NTNU – Trondheim
Norwegian University of
Science and Technology

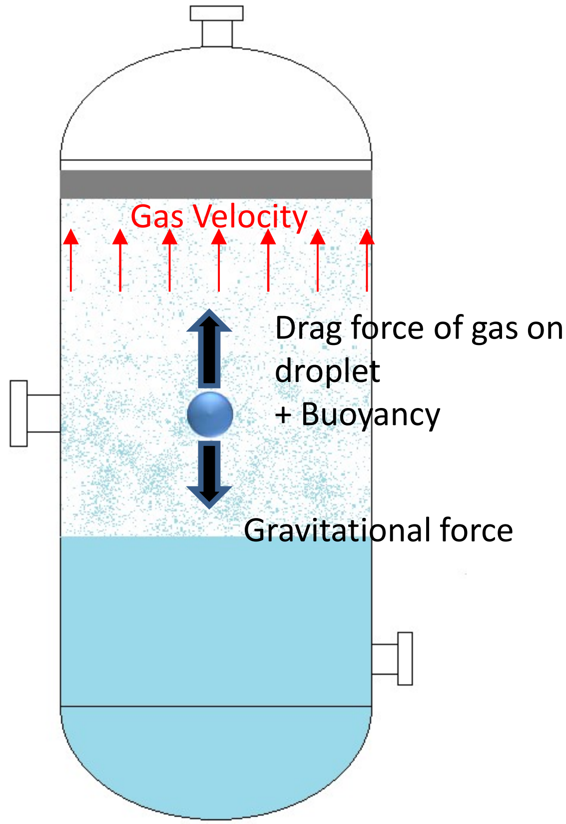
Production Technology

Field Processing and Systems

Postdoc Mariana Díaz
01 /28/2019

Bubble and Droplet Mechanism

Gravitational forces > Drag force of gas on droplet + Buoyancy



Terminal Velocity (Vt)

$$F_g = F_d + F_b$$

Weight

Drag

Buoyancy

Postdoc Mariana Díaz

Bubble and Droplet Mechanism

$$V_t = \sqrt{\frac{4\, D_P\, g\, (\rho_P - \rho_f)}{3\, C_d\, \rho_f}}$$

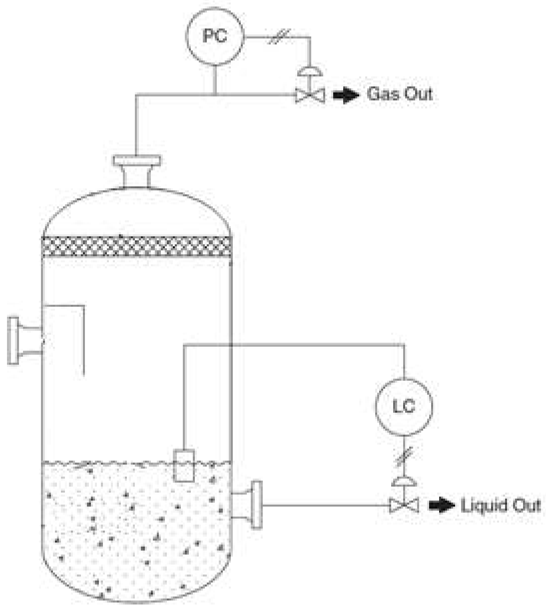
1. Droplet settling theory
    - Trial and error solution
    - Graphical solution
    - Correlations
2. Souders-Brown approach

$$K_{SB} = \sqrt{\frac{4\, D_P\, g}{3\, C_d}} = V_t \sqrt{\frac{\rho_f}{(\rho_P - \rho_f)}}$$

f(mist extractor, separator geometry, flow rates, fluid properties)

Postdoc Mariana Díaz

Separator sizing



1. Vapor Capacity → Cross-sectional area
2. Liquid Capacity → Residence time to “de-gas”
3. Operability → Ability to deal with solids, liquid slugs, turn-down, etc

Lsem/Dv

Postdoc Mariana Díaz

Vertical separator sizing

1. **Vapor Capacity**

$$Q_g = V_t A_v \quad \text{(Actual Conditions)}$$

$$Q_g^{s.c} = Q_g \left(\frac{P}{P_{s.c}}\right)\left(\frac{T_{s.c}}{T}\right)\frac{1}{z} \quad \text{(s.c. = standard conditions)}$$

15 C
1 atm (1.01325 bara)

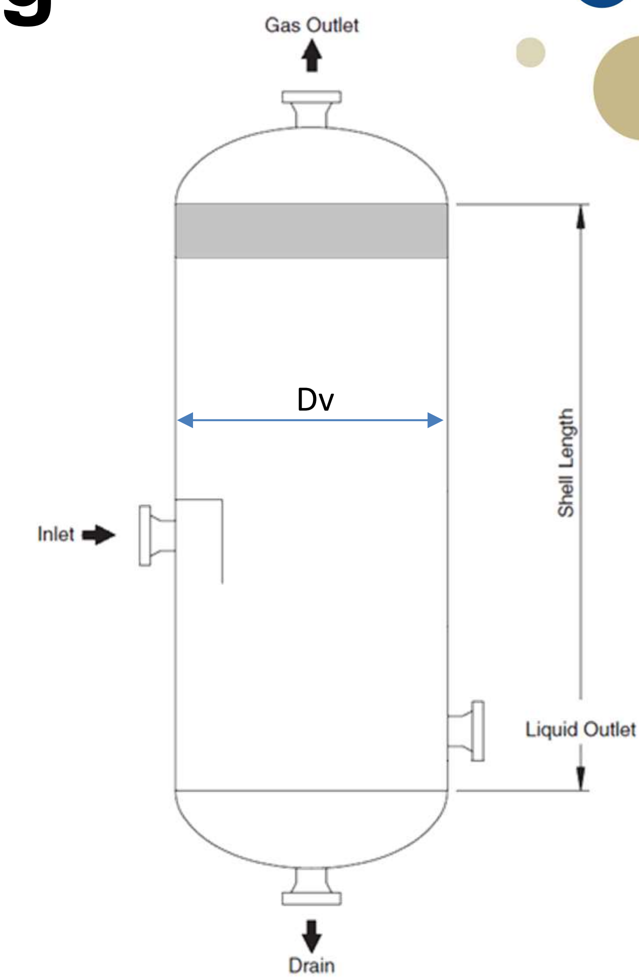
Calculate V_t

↓

Calculate A_v

↓

Calculate D_v **Minimum value*



(Stewart and Arnold, 2008)

Postdoc Mariana Díaz

Design criteria

For the gravity settling section → Droplet size $\approx 140 - 150\mu m$

Vent scrubbers → Droplet size $\approx 300 - 500\mu m$

Retention time in most application → 30 s and 3 min →

Retention Time for Two-Phase Separators

°API Gravity	Retention Time (Minutes)
35+	0.5 to 1
30	2
25	3
20+	4+

1. If foam exists, increase above retention times by a factor of 2 to 4.
2. If high CO_2 exists, use a minimum of 5-minute retention time.

Horizontal Liquid volume → 50% full liquid

L/D relation

Vertical Separator are normally L/D = 2 to 4

Horizontal Separator are normally L/D = 2.5 to 5

Vertical Separator sizing

EXERCISE

Postdoc Mariana Díaz

Vertical separator sizing

Exercise

$Q_g = 11803\ scm/hr$

$Q_o = 13.25\ m^3/hr$

$\rho_g = 59.6\ kg/m^3$

$\rho_o = 825\ kg/m^3$

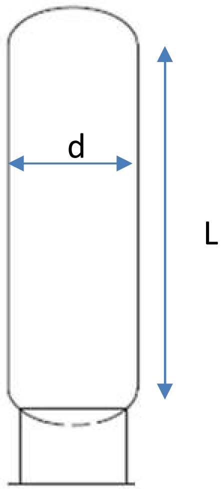
$\mu_g = 0.013\ cp$

$d_m = 140 \mu m$

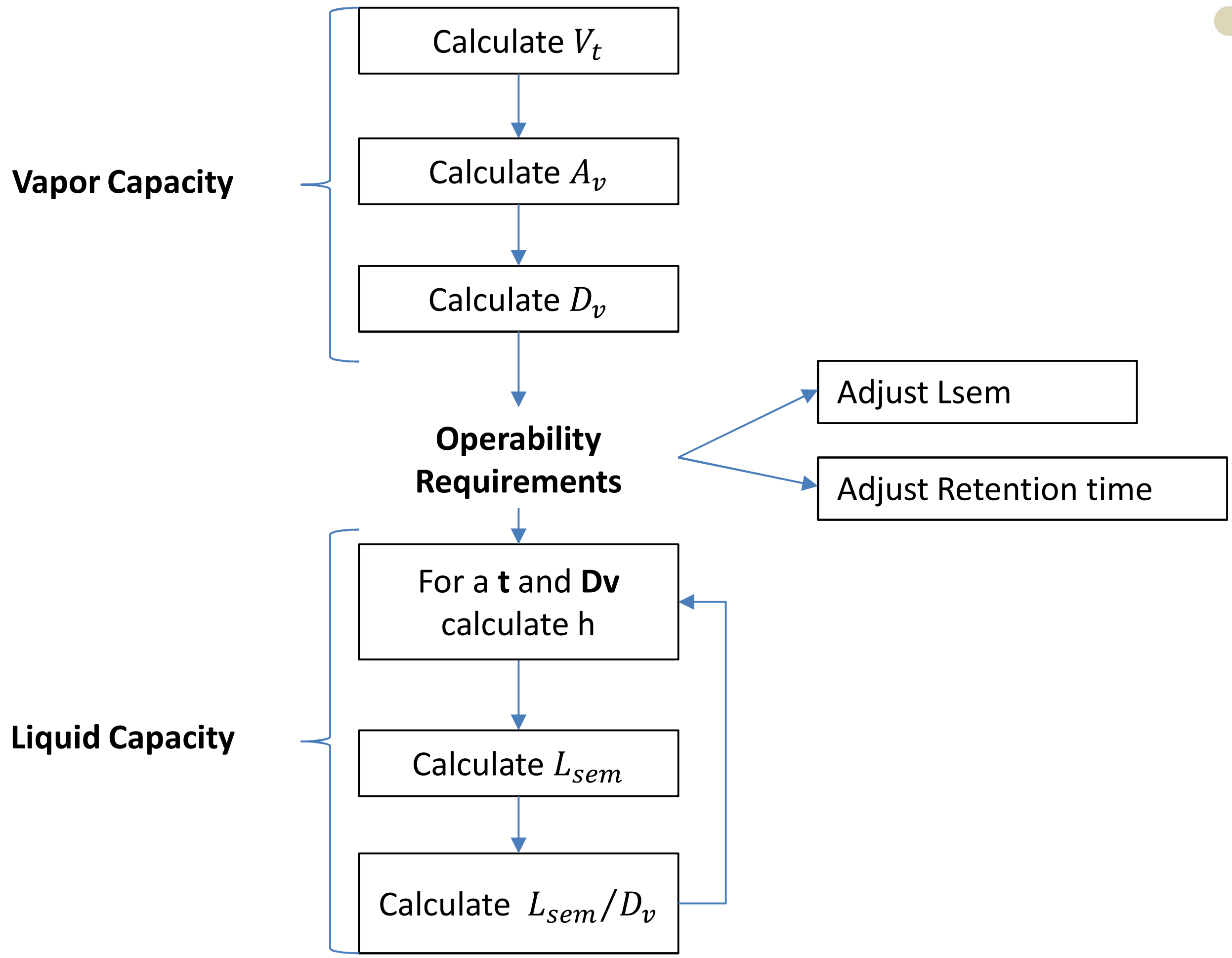
$z = 0.84$

$P = 6900\ kPa$

$T = 15.6\ C$



Postdoc Mariana Díaz



Postdoc Mariana Díaz

Vertical separator sizing

Exercise

$Q_g = 11803\ scm/hr$

$Q_o = 13.25\ m^3/hr$

$\rho_g = 59.6\ kg/m^3$

$\rho_o = 825\ kg/m^3$

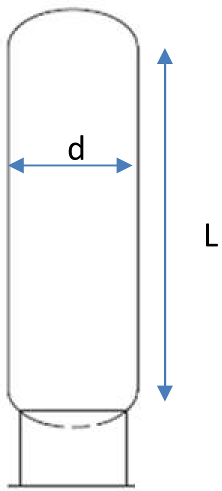
$\mu_g = 0.013\ cp$

$d_m = 140\mu m$

$z = 0.84$

$P = 6900\ kPa$

$T = 15.6\ C$



<u>Option 1</u> *Trial and error solution*

$\left.\begin{array}{l}\text{Cd}\\\text{Re}\\\text{Vt}\end{array}\right\}\quad ?$

Postdoc Mariana Díaz

Bubble and Droplet Mechanism

1. Droplet settling theory

Trial and error solution

Assuming $C_d^* = 0.34$

$$V_t = \sqrt{\frac{4\, D_P\, g\, (\rho_P - \rho_f)}{3\, C_d\, \rho_f}}$$

$$Re = \frac{D_P V_t \rho_f}{\mu_f}$$

$$C_d = \frac{24}{Re} \qquad Re < 2 \qquad \text{Stokes drag coefficient}$$

$$C_d = \frac{24}{Re} + (1 + 0.15 Re^{0.687}) \qquad 2 < Re < 10^3$$

$$C_d = 0.44 \qquad 10^3 < Re < 10^5$$

$$C_d = 0.1 \qquad 10^5 < Re < 10^6$$

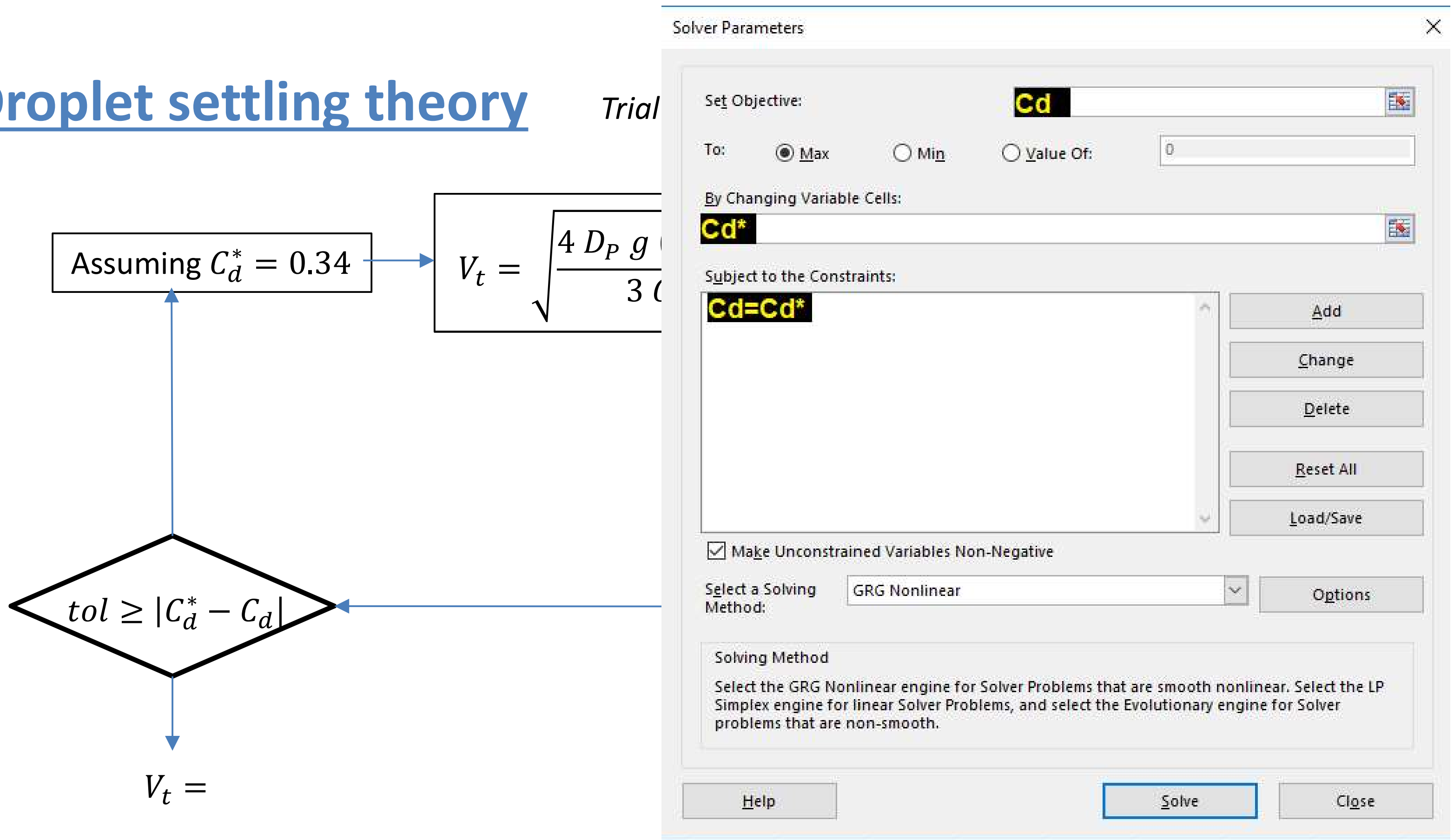
$$tol \geq |C_d^* - C_d|$$

$$V_t =$$

Postdoc Mariana Díaz

Bubble and Droplet Mechanism

1. Droplet settling theory



Vertical separator sizing

Exercise

$Q_g = 11803\ scm/hr$

$Q_o = 13.25\ m^3/hr$

$\rho_g = 59.6\ kg/m^3$

$\rho_o = 825\ kg/m^3$

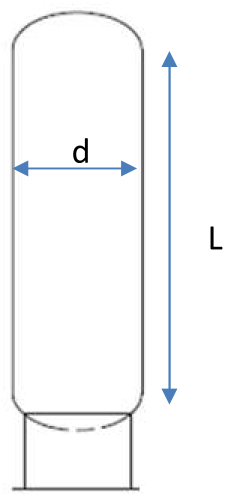
$\mu_g = 0.013\ cp$

$d_m = 140\mu m$

$z = 0.84$

$P = 6900\ kPa$

$T = 15.6\ C$



<u>Option 1</u> *Trial and error solution*

Cd=1.13
Re=92.5
Vt = 0.144 m/s

<u>Option 2</u> *Gravity Settling Laws*

$$K_{CR} = D_p \left[\frac{g\rho_f(\rho_p - \rho_f)}{\mu^2}\right]^{0.33} = 0.18$$

Postdoc Mariana Díaz

Bubble and Droplet Mechanism

$\rho \ldots kg/m^3$

$\mu \ldots mPa\,s$

$D \ldots m$

1.2 Droplet settling theory

Gravity Settling Laws

$C_d = \dfrac{24}{Re}$

- **Stoke's Law** $Re < 2$

  $K_{CR}(Re = 2) = 0.033$

$$V_t = \frac{1000 g D_p^2 (\rho_p - \rho_f)}{18\mu}$$

$C_d = \dfrac{18.5}{Re^{0.6}}$

- **Intermediate Law** $2 < Re < 500$

  $K_{CR}(Re = 500) = 0.435$

$$V_t = \frac{2.94 g^{0.71} D_p^{1.14} (\rho_p - \rho_f)^{0.71}}{\rho_f^{0.29} \mu^{0.43}}$$

$C_d = 0.44$

- **Newton's Law** $500 < Re < 2 * 10^5$

  $K_{CR}(Re = 2e5) = 23.64$

$$V_t = 1.74 \sqrt{\frac{D_P\, g\, (\rho_P - \rho_f)}{\rho_f}}$$

$$D_p = K_{CR} \left[\frac{\mu^2}{g \rho_f (\rho_p - \rho_f)} \right]^{0.33}$$

$K_{CR} \ldots proportional\ constant$

(Bahadori, A. 2014)

Postdoc Mariana Díaz

Vertical separator sizing

Exercise

$Q_g = 11803\ scm/hr$

$Q_o = 13.25\ m^3/hr$

$\rho_g = 59.6\ kg/m^3$

$\rho_o = 825\ kg/m^3$

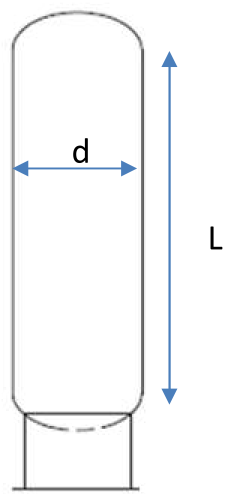
$\mu_g = 0.013\ cp$

$d_m = 140\mu m$

$z = 0.84$

$P = 6900\ kPa$

$T = 15.6\ C$



<u>Option 1</u> *Trial and error solution*

Cd=1.13
Re=92.5
Vt = 0.144 m/s

<u>Option 2</u> *Gravity Settling Laws*

$$K_{CR} = D_p \left[\frac{g\rho_f(\rho_p - \rho_f)}{\mu^2}\right]^{0.33} = 0.18$$

$$V_t = \frac{2.94 g^{0.71} D_p^{1.14} (\rho_p - \rho_f)^{0.71}}{\rho_f^{0.29} \mu^{0.43}} = 0.133\ m/s$$

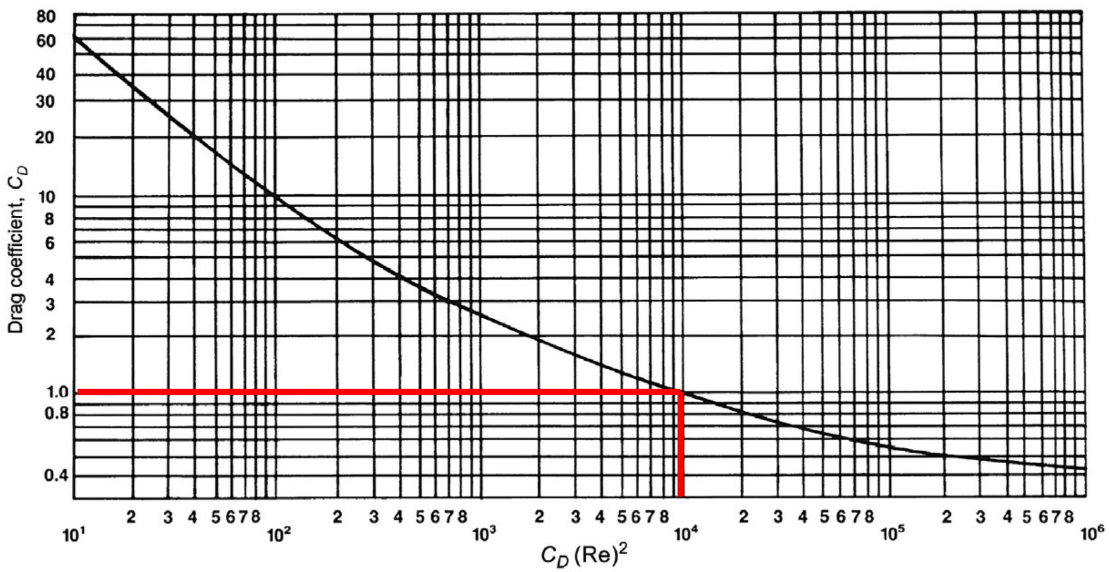
Postdoc Mariana Díaz

Vertical separator sizing

Exercise

Option 3 *Diagram*

$Q = 11803\ scm/hr$



$$C_D Re^2 = \frac{1.31 * 10^7 \rho_f D_p^3 (\rho_p - \rho_f)}{\mu^2}$$

$\rho \ldots kg/m^3$

$\mu \ldots mPa\ s$

$D \ldots m$

$$C_D \approx 1$$

$$V_t = \sqrt{\frac{4\ D_P\ g\ (\rho_P - \rho_f)}{3\ C_d\ \rho_f}} = 0.153 m/s$$

Postdoc Mariana Díaz

Vertical separator sizing

Exercise

$Q_g = 11803\ scm/hr$

$Q_o = 13.25\ m^3/hr$

$\rho_g = 59.6\ kg/m^3$

$\rho_o = 825\ kg/m^3$

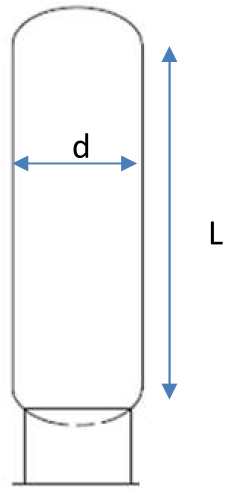
$\mu_g = 0.013\ cp$

$d_m = 140\mu m$

$z = 0.84$

$P = 6900\ kPa$

$T = 15.6\ C$



Option 1 — *Trial and error solution*

$V_t = 0.144\ m/s$

Option 2 — *Gravity Settling Laws*

$V_t = 0.133\ m/s$

Option 3 — *Diagram*

$V_t = 0.153 m/s$

Option 4 — Souders-Brown approach

$$V_t = K_{SB}\sqrt{\frac{(\rho_P - \rho_f)}{\rho_f}}$$

$K_{SB} = 0.040 m/s \longrightarrow V_t = 0.145 m/s$

Postdoc Mariana Díaz

Vertical separator sizing

Exercise

$Q_g = 11803\ scm/hr$

$Q_o = 13.25\ m^3/hr$

$\rho_g = 59.6\ kg/m^3$

$\rho_o = 825\ kg/m^3$

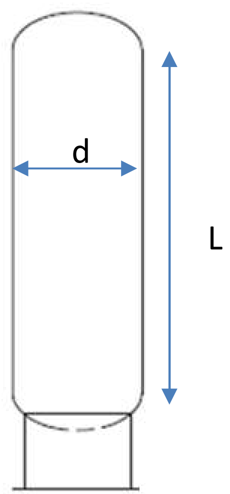
$\mu_g = 0.013\ cp$

$d_m = 140 \mu m$

$z = 0.84$

$P = 6900\ kPa$

$T = 15.6\ C$



<u>Option 1</u> *Trial and error solution*

$V_t = 0.144\ m/s$

<u>Option 2</u> *Gravity Settling Laws*

$V_t = 0.133\ m/s$

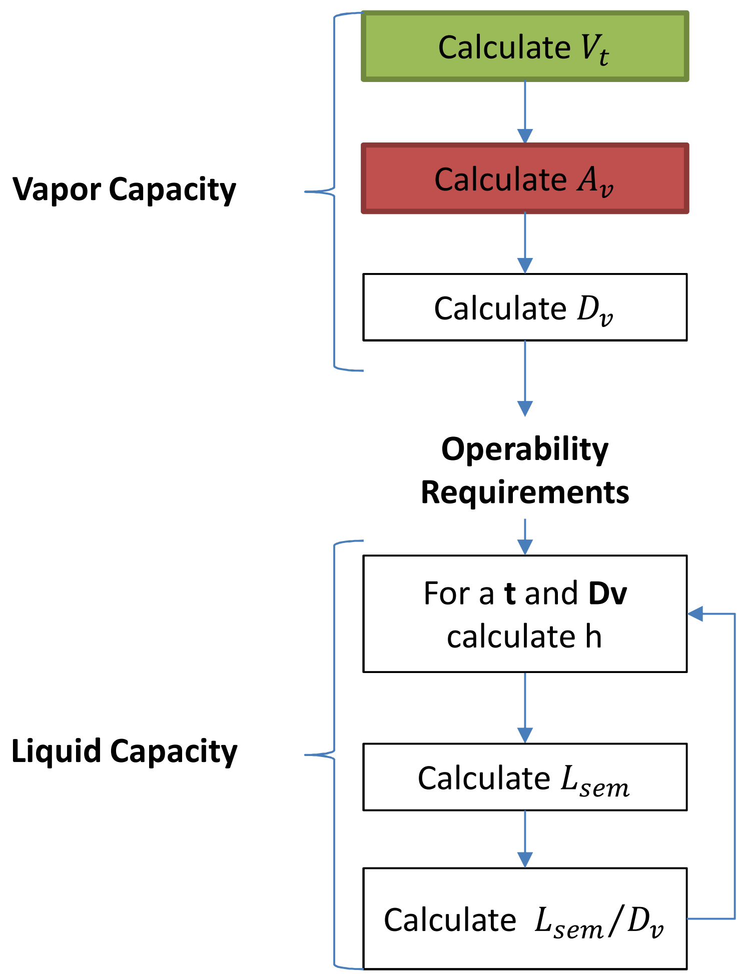
<u>Option 3</u> *Diagram*

$V_t = 0.153 m/s$

<u>Option 4</u> Souders-Brown approach

$V_t = 0.145 m/s$

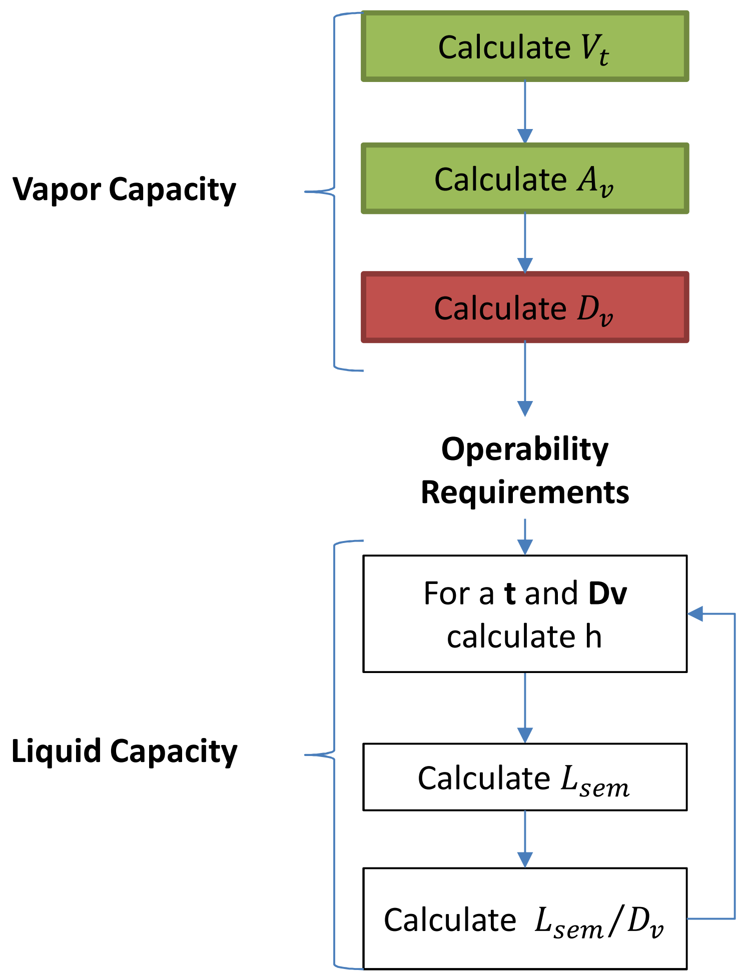
Postdoc Mariana Díaz



$$V_t = 0.144\ m/s$$

$$A_v = \frac{Q_g^{a.c}}{V_t} = 0.28m^2$$

Postdoc Mariana Díaz

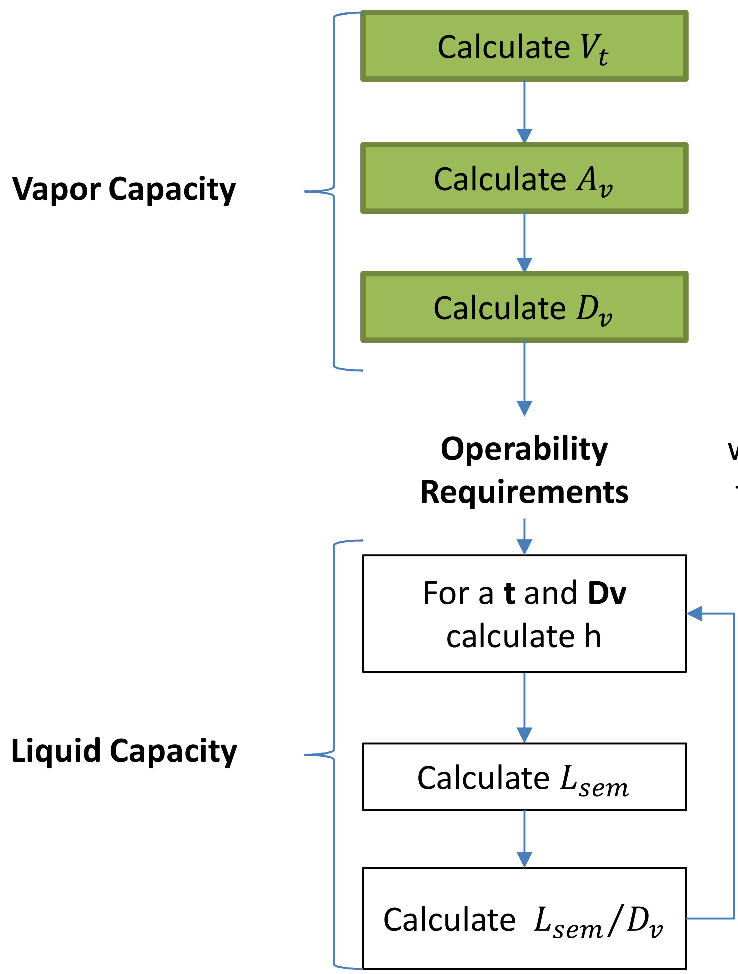


$$V_t = 0.144\ m/s$$

$$A_v = \frac{Q_g^{a.c}}{V_t} = 0.28m^2$$

$$D_v^{min} = \sqrt{\frac{4A_v}{\pi_t}} = 0.598m = 598mm = 23.5in$$

Postdoc Mariana Díaz



$$V_t = 0.144\ m/s$$

$$A_v = \frac{Q_g^{a.c}}{V_t} = 0.28m^2$$

$$D_v^{min} = \sqrt{\frac{4A_v}{\pi_t}} = 0.598m = 598mm = 23.5in$$

with mist Extractor, bulk separation, two phase flow, regular service

Postdoc Mariana Díaz

Vapor Capacity

Calculate V_t

$V_t = 0.144\ m/s$

Calculate A_v

$$A_v = \frac{Q_g^{a.c}}{V_t} = 0.28m^2$$

Calculate D_v

$$D_v^{min} = \sqrt{\frac{4A_v}{\pi_t}} = 0.598m = 598mm = 23.5in$$

Operability Requirements

with mist Extractor, bulk separation, two phase flow, regular service

Liquid Capacity

For a t and Dv calculate h

$D_v = (120\%\ to\ 130\%)D_v^{min} \approx 30"$

$t \ldots 2\ to\ 4min \rightarrow 3min$

$$h = \frac{t\ Q_l\ 4}{\pi\ D_v^2} = 1.45m = 57.19in$$

Calculate L_{sem}

Calculate L_{sem}/D_v

Postdoc Mariana Díaz

Vapor Capacity

Calculate V_t

$V_t = 0.144\ m/s$

Calculate A_v

$$A_v = \frac{Q_g^{a.c}}{V_t} = 0.28m^2$$

Calculate D_v

$$D_v^{min} = \sqrt{\frac{4A_v}{\pi_t}} = 0.598m = 598mm = 23.5in$$

Operability Requirements

with mist Extractor, bulk separation, two phase flow, regular service

Liquid Capacity

For a **t** and **Dv** calculate h

$D_v = (120\%\ to\ 130\%) D_v^{min} \approx 30"$

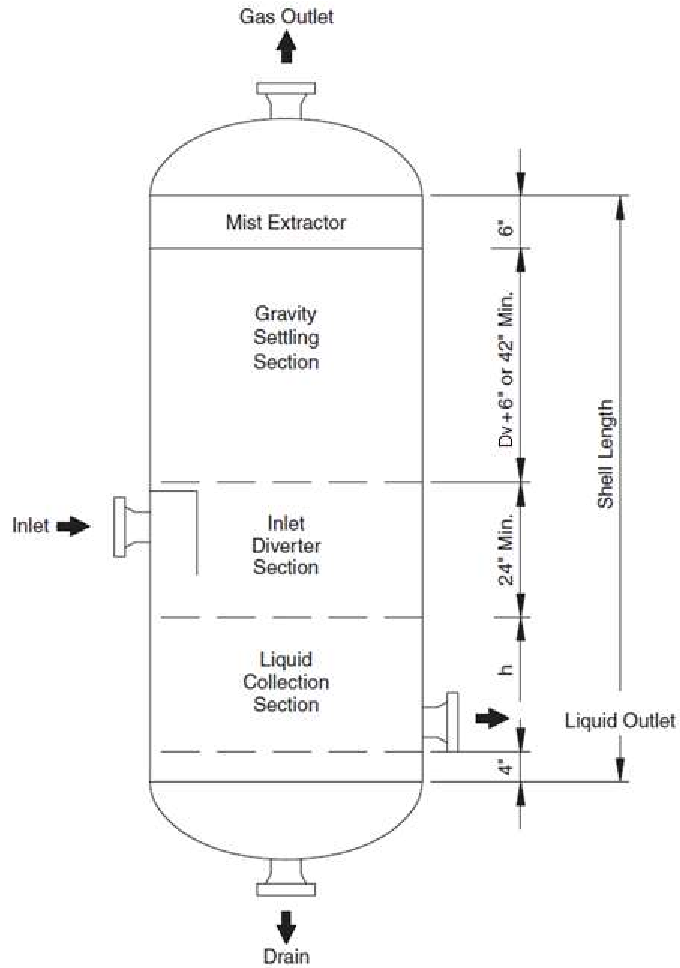
$t \ldots 2\ to\ 4min \rightarrow 3min$

$$h = \frac{t\ Q_l\ 4}{\pi\ D_v^2} = 1.45m = 57.19in$$

Calculate L_{sem}

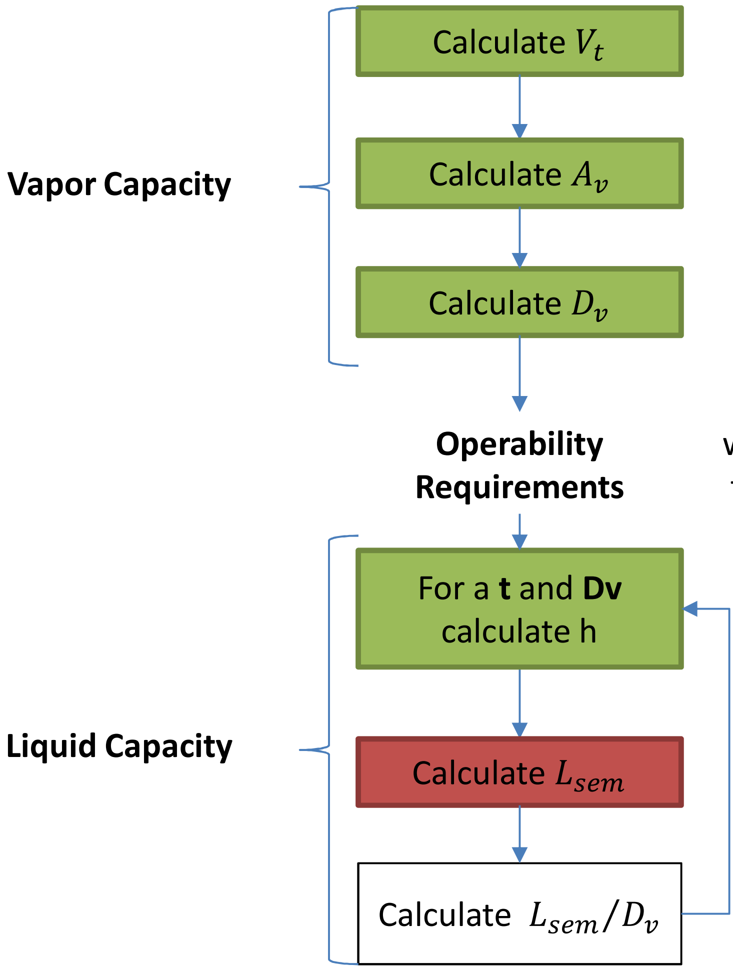
Calculate L_{sem}/D_v

Postdoc Mariana Díaz



$$Lsem = 4" + \underbrace{\max(h; 36")}_{h\,=\,57.19in} + \underbrace{max(2 * ID; 24)}_{=\,24in} + \underbrace{\max(D_V+6; 42")}_{=\,42in} + 6"$$

Postdoc Mariana Díaz



$$V_t = 0.144\ m/s$$

$$A_v = \frac{Q_g^{a.c}}{V_t} = 0.28m^2$$

$$D_v^{min} = \sqrt{\frac{4A_v}{\pi_t}} = 0.598m = 598mm = 23.5in$$

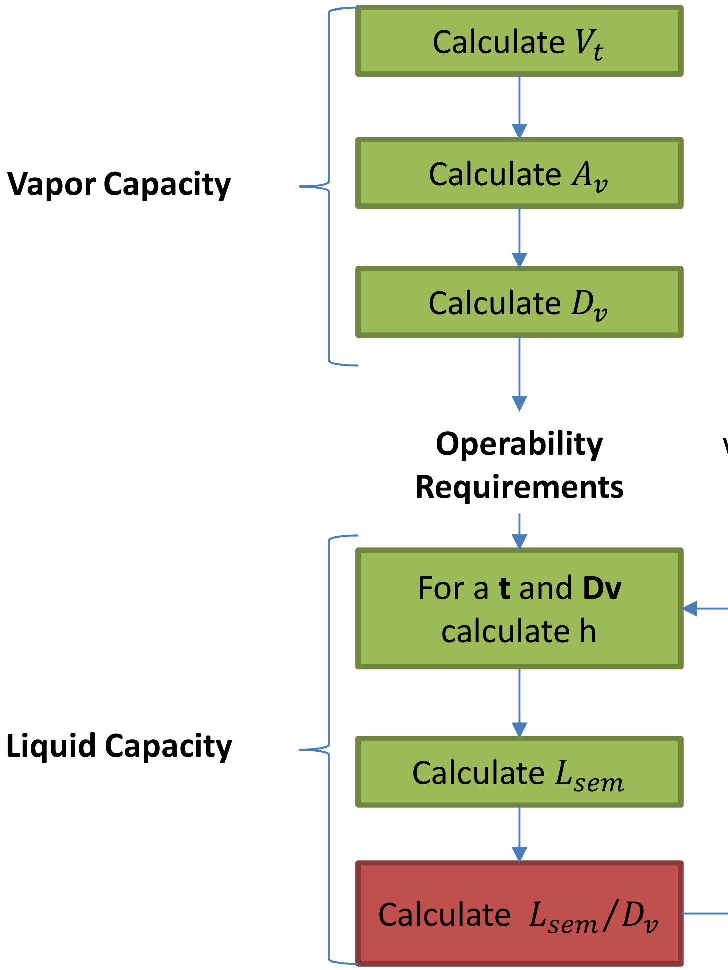
with mist Extractor, bulk separation, two phase flow, regular service

$$D_v = (120\%\ to\ 130\%)D_v^{min} \approx 30"$$

$$t \ldots 2\ to\ 4min \rightarrow 3min$$

$$h = \frac{t\ Q_l\ 4}{\pi\ D_v^2} = 1.45m = 57.19in$$

Postdoc Mariana Díaz



$V_t = 0.144\ m/s$

$$A_v = \frac{Q_g^{a.c}}{V_t} = 0.28m^2$$

$$D_v^{min} = \sqrt{\frac{4A_v}{\pi_t}} = 0.598m = 598mm = 23.5in$$

with mist Extractor, bulk separation, two phase flow, regular service

$D_v = (120\%\ to\ 130\%)D_v^{min} \approx 30"$

$t \ldots 2\ to\ 4min \rightarrow 3min$

$$h = \frac{t\ Q_l\ 4}{\pi\ D_v^2} = 1.45m = 57.19in$$

$Lsem = 133.19IN$
$= 3.38m$

$$\frac{Lsem}{D_v} = 4.44$$

Postdoc Mariana Díaz

Results

tr (min)	Dv (in)	Dv(m)	h(m)	h(in)	Lgas(in)	Linlet(in)	Lss(in)	Lss(m)	Lss/Dv
3	24.00	0.61	2.27	89.37	42.00	24	165.37	4.20	6.89
3	30.00	0.76	1.45	57.19	42.00	24	133.19	3.38	4.44
3	36.00	0.91	1.01	39.72	42.00	24	115.72	2.94	3.21
3	42.00	1.07	0.74	36.00	48.00	24	118.00	3.00	2.81
3	48.00	1.22	0.57	36.00	54.00	24	124.00	3.15	2.58
2	24.00	0.61	1.51	59.58	42.00	24	135.58	3.44	5.65
2	30.00	0.76	0.97	38.13	42.00	24	114.13	2.90	3.80
2	36.00	0.91	0.67	36.00	42.00	24	112.00	2.84	3.11
2	42.00	1.07	0.49	36.00	48.00	24	118.00	3.00	2.81
2	48.00	1.22	0.38	36.00	54.00	24	124.00	3.15	2.58
1	24.00	0.61	0.76	36.00	42.00	24	112.00	2.84	4.67
1	30.00	0.76	0.48	36.00	42.00	24	112.00	2.84	3.73
1	36.00	0.91	0.34	36.00	42.00	24	112.00	2.84	3.11
1	42.00	1.07	0.25	36.00	48.00	24	118.00	3.00	2.81
1	48.00	1.22	0.19	36.00	54.00	24	124.00	3.15	2.58

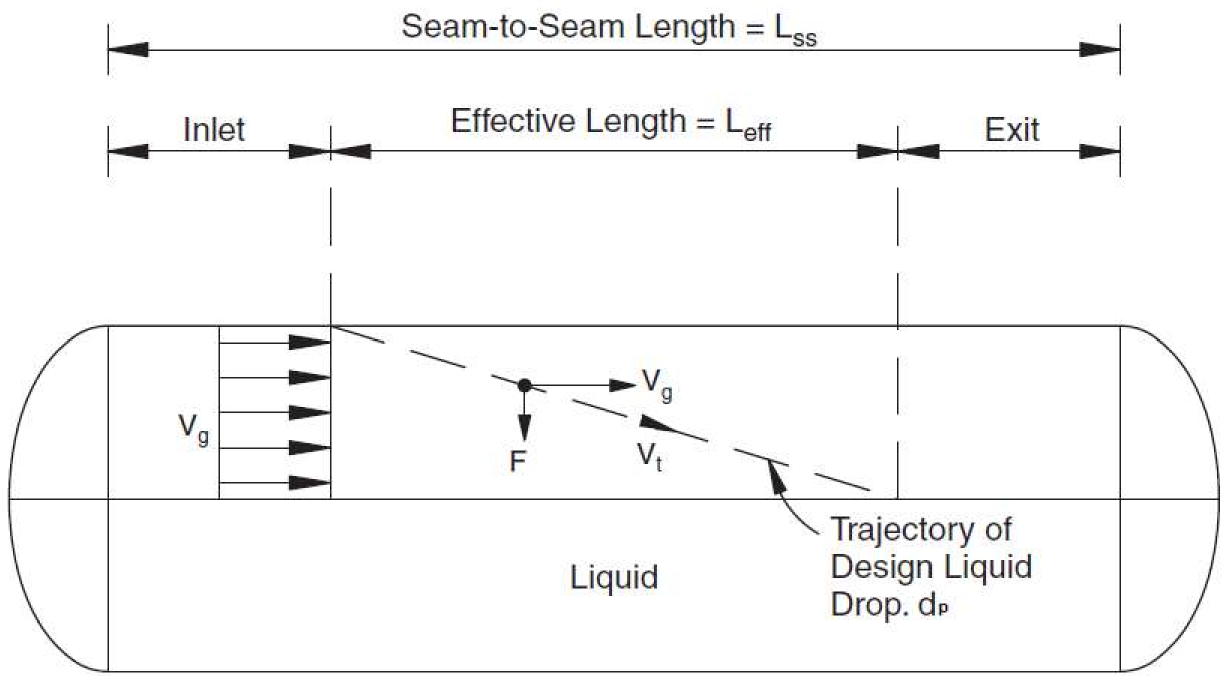
Postdoc Mariana Díaz

Separator sizing

CONTINUATION

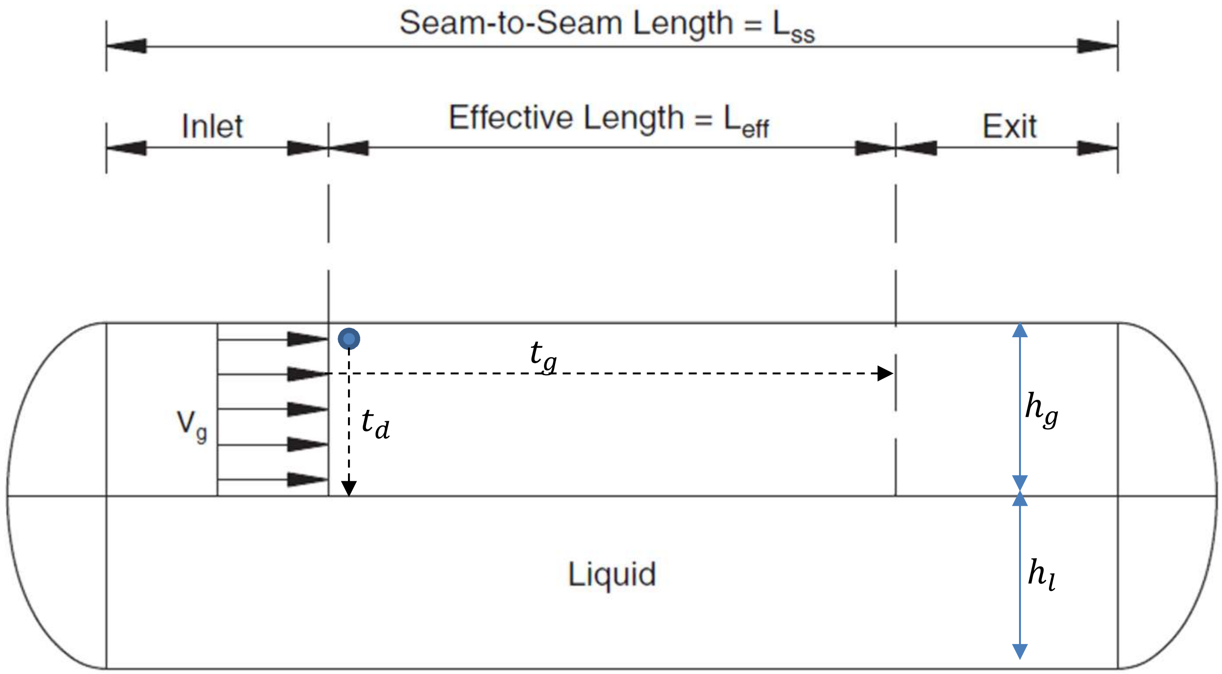
Postdoc Mariana Díaz

Horizontal separator sizing



Postdoc Mariana Díaz

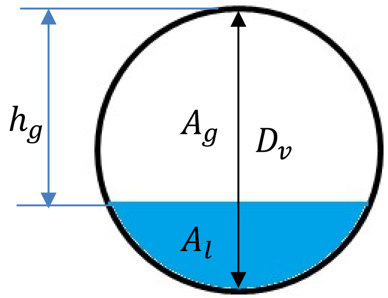
Horizontal separator sizing



$$\boldsymbol{t_d < t_g}$$

Postdoc Mariana Díaz

Horizontal separator sizing



$$A_v = A_g + A_l$$

$$\frac{\pi D_v^2}{4} = A_g + A_l$$

$$t_d < t_g \longrightarrow \frac{h_g}{V_t} < \frac{L_{eff}}{V_g}$$

A.C.

$$\frac{V_g}{V_t} < \frac{L_{eff}}{h_g} \longrightarrow \frac{(Q_g/A_g)}{V_t} < \frac{L_{eff}}{h_g} \longrightarrow \frac{Q_g}{V_t} < \frac{L_{eff}A_g}{h_g}$$

Gas Capacity $\longrightarrow$ $\boxed{\frac{L_{eff}A_g}{h_g} > \frac{Q_g}{V_t}}$

<u>Half Full</u>

$$h_g = h_l = \frac{D_v}{2} \longrightarrow A_g = A_l = \frac{A_v}{2} = \frac{\pi D_v^2}{8} \longrightarrow \boxed{L_{eff}D_v > \frac{4}{\pi}\frac{Q_g}{V_t}}$$

Postdoc Mariana Díaz

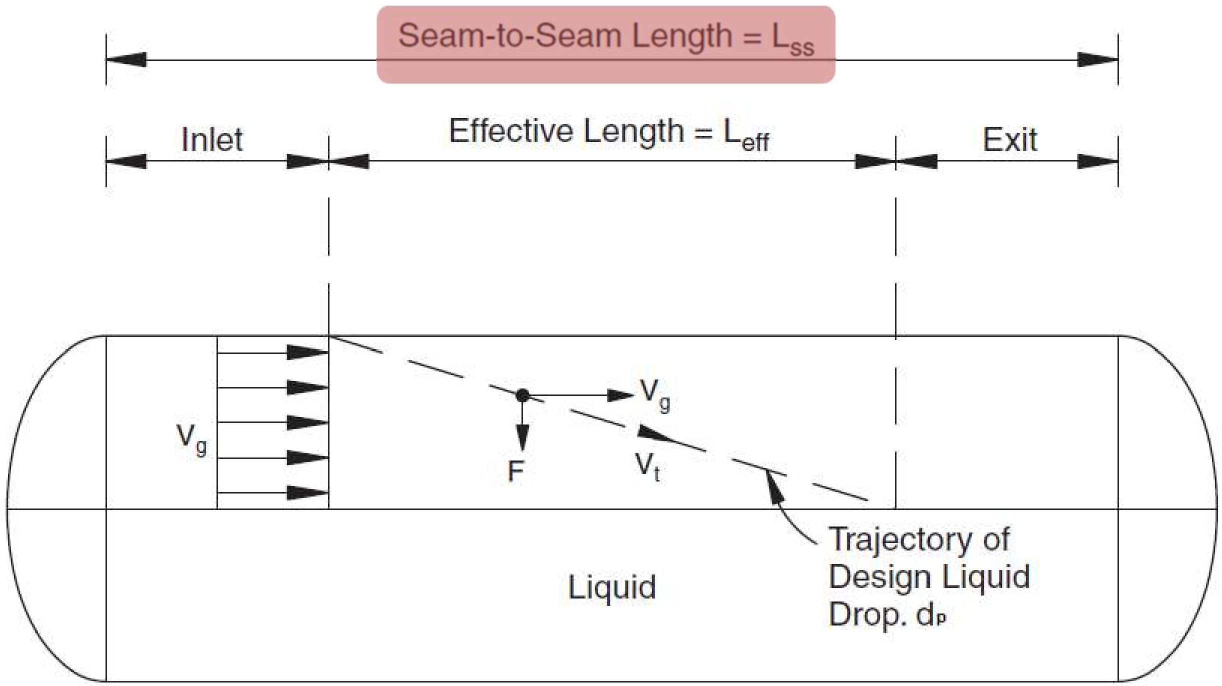
Horizontal separator sizing

Liquid Capacity $t\ Q_l = L_{eff} A_l$

<u>**Half Full**</u> $L_{eff} D_v^2 = \dfrac{t\ Q_l 8}{\pi}$

Postdoc Mariana Díaz

Horizontal separator sizing



$$\text{Max}\left(L_{ss}^{Gas} = L_{eff} + d \;;\quad L_{ss}^{Liq} = \frac{4}{3} L_{eff} \right)$$

Postdoc Mariana Díaz

Horizontal separator sizing

Exercise

$Q_g = 11803\ scm/hr$

$Q_o = 13.25\ m^3/hr$

$\rho_g = 59.6\ kg/m^3$

$\rho_o = 825\ kg/m^3$

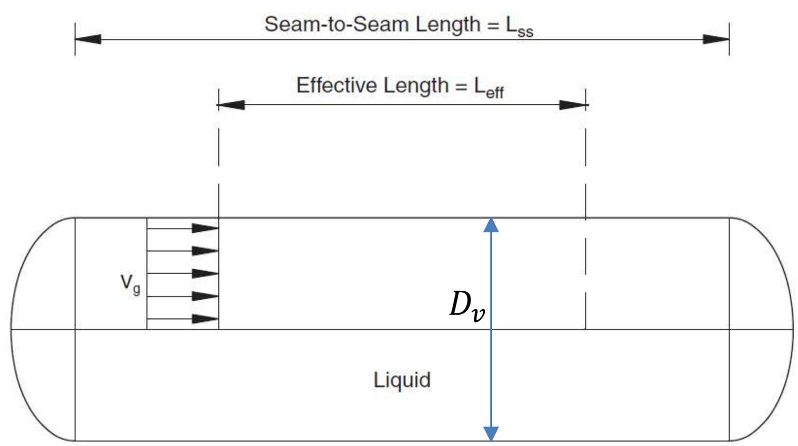
$\mu_g = 0.013\ cp$

$d_m = 140 \mu m$

$z = 0.84$

$P = 6900\ kPa$

$T = 15.6\ C$



Postdoc Mariana Díaz

Horizontal separator sizing

Exercise

$Q_g = 11803\ scm/hr$

$Q_o = 13.25\ m^3/hr$

$\rho_g = 59.6\ kg/m^3$

$\rho_o = 825\ kg/m^3$

$\mu_g = 0.013\ cp$

$d_m = 140\mu m$

$z = 0.84$

$P = 6900\ kPa$

$T = 15.6\ C$

$V_t = 0.144\ m/s$

Gas Capacity

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

Liquid Capacity

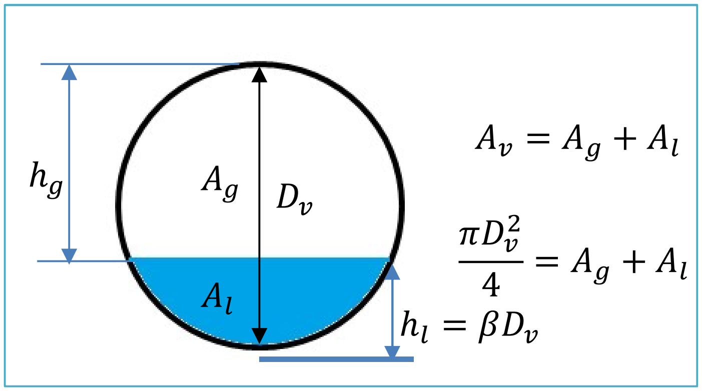
$$L_{eff} D_v^2 = \frac{t\ Q_l 8}{\pi}$$

t(min)	Dv (in)	Dv(m)	Gas Leff (m)	Liquid Leff(m)	Lss(m)	Sr =Lss/D
3.00	16	0.406	0.88	10.21	13.62	33.51
3.00	20	0.508	0.70	6.54	8.72	17.16
3.00	24	0.610	0.59	4.54	6.05	9.93
3.00	30	0.762	0.47	2.91	3.87	5.08
3.00	36	0.914	0.39	2.02	2.69	2.94
3.00	42	1.067	0.34	1.48	1.98	1.85
3.00	48	1.219	0.29	1.13	1.51	1.24

$t = 3min \quad D_v = 0.914m = 36in \quad L_{ss} = 2.69m$

Postdoc Mariana Díaz

Horizontal separator sizing-Other than half full



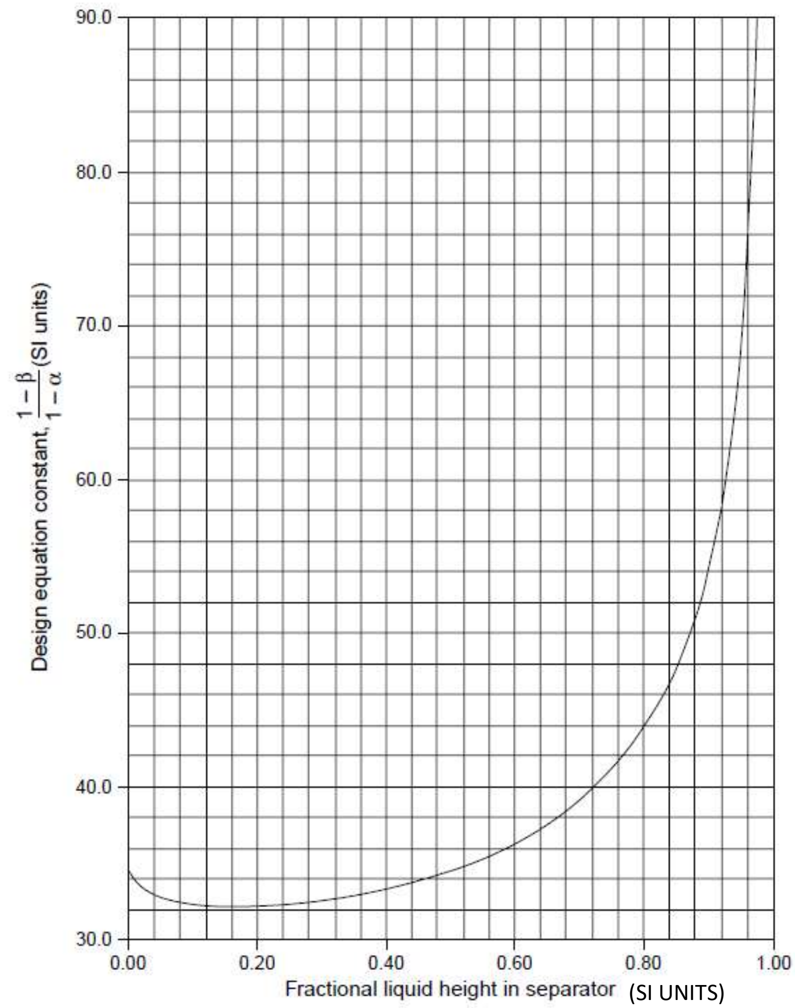
$$A_l = \alpha A_v \qquad A_g = A_v(1-\alpha)$$

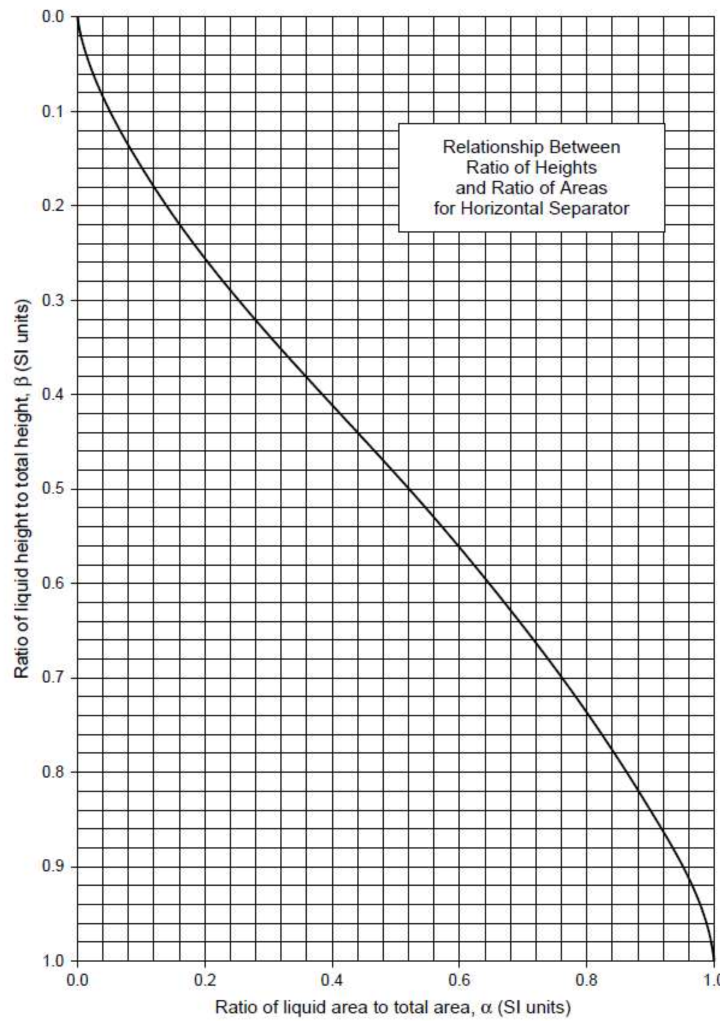
$$h_l = \beta D_v \qquad h_g = D_v(1-\beta)$$

Gas Capacity

$$\frac{L_{eff} A_g}{h_g} > \frac{Q_g}{V_t} \rightarrow L_{eff} D_v > \frac{Q_g}{V_t} \frac{4}{\pi} \frac{(1-\beta)}{(1-\alpha)}$$

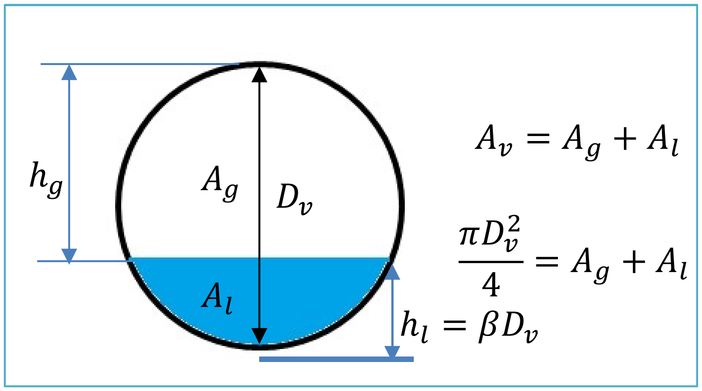
Postdoc Mariana Díaz





Postdoc Mariana Díaz

Horizontal separator sizing- Other than half full



$$A_l = \alpha A_v \qquad A_g = A_v(1-\alpha)$$

$$h_l = \beta D_v \qquad h_g = D_v(1-\beta)$$

Gas Capacity

$$\frac{L_{eff} A_g}{h_g} > \frac{Q_g}{V_t} \longrightarrow L_{eff} D_v > \frac{Q_g}{V_t}\frac{4}{\pi}\frac{(1-\beta)}{(1-\alpha)}$$

Liquid Capacity

$$t\, Q_l = L_{eff} A_l \longrightarrow L_{eff} D_v^2 = \frac{t\, Q_l 4}{\pi \alpha}$$

Postdoc Mariana Díaz