho g V_t} = \frac{663.7995}{(955 - 881) * 9.81 * 0.1047} = 8.7 \text{ min}$$

$$V = \frac{Q_i P}{\rho g V_t} = \frac{1.2 * 663.7995}{9.81 * 0.1047 * (955 - 881)} = \frac{796.5594}{76.0059} = 10.4802 \text{ m}^3$$

$$L = \frac{Q_i P}{W D \rho g V_t} = \frac{1.2 * 663.7995}{0.9144 * 1.8288 * 9.81 * 0.1047 (955 - 881)} = 6.2671 \text{ m}$$

$$E = \frac{C_i V \rho g V_t P^{-1} - C_o Q_o}{C_i V \rho g V_t P^{-1}}$$

We have assume the following:

$$Q_o = Q_i - 0.06(Q_i)$$

$$Q_o = 1.2 - 0.06(1.2) = 1.2 - 0.07 = 1.128 \text{ m/min}$$

$$C_o = C_i - 0.95(C_i)$$

$$C_o = 0.283 - 0.95(0.283) = 0.283 - 0.2688 = 0.0141 \text{ kg/m}^3.$$

$$E = 1 - \frac{C_o Q_o}{C_i V \rho g V_t P^{-1}} = \frac{0.0159}{0.3395} = 0.9532 = 95.32\%$$

$$\begin{aligned} R &= \frac{Q_i P}{\rho g V_t W^2 D} \\ &= \frac{1.2 * 663.7995}{(955 - 881) * 9.81 * 0.1047 * 1.8288^2 * 0.9144} \\ &= \frac{796.5594}{232.4427} = 3.4269 \end{aligned}$$

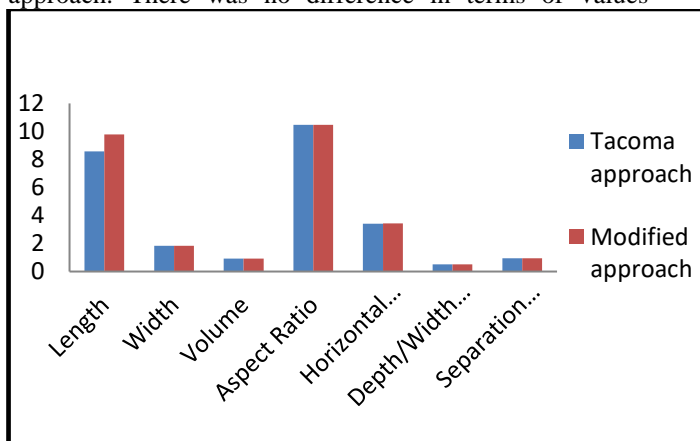
$$\text{Design length of separator} = \text{initial length} * F = 6.2671 * 1.5618 = 9.7878$$

**Table 4:** Comparison of City of Tacoma design approach and Modified Design methods

Type	Length (m)	Width (m)	Depth (m)	Volume (m <sup>3</sup> )	Aspect ratio (Length to Width)	Horizontal Vel, V <sub>H</sub> (m/min)	Depth to width ratio	Design oil separation efficiency %
City of Tacoma design approach	8.572	1.8288	0.9144	10.480	3.4230	0.7175	0.5	95.32
Modified Design methods	9.787	1.8288	0.9144	10.480	3.4269	0.7175	0.5	95.32

Designing the conventional oil-water separator with the City of Tacoma design approach and the Modified design method approach all satisfied the API design criteria. The City of Tacoma design approach is a standard method and procedure for designing conventional oil-water separator with respect to API criteria. In most design approach relating to oil-water separator design, pressure was never inclusive; hence the need to incorporate pressure into the design approach named modified design method became important part of this work. The API design criterion was same as applicable to both City of Tacoma design approach and the modified design method. It is interesting to note that from the summary of Table 4.0 the various parameter calculated seems to be in tandem with each other when considering the two design methods or approach. There was no difference in terms of values

obtained for the width, depth, volume, horizontal velocity, depth to width ratio, separation efficiency. However, there was a significant difference in the design length of the separator considering the two approaches. The modified design method shows great improvement in the overall length of the separator which is a cardinal property of gravity separator. However, there was a negligible difference in the Aspect ratio (Length to width ratio) value between the two design approaches. This value as could be seen from Table 4.0 is 0.0039 representing 0.114%. Incorporating pressure into the design of separator is in agreement with the works of [6] where he extended the API design criteria to design free-water knockout vessels for better capacity and performance.



**Fig. 1.** Comparison between the City of Tacoma design approach and Modify design approach.

#### 4. Conclusions

Considering the oil separation efficiency, the values obtained using the two approaches were absolutely relevant in mitigating the effect of oil pollution by controlling effluent oil limit in the design of conventional oil-water separator. Equally useful was incorporating pressure into the design approach as seen in the literature, since oil-water separator are called pressure vessels. Knowing initial pressure of the vessel prior to hydro-testing through the design approach can enhance proper working of the vessel. It can also reduce the time spent in determining minimum and maximum pressure rating for the vessel including leak-off test.

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