BIOPROCESS EQUIPMENT DESIGN

LIQUID-LIQUID SEPARATORS

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Separation of two liquid phases, immiscible or partially miscible liquids, is a common requirement in the process industries. For example, in the unit operation of liquid-liquid extraction the liquid contacting step must be followed by a separation stage. The simplest form of equipment used to separate liquid phases is the gravity settling tank (decanter). Decanters are used to separate liquids where there is a sufficient difference in density between the liquids for the droplets to settle readily. In an operating decanter there will be three distinct zones or bands: clear heavy liquid; separating dispersed liquid; and clear light liquid. Liquid-liquid separators are very widely used in a great many industries and applications such as:

- **Oil refineries**
- **Petrochemical industries**
- **chemical industries**
- **biochemical plants**
- **Food industries**
- **Pharmaceutical industries**

Typical designs are shown in figures below. The position of the interface can be controlled, with or without the use of instruments. The height of the take-off can be determined by making a pressure balance. Neglecting friction loss in the pipes, the pressure exerted by the combined height of the heavy and light liquid in the vessel must be balanced by the height of the heavy liquid in the take-off leg.

$$\rho_1 g(H_1 - H_3) + \rho_2 g\, H_3 = \rho_2 H_2 g$$

$$H_2 = H_3 + \frac{(H_1 - H_3)\rho_1}{\rho_2}$$

where

ρ_1 = density of the light liquid, kg/m3.

ρ_2 =density of the heavy liquid, kg/m3.

H_1 = height from datum to light liquid overflow, m.

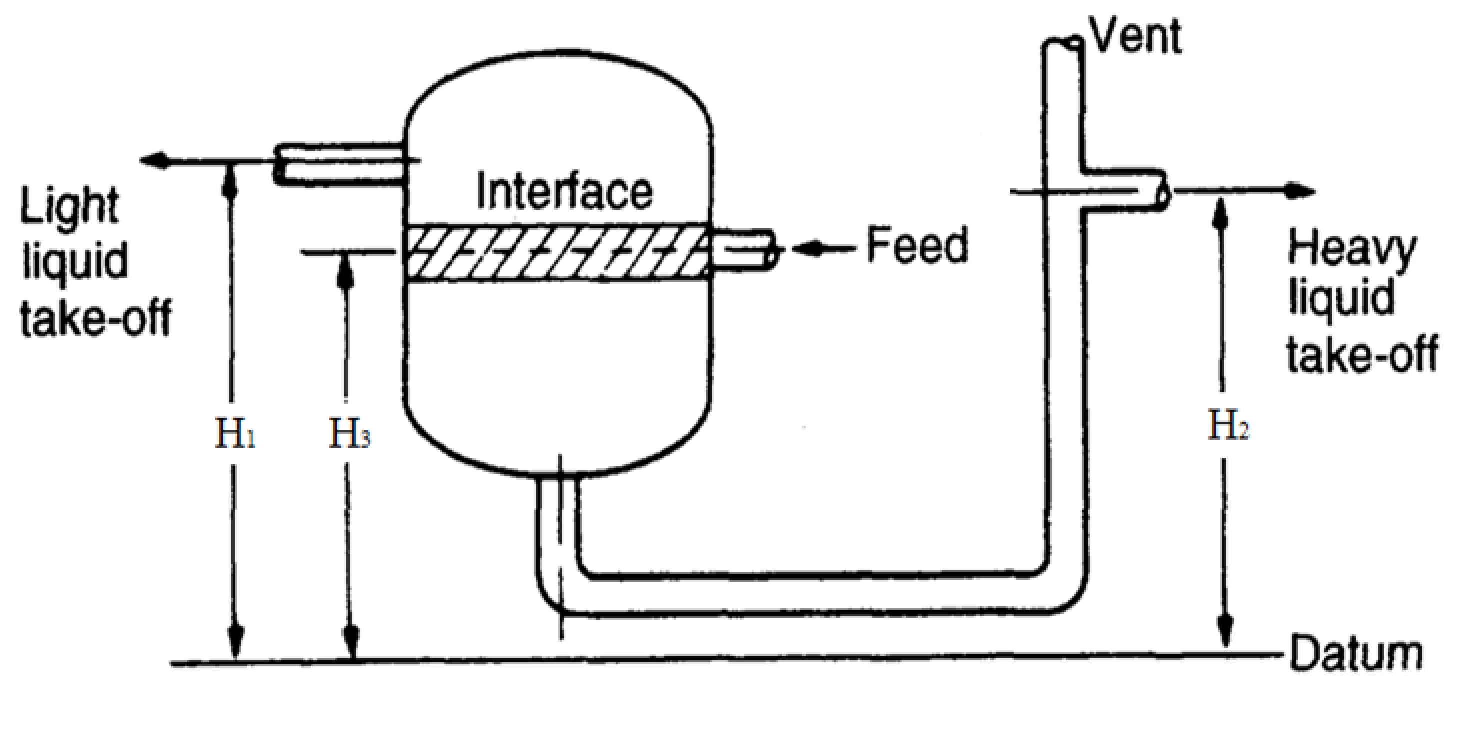
H_2 = height from datum to heavy liquid overflow, m.

H_3 = height from datum to the interface, m.

The height of the liquid interface should be measured accurately when the liquid densities are close.

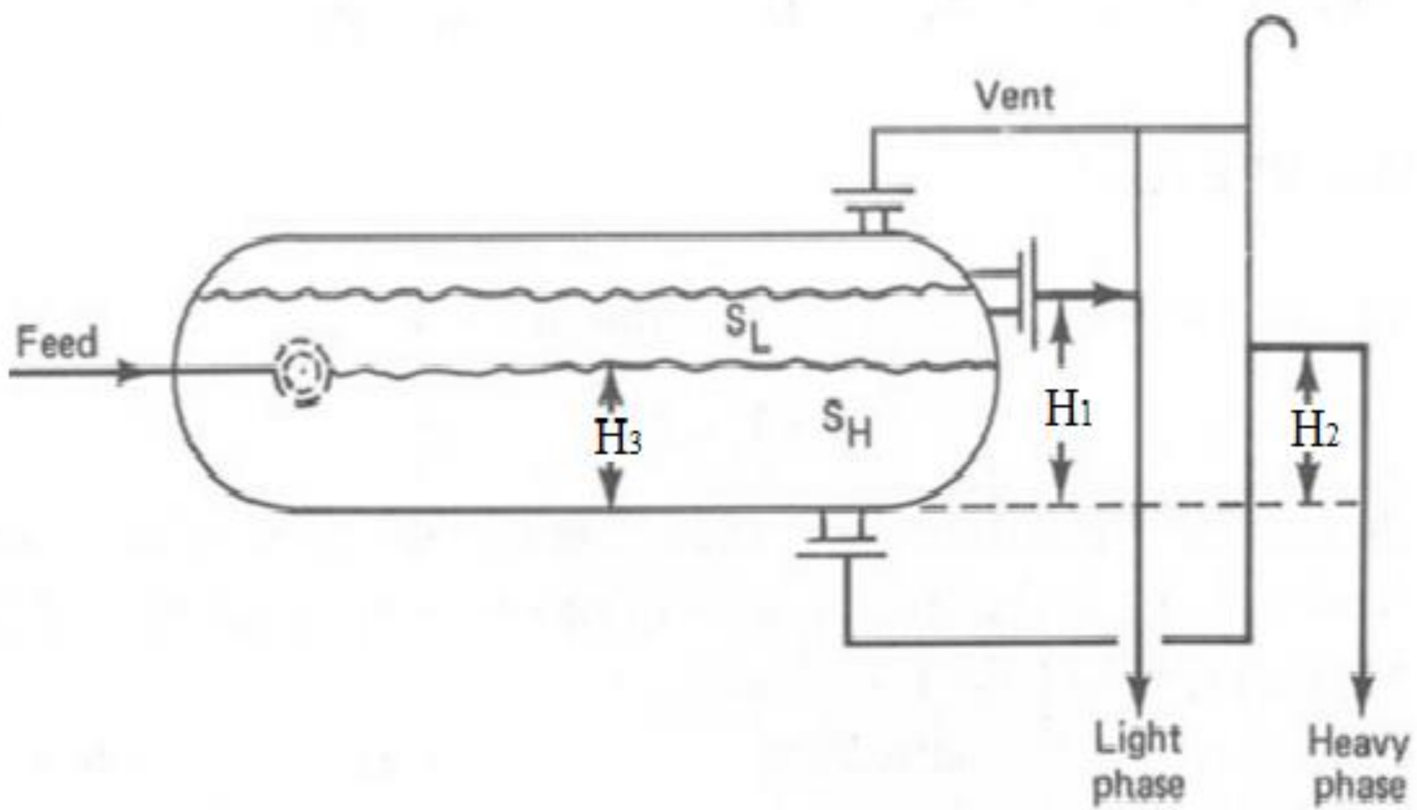
Two types of separators are generally used

- Vertical separator



Vertical decanter

- Horizontal separator



Horizontal Decantor

Decanter Design

A rough estimate of the decanter volume required can be made by taking a hold-up time of 2 to 10 min, which is usually sufficient where emulsions are not likely to form. The decanter vessel is sized on the basis that the velocity of the continuous phase must be less than settling velocity of the droplets of the dispersed phase. Plug flow is assumed, and the velocity of the continuous phase calculated using the area of the interface:

$$u_c = \frac{L_c}{A_i} \leq u_d$$

where

u_d = settling velocity of the dispersed phase droplets, m/s.

u_c = velocity of the continuous phase, m/s.

L_c = continuous phase volumetric flow rate, m^3/s.

A_i = area of the interface, m^2.

Stocks' law is used to determine the settling velocity of the droplet

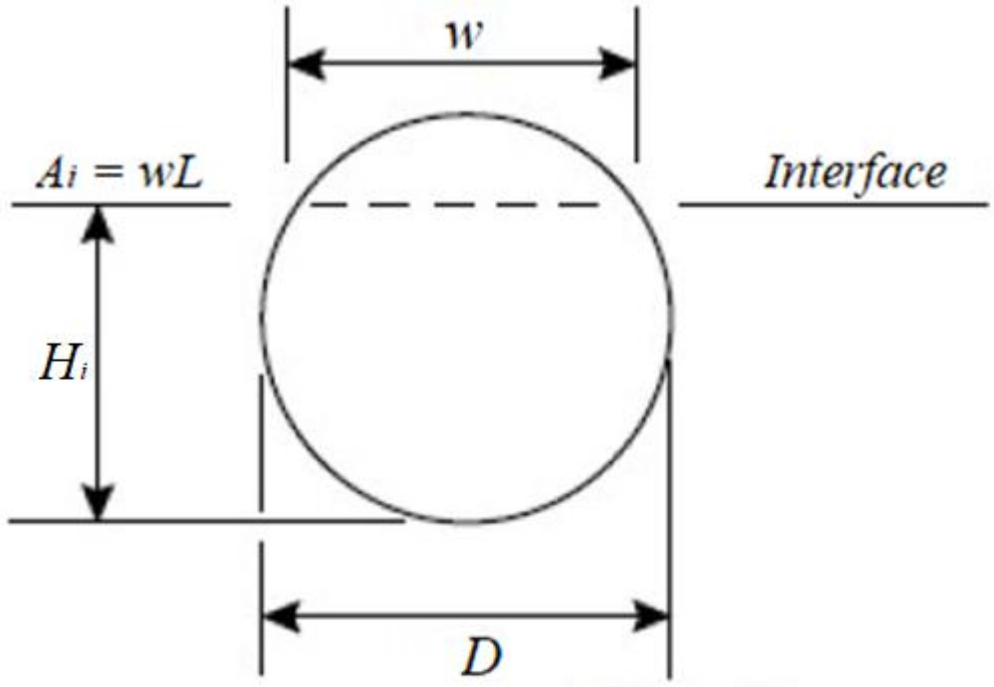
$$u_d = \frac{g d_d^2 (\rho_d - \rho_c)}{18 \mu_c}$$

where
d_d = droplet diameter, m,
u_d = settling (terminal) velocity of the dispersed phase droplets, m/s.
ρ_c = density of the continuous phase, kg/m^3.
ρ_d = density of the dispersed phase, kg/m^3.
μ_c = viscosity of the continuous phase, N s/m^2.
g = gravitational acceleration, 9.81 m/s^2.

This equation is used to calculate the settling velocity with an assumed droplet size of 150 μm, which is well below the droplet sizes normally found in decanter feeds. If the calculated settling velocity is greater than 4×10^{-3} m/s, then a figure of 4×10^{-3} m/s is used.

For a horizontal, cylindrical, decanter vessel, the interfacial area will depend on the position of the interface.

$$w = 2(H_i D - H_i^2)^{0.5}$$



where

w = width of the interface, m.

L= length of the cylinder, m

D = diameter of the cylinder, m.

A_i = area of the interface, m^2.

H_i = height of the interface from the base of the vessel, m.

The depth of the dispersion band is a function of the liquid flow rate and the interfacial area. A value of 10 % of the decanter height is usually taken for design purposes and length to decanter diameter ratio of 3-5:1

Ex.1

Design a vertical decanter to separate a light oil from water. The oil is the dispersed phase. Oil, flow rate 1000 kg/h, density 900 kg/m^3, viscosity 3 mN s/m^2. Water, flow rate 5000 kg/h, density 1000 kg/m^3, viscosity 1 mN s/m^2.

Use H=2D and d_d = 150 μm.

$$u_d = \frac{g d_d^2 (\rho_d - \rho_c)}{18\mu_c}$$

$$u_d = \frac{9.81 \times 150 \times 10^{-6}\,(900 - 1000)}{18 \times 1 \times 10^{-3}} = 1.2\times 10^{-3} \text{ m/s}$$

$$L_c = \frac{5000}{1000} \times \frac{1}{3600} = 1.39\times 10^{-3} \text{ m}^3\text{/s}$$

$$u_c = \frac{L_c}{A_i} \leq u_d$$

$$A_i = \frac{L_c}{u_d} = \frac{1.39\times10^{-3}}{1.2\times10^{-3}} = 1.16\ \text{m}^2$$

$$D = \sqrt{\frac{A_i}{4}} = \sqrt{\frac{1.16}{\pi}} = 1.2\ m$$

Take the height as twice the diameter, a reasonable value for a cylinder:
Height (H) = 2.4 m
Take the dispersion band as 10 % of the height = 0.24 m
Check the residence time of the droplets in the dispersion band

$$t_r = \frac{0.1H}{u_d} = \frac{0.24}{0.0012} = 200\ Sec = 3.334\ min$$

This is satisfactory, a time of 2 to 5 min is normally recommended. Check the size of the water (continuous, heavy phase) droplets that could be entrained with the oil (light phase).

$$\text{Velocity of oil phase} = \frac{1000}{900} \times \frac{1}{3600} \times \frac{1}{1.16}$$

$$= 2.7 \times 10^{-4} \text{ m/s}$$

$$d_d = \left[\frac{18\mu_c u_d}{g\,(\rho_d - \rho_c)}\right]^{0.5}$$

$$d_d = \left[\frac{18 \times 3 \times 10^{-3} \times 2.7 \times 10^{-4}}{9.81\,(1000 - 900)}\right]^{0.5} = 1.2 \times 10^{-4} \text{ m}$$

$$d_d = 150\ \mu\text{m}.$$

which is satisfactory; below 150 μm.

Piping arrangement

To minimize entrainment by the jet of liquid entering the vessel, the inlet velocity for a decanter should keep below 1 m/s.

$$\text{Flowrate} = \left[\frac{1000}{900} + \frac{5000}{1000}\right] \times \frac{1}{3600} = 1.7 \times 10^{-3}\ m^3/\text{s}$$

$$\text{Area of pipe(Ap)} = \left[\frac{Flowrate}{Velocity}\right] = \frac{1.7 \times 10^{-3}}{1} = 1.7 \times 10^{-3}\text{m}^2$$

$$\text{Pipe diameter} = \sqrt{\frac{A_p}{\pi/4}} = \sqrt{\frac{1.7\times10^{-3}}{\pi/4}} = 0.047\ m,\ \ Say\ 50\ mm$$

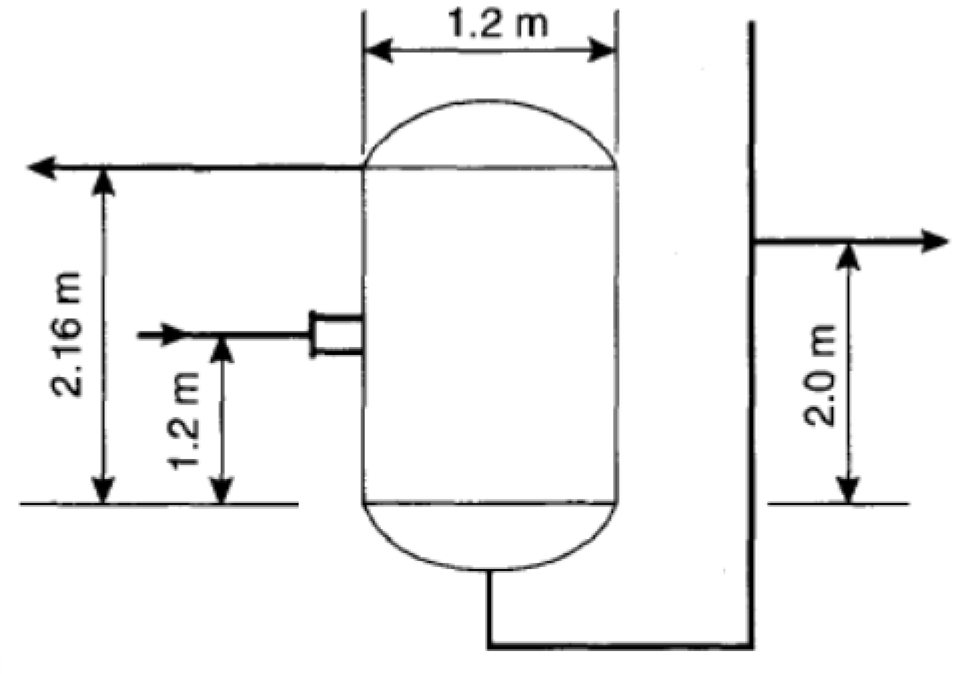
Take the position of the interface as half-way up the vessel and the light liquid off take as at 90 % of the vessel height:

$$H_1 = 0.9 \times 2.4 = 2.16\, m$$

$$H_3 = 0.5 \times 2.4 = 1.2\, m$$

$$H_2 = H_3 + \frac{(H_1 - H_3)\rho_1}{\rho_2} = 1.2 + \frac{(2.16 - 1.2)x900}{1000} = 2 \text{ m}$$

Proposed design;



Ex.2

Design horizontal decanter to separate a light oil from water. The oil is the dispersed phase. Oil, flow rate 5000 kg/h, density 900 kg/m^3, viscosity 3 mN s/m^2. Water, flow rate 25000 kg/h, density 1000 kg/m^3, viscosity 1 mN s/m^2.

Use L=4D and d_d = 150 μm.

$$u_d = \frac{g d_d^2 (\rho_d - \rho_c)}{18\mu_c}$$

$$u_d = \frac{9.81 \times (150 \times 10^{-6})^2 \, (900 - 1000)}{18 \times 1 \times 10^{-3}} = 1.2 \times 10^{-3} \text{ m/s}$$

$$L_c = \frac{25000}{1000} \times \frac{1}{3600} = 6.9444 \times 10^{-3} \text{ m}^3/\text{s}$$

$$A_i = \frac{L_c}{u_d} = \frac{6.9444 \times 10^{-3}}{1.2 \times 10^{-3}} = 5.787 \text{ m}^2$$

$$w = 2(H_i D - H_i^2)^{0.5}$$

Let $H_i = 0.5\ H = 0.5D$

$$A_i = wL = 2L(H_i D - H_i^2)^{0.5}$$

$$A_i = 4wD = 8xD(0.5D^2 - 0.25D^2)^{0.5}$$

$$5.787 = 8xD(0.5xD^2 - 0.25xD^2)^{0.5}$$

$$D = 1.2028 \text{ m}$$

$$L = 4 \times D = 4 \times 1.2028 = 4.8112 \text{ m}$$

Take the height as the diameter, a reasonable value for a cylinder:
Height (H) = D = 1.2028 m
Take the dispersion band as 10 % of the height = 0.12028 m
Check the residence time of the droplets in the dispersion band

$$t_r = \frac{0.1H}{u_d} = \frac{0.12028}{0.0012} = 100.2333\,Sec = 1.67\,min$$

This is unsatisfactory, a time of 2 to 10 min is normally recommended. Check the size of the water (continuous, heavy phase) droplets that could be entrained with the oil (light phase), or we can increase the interphase thickness to 20% H and recalculate the residence time.

$$\text{Velocity of oil phase} = \frac{5000}{900} \times \frac{1}{3600} \times \frac{1}{5.787}$$

$$= 2.6667 \times 10^{-4} \text{ m/s}$$

$$d_d = \left[\frac{18\mu_c u_d}{g\,(\rho_d - \rho_c)}\right]^{0.5}$$

$$d_d = \left[\frac{18\times3\times10^{-3}\times2.6667\times10^{-4}}{9.81\,(1000-900)}\right]^{0.5} = 1.21\times 10^{-4} \text{ m}$$

$$d_d = 150 \text{ µm.}$$

which is satisfactory; below 150 µm.

Piping arrangement

To minimize entrainment by the jet of liquid entering the vessel, the inlet velocity for a decanter should keep below 1 m/s.

$$\text{Flowrate} = \left[\frac{5000}{900} + \frac{25000}{1000}\right] \times \frac{1}{3600} = 2.932 \times 10^{-3}\ m^3/\text{s}$$

$$\text{Area of pipe(Ap)} = \left[\frac{Flowrate}{Velocity}\right] = \frac{2.932 \times 10^{-3}}{1} = 2.932 \times 10^{-3}\text{m}^2$$

$$\text{Pipe diameter} = \sqrt{\frac{A_p}{\pi/4}} = \sqrt{\frac{2.932\times 10^{-3}}{\pi/4}} = 0.061\ m,\ \ Say\ 65\ mm$$

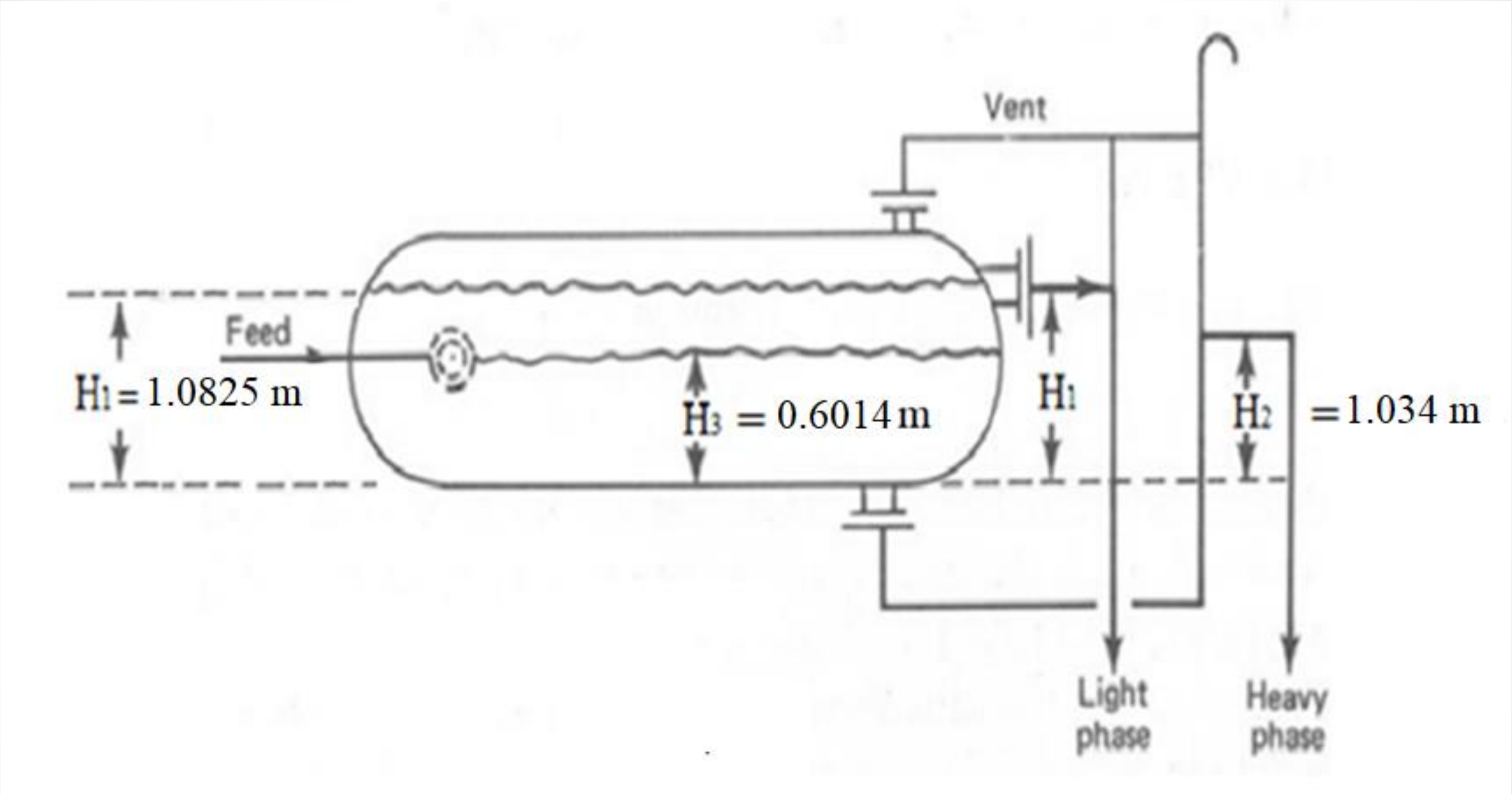
Take the position of the interface as half-way up the vessel and the light liquid off take as at 90 % of the vessel diameter:

$$H_1 = 0.9 \times 1.2028 = 1.0825\, m$$

$$H_3 = 0.5 \times 21.2028 = 0.6014\, m$$

$$H_2 = H_3 + \frac{(H_1 - H_3)\rho_1}{\rho_2} = 0.6014 + \frac{(1.0825 - 0.6014) x 900}{1000} = 1.034 \text{ m}$$

Proposed design;



Q.1/

A horizontal cylindrical continuous decanter is to separate 60 m3/h of a liquid glycerin from an equal volume of wash acid. The oil is the continuous phase and at the operating temperature has a viscosity of 1.1 cP and a density of 865 kg/m3. The density of the acid is 1153 kg/m3 viscosity of 1.05 cP. Compute (a) the size of the vessel, and (b) the height of the acid overflow above the vessel floor. Use L=5D and d_d = 150 μm.

Q.2/

Design a vertical decanter to separate castor oil from water. The oil is the dispersed phase. Oil, flow rate 2500 kg/h, density 850 kg/m^3, viscosity 2 mN s/m^2. Water, flow rate 7500 kg/h, density 9800 kg/m^3, viscosity 0.95 mN s/m^2.

Use H= 3D and d_d = 150 μm.