NTNU – Trondheim
Norwegian University of
Science and Technology

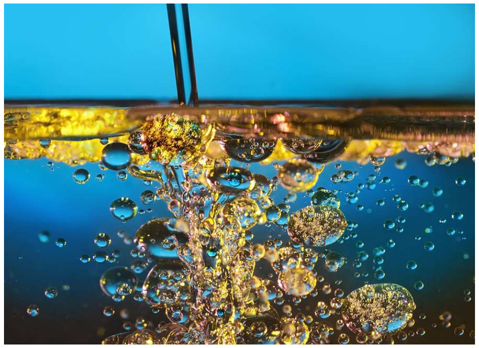
Production Technology

Field Processing and Systems

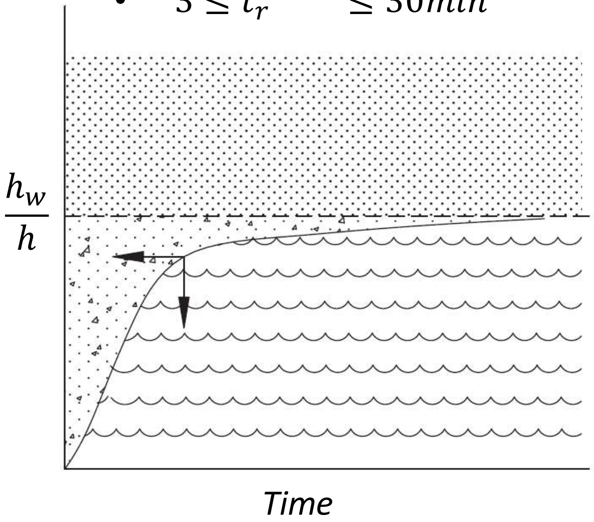
Postdoc Mariana Díaz
02 /04/2019

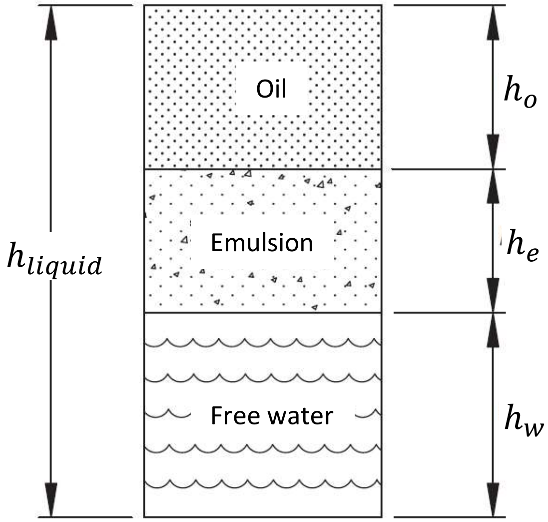
OIL-WATER SEPARATION

- Separation of two immiscible liquid phases



- Settling time
- $3 \leq t_r^{water} \leq 30min$





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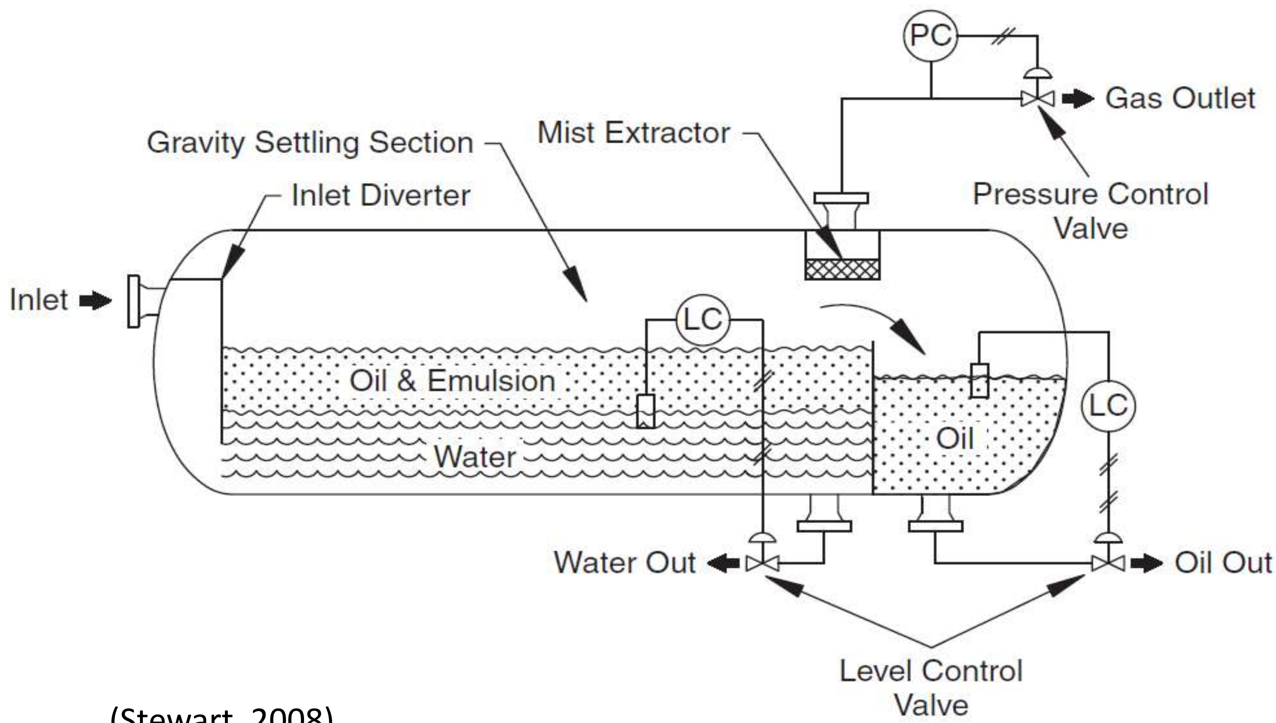
OIL-WATER SEPARATION



(Stewart, 2008)

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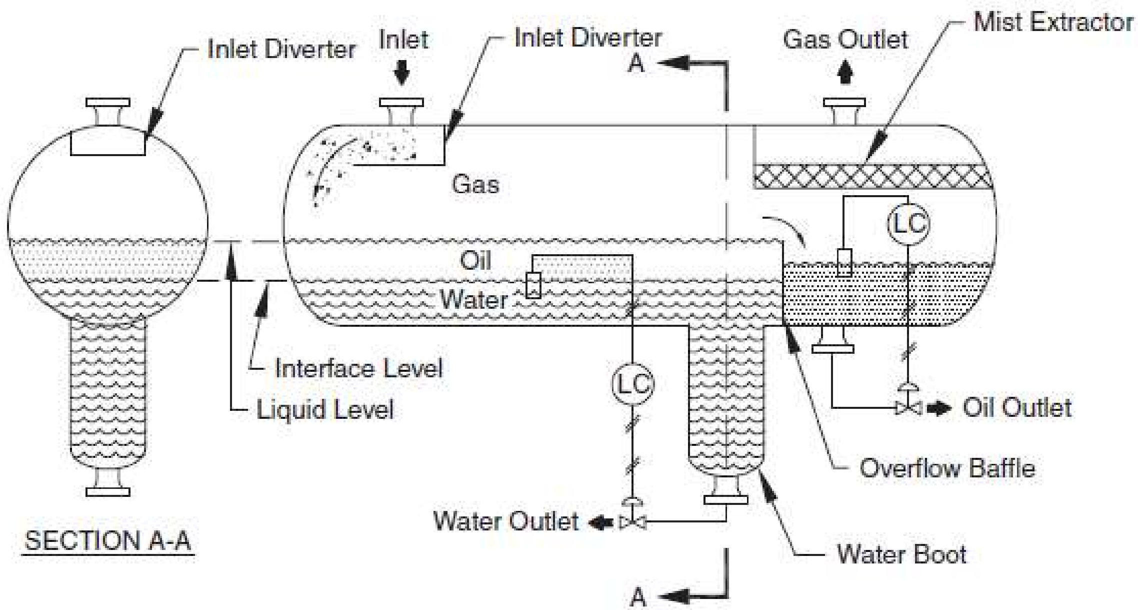
Horizontal configurations

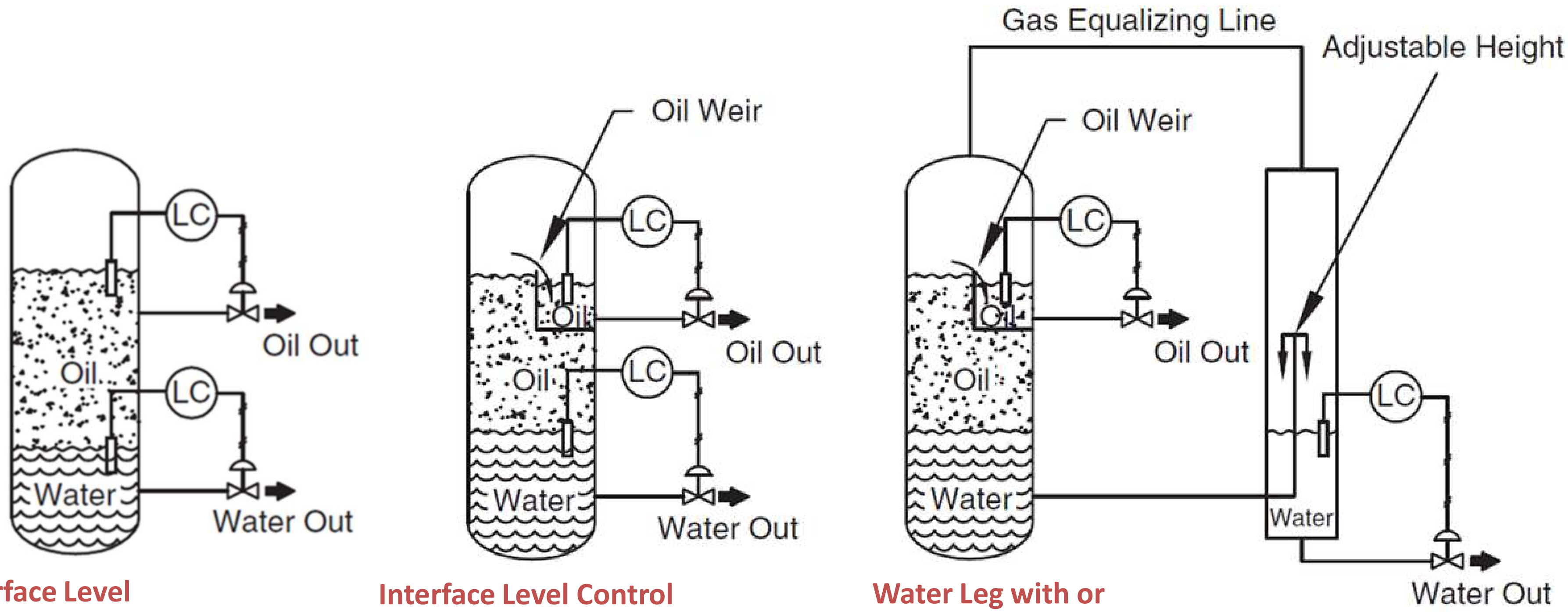
Liquid "Boot"



(Stewart, 2008)

- Water flow rate is very low relative to the oi flow rate

Vertical Liquid Control Strategies



Interface Level Control

Interface Level Control with oil chamber

Water Leg with or without Oil Chamber

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DESIGN THEORY-THREE PHASE HORIZONTAL SEP

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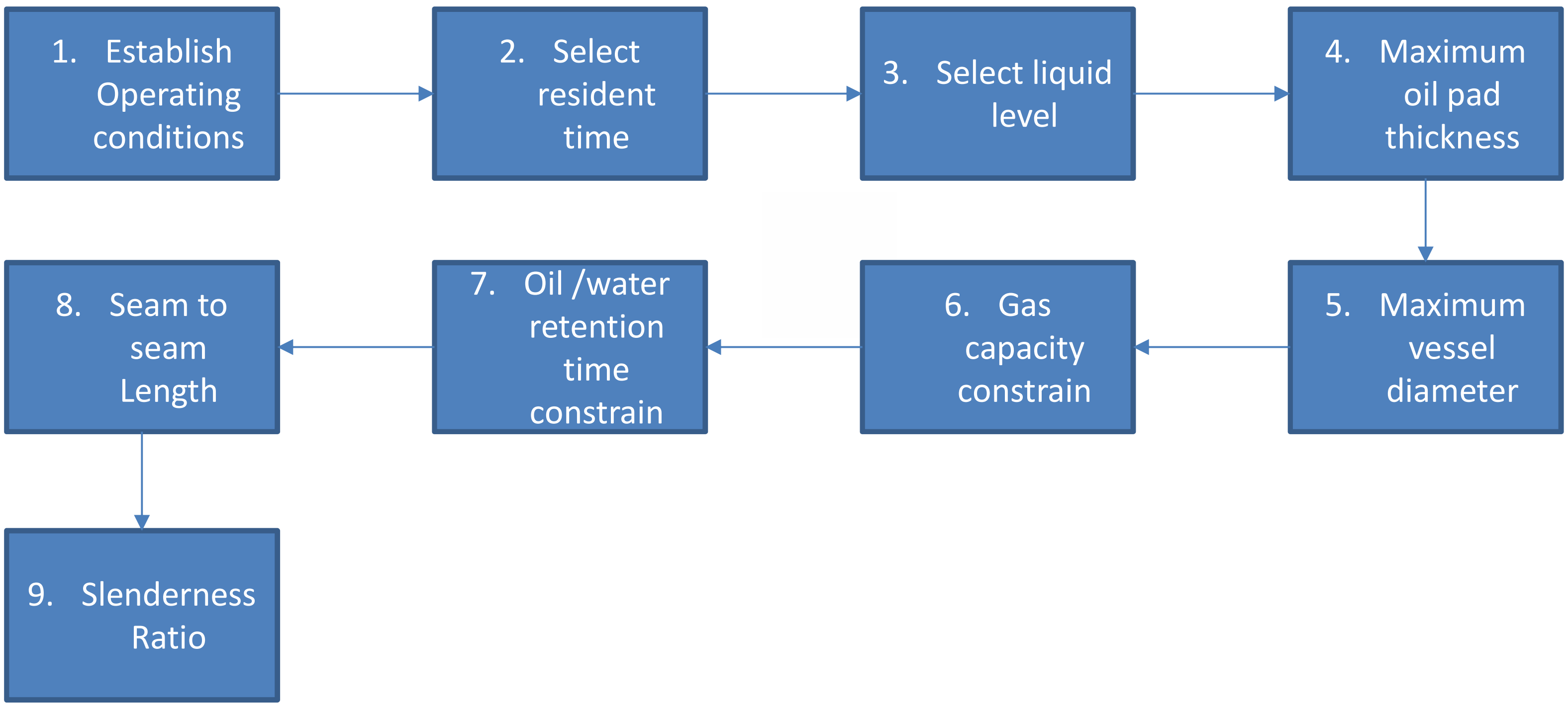
Design Theory-Horizontal Vessel



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Design Theory-Horizontal Vessel

1. Establish Operating conditions → 2. Select resident time → 3. Select liquid level → 4. Maximum oil pad thickness

1. Establish Operating conditions

Q_{oil}^{max}

Q_{water}^{max}

P, T

d_p^{oil} $(200\mu m)$

d_p^{water} $(500\mu m)$

d_p^{liq} $(150\mu m)$

2. Select resident time

t_r^o

t_r^w

Oil retention time

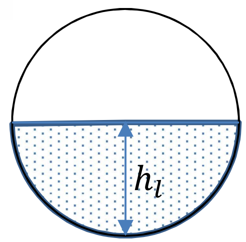
°API Gravity	Time (Min)
Condensate	2–5
Light crude oil (30°–40°)	5–7.5
Intermediate crude oil (20°–30°)	7.5–10
Heavy crude oil (less than 20°)	10+

Note: If an emulsion exists in inlet stream, increase above retention times by a factor of 2–4.

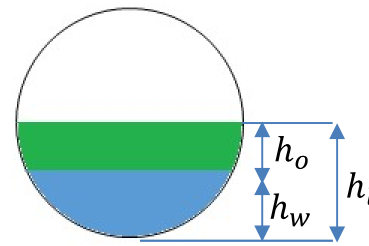
3. Select liquid level

- 50%-75%

Half-full



4. Maximum oil pad thickness



$$h_o^{max} = V_t^{wd} t_r^o$$

- **Stoke's Law**

$$V_t^{wd} = \frac{1000g\left(d_p^{water}\right)^2(\rho_p - \rho_f)}{18\mu}$$

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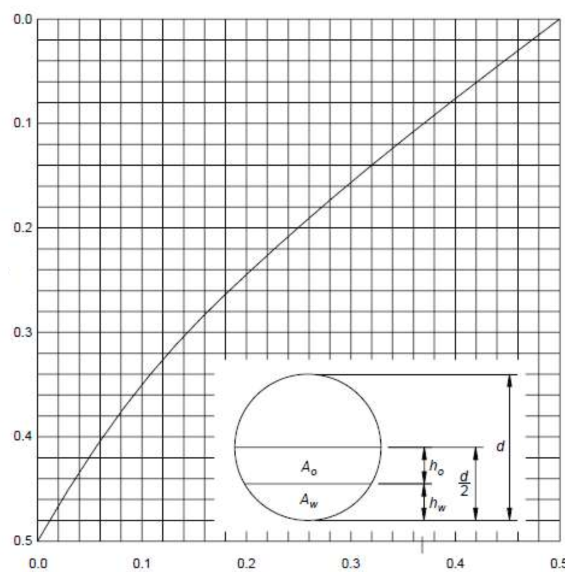
Design Theory-Horizontal Vessel

5. Maximum vessel diameter

$$\frac{A_w}{A_t} \rightarrow A = \frac{Q\ t}{L} \rightarrow \boxed{\frac{A_w}{A_t} = \frac{Q_w t_r^w}{2(Q_w t_r^w + Q_o t_r^o)}}$$

Half-full $A_t = 2\ A_l$ $\rightarrow$ $\beta = \frac{h_o}{D_v}$



$$\frac{A_w}{A_t}$$

$$\rightarrow \boxed{D_v^{max} = \frac{h_o^{max}}{\beta}}$$

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Design Theory-Horizontal Vessel

6. Gas capacity constrain → 7. Oil /water retention time constrain → 8. Seam to seam Length → 9. Slenderness Ratio

Half-full

$$L_{eff} D_v > \frac{4}{\pi} \frac{Q_g}{V_t}$$

$$Vol_{liq} = Vol_o + Vol_w$$

Half-full $Vol_{liq} = \frac{1}{2} Vol_T$

$$L_{eff}(D_v)^2 = \frac{8}{\pi}(Q_w t_r^w + Q_o t_r^o)$$

- Gas capacity

$$L_{ss}^{g.c} = L_{eff} + D_v$$

- Liquid capacity

$$L_{ss}^{l.c} = \frac{4}{3} L_{eff}$$

$$L_{ss} = \max(L_{ss}^{g.c}; L_{ss}^{l.c})$$

$$SR = \frac{L_{ss}}{D_v}$$

$3 < SR < 5$

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Design Theory-Horizontal Vessel

Exercise

$Q_o = 5000\ BOPD$

$Q_w = 3000\ BWPD$

$Q_g = 5\ MMscfd$

$P = 690\ kpa$

$T = 32.2\ °C$

OIL $30\ API$

$sg^w = 1.07$

$sg^g = 0.6$

$Cd = 2.01$

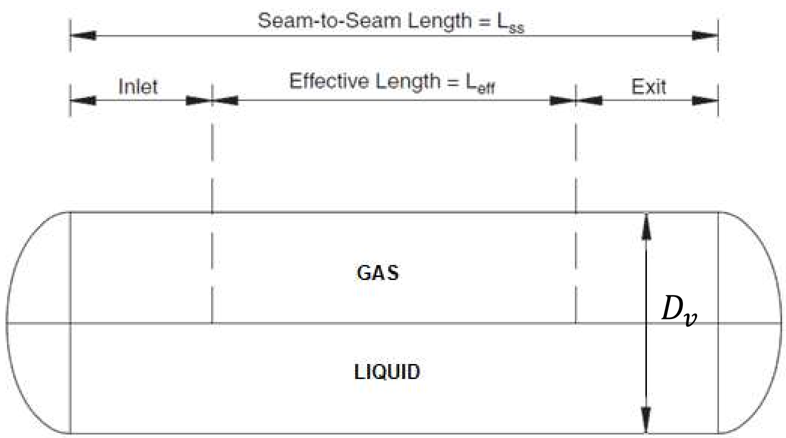
$d_p^l = 100\mu m$

$d_p^o = 200\mu m$

$d_p^w = 500\mu m$

$Z = 0.84$

$t_r^w = t_r^o = 10min$



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Design Theory-Horizontal Vessel

Exercise

$Q_o = 5000\ BOPD$

$Q_w = 3000\ BWPD$

$Q_g = 5\ MMscfd$

$P = 690\ kpa$

$T = 32.2\ °C$

OIL $30\ API \longrightarrow 875.3\ kg/m^3$

$sg^w = 1.07 \rightarrow 1068.9\ kg/m^3$

$sg^g = 0.6 \longrightarrow 0.733\ kg/m^3 \longrightarrow a.c. \rightarrow 5.6\ kg/m^3$

$Q_g^{a.c} = 770\ m^3/h$

$Cd = 2.01$

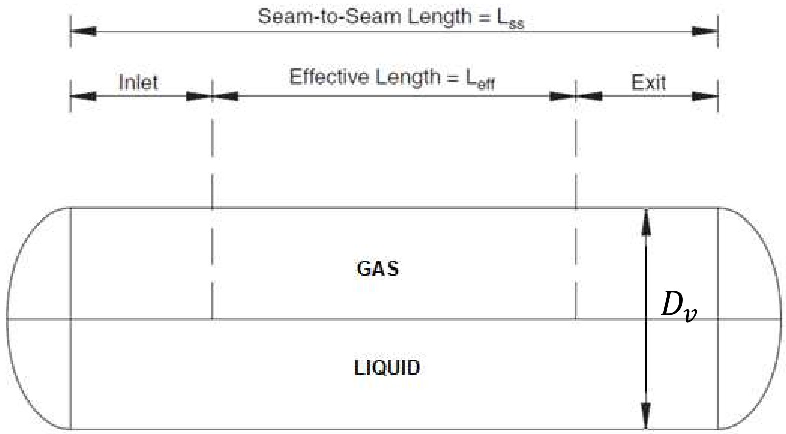
$d_p^l = 100 \mu m$

$d_p^o = 200 \mu m$

$d_p^w = 500 \mu m$

$Z = 0.84$

$t_r^w = t_r^o = 10 min$



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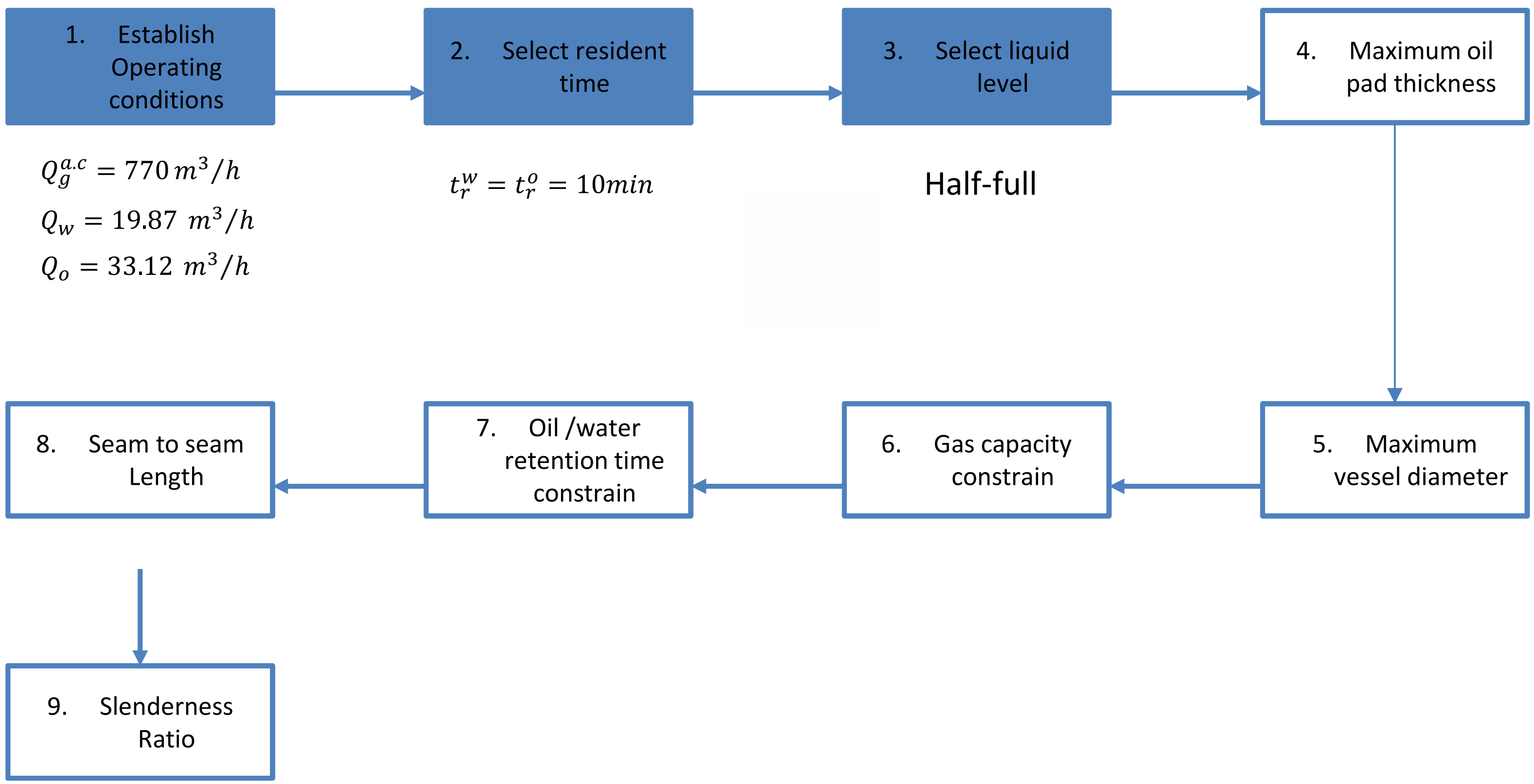
Design Theory-Horizontal Vessel

Exercise



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Design Theory-Horizontal Vessel

Exercise

1. Establish Operating conditions

$$Q_g^{a.c} = 770\, m^3/h$$
$$Q_w = 19.87\ m^3/h$$
$$Q_o = 33.12\ m^3/h$$

2. Select resident time

$$t_r^w = t_r^o = 10min$$

3. Select liquid level

Half-full

4. Maximum oil pad thickness

$$V_t^{wd} = \frac{1000g\left(d_p^{water}\right)^2(\rho_w - \rho_o)}{18\mu_o}$$
$$V_t^{wd} = 0.00264 m/s$$
$$h_o^{max} = 1.58m$$

5. Maximum vessel diameter
6. Gas capacity constrain
7. Oil /water retention time constrain
8. Seam to seam Length
9. Slenderness Ratio

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Design Theory-Horizontal Vessel

Exercise

1. Establish Operating conditions

$Q_g^{a.c} = 770\, m^3/h$

$Q_w = 19.87\ m^3/h$

$Q_o = 33.12\ m^3/h$

2. Select resident time

$t_r^w = t_r^o = 10min$

3. Select liquid level

Half-full

4. Maximum oil pad thickness

$$V_t^{wd} = \frac{1000g\left(d_p^{water}\right)^2(\rho_w - \rho_o)}{18\mu_o}$$

$V_t^{wd} = 0.00264m/s$

$h_o^{max} = 1.58m$

5. Maximum vessel diameter

$$\frac{A_w}{A_t} = \frac{Q_w t_r^w}{2(Q_w t_r^w + Q_o t_r^o)} = 0.1875$$

$$D_v^{max} = \frac{h_o^{max}}{\beta} = 6.10m$$

6. Gas capacity constrain

7. Oil /water retention time constrain

8. Seam to seam Length

9. Slenderness Ratio

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Design Theory-Horizontal Vessel

Exercise

1. Establish Operating conditions

$$Q_g^{a.c} = 770\, m^3/h$$

$$Q_w = 19.87\ m^3/h$$

$$Q_o = 33.12\ m^3/h$$

2. Select resident time

$$t_r^w = t_r^o = 10min$$

3. Select liquid level

Half-full

4. Maximum oil pad thickness

$$V_t^{wd} = \frac{1000g\left(d_p^{water}\right)^2(\rho_w - \rho_o)}{18\mu_o}$$

$$V_t^{wd} = 0.00264m/s$$

$$h_o^{max} = 1.58m$$

5. Maximum vessel diameter

$$\frac{A_w}{A_t} = \frac{Q_w t_r^w}{2(Q_w t_r^w + Q_o t_r^o)} = 0.1875$$

$$D_v^{max} = \frac{h_o^{max}}{\beta} = 6.10m$$

6. Gas capacity constrain

$$V_t^{ld} = \sqrt{\frac{4\left(d_p^{liq}\right)g\left(\rho_l - \rho_g\right)}{3\, C_d\, \rho_g}}$$

V_t^{ld} =0.335m/s

$$L_{eff} D_v > \frac{4}{\pi}\frac{Q_g}{V_t}$$

7. Oil /water retention time constrain

$$L_{eff}(D_v)^2 = \frac{8}{\pi}(Q_w t_r^w + Q_o t_r^o)$$

8. Seam to seam Length

$$L_{ss} = \max(L_{ss}^{g.c}; L_{ss}^{l.c})$$

9. Slenderness Ratio

$$SR = \frac{L_{ss}}{D_v}$$

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Design Theory-Horizontal Vessel

Exercise

1. Establish Operating conditions → 2. Select resident time → 3. Select liquid level → 4. Maximum oil pad thickness → 5. Maximum vessel diameter

1. Establish Operating conditions

$$Q_g^{a.c} = 770\, m^3/h$$

$$Q_w = 19.87\ m^3/h$$

$$Q_o = 33.12\ m^3/h$$

2. Select resident time

$$t_r^w = t_r^o = 10min$$

3. Select liquid level

Half-full

4. Maximum oil pad thickness

$$V_t^{wd} = \frac{1000g\left(d_p^{water}\right)^2(\rho_w - \rho_o)}{18\mu_o}$$

$$V_t^{wd} = 0.00264m/s$$

$$h_o^{max} = 1.58m$$

5. Maximum vessel diameter

$$\frac{A_w}{A_t} = \frac{Q_w t_r^w}{2(Q_w t_r^w + Q_o t_r^o)} = 0.1875$$

$$D_v^{max} = \frac{h_o^{max}}{\beta} = 6.10m$$

Dv		Leff_gas	Leff_liquid	Lss_gas	Lss_liquid	Lss	SR
(in)	(m)	(m)	(m)	(m)	(m)	(m)	
60	1.5	0.5	9.7	11.2	12.9	12.9	8.5
72	1.8	0.4	6.7	8.6	9.0	9.0	4.9
84	2.1	0.4	4.9	7.1	6.6	7.1	3.3
96	2.4	0.3	3.8	6.2	5.0	6.2	2.6
108	2.7	0.3	3.0	5.7	4.0	5.7	2.1

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Design Theory-Horizontal Vessel

Exercise

$Q_o = 5000\ BOPD$

$Q_w = 3000\ BWPD$

$Q_g = 5\ MMscfd$

$P = 690\ kpa$

$T = 32.2\ °C$

OIL $30\ API$

$sg^w = 1.07$

$sg^g = 0.6$

$Cd = 2.01$

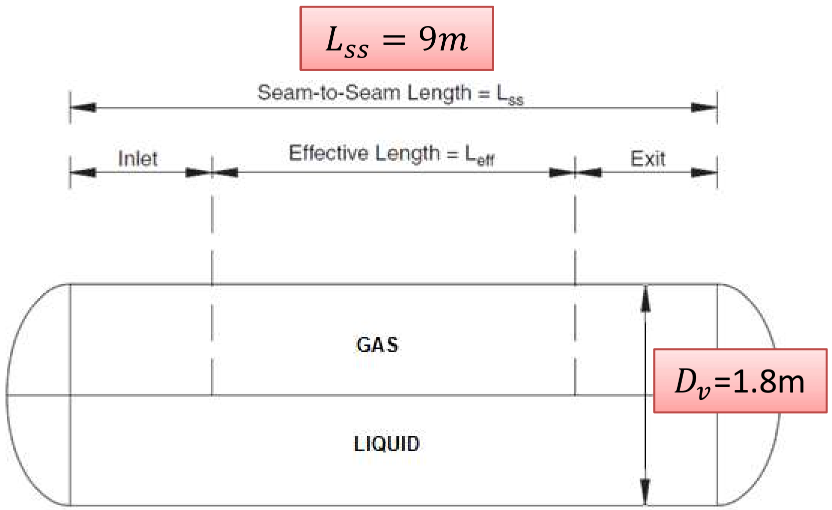
$d_p^l = 100\mu m$

$d_p^o = 200\mu m$

$d_p^w = 500\mu m$

$Z = 0.84$

$t_r^w = t_r^o = 10min$



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Design Theory-Vertical Vessel for Liquid/Liquid

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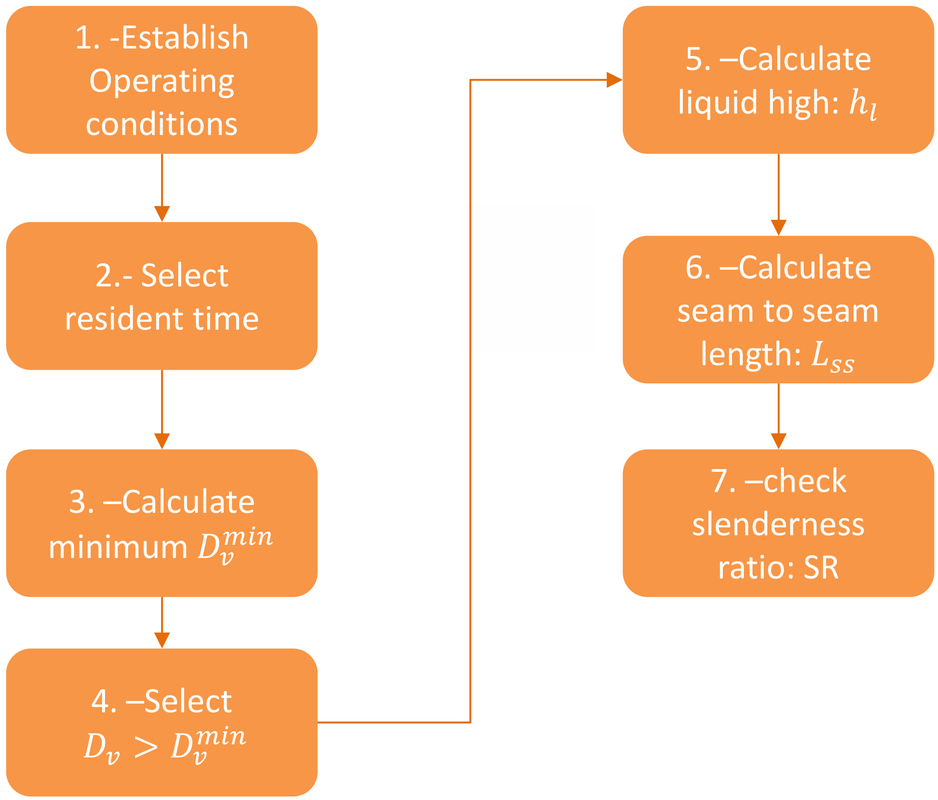
Design Theory-Vertical Vessel



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Design Theory-Vertical Vessel

1. -Establish Operating conditions

Q_{oil}^{max} ; Q_{water}^{max}; P, T ; d_p^{oil}; d_p^{water} ; d_p^{liq}

(200μm) (500μm) (150μm)

2.- Select resident time

t_r^o ; t_r^w

Oil retention time

°API Gravity	Time (Min)
Condensate	2–5
Light crude oil (30°–40°)	5–7.5
Intermediate crude oil (20°–30°)	7.5–10
Heavy crude oil (less than 20°)	10+

Note: If an emulsion exists in inlet stream, increase above retention times by a factor of 2–4.

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Design Theory-Vertical Vessel

3. –Calculate minimum D_v^{min}

$$V_{continuous\ phase} < V_{t\_particle}$$

$$D_v^{min} = \max(D_v^{gas};\ D_v^{water};\ D_v^{oil})$$

2.1. -Gas capacity constrain

$$D_v^{gas} = \sqrt{\frac{Q_g^{a.c}}{V_t}\frac{4}{\pi}}$$

$$V_t \rightarrow f\left(d_p^{liq}, \rho_l, \rho_g\right)$$

$$\rho_l = wc * \rho_w + (1 - wc) * \rho_o$$

2.2. –Water droplets settling

$$D_v^{water} = \sqrt{\frac{Q_o}{V_t}\frac{4}{\pi}}$$

- **Stoke's Law**

$$V_t^{wd} = \frac{1000g\left(d_p^{water}\right)^2\left(\rho_p - \rho_f\right)}{18\mu}$$

2.3. –Oil droplets rise

$$D_v^{oil} = \sqrt{\frac{Q_w}{V_t}\frac{4}{\pi}}$$

- **Stoke's Law**

$$V_t^{od} = \frac{1000g\left(d_p^{oil}\right)^2\left(\rho_p - \rho_f\right)}{18\mu}$$

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Design Theory-Vertical Vessel

4. –Select $D_v > D_v^{min}$

5. –Calculate liquid high: h_l

$$Vol_{liq} = Vol_o + Vol_w$$

$$Vol_{liq} = A_v * h_{liq}$$

$$h_{liq} = (h_w + h_o) = \frac{t_r^o Q_o + t_r^w Q_w}{A_v}$$

6. –Calculate seam to seam length: L_{ss}

$$Lss = 4" + \max(h_l; 36") + max(2 * ID; 24) + \max(\mathrm{D_V}+6; 42") + 6"$$

7. –check slenderness ratio: SR

$$SR = \frac{L_{ss}}{D_v}$$

$$1.5 < SR < 3$$

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Design Theory-Vertical Vessel

Exercise

$Q_o = 5000\ BOPD$

$Q_w = 3000\ BWPD$

$Q_g = 5\ MMscfd$

$P = 690\ kpa$

$T = 32.2\ °C$

OIL 30 $API \longrightarrow$ $875.3\ kg/m^3$

$sg^w = 1.07 \rightarrow$ $1068.9\ kg/m^3$

$sg^g = 0.6 \longrightarrow$ $0.733\ kg/m^3 \longrightarrow$ $a.c. \rightarrow 5.6\ kg/m^3$

$Q_g^{a.c} = 770\ m^3/h$

$Cd = 2.01$

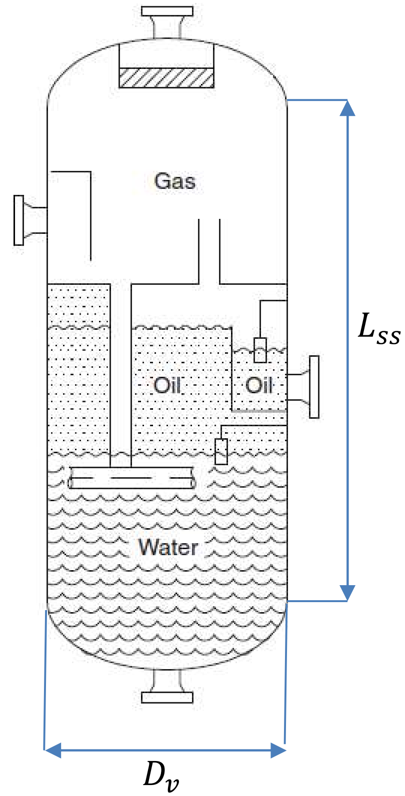
$d_p^l = 100\mu m$

$d_p^o = 200\mu m$

$d_p^w = 500\mu m$

$Z = 0.84$

$t_r^w = t_r^o = 10min$



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Design Theory-Vertical Vessel

1. -Establish Operating conditions

$$Q_g^{a.c} = 770\, m^3/h$$
$$Q_w = 19.87\ m^3/h$$
$$Q_o = 33.12\ m^3/h$$

2.- Select resident time

$$t_r^w = t_r^o = 10min$$

3. –Calculate minimum D_v^{min}

4. –Select $D_v > D_v^{min}$

5. –Calculate liquid high: h_l

6. –Calculate seam to seam length: L_{ss}

7. –check slenderness ratio: SR

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Design Theory-Vertical Vessel

1. -Establish Operating conditions

$Q_g^{a.c} = 770\, m^3/h$

$Q_w = 19.87\ m^3/h$

$Q_o = 33.12\ m^3/h$

2.- Select resident time

$t_r^w = t_r^o = 10min$

3. –Calculate minimum D_v^{min}

$$D_v = \sqrt{\frac{Q_x^{a.c}}{V_t}\frac{4}{\pi}}$$

2.1. -Gas capacity constrain	$V_t^{Ld} = 0.335\ m/s$	$D_v^{min} = 0.90m$
2.2. –Water droplets settling	$V_t^{Wd} = 0.00264\ m/s$	$D_v^{min} = 2.11m$
2.3. –Oil droplets rise	$V_t^{Od} = 0.00422\ m/s$	$D_v^{min} = 1.29m$

4. –Select $D_v > D_v^{min}$

5. –Calculate liquid high: h_l

6. –Calculate seam to seam length: L_{ss}

7. –check slenderness ratio: SR

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Design Theory-Vertical Vessel

1. -Establish Operating conditions

$Q_g^{a.c} = 770\, m^3/h$

$Q_w = 19.87\ m^3/h$

$Q_o = 33.12\ m^3/h$

2.- Select resident time

$t_r^w = t_r^o = 10min$

3. –Calculate minimum D_v^{min}

2.1. -Gas capacity constrain	$V_t^{Ld} = 0.335\ m/s$	$D_v^{min} = 0.90m$
2.2. –Water droplets settling	$V_t^{Wd} = 0.00264\ m/s$	$D_v^{min} = 2.11m$
2.3. –Oil droplets rise	$V_t^{Od} = 0.00422\ m/s$	$D_v^{min} = 1.29m$

4. –Select $D_v > D_v^{min}$

$$D_v > D_v^{min} = 2.11m = 83in$$

5. –Calculate liquid high: h_l

6. –Calculate seam to seam length: L_{ss}

7. –check slenderness ratio: SR

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Design Theory-Vertical Vessel

1. -Establish Operating conditions

$Q_g^{a.c} = 770\, m^3/h$

$Q_w = 19.87\ m^3/h$

$Q_o = 33.12\ m^3/h$

2.- Select resident time

$t_r^w = t_r^o = 10min$

3. –Calculate minimum D_v^{min}

2.1. -Gas capacity constrain	$V_t^{Ld} = 0.335\ m/s$	$D_v^{min} = 0.90m$
2.2. –Water droplets settling	$V_t^{Wd} = 0.00264\ m/s$	$D_v^{min} = 2.11m$
2.3. –Oil droplets rise	$V_t^{Od} = 0.00422\ m/s$	$D_v^{min} = 1.29m$

4. –Select $D_v > D_v^{min}$

$$D_v > D_v^{min} = 2.11m = 83in$$

5. –Calculate liquid high: h_l

$$h_{liq} = (h_w + h_o) = \frac{t_r^o Q_o + t_r^w Q_w}{A_v}$$

6. –Calculate seam to seam length: L_{ss}

$$Lss = 4" + \max(h_l; 36") + max(2 * ID; 24) + \max(D_v + 6; 42") + 6"$$

7. –check slenderness ratio: SR

$$SR = \frac{L_{ss}}{D_v}$$

$1.5 < SR < 3$

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Design Theory-Vertical Vessel

1. -Establish Operating conditions

$Q_g^{a.c} = 770\, m^3/h$

$Q_w = 19.87\ m^3/h$

$Q_o = 33.12\ m^3/h$

2.- Select resident time

$t_r^w = t_r^o = 10min$

3. –Calculate minimum D_v^{min}

- 2.1. -Gas capacity constrain: $V_t^{Ld} = 0.335\ m/s$, $D_v^{min} = 0.90m$
- 2.2. –Water droplets settling: $V_t^{Wd} = 0.00264\ m/s$, $D_v^{min} = 2.11m$
- 2.3. –Oil droplets rise: $V_t^{Od} = 0.00422\ m/s$, $D_v^{min} = 1.29m$

4. –Select $D_v > D_v^{min}$

$D_v > D_v^{min} = 2.11m = 83in$

5. –Calculate liquid high: h_l

$h_{liq} = (h_w + h_o) = \frac{t_r^o Q_o + t_r^w Q_w}{A_v}$

6. –Calculate seam to seam length: L_{ss}

$Lss = 4" + \max(h_l; 36") + max(2 * ID; 24) + \max(D_v + 6; 42") + 6"$

7. –check slenderness ratio: SR

$SR = \frac{L_{ss}}{D_v}$

$1.5 < SR < 3$

Dv (in)	Dv (m)	hw+ho (m)	Lss (m)	SR -
84	2.13	2.47	5.62	2.63
90	2.29	2.15	5.45	2.39
96	2.44	1.89	5.35	2.19
102	2.59	1.68	5.28	2.04

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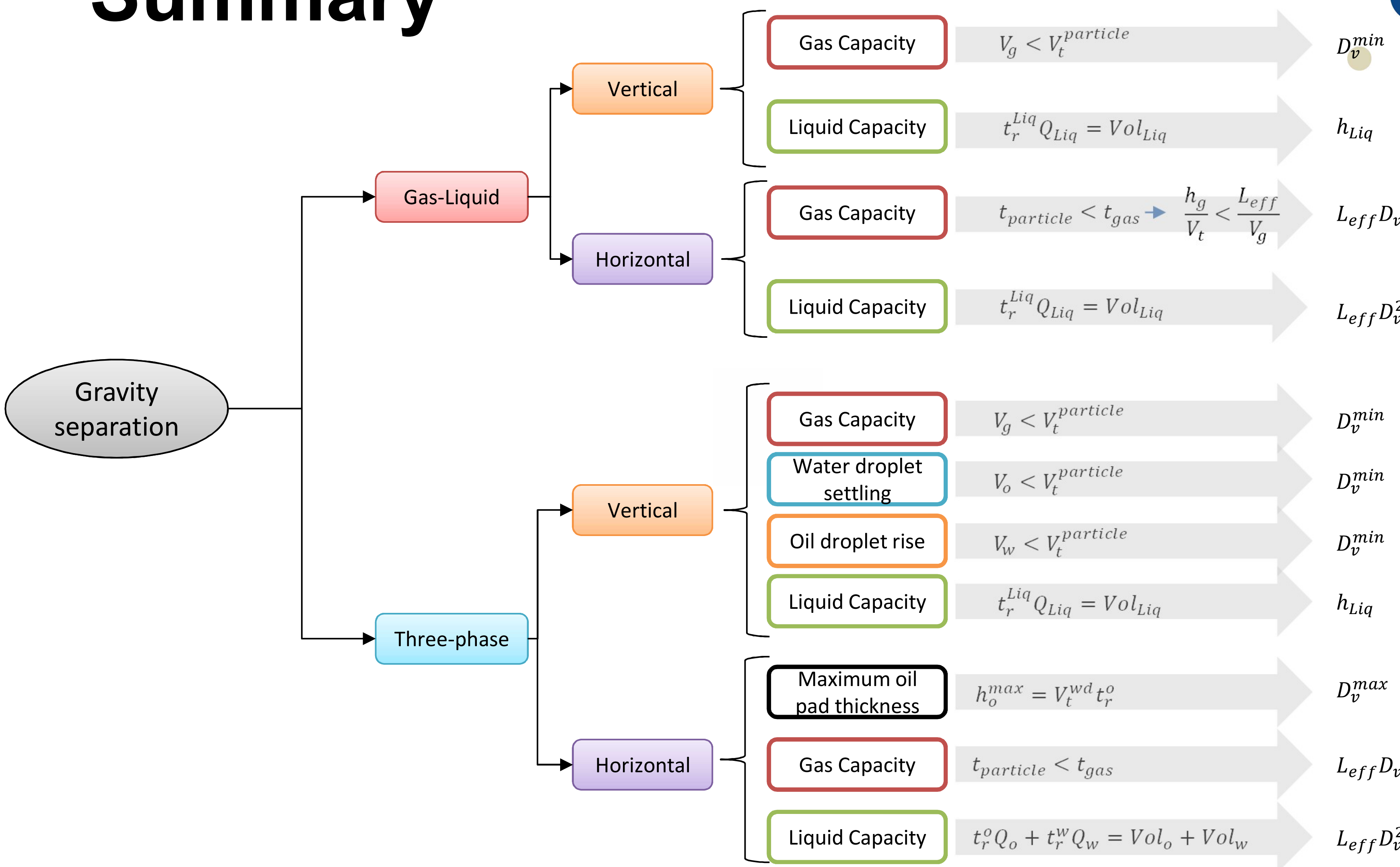
Summary



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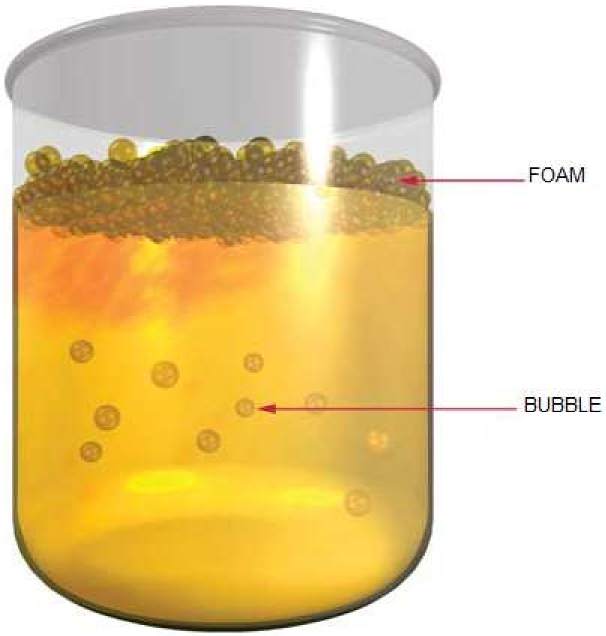
Operational Problems

- ## Foamy crude

  - Due to presence of impurities other than water, i.e CO2
  - Problems:
    - Mechanical control of liquid levels are more difficult because must deal with three liquid phases instead of two
    - Foam volume has large volume-to-weight ratio that take space from the liquid or gravity settling section
    - It can become more difficult to separate the phases without some entrainment of the foam material through any of the phase outlets



- Oil foaming tendencies is determined with laboratory test
- The foam requires good internals design to ensure sufficient coalescing surface or residence time for the foam to break
- When sizing a separator sufficient capacity should be provided to handle the foam problems without use of a foam inhibitor, this because characteristics of the crude and the foam may change during the life of the field

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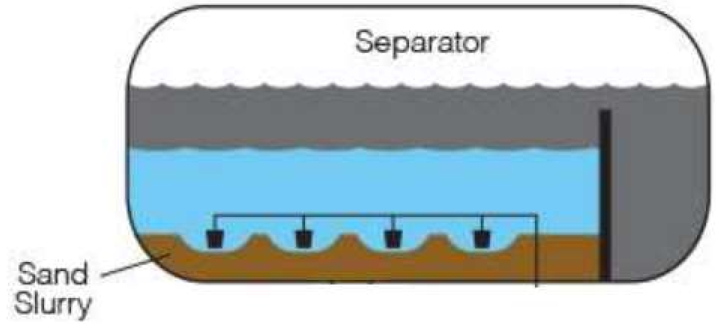
Operational Problems

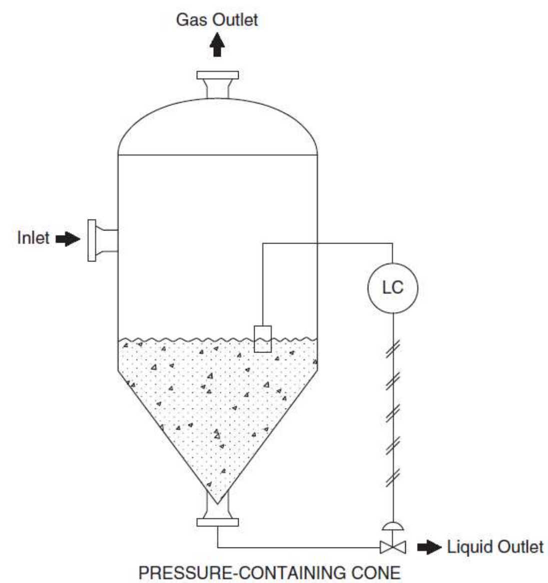
(a) Asphaltene (b) Wax

- Paraffin and waxes
  - The separation performance can be affected by an accumulation of paraffin.
  - Internals such coalescing plate and mesh pad mist extractors are prone to plugging, therefore when paraffin accumulation is a potential problem the use of plate-type or centrifugal mist extractor should be considered
  - The temperature of the liquid should always be kept above the cloud point of the crude
    - Cloud Point: temperature at which paraffin begin to come out of solutions
    - Pout Point: temperature at which the crude oil no longer flows (it might forms wax crystal)
  - The separator design should provide handholds and nozzles to allow cleaning the separator internals
- Asphaltenes

Operational Problems

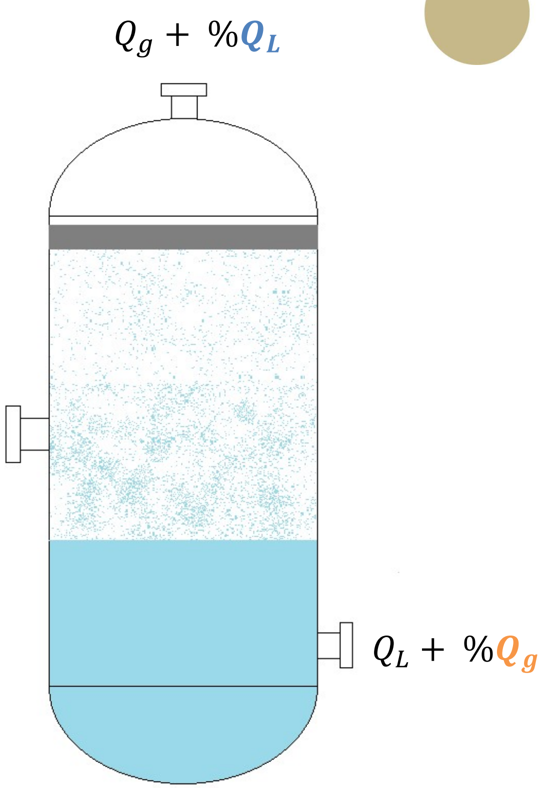


- Sand
  - It can cause cutout of valve trim, plugging separator internals and accumulation in the bottom of the separators
  - The sand accumulation can be removed by periodically injecting water or steam in the bottom of the vessel
  - If sand production is a major problem the vertical separator can be fitted with a cone bottom
  - It is necessary a balance on the internals design that allow a god separation performance but avoid areas for sand accumulation



Operational Problems

- **Liquid carryover**
  - It occurs when free liquid escapes with the gas phase.
  - It is an indication of high liquid level, damage internals, foam, improper design, plugged liquid outlets, or a flow rate that exceeds the vessel's design rate
  - Liquid carry over can be prevented by installing a **level safety high (LSH) sensor** that shuts in the inlet flow when the liquid level exceeds the normal maximum liquid level
- **Gas Blowby**
  - It occurs when free gas escapes with the liquid phase.
  - It can be an indication of low liquid level, vortexing, or level control failure
  - Gas blowby can usually be prevented by installing a **level safety low sensor (LSL)** that shuts in the inflow or outflow when the liquid level drops to 10-15% below the lowest operating level.
  - Additionally, downstream process components should be equipped with a pressure safety high (PSH) sensor and a pressure safety valve (PSV) sized for gas blowby



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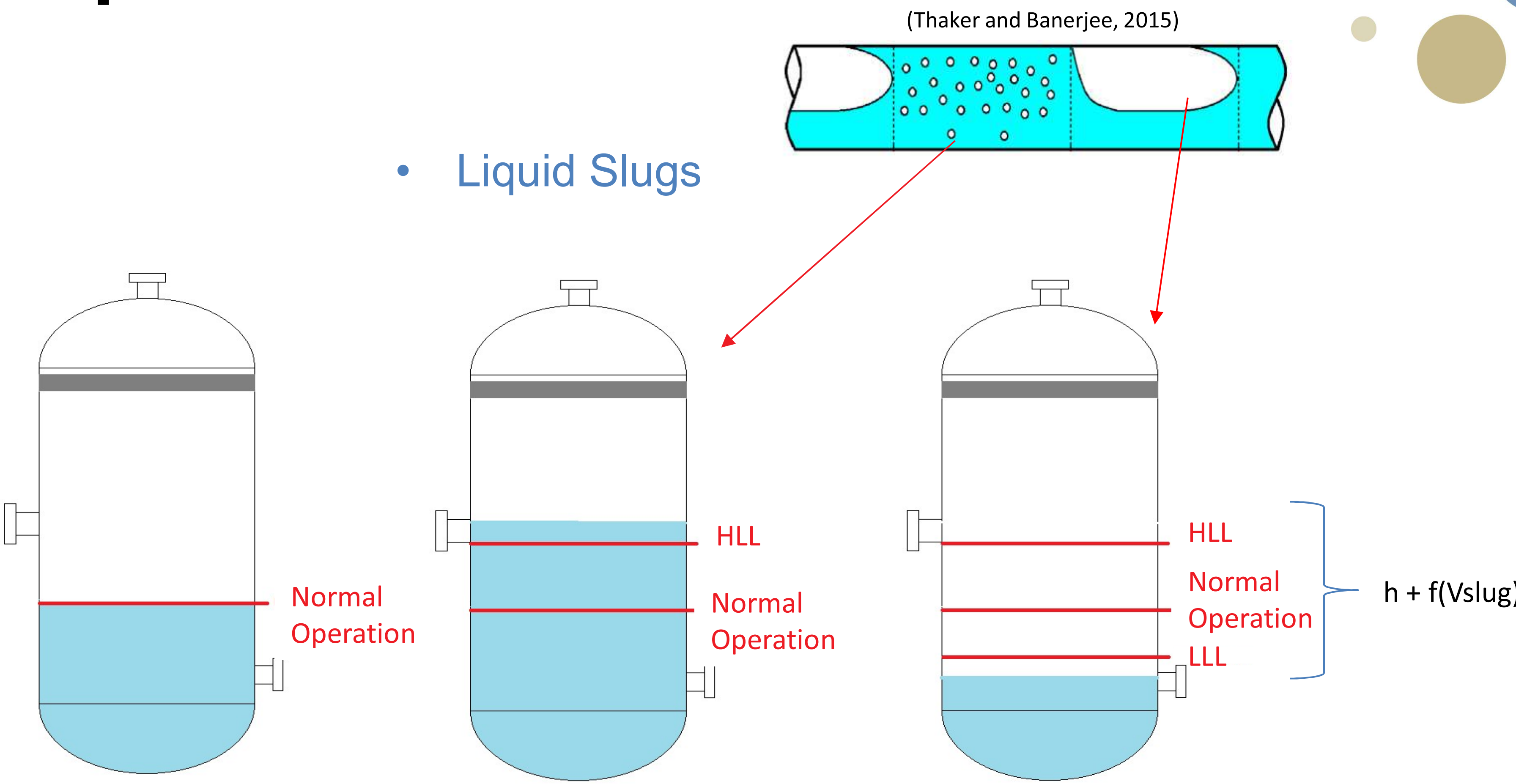
Operational Problems

- Liquid Slugs



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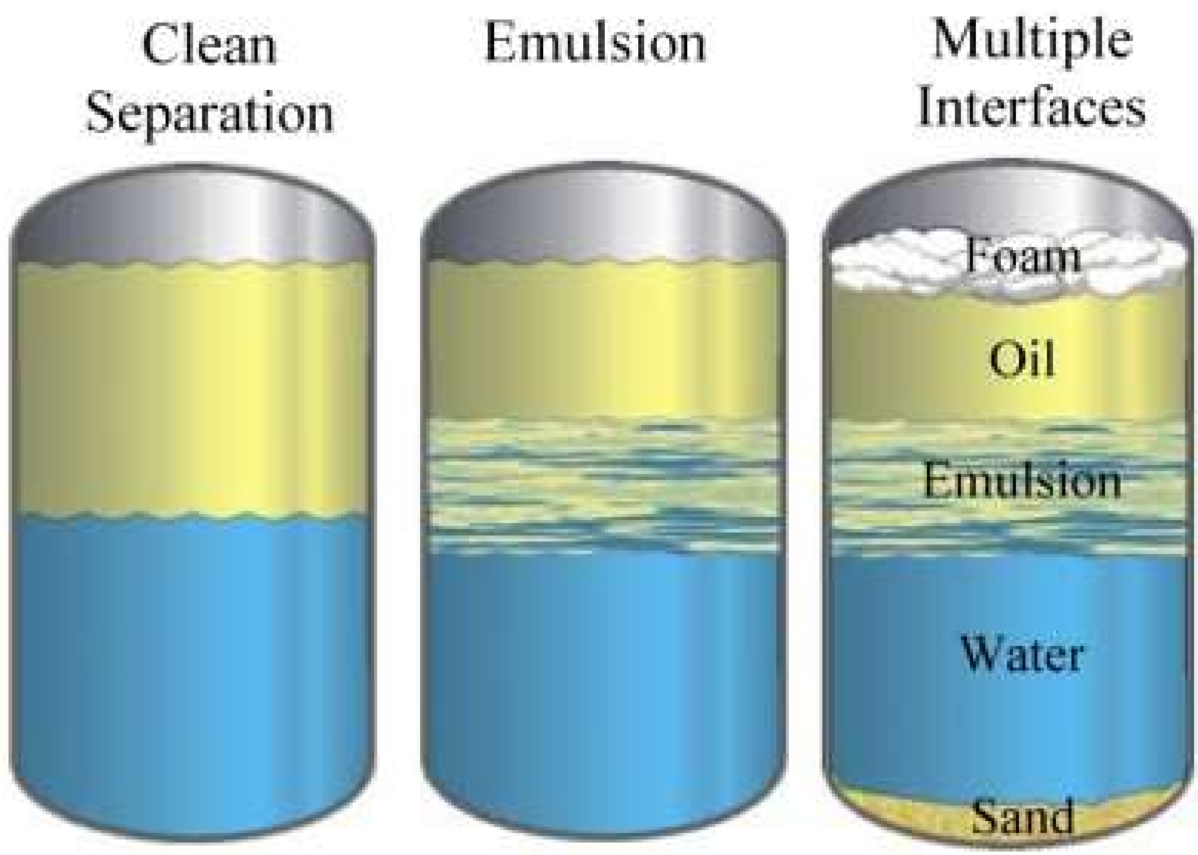
Operational Problems

- Liquid Slugs
  - Situation in which liquid slugs my occurs should be identified prior to the design of a separator and the slug volume must be established
  - The normal operating level and the high level shutdown on the vessel must be spaced far enough apart to accommodate the anticipated slug volume
  - The separator size must still ensure that sufficient gas capacity is provided even when the liquid is at the high-level set point.

Potential Operating Problems

- Emulsions.



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Potential Operating Problems

- Emulsions.

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Potential Operating Problems

- Emulsions.
  - May develop problems with emulsions can be particularly troublesome in the operation of three-phase separators.
  - Adverse effects on the liquid level control,
  - Decrease the effective oil or water retention time in the separator, with a resultant decrease in water–oil separation efficiency.
  - Addition of chemicals and/or heat often minimizes this difficulty.