Successfully Specify Three-Phase Separators

Here is a stepwise procedure for designing liquid/liquid/vapor separators.

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It is often necessary to separate two immiscible liquids, the light and heavy phases, and a vapor. A typical example in petroleum refining is the separation of water, and a hydrocarbon liquid and vapor. Little has been published on three-phase (liquid/liquid/vapor) separation, with most information available only in corporate design files. This article attempts to alleviate this situation by covering the basics of three-phase separator design. The authors provide a Step-by-Step procedure and worked out examples. Further, the examples offer guidance on making assumptions for the calculations.

Selecting three-phase separators

As with two-phase designs, three-phase units can be either vertical or horizontal, although they typically are horizontal (see Figures 1 and 2). The vertical orientation, Figure 1, is only used if there is a large amount of vapor to be separated from a small amount of the light and heavy liquid (< 10–20% by weight). Unfortunately, there are no simple rules for separator selection. Sometimes, both configurations should be evaluated to decide which is more economical. Further, the available plot space (footprint) may be a factor.

The design of three-phase separators is similar to their two-phase counterparts, except that the liquid section differs. For the vertical type, a baffle commonly keeps the liquid separation section calm to promote the separation.

There are different variations of horizontal three-phase vapor-liquid separators. The liquid separation section is usually a variation of a device to provide interface level control, which may include a boot or a weir. A boot typically is specified when the volume of heavy liquid is not substantial (< 15–20% of total liquid by weight), while a weir is used when the volume is substantial. These horizontal separators are illustrated in Figure 2. The bucket-and-weir type design is used when interface level control may be difficult, such as with heavy oils or when large amounts of an emulsion or a paraffin are present *(1)*.

Stokes' law applies

Separating a vapor from a light liquid (two-phase separation) has been covered in a previous article *(2)* and will not be discussed here. However, all necessary information for performing this part of the calculation is provided here. The following discussion covers the separation of light and heavy liquids.

The flow of rising light droplets in the heavy liquid phase or settling heavy droplets in the light liquid phase is considered laminar and is governed by Stokes' law:

$$U_T = \frac{1{,}488 g_c D_p^2(\rho_H - \rho_L)}{18\mu} \quad (1)$$

where 1,488 converts viscosity of the

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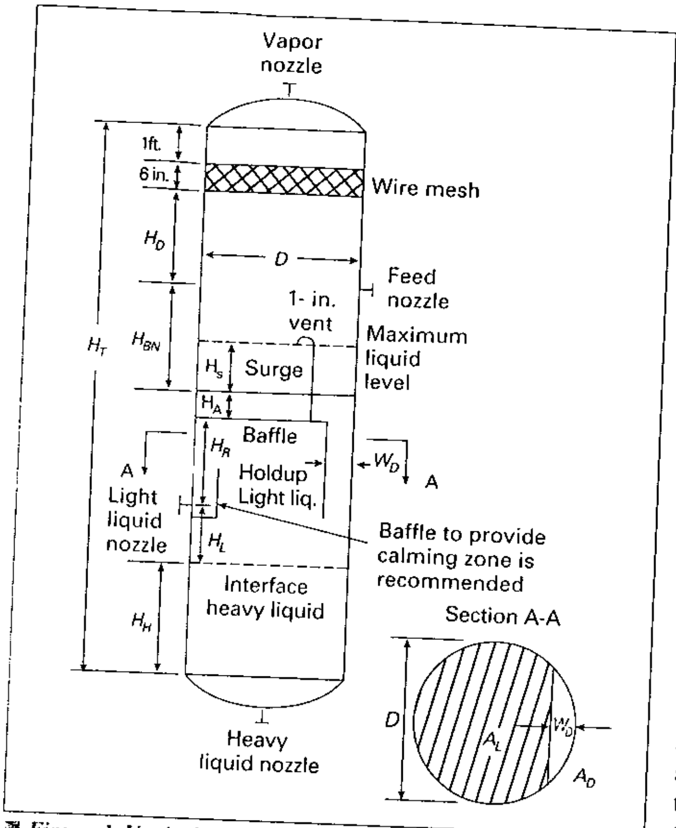


■ *Figure 1. Vertical three-phase separators are used with high vapor loadings.*

continuous phase from lb/(ft)(s) to cP.

Simplifying Eq. 1 and converting the units of the terminal settling velocity to in./min from ft/s results in:

$$U_T = \frac{2.06151 \times 10^{-5} D_P^2 (\rho_H - \rho_L)}{\mu} \quad (2)$$

where D_P is in microns (1 micron = 3.28084×10^{-6} feet) and U_T, in./min.

Eq. 2 may be rewritten as:

$$U_T = \frac{k_S (\rho_H - \rho_L)}{\mu} \quad (3)$$

where

$$k_S = 2.06151 \times 10^{-5} D_P^2 .$$

Values of k_S are given for some systems in Table 1.

From Eqs. 1–3, it can be seen that the settling velocity of a droplet is inversely proportional to the viscosity of the continuous phase. Hence, it is more difficult (requires more time) to settle the droplets out of the continuous phase with the greater viscosity, since U_T is lower. Practically speaking, U_T is typically limited in calculations to 10 in./min maximum.

For vertical separators, the diameter required for vapor disengagement is calculated as in our previous article *(2)*. In sizing a separator, the heights of the light and heavy liquids are assumed, and the settling velocities and settling times are then calculated.

The residence times of the light and heavy liquids are determined next. For the liquids to separate, the residence time of the light liquid must be greater than the time required for the heavy droplets to settle out of the light liquid phase; and the residence time of the heavy liquid must be greater than the time required for the light liquid droplets to rise out of the heavy liquid phase. If these conditions are not satisfied, then liquid separation is controlling and the vessel diameter must be increased. Holdup time for liquids must be added to residence time. The height of the vertical three-phase separator is calculated in the same manner as for the two-phase case.

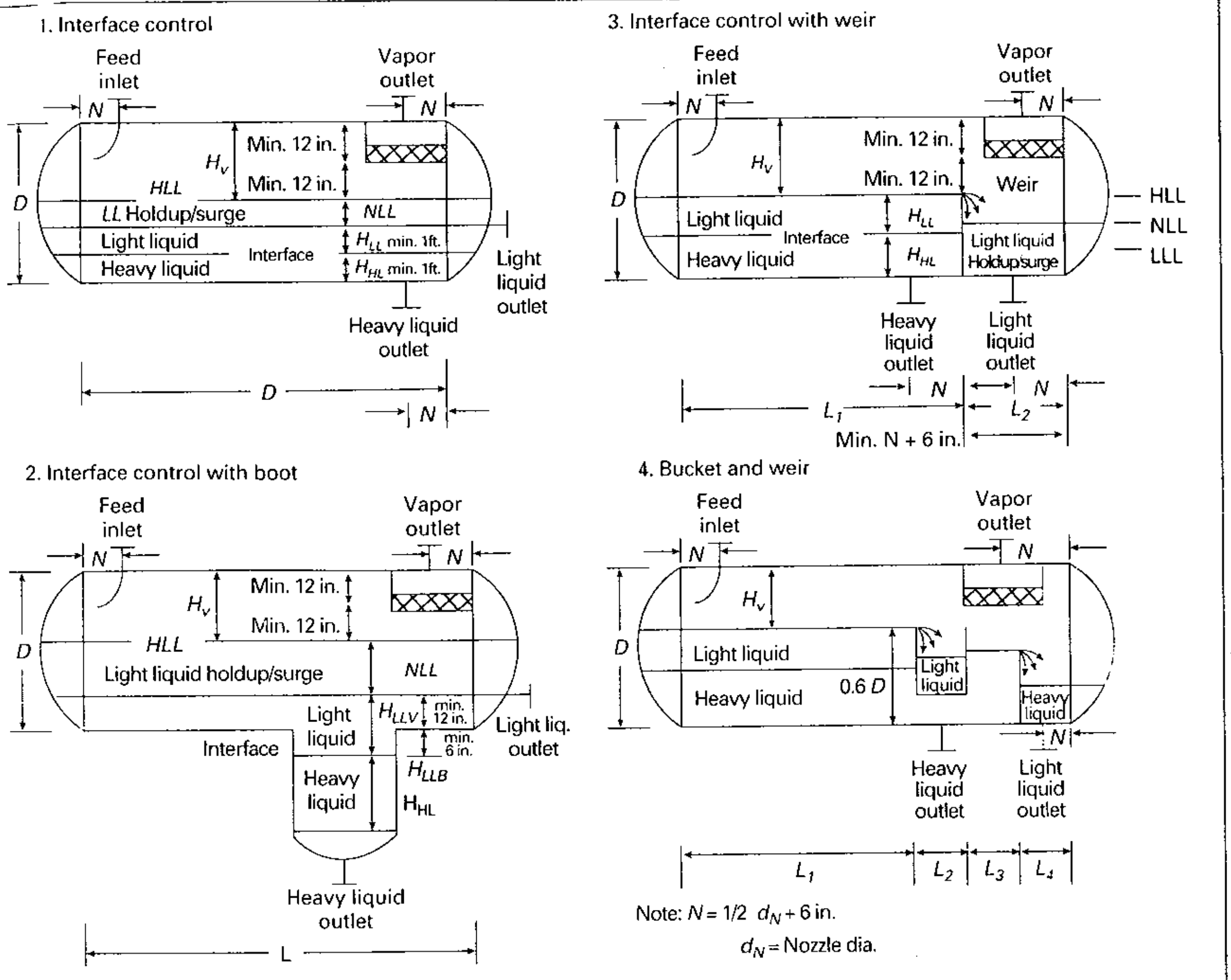
For horizontal separators with a given diameter, the heights of the light and heavy liquids are assumed so that the cross-sectional area can be calculated. With the vapor disengagement area set by guidelines, the lengths required by holdup requirements and vapor/liquid separation are calculated. Then, with the assumed heights of the light and heavy liquids and calculated values of settling velocities, the settling times are calculated.

The actual residence times for the light and heavy liquids are subsequently calculated and compared with the required settling times, as in the vertical case. If the residence times are not greater than the required settling times, then either the diameter should be increased or, for a given diameter, the length should be increased (liquid separation is controlling). In the subsequent design procedures, the latter approach is used, along with the procedures discussed in our previous paper for vapor/liquid separation *(2)*.

The following design procedures and heuristics are a result of a review of literature sources and accepted industrial design guidelines. Horizontal design procedures are presented for the four separator types shown in Figure 2. The horizontal design procedures incorporate optimizing the diameter and length by minimizing the approximate weight of the shell and heads. To add a degree of conservatism to the design, the volume available in the heads is ignored.

Table 1. Typical values of k_S for liquid-liquid separations.

Light Phase	Heavy Phase	Minimum droplet dia., μm	k_S
Hydrocarbons			
S_G at 60°F < 0.85	Water or caustic	127	0.333
S_G at 60°F < 0.85	Water or caustic	89	0.163
Water	Furfural	89	0.163
Methylethyl ketone	Water	89	0.163
sec-Butyl alcohol	Water	89	0.163
Methyl isobutyl ketone	Water	89	0.163
Nonyl alcohol	Water	89	0.163



■ *Figure 2. Basic designs of horizontal three-phase separators.*

Vertical design procedure

Refer to Figure 1 for dimensions:

1. Calculate the vertical terminal vapor velocity:

$$U_T = K\left(\frac{\rho_L - \rho_V}{\rho_V}\right)^{1/2} \quad (4)$$

Calculate the K value, using one of the methods in Table 2 and set $U_V = 0.75U_T$ for a conservative design.

2. Calculate the vapor volumetric flow rate:

$$Q_V = \frac{W_V}{3{,}600\rho_V} \quad (5)$$

3. Calculate the vessel internal diameter, D_{VD}:

$$D_{VD} = \left(\frac{4Q_V}{\pi U_V}\right)^{1/2} \quad (6)$$

If there is a mist eliminator, add 3–6 in. to D_{VD} to accommodate a support ring and round up to the next 6-in. increment to obtain D; if there is no mist eliminator, $D = D_{VD}$.

4. Calculate the setting velocity of the heavy liquid out of the light liquid using Stokes' law (the maximum is 10 in./min):

$$U_{HL} = \frac{k_S(\rho_H - \rho_L)}{\mu_L} \quad (7)$$

where k_S is obtained from Table 1 or is calculated (see Eq. 3).

5. Similarly, calculate the rising velocity of the light liquid out of the heavy liquid phase using Stokes' law:

$$U_{LH} = \frac{k_S(\rho_H - \rho_L)}{\mu_H} \quad (8)$$

6. Calculate the light and heavy liquid volumetric flow rates, Q_{LL} and Q_{HL}:

$$Q_{LL} = \frac{W_{LL}}{60\rho_L} \quad (9)$$

$$Q_{HL} = \frac{W_{HL}}{60\rho_H} \quad (10)$$

7. Assume H_L = 1 ft (minimum) and calculate the settling time for the

Table 2. Separator K values.

York Demister

$1 \leq P \leq 15$ $K = 0.1821 + 0.0029P + 0.0460 \ln(P)$
$15 \leq P \leq 40$ $K = 0.35$
$40 \leq P \leq 5{,}500$ $K = 0.430 - 0.023 \ln(P)$
where P is in psia.

Gas Processors Suppliers' Association

$0 \leq P \leq 1{,}500$ $K = 0.35 - 0.0001(P - 100)$

For most vapors under vacuum, $K = 0.20$
For glycol and amine solutions, multiply K by 0.6–0.8
For vertical vessels without demisters, divide K by 2
For compressor suction scrubbers, mole sieve scrubbers and expander inlet separators, multiply K by 0.7–0.8 where P is in psig.

Theoretical (no mist eliminator)

$$K = \sqrt{\frac{4gD_P}{3C_D}}$$

where D_P is in ft.
$C_D = \exp(y)$

$$y = 8.411 - 2.243x + 0.273x^2 - 1.865 \times 10^{-2}x^3 + 5.201 \times 10^{-4}x^4$$

$$x = \ln\left(\frac{0.95 \times 10^8 \rho_V D_P^3 (\rho_L - \rho_V)}{\mu_V^2}\right)$$

where D_P is in ft.
Note: 1 micron = 3.28084×10^{-6} ft

$$A_D = \left(\frac{7.48 \text{ gal}}{\text{ft}^3}\right)\left(\frac{60 \text{ min}}{\text{h}}\right)\left(\frac{(Q_{LL} + Q_{HL})}{G}\right)$$

■ *Equation 13*

$$U_T = 0.313\sqrt{\frac{53.95 - 0.6973}{0.6973}} = 2.74 \text{ ft/s}$$

■ *Equation E1*

$$Q_V = \frac{415{,}000 \text{ lb/h}}{3{,}600 \text{ s/h} \times 0.6973 \text{ lb/ft}^3} = 165.32 \text{ ft}^3\text{/s}$$

■ *Equation E2*

$$D_{VD} = \sqrt{\frac{4 \times 165.32 \text{ ft}^3\text{/s}}{\pi \, 2.05 \text{ ft/s}}} = 10.13 \text{ ft}$$

■ *Equation E3*

$$Q_{LL} = \frac{16{,}5000 \text{ lb/h}}{60 \text{ min/h} \times 53.95 \text{ lb/ft}^3} = 5.10 \text{ ft}^3\text{/min}$$

■ *Equation E4*

$$Q_{HL} = \frac{1{,}300 \text{ lb/h}}{60 \text{ min/h} \times 62.11 \text{ lb/ft}^3} = 0.35 \text{ ft}^3\text{/min}$$

■ *Equation E5*

heavy liquid droplets to settle through this distance (12 is a conversion factor for ft to in.):

$$t_{HL} = \frac{12H_L}{U_{HL}} \quad (11)$$

8. Assume H_H = 1 ft (minimum) and calculate the settling time for the light liquid droplets to rise through this distance:

$$t_{LH} = \frac{12H_H}{U_{LH}} \quad (12)$$

9. If there is a baffle plate, calculate the area:

a. Calculate $(\rho_L - \rho_V)$.
b. Assume H_R (use 9 in. as a minimum) and calculate $H_L + H_R$.
c. Use Figure 3 to obtain G.
d. Calculate A_D:
See Eq. (13) in the box.
e. Assume W_D = 4 in.
f. Calculate W_D/D.
g. Use Table 3 to determine A_D/A.
h. Calculate $A = (\pi/4)D^2$.
i. Calculate A_D.
j. Select the larger value of A_D.
k. Calculate the area of the baffle plate = settling area for the light liquid; $A_L = A - A_D$.

10. Calculate the residence time of each phase based on the volumes occupied by the light and heavy phases:

$$\theta_{LL} = \frac{H_L A_L}{Q_{LL}} \quad (14a)$$

$$\theta_{HL} = \frac{H_H A_H}{Q_{HL}} \quad (14b)$$

If $\theta_{LL} < t_{HL}$ or $\theta_{HL} < t_{LH}$, increase the diameter and repeat the procedure from Step 7 (liquid separation is controlling). Note that $A_H = A$.

11. Calculate the height of the light liquid above the outlet (holdup height) based on the required holdup time:

$$H_R = \frac{Q_{LL}T_H}{A_L} \quad (15)$$

Check this value with that assumed in Step 9b to ensure that the assumed value is reasonable. If surge is not specified, calculate the surge height based on surge time:

$$H_S = \frac{(Q_{LL} + Q_{HL})T_S}{A} \quad (16)$$

The minimum is 6 in.

12. Calculate the vessel height using the guidelines:
H_A = 6 in. minimum.
H_{BN} = ½ d_N + greater of (2 ft or H_S + 0.5 ft).
H_D = 0.5D or a minimum of:
36 in. + ½d_N (without mist eliminator), or
24 in. + ½d_N (with mist eliminator):

Table 3. Cylindrical height and area conversions.

$$y = \frac{a + cx + ex^2 + gx^3 + ix^4}{1.0 + bx + dx^2 + fx^3 + hx^4}$$

H/D* to *A/A$_T$*

$y = A/A_T$
$x = H/D$

$a = -4.755930 \times 10^{-5}$
$b = 3.924091$
$c = 0.174875$
$d = -6.358805$
$e = 5.668973$
$f = 4.018448$
$g = -4.916411$
$h = -1.801705$
$i = -0.145348$

A/A$_T$* to *H/D*

$y = H/D$
$x = A/A_T$

$a = 0.00153756$
$b = 26.787101$
$c = 3.299201$
$d = -22.923932$
$e = 24.353518$
$f = -14.844824$
$g = -36.999376$
$h = 10.529572$
$i = 9.892851$

* = Or equivalent expressions, such as H_N/D to A_N/A_T.

$$H_T = H_H + H_L + H_R + H_N + H_{BN} + H_D \quad (17)$$

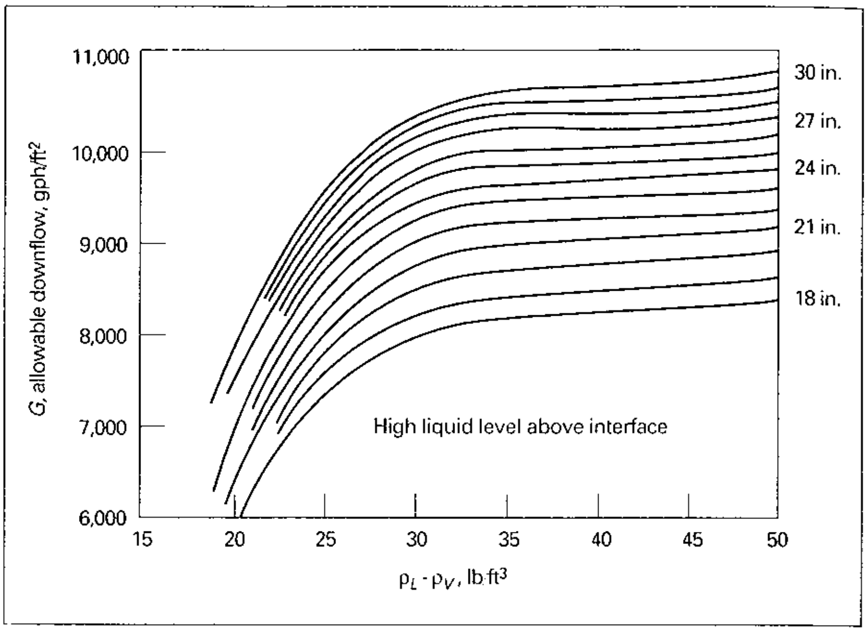
If a mist eliminator pad is used, additional height is added as shown in Figure 1.

Example 1

Size a vertical separator with a baffle plate and wire-mesh mist eliminator to separate the mixture given in Table 4. The operating pressure is 165 psia, and it is necessary to have a hydrocarbon liquid holdup time of 25 min and a surge time of only 5 min.

1. Calculate the vertical terminal velocity. Using Table 2, calculate K using the York Demister equations, see Eq. E1 in the box.

and $U_V = 0.75 \times 2.74 = 2.05$ ft/s.



■ *Figure 3. G is found from the downcomer allowable flow.*

Table 4. Data for Example 1.

	Mass Flow, lb/h	ρ, lb/ft³	μ, cP
Hydrocarbon Gas	$W_V = 415{,}000$	$\rho_V = 0.6973$	—
Hydrocarbon Liquid	$W_{LL} = 16{,}500$	$\rho_L = 53.95$	$\mu_L = 0.630$
Water	$W_{HL} = 1{,}300$	$\rho_H = 62.11$	$\mu_H = 0.764$

2. Calculate the vapor volumetric flow rate, see Eq. E2 in the box.

3. Calculate the vessel inner diameter, see Eq. E3 in the box.

Use $D = 10.5$ ft.

4. Calculate the settling velocity of the heavy liquid out of the light liquid phase. Using Table 1, $k_S = 0.163$. Then:

$U_{HL} = 0.163(62.11 - 53.95)/0.630 = 2.11$ in./min

5. Calculate the settling velocity of the light liquid out of the heavy liquid phase:

$U_{LH} = 0.163(62.11 - 53.95)/0.764 = 1.74$ in./min

6. Calculate the light and heavy liquid volumetric flow rates, see Eq. E4 and E5 in the box.

7. Assume $H_L = 1$ ft and calculate the time for the heavy liquid to settle out of the light liquid phase:

$t_{HL} = (12)(1.0)/2.11 = 5.7$ min

8. Assume $H_H = 1$ ft and calculate the time for the light liquid to rise out of the heavy liquid phase:

$t_{LH} = (12)(1.0)/1.74 = 6.9$ min

9. Calculate the baffle plate area:

$\rho_L - \rho_V = 53.95 - 0.6973 = 53.25$ lb/ft³

• Assume $H_R = 12$ in., $H_L + H_R = 24$ in. Using Figure 3, $G = 9{,}800$ gph/ft².

$A_D = (7.48\ \text{gal/ft}^3)(60\ \text{min/h})(5.10 + 0.35)(\text{ft}^3)/9{,}800\ \text{gph/ft}^3 = 0.25\ \text{ft}^2$

• Assume $W_D = 4$ in.:

$W_D/D = 4/(12 \times 10.5) = 0.0317$

Table 5. Inlet nozzle sizing.

$$d_N \geq \left(\frac{4Q_m}{60\pi/\sqrt{\rho_M}}\right)^{1/2}$$

$$\rho_M = \rho_L\lambda + \rho_V(1 - \lambda)$$

$$\lambda = \frac{Q_L}{Q_L + Q_V}$$

$$Q_{MIN} = Q_L + Q_V \quad \text{ft}^3/\text{s}$$

$$\frac{Q_M}{\frac{\pi}{4}d_N^2} = U_M \leq \frac{60}{\sqrt{\rho_M}}$$

Table 6. Liquid holdup and surge times.

Service	Holdup time, min (NLL — LLL)	Surge time, min (NLL — HLL)
A. Unit feed drum	10	5
B. Separators		
1. Feed to column	5	3
2. Feed to other drum or tankage		
a. With pump or through exchanger	5	2
b. Without pump	2	1
3. Feed to fired heater	10	3
C. Reflux or product accumulator		
1. Reflux only	3	2
2. Reflux and product	3+	2+
(Based on reflux (3 min) plus appropriate holdup time of overhead product (as per B 1–3)		
D. Column bottoms		
1. Feed to another column	5	2
2. Feed to other drum or tankage		
a) With pump or through exchanger	5	2
b) Without pump	2	1
3. Feed to fired reboiler	5–8	2–4
(Based on reboiler vapor expressed as liquid (3 min) plus appropriate holdup time for the bottom product(as per D 1, 2)		
E. Compressor suction/interstage scrubber 3 min between *HLL* (high liquid alarm) and high level shutdown 10 min from bottom tangent line to high liquid alarm		
F. Fuel gas knock-out drum 20 ft. slug in the incoming fuel gas line between *NLL* and high level shutdown		
G. Flare Knock-out drum 20 to 30 min to *HLL*		

Multiply by the following factors (optional):

Personnel	Factor	Instrumentation	Factor
Experienced	1.0	Well Instrumented	1.0
Trained	1.2	Standard Instrumented	1.2
Inexperienced	1.5	Poorly Instrumented	1.5

$$\rho_L = \frac{16{,}500}{17{,}800} \times 53.95 + \frac{1{,}300}{17{,}800} \times 62.11 = 54.55 \text{ lb/ft}^3$$

■ *Equation E6*

$$d_N \geq \left(\frac{4 \times 165.41}{60\ \pi/\sqrt{0.730}} \right)^{1/2} = 1.73 \text{ ft}$$

■ *Equation E7*

• Using Table 3, $A_D/A = 0.00$
$A = (\pi/4)(10.5 \text{ ft})^2 = 86.59 \text{ ft}^2$
$A_D = (0.0095)\ (86.59 \text{ ft}^2) = 0.8$
• Use $A_D = 0.82 \text{ ft}^2$.
$A_L = 86.59 - 0.82 = 85.77 \text{ ft}^2$

10. Calculate the residence tin each phase:

θ_{LL} = (1.0 ft) (85.77 ft^2)/ ft^3/min = 16.8 min

θ_{HL} = (1.0 ft) (86.59 ft^2)/(ft^3/min = 247.4 min

11. Calculate the height of the l liquid above the outlet, based holdup:

H_R = (5.10 ft^3/min) (25 min)/85 ft^2 = 1.5 ft

H_S = (5.10 + 0.35)(ft^3/min) min)/86.59 ft^2 = 0.31 ft

Use $H_S = 0.5$ ft.

12. Calculate d_N according Table 5:

$\lambda = Q_L/(Q_L + Q_V) = (5.10$ $0.35)/(5.10 + 0.35 + 165.32 \times 60)$ 0.0006

Use Eq. E6 (see box) to calcula ρ_L.

$\rho_M = \rho_L\lambda + \rho_V(1 - \lambda) = (54.5$ $(0.0006) + (0.6973)\ (1 - 0.0006)$ 0.730

$Q_M = 165.32 + (5.10 + 0.35)/60$ $165.41 \text{ ft}^3/\text{s}$

Use Eq. E7 (see box) to calculate d $d_N \geq 21$ in.; use $d_N = 24$ in Calculate H_D:

$H_D = 0.5\ (10.5) = 5.25$ ft or

$H_D = 24 + 24/2 = 36$ in. $= 3.0$ f (minimum)

Use $H_D = 5.5$ ft. From Figure 1, H_I = 1 ft and $s = 0.5$ ft. Calculate H_{BN}:

$H_{BN} = \frac{1}{2}\ (2.0 \text{ ft}) + 2 \text{ ft} = 3 \text{ ft}$

Set $H_A = 0.5$ ft. Final dimensions: $D = 10.5$ ft, $H_H = 1.0$ ft, $H_L = 1.0$ ft. $H_R = 1.5$ ft, $H_A = 0.5$ ft, $H_{BN} = 3.0$ ft. and $H_D = 5.5$ ft. Add 1.5 ft for the mist eliminator.

$H_T = 14.0$ ft

$H_T/D = 14.0/10.5 = 1.3$

Add 2 ft to H_T ($H_R = 2.0$ ft, H_D = 7.0 ft) so that $H_T/D = 1.52$ (H_T/D should be in the range of 1.5 to 6.0).

Horizontal design procedure: no boot or weir

1. Calculate the vapor volumetric flow rate, Q_V, using Eq. 5.

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2. Calculate the light and heavy liquid volumetric flow rates, Q_{LL} and Q_{HL}, using Eqs. 9 and 10.

3. Calculate the vertical terminal velocity, U_T, using Eq. 4. (select a K value from Table 2) and set U_V = $.75U_T$.

4. Select holdup and surge times from Table 6 and calculate the holdup and surge volumes, V_H and V_S, (unless surge is otherwise specified, such as a slug volume):

$$V_H = T_H Q_L \tag{18}$$

$$V_S = T_S Q_l \tag{19}$$

5. Obtain an L/D from Table 7 and initially calculate the diameter according to:

$$D = \left(\frac{4(V_H + V_S)}{0.5\pi(L/D)}\right)^{1/3} \tag{20}$$

Calculate the total cross-sectional area:

$$A_T = \frac{\pi D^2}{4} \tag{21}$$

6. Set the vapor space height, H_V, to the larger of $0.2D$ or 2 ft; 1 ft if there is no mist eliminator. Using H_V/D in Table 3, obtain A_V/A_T and calculate A_V.

7. Set the heights of the heavy and light liquids, H_{HL} and H_{LL}.

8. Find $(A_{HL} + A_{LL})/A_T$, using $(H_{HL} + H_{LL})/D$ in Table 3, and calculate $A_{HL} + A_{LL}$.

9. Calculate the minimum length to accommodate the liquid holdup/surge:

$$L = \frac{V_H + V_S}{A_T - A_V - (A_{HL} + A_{LL})} \tag{22}$$

10. Calculate the liquid dropout time:

$$\phi = H_V/U_V \tag{23}$$

11. Calculate the actual vapor velocity:

Table 7. L/D ratio guidelines.

Vessel operating pressure, psig	L/D
$0 < P \leq 250$	1.5–3.0
$250 < P < 500$	3.0–4.0
$500 < P$	4.0–6.0

$$U_{VA} = Q_V/A_V \tag{24}$$

12. Calculate the minimum length required for vapor/liquid separation:

$$L_{MIN} = U_{VA}\,\phi \tag{25}$$

13. If $L < L_{MIN}$, then set $L = L_{MIN}$ (here, vapor/liquid separation controls). This simply results in some extra holdup and residence time. If $L << L_{MIN}$, then increase H_V and recalculate A_V, and repeat, starting from Step 9. If $L > L_{MIN}$, the design is acceptable for vapor/liquid separation. If $L >> L_{MIN}$ (liquid holdup controls), L can only be reduced and L_{MIN} increased if H_V is reduced. H_V may only be reduced if it is greater than the minimum specified in Step 6. (With reduced H_V, recalculate A_V and repeat the procedure from Step 9.) **Note:** For this and other calculations, "much greater than" (>>) and "much less than" (<<) mean a variance of greater than 20%.

14. Calculate the settling velocities of the heavy liquid out of the light liquid phase and the light liquid out of the heavy liquid phase, U_{HL} and U_{LH}, using Eqs. 7 and 8 (find k_S from Table 1).

15. Calculate the settling times of the heavy liquid out of the light phase and the light liquid out of the heavy phase:

$$t_{HL} = 12\,(D - H_V - H_{HL})/U_{HL} \tag{26}$$

$$t_{LH} = 12\,H_{HL}/U_{LH} \tag{27}$$

16. Calculate the residence times of the light and heavy liquids:

$$\theta_{HL} = A_{HL}L/Q_{HL} \tag{28}$$

$$\theta_{LL} = \frac{(A_T - A_V - A_{HL})L}{Q_{LL}} \tag{29}$$

17. If $\theta_{HL} < t_{LH}$ or $\theta_{LL} < t_{HL}$ then increase the vessel length (liquid separation controls):

$$L = \max\left(\frac{t_{LH}Q_{HL}}{A_{HL}},\ \frac{t_{HL}Q_{LL}}{(A_T - A_V - A_{HL})}\right) \tag{30}$$

18. Calculate L/D. If $L/D << 1.5$, decrease D (unless it is already at its minimum), and if $L/D >> 6.0$ then increase D; repeat from Step 5.

19. Calculate the thickness of the shell and heads according to Table 8.

20. Calculate surface area of the shell and heads according to Table 8.

21. Calculate the approximate vessel weight according to Table 8.

22. Increase or decrease the vessel diameter by 6-in. increments and repeat the calculations until the L/D ratio ranges from 1.5–6.0.

23. Using the optimum vessel size (minimum weight), calculate the normal and high liquid levels:

$$H_{HLL} = D - H_V \tag{31}$$

$$A_{NLL} = (A_{HL} + A_{LL}) + V_H/L \tag{32}$$

Obtain H_{NLL} using Table 3 with the value of A_{NLL}/A_T.

Horizontal design procedure: heavy liquid boot

1. Calculate the vapor volumetric flow rate, Q_V, using Eq. 5.

2. Calculate the light and heavy liquid volumetric flow rates, Q_{LL} and Q_{HL}, per Eqs. 9 and 10.

3. Calculate the vertical terminal velocity, U_T, using Eq. 4 (the K value comes from Table 2) and set U_V = 0.75 U_T.

4. Select holdup and surge times from Table 6 and calculate the holdup and surge volumes, V_H and V_S, from Eqs. 18 and 19 (unless surge is other-

wise specified, such as slug volume).

5. Obtain L/D from Table 7 and initially set the diameter according to:

$$D = \left(\frac{4(V_H + V_S)}{0.6\pi(L/D)} \right)^{1/3} \quad (33)$$

Then calculate the total cross-sectional area, A_T, using Eq. 21.

6. Set the vapor space height, H_V, to the larger of $0.2D$ or 2 ft (1 ft if there is no mist eliminator). Using H_V/D in Table 3, obtain A_V/A_T and calculate A_V.

7. Set the light liquid heights in the vessel and boot, H_{LLV} and H_{LLB}.

8. Calculate the cross-sectional area of the light liquid above the bottom of the vessel, A_{LLV}, using H_{LLV}/D in Table 3.

9. Calculate the minimum length to accommodate the liquid holdup/surge:

$$L = \frac{V_H + V_S}{A_T - A_V - A_{LLV}} \quad (34)$$

10. Calculate the liquid dropout time, ϕ, using Eq. 23.

11. Calculate the actual vapor velocity, U_{VA}, using Eq. 24.

12. Calculate the minimum length required for liquid/vapor separation, L_{MIN}, using Eq. 25.

13. If $L < L_{MIN}$, then set $L = L_{MIN}$ (vapor/liquid separation controls). This simply results in some extra holdup and residence time. If $L << L_{MIN}$, then increase H_V and recalculate A_V, then repeat from Step 9. If $L > L_{MIN}$, the design is acceptable for vapor/liquid separation. If $L >> L_{MIN}$, liquid holdup controls. L can only be reduced and L_{MIN} increased if H_V is reduced. H_V may only be reduced if it is greater than the minimum specified in Step 6.

With reduced H_V, recalculate A_V and repeat from Step 9.

14. Calculate the settling velocity of the heavy liquid out of the light liquid phase, U_{HL}, using Eq. 7 (obtain k_S from Table 1).

15. Calculate the settling time of the heavy liquid out of the light liquid phase:

$$t_{HL} = 12\,(H_{LLB} + D - H_V)/U_{HL} \quad (35)$$

16. Calculate the residence time of the light liquid:

$$\theta_{LL} = \frac{(A_T - A_V)L}{Q_{LL}} \quad (36)$$

Note: This volume of light liquid ignores the light liquid volume in the boot.

17. If $\theta_{LL} < t_{HL}$ then increase the vessel length (liquid separation controls):

$$L = \frac{t_{HL} Q_{LL}}{(A_T - A_V)} \quad (37)$$

18. Calculate L/D. If $L/D << 1.5$ then decrease D (unless it is already at a minimum) and if $L/D >> 6.0$ then increase D; repeat from Step 5.

19. Calculate the thickness of the shell and heads according to Table 8.

20. Calculate the surface area of the shell and heads according to Table 8.

21. Calculate the approximate weight of the shell and heads according to Table 8.

22. Increase or decrease the vessel diameter by 6-in. increments and repeat the calculations until L/D ranges from 1.5–6.0.

23. With the optimum vessel size (minimum weight), calculate the normal and high liquid levels:

$$H_{HLL} = D - H_V \quad (38)$$

$$A_{NLL} = A_{LLV} + V_H/L \quad (39)$$

Determine H_{NLL} using Table 3 from A_{NLL}/A_T.

24. Design the heavy liquid boot: Set the height of the heavy liquid, H_{HL}; calculate the rising velocity of the light liquid out of the heavy liquid phase, U_{LH}, using Eq. 8 (find k_S from

Table 8. Wall thickness, surface area, and approximate vessel weight.

Component	Wall Thickness, in.	Surface Area, ft²
Shell	$\frac{PD}{2SE - 1.2P} + t_C$	πDL
2:1 Elliptical Heads	$\frac{PD}{2SE - 0.2P} + t_C$	$1.09\,D^2$
Hemispherical Heads	$\frac{PD}{4SE - 0.4P} + t_C$	$1.571\,D^2$
Dished Heads	$\frac{0.885PD}{SE - 0.1P} + t_C$	$0.842\,D^2$

Approximate Vessel Weight

$$W = \left(\frac{490\ \text{lb}}{\text{ft}^3}\right)\left(\frac{t}{12}\right)\left(A_{Shell} + 2A_{Head}\right)$$

Notes: The design pressure, P, is typically either the operating pressure with 15 to 30 psi added to it or the operating pressure + 10%, whichever is greater. For the allowable stress, S, see Reference (3). The joint efficiency, E, ranges from 0.6 to 1; use 0.85 for spot-examined joints, and 1 for 100% X-rayed joints. The corrosion allowance, t_C, typically ranges from 1/16 to 1/8 in. The vessel thickness, t, is the larger of t_S and t_H up to the nearest 1/8 in.

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ble 1): set $U_P = 0.75\ U_{LH}$; calculate e heavy liquid boot diameter:

$$D_B = \sqrt{\frac{4 \times 12 Q_{HL}}{\pi U_P}} \quad (40)$$

n calculate the settling time of the light liquid out of the heavy liquid phase:

$$t_{LH} = 12 H_{HL}/U_{LH} \quad (41)$$

Calculate the residence time of the vy liquid:

$$\theta_{HL} = \frac{\pi D_P^2 H_{HL}}{4 Q_{HL}} \quad (42)$$

If $\theta_{HL} < t_{LH}$, then increase the boot diameter.

Horizontal design procedure: weir

1. Calculate the vapor volumetric flow rate, Q_V, using Eq. 5.

2. Calculate the light and heavy liquid volumetric flow rates, Q_{LL} and Q_{HL}, as per Eqs. 9 and 10.

3. Calculate the vertical terminal vapor velocity, U_T, using Eq. 4 (find K from Table 2) and set $U_V = 0.75 U_T$.

4. Select holdup and surge times from Table 6, and calculate the holdup and surge volumes, V_H and V_S, from Eqs. 18 and 19 (unless surge is otherwise specified, such as a slug volume).

5. Obtain L/D from Table 7 and initially calculate the diameter according to:

$$D = \left(\frac{16 (V_H + V_S)}{0.6 \pi (L/D)} \right)^{1/3} \quad (43)$$

Then calculate the total cross-sectional area, A_T, using Eq. 21.

6. Set the vapor space height, H_V, to the larger of 0.2D or 2 ft (1 ft if there is no mist eliminator). Using H_V/D in Table 3, obtain A_V/A_T and calculate A_V.

7. Calculate the low liquid level in the light liquid compartment using Eq. 44 or read it from Table 9.

Table 9. Low liquid level height.

Vessel dia., ft	Vertical LLL, in. < 300 psia	Vertical LLL, in. > 300 psia	Horizontal LLL, in.
≤4,	15	6	9
6	15	6	10
8	15	6	11
10	6	6	12
12	6	6	13
16	6	6	15

$$H_{LLL} = 0.5D + 7 \quad (44)$$

where D is in feet and H_{LLL} in inches (round up to nearest in.). If $D \leq 4.0$ ft, then H_{LLL} = 9 in. Using H_{LLL}/D in Table 3, Calculate A_{LLL}.

8. Calculate the weir height:

$$H_W = D - H_V \quad (45)$$

If H_W < 2 ft, increase D, and repeat the calculations from Step 6.

9. Calculate the minimum length of the light liquid compartment to accommodate holdup/surge, L_2 in Figure 2 :

$$L_2 = \frac{V_H + V_S}{A_T - A_V - A_{LLL}} \quad (46)$$

Round to the nearest ½ ft. The minimum for $L_2 = d_N$ + 12 in.

10. Set the interface at the height $H_W/2$, obtaining the heights of the heavy and light liquids, H_{HL} and H_{LL}.

11. For the liquid settling compartment, calculate the cross-sectional area of the heavy liquid, using H_{HL}/D in Table 3 and calculate the cross-sectional area of the light liquid from:

$$A_{LL} = A_T - A_V - A_{HL} \quad (47)$$

12. Calculate the settling velocity of the heavy liquid out of the light liquid phase, U_{HL}, and the light liquid out of the heavy liquid phase, U_{LH}, using Eqs 7 and 8 (find k_S from Table 1).

13. Calculate the settling times of the heavy liquid out of the light liquid phase and the light liquid out of the heavy liquid phase:

$$t_{HL} = 12 H_{LL}/U_{HL} \quad (48)$$

$$t_{LH} = 12 H_{HL}/U_{LH} \quad (49)$$

14. Calculate minimum L_1 to facilitate liquid-liquid separation as the larger of:

$$L_1 = \max\left(\frac{t_{LH} Q_{HL}}{A_{HL}}, \frac{t_{HL} Q_{LL}}{A_{LL}} \right) \quad (50)$$

Round to the nearest ½ ft.

15. Find L:

$$L = L_1 + L_2 \quad (51)$$

16. Calculate the liquid dropout time, ϕ, using Eq. 23.

17. Calculate the actual vapor velocity, U_{VA}, using Eq. 24.

18. Calculate the minimum length required for vapor//liquid separation, L_{MIN}, using Eq. 25.

19. If $L < L_{MIN}$, then set $L = L_{MIN}$ (vapor/liquid separation controls). This simply results in some extra holdup and residence time. If $L << L_{MIN}$, then increase H_V, recalculate A_V and repeat the calculations from Step 6. If $L > L_{MIN}$, the design is acceptable for vapor/liquid separation. If $L >> L_{MIN}$ (liquid separation and holdup control), L can only be reduced and L_{MIN} increased if H_V is reduced. H_V may only be reduced if it is greater than the minimum specified in Step 9. With reduced H_V, recalculate A_V and repeat from Step 9.

20. Calculate L/D. If L/D << 1.5, then decrease D (unless it is already at a minimum) and repeat from Step 6. If L/D >> 6.0, then increase D and repeat from Step 5.

21. Calculate the thickness of the shell and heads according to Table 8.

22. Calculate the surface area of the shell and heads according to Table 8.

23. Calculate the approximate vessel weight according to Table 8.

24. Increase or decrease the diameter by 6-in. increments and repeat the calculations until L/D ranges from 1.5–6.0.

25. With the optimum vessel size (minimum weight), calculate normal and high liquid levels:

$$H_{HLL} = D - H_V \qquad (52)$$

$$A_{NLL} = A_{LLL} + V_H/L_2 \qquad (53)$$

Obtain H_{NLL} using Table 3 with A_{NLL}/A_T.

Horizontal design procedure: bucket and weir

1. Calculate the vapor volumetric flow rate, Q_V, using Eq. 5.

2. Calculate the light and heavy liquid volumetric flow rates, Q_{LL} and Q_{HL} per Eqs. 9 and 10.

3. Calculate the vertical terminal vapor velocity, U_T, using Eq. 4 (find K from Table 2) and set $U_V = 0.75\ U_T$.

4. Select residence times for light and heavy liquids, θ_{LL} and θ_{HL}. For sour water stripper feed drums, θ_{HL} = 60 min for refinery service, or 10–15 min for chemical-plant service. For amine regenerator feed drums, θ_{HL} = 10–15 min.

5. Obtain L/D from Table 7 and initially set the diameter according to:

$$D = \left(\frac{4\left(Q_{LL}\theta_{LL} + Q_{HL}\theta_{HL}\right)}{0.70\pi\left(L/D\right)} \right)^{1/3} \qquad (54)$$

Then calculate the total cross-sectional area, A_T, using Eq. 21.

6. Set the vapor space height, H_V, to the larger of 0.2D or 2 ft (1 ft if there is no mist eliminator). U... H_V/D in Table 3, obtain A_V/A_T and ... culate A_V.

7. Calculate L_1:

$$L_1 = \frac{\left(Q_{LL}\theta_{LL} + Q_{HL}\theta_{HL}\right)}{A_T - A_V} \qquad (5$$

8. Calculate the liquid drop... time, ϕ, using Eq. 23.

9. Calculate the actual vapor vel... ity, U_{VA}, using Eq. 24.

10. Calculate the minimum leng... required for vapor/liquid separatio... L_{MIN}, using Eq. 25.

11. If $L_1 < L_{MIN}$, then set $L_2 = L_{...}$ (vapor/liquid separation controls... This simply results in some ext... holdup and residence time. If $L_1 <$ L_{MIN}, then increase H_V, recalculate A... and repeat the calculations from Ste... 7. If $L_1 > L_{MIN}$, the design is accept... able for vapor/liquid separation.

12. Calculate the light liquid laye... thickness based on the heavy liqui... settling out:

Literature Cited

1. Arnold, K., and M. Stewart, "Surface Production Operations," Chapter 5, Gulf Publishing Co., Houston, pp. 123–149 (1986).
2. Svrcek, W. Y., and W. D. Monnery, "Design Two-Phase Separators Within the Right Limits," *Chem. Eng. Progress*, 89(10), pp. 53-60 (Oct.1993).
3. American Society of Mechanical Engineers, "ASME Pressure Vessel Code," Sec. VIII, Div. 1, Table UCS-23, ASME, New York, pp. 270-271 (1986).

$$Q_V = \frac{235{,}000 \text{ lb/h}}{3{,}600 \text{ s/h} \times 0.190 \text{ lb/ft}^3} = 343.57 \text{ ft}^3\text{/s}$$

■ *Equation E8*

$$Q_{LL} = \frac{45{,}000 \text{ lb/h}}{60 \text{ min/h} \times 40.5 \text{ lb/ft}^3} = 18.52 \text{ ft}^3\text{/min}$$

■ *Equation E9*

$$Q_{HL} = \frac{7{,}500 \text{ lb/h}}{60 \text{ min/h} \times 62.0 \text{ lb/ft}^3} = 2.02 \text{ ft}^3\text{/min}$$

■ *Equation E10*

$$U_T = 0.175\sqrt{\frac{40.5 - 0.19}{0.19}} = 2.55 \text{ ft/s}$$

■ *Equation E11*

$$D = \left(\frac{4 \times 277.80}{0.6\pi \times 1.7 \times 1/4}\right)^{1/3} = 11.15 \text{ ft, use } 11.0 \text{ ft}$$

■ *Equation E12*

$$L_2 = \frac{277.80}{95.03 - 71.08 - 4.85} = 14.54 \text{ ft}$$

■ *Equation E13*

$$\frac{t_{LL}Q_{HL}}{A_{HL}} = \frac{2.0 \text{ min} \times 2.02 \text{ ft}^3\text{/min}}{8.93 \text{ ft}^2} = 0.45 \text{ ft}$$

■ *Equation E14*

$$\frac{t_{HL}Q_{LL}}{A_{LL}} = \frac{2.0 \text{ min} \times 18.52 \text{ ft}^3\text{/min}}{15.02 \text{ ft}^2} = 2.47 \text{ ft}$$

■ *Equation E15*

$$U_{VA} = \frac{Q_V}{A_V} = \frac{343.57 \text{ ft}^3\text{/s}}{71.08 \text{ ft}^2} = 4.83 \text{ ft/s}$$

■ *Equation E16*

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$$H_{LL} = \frac{0.00128\theta_{LL}(\Delta S_G)D_P^2}{\mu_L} \quad (56)$$

where D_P is in microns.

13. Calculate the difference in height between the light and heavy liquid weirs:

$$\Delta H = H_{LL}\left(1 - \frac{\rho_L}{\rho_H}\right) \quad (57)$$

14. Design the light liquid bucket: Set the top of light liquid weir = $D - H_V$; assume the bottom is at $0.125D$; assume a holdup/surge (typically, 5–15 min.); assume HLL is 6 in. below the weir height and LLL is 6 in. above the bottom of the bucket. Using Table 3 with H_{HLL}/D and H_{LLL}/D, calculate A_{HLL} and A_{LLL}. Calculate L_2:

$$L_2 = \frac{(T_H + T_S)Q_{LL}}{(A_{HLL} - A_{LLL})} \quad (58)$$

15. Assume L_3 is the larger of $D/12$ or 12 in.

16. Design the heavy liquid compartment: Set the top of the heavy liquid weir = $D - H_V - \Delta H$; assume a holdup/surge (typically, 5–15 min); assume HLL is about 6 in. below the weir height and LLL is about 6 in. above the bottom of the vessel. Using Table 3 with H_{HLL}/D and H_{LLL}/D, calculate A_{HLL} and A_{LLL}.

Calculate L_4:

$$L_4 = \frac{(T_H + T_S)Q_{HL}}{(A_{HLL} - A_{LLL})} \quad (59)$$

17. Calculate $L = L_1 + L_2 + L_3 + L_4$.

18. Calculate L/D. If $L/D \ll 1.5$, then decrease D and repeat from Step 5. If $L/D \gg 6.0$, then increase D and repeat from Step 5.

19. Calculate the thickness of the shell and heads according to Table 8.

20. Calculate the surface area of

Nomenclature

- A = vertical vessel cross-sectional area, ft²
- A_D = downcomer cross-sectional area, ft²
- A_{LLV} = area of light liquid above vessel bottom, ft²
- A_T = total cross-sectional area, ft²
- C_D = drag coefficient, dimensionless
- d_N = nozzle dia., in. (inlet or outlet vapor/liquid as specified)
- D = vessel diameter, ft or in.
- D_B = boot dia., ft
- D_P = droplet dia., ft, or microns
- D_{VD} = vapor disengagement dia., ft
- E = welded joint efficiency, dimensionless
- g_c = gravitational constant, 32.17 ft/s²
- G = baffle liquid load, gph/ft²
- H = height, ft
- H_A = liquid level above baffle, in. or ft
- H_{BN} = liquid height from above baffle to feed nozzle, ft
- H_D = disengagement height, ft
- H_H = holdup height, ft
- H_L = height from liquid interface to LL nozzle, ft
- H_{LIN} = HLL to inlet nozzle centerline height, ft
- H_{LLB} = light liquid height in boot, ft
- H_{LLT} = light layer thickness, in.
- H_{LLV} = light liquid height in vessel, ft
- H_{ME} = mist eliminator to top tan. height, ft
- H_R = height from light liquid nozzle to baffle, ft
- H_S = surge height, ft
- H_T = total vertical separator height, ft
- H_V = vapor disengagement area height, ft
- H_W = weir height, ft
- ΔH = height difference between light and heavy liquid weirs, in.
- k_S = Stokes' law terminal velocity constant, (in./min)(cP)/(lb/ft³)
- K = terminal velocity constant, ft/s
- L = vessel length, ft
- L_{MIN} = vapor/liquid separation minimum length, ft
- L_{1-4} = as defined in Figure 2
- P = pressure, psig or psia
- Q = volumetric flow, ft³/s or ft³/min
- S = vessel material stress value, psi
- ΔS_G = specific gravity difference between light and heavy liquids
- t_C = corrosion allowance, in.
- t_H = head thickness, in.
- t_{HL} = settling time for heavy liquid droplets out of light liquid, min
- t_{LH} = rise time for light liquid droplets out of heavy liquid, min
- t_S = shell thickness, in.
- T_H = holdup time, min
- T_S = surge time, min.
- U_{AH} = allowable horizontal velocity, ft/s
- U_{HL} = settling velocity of heavy liquid droplets out of light liquid, in./min
- U_{LH} = rising velocity of light liquid droplets out of heavy liquid, in./min
- U_M = mixture velocity, ft/s
- U_P = boot velocity, in./min
- U_T = terminal velocity, ft/s or in./min
- U_V = vapor velocity, ft/s
- U_{VA} = actual vapor velocity, ft/s
- V_H = holdup volume, ft³
- V_{LLL} = LLL volume, ft³
- V_S = surge volume, ft³
- W = vessel weight, lb
- W_D = downcomer chord width, in.

Greek letters

- θ = liquid residence time, min
- λ = mixture liquid fraction
- μ = viscosity, cP
- ρ = density, lb/ft³
- ϕ = liquid dropout time, s

Subscripts

- H, HL = heavy liquid
- HLL = high liquid level
- L, LL = light liquid
- LLL = low liquid level
- M = mixture
- NLL = normal liquid level
- V = vapor

Table 10. Data for Example 2.

Component	Mass Flow, lb/h	ρ, lb/ft³	μ, cP
Hydrocarbon vapor	$W_V = 235{,}000$	$\rho_V = 0.190$	—
Hydrocarbon liquid	$W_{LL} = 45{,}000$	$\rho_L = 40.5$	$\mu_L = 0.24$
Water	$W_{HL} = 7{,}500$	$\rho_H = 62.0$	$\mu_H = 0.682$

Table 11. Selection of vessel heads.

Conditions	Typical Heads Used
$D < 15$ ft and $P < 100$ psig	Dished with knuckle radius = 0.06 D
$D < 15$ ft and $P > 100$ psig	2:1 Elliptical
$D > 15$ ft, regardless of pressure	Hemispherical

where: P = design pressure and D = drum dia.

shell and heads according to Table 8.

21. Calculate the approximate vessel weight according to Table 8.

22. Increase or decrease the diameter by 6-in. increments and repeat the calculations until L/D ranges from 1.5–6.0.

Example 2

Design a three-phase horizontal separator with a weir to separate the mixture in Table 10. The operating pressure and temperature are 25 psig and 100, respectively, and it is necessary to have a liquid holdup and surge time of 15 min.

1. See Eq. E8, box, p. 38

2. See Eqs. E9 and E10, box, p. 38

3. $K = 0.175$ (the Gas Processors Suppliers' Association value in Table 2 was divided by 2 since there is no mist eliminator).

See Eq. E11, box, p. 38

$U_V = 0.75 \times 2.55 = 1.91$ ft/s

4. Holdup + surge as specified = 15 min.

$V_H + V_S = (15 \text{ min})\,(18.52 \text{ ft}^3/\text{min}) = 277.80 \text{ ft}^3$

Assume 10 min holdup, 5 min surge.

5. Assume $L/D = 1.7$.

See Eq. E12, box, p. 38

$A_T = \pi/4\,(11.0 \text{ ft})^2 = 95.03 \text{ ft}^2$

6. Since the mass rate of vapor is about 82% of the loading, set H_V to be much greater than the minimum. Assume $H_V = 0.70D = (0.70)(11.0 \text{ ft}) = 7.70$ ft. Using Table 3, $A_V/A_T = 0.748$, $A_V = 71.08 \text{ ft}^2$

7. $H_{LLL} = (0.5)(11.0) + 7 = 12.5$ in., use 13 in.

$H_{LLL}/D = 13/(11.0 \times 12) = 0.098$

Using Table 3, $A_{LLL}/A_T = 0.051$

$A_{LLL} = (0.051)(95.03 \text{ ft}^2) = 4.85 \text{ ft}^2$

8. $H_W = 11.0 - 7.70 = 3.30$ ft

9. See Eq. E13, box, p. 38

Use $L_2 = 15.0$ ft.

10. $H_{HL} = H_{LL} = 3.30/2 = 1.65$ ft

11. $H_{HL}/D = 1.65/11.0 = 0.150$

From Table 3, $A_{HL}/A_T = 0.094$

$A_{HL} = (0.094)(95.03 \text{ ft}^2) = 8.93 \text{ ft}^2$

$A_{LL} = 95.03 - 71.08 - 8.93 = 15.02 \text{ ft}^2$

12. From Table 1, $k_S = 0.333$

$U_{HL} = (0.333)(62.0 - 40.5)/0.24 = 29.83$ in./min

Use 10 in./min (maximum)

$U_{LH} = (0.333)(62.0 - 40.5)/0.682 = 10.50$ in./min

Use 10 in./min (maximum)

13. $t_{HL} = (12 \text{ in./ft})(1.65 \text{ ft})/10 \text{ in./min} = 1.98$ min, use 2.0 mins

$t_{LH} = t_{HL} = 2.0$ min

14. See Eqs. E14 and E15, box, p. 38

Use $L_1 = 3.0$ ft.

15. $L = 3.0 + 15.0 = 18.0$ ft

16. $\phi = 7.70 \text{ ft}/1.91 \text{ ft/s} = 4.03$ s

17. See Eq. E16, box, p. 38

18. $L_{MIN} = (4.83 \text{ ft/s})(4.03 \text{ s}) = 19.5$ ft

19. Since $L < L_{MIN}$, set $L = 19.5$ ft (set $L_2 = 16.0$ ft, $L_1 = 3.5$ ft)

20. $L/D = 19.5/11.0 = 1.78$

21. Assume dished heads per Table 11.

Assume $E = 0.85$

Use SA-516 70 carbon steel, design temperature = 650°

$S = 17{,}500$ psi; from Ref. *(3)*.

Corrosion allowance = 1/16 in.

$P = 25 + 30 = 55$ psig

See Eq. E17, box on this page.

Use t_S = 3/8 in.

See Eq. E18, box on this page.

Use t_H = 1/2 in.; use t = 1/2 in.

22. $A_S = \pi(11.0 \text{ ft})\,(19.5 \text{ ft}) = 673.87 \text{ ft}^2$

$A_H = (0.842)\,(11.0 \text{ ft})^2 = 101.88 \text{ ft}^2$

23. See Eq. E19, box on this page.

24. In this example, calculations were performed for only one diameter. However, nearly the minimum L/D corresponded to a diameter of 11.0 ft; therefore, the next diameter should be smaller, resulting in a larger L/D. Also, calculations should be performed using a diameter of 11.5 ft.

25. For the light liquid compartment:

$H_{HLL} = H_W = 3.3$ ft ~ 3 ft, 4 in.

$A_{NLL} = 4.85 + 185.20/16.0 = 16.43 \text{ ft}^2$

$A_{NLL}/A_T = 16.43/95.03 = 0.173$

Using Table 3, $H_{NLL}/D = 0.229$

$H_{NLL} = (0.229)\,(11.0) = 2.52$ ft ~ 2 ft, 6 in.

$H_{LLL} = 13$ in.

Comment: Due to the small amount of heavy liquid and large amount of vapor, a better design would have used a boot. A vertical vessel should be compared, as well.

$$t_S = \frac{55 \times 132}{2 \times 17{,}500 \times 0.85 - 1.2 \times 55} + 1/16 = 0.307 \text{ in.}$$

■ *Equation E17*

$$t_H = \frac{0.885 \times 55 \times 132}{2 \times 17{,}500 \times 0.85 - 0.1 \times 55} + 1/16 = 0.495 \text{ in.}$$

■ *Equation E18*

$$W = \frac{490 \text{ lb}}{\text{ft}^3} \times \frac{0.500 \text{ in.}}{12 \text{ in./ft}}\left(673.87 \text{ ft}^2 + 2 \times 101.88 \text{ ft}^2\right) = 17{,}920 \text{ lb}$$

■ *Equation E19*

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