

Solutions Manual for
Fluid Mechanics for
Chemical Engineers
Second Edition
with Microfluidics and CFD

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Units Conversion

$$(a) \quad \frac{1}{640} \times 5280^2 = \underline{\underline{4.36 \times 10^4 \text{ ft}^3}}$$

$$\text{acre ft} \frac{\text{mile}^2}{\text{acre}} \frac{\text{ft}^2}{\text{miles}^2}$$

$$(b) \quad 4.36 \times 10^4 \text{ ft}^3 \times 7.48 \frac{\text{gal}}{\text{ft}^3} = \underline{\underline{3.26 \times 10^5 \text{ gal}}}$$

$$(c) \quad 4.36 \times 10^4 \text{ ft}^3 \times \frac{1}{3.281^3} \frac{\text{m}^3}{\text{ft}^3} = \underline{\underline{1,233 \text{ m}^3}}$$

$$(d) \quad M = \rho V$$

$$= 1,233 \text{ m}^3 \times 1,000 \frac{\text{kg}}{\text{m}^3} = 1.233 \times 10^6 \text{ kg}$$

$$= \underline{\underline{1,233 \text{ tonnes (t)}}}$$

1.2

Units Conversion

Viscosity

$$\mu = 10 \text{ Centipoise} = 10 \times 0.01 \times 10^{-1} \frac{\text{kg}}{\text{m s}} = 0.01 \frac{\text{kg}}{\text{m s}}$$

1 poise

$$= 0.01 \times \frac{0.3048}{0.4536} = 6.72 \times 10^{-3} \frac{\text{lbm}}{\text{ft s}}$$

$\frac{\text{kg}}{\text{m s}} \quad \frac{\text{lbm}}{\text{kg}} \quad \frac{\text{m}}{\text{ft}}$

(Useful conversion factors: $1 \text{ cp} = 0.000672 \text{ lbm/ft s}$
 $= 2.42 \text{ lbm/ft hr}$)

Density

$$\rho = 0.8 \times 1 \times \frac{(100)^3}{1000} = 800 \frac{\text{kg}}{\text{m}^3}$$

$\frac{\text{g}}{\text{cm}^3} \quad \frac{\text{kg}}{\text{g}} \quad \left(\frac{\text{cm}}{\text{m}}\right)^3$

$$= 0.8 \times 62.4 = 49.9 \frac{\text{lbm}}{\text{ft}^3}$$

1.3
Units Conversion

Gravitational Acceleration

$$g = \frac{981}{100} \frac{\text{cm}}{\text{s}^2} \frac{\text{m}}{\text{cm}} = 9.81 \frac{\text{m}}{\text{s}^2}$$

Pressure

$$p = \frac{14.7 \times 32.2 \times 144 \times 3.281}{2.205}$$

$$\frac{\text{lbf}}{\text{in}^2} \frac{\text{lbm ft}}{\text{lbf s}^2} \frac{\text{in}^2}{\text{ft}^2} \frac{\text{kg}}{\text{lbm}} \frac{\text{ft}}{\text{m}}$$

$$= 1.01 \times 10^5 \frac{\text{kg}}{\text{m s}^2} = \frac{\text{N}}{\text{m}^2} = \text{Pa}$$

Since $1 \text{ bar} = 10^5 \text{ Pa}$

$$\underline{\underline{p = 1.01 \text{ bar}}}$$

1.4

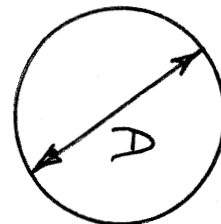
Meteorite Density

$$\text{Mass } M = \frac{\pi D^3}{6} \rho$$

$$\rho = \frac{6M}{\pi D^3} = \frac{6 \times 10^6 \times 1000}{\pi \times 60^3}$$

$$\rho = 8,842 \frac{\text{kg}}{\text{m}^3}$$

$$s = \frac{8,842}{1,000} = 8.84$$



Specific gravities of some elements are

| | | | | | |
|----|------|----|------|----|------|
| Fe | 7.86 | Co | 8.9 | Ag | 10.5 |
| Ni | 8.9 | Pb | 11.3 | Au | 19.3 |
| | | | | U | 18.5 |

Most likely candidate is iron, the deviation being due to the "ball park" figures in the article.

Kinetic Energy

$$\frac{1}{2} M u^2 = \frac{1}{2} 10^9 \times (15000)^2 = 1.125 \times 10^{17} \text{ J}$$

$$\text{TNT Equivalent} = \frac{1.125 \times 10^{17}}{5 \times 10^9} = 2.25 \times 10^7 \text{ tonnes}$$

1.5

Reynolds Number

Cross-sectional area

$$A = \frac{\pi D^2}{4} = \frac{\pi \left(\frac{1.05}{12}\right)^2}{4} = 0.00601 \text{ ft}^2$$

Volumetric flow rate

$$Q = \frac{35}{7.48 \times 60} = 0.0780 \frac{\text{ft}^3}{\text{s}}$$

Mean velocity

$$u_m = \frac{Q}{A} = \frac{0.0780}{0.00601} = 12.98 \frac{\text{ft}}{\text{s}}$$

Reynolds number

$$Re = \frac{\rho u_m D}{\mu} = \frac{62.3 \times 12.98 \times 1.05/12}{1.2 \times 0.000672}$$

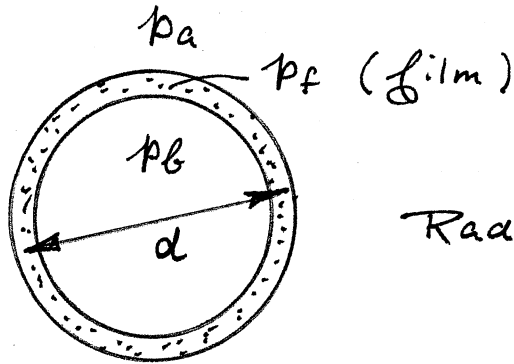
$$\frac{\frac{\text{lbm}}{\text{ft}^3} \frac{\text{ft}}{\text{s}} \text{ft}}{\text{cP} \frac{\text{cP}}{\text{lbm} \cdot \text{ft} \cdot \text{s}}} \left. \vphantom{\frac{\text{lbm}}{\text{ft}^3}} \right\} \text{All units cancel}$$

$$= \underline{\underline{87,740}} \quad (\text{dimensionless})$$

1.6

Pressure in Bubble

Atmosphere



$$\text{Radius } a = \frac{d}{2}$$

From notes, The increase in pressure as we go inwards across a convex surface is

$$\left. \begin{aligned} p_f - p_a &= \frac{2\sigma}{a} \\ p_b - p_f &= \frac{2\sigma}{a} \end{aligned} \right\} \begin{array}{l} \text{Two surfaces} \\ \text{are involved} \end{array}$$

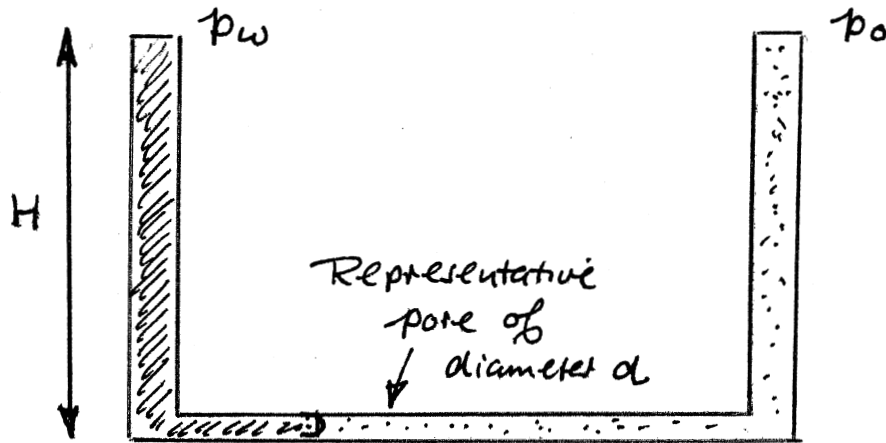
Hence, by addition,

$$p_b - p_a = \frac{4\sigma}{a} = \frac{8\sigma}{d}$$

$$p_b = p_a + \frac{8\sigma}{d}$$

1.7

Reservoir Water-Flooding



$$p_o + \rho_o g H + \frac{4\sigma}{d} = p_w + \rho_w g H$$

Increase in pressure
from oil into water

Hence required water inlet pressure is

$$p_w = p_o - \underbrace{(\rho_w - \rho_o) g H}_{\text{Positive}} + \frac{4\sigma}{d}$$

1.8-1

Barometer Reading

② • House $z_2 = 950 \text{ ft}$ $p_2 = ?$
 $H_2 = ?$

① • Weather Station $z_1 = 700 \text{ ft}$ $p_1 = 0.966 \text{ bar}$
 $H_1 = ?$

At the weather station

The atmospheric pressure p_1 is balanced by a column of mercury of height H_1 :

$$p_1 = \rho_M g H_1$$

Hence

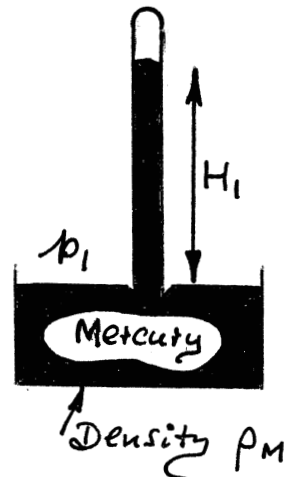
$$H_1 = \frac{p_1}{\rho_M g} = \frac{0.966 \times 10^5 \times 3.281 \times 12}{13.57 \times 1000 \times 9.81}$$

$$\frac{\frac{\text{kg}}{\text{m}^2} \frac{\text{m}}{\text{s}^2}}{\frac{\text{m}^3}{\text{kg}} \frac{\text{s}^2}{\text{m}} \frac{\text{in}}{\text{m}}} = \text{in}$$

$$= \underline{\underline{28.57 \text{ in mercury}}}$$

(Note: $g = 9.81 \text{ m/s}^2$, $3.281 \text{ ft} = 1 \text{ m}$,

$$\rho_W = 1000 \frac{\text{kg}}{\text{m}^3}, \quad 1 \text{ bar} = 10^5 \text{ pascal} = 10^5 \frac{\text{kg} \frac{\text{m}}{\text{s}^2}}{\text{m}^2})$$



1.8-2

Correction for elevation increase. Since $z_2 - z_1$ is "small" for air, we can take p_A as essentially constant between ① and ②. Now pressure at weather station is

$$0.966 \text{ bat} \times \frac{14.7 \text{ psia}}{1.01 \text{ bat}} \left(\begin{array}{c} \text{see} \\ \text{Problem} \\ 3 \end{array} \right) = 14.06 \text{ psia}$$

Hence the appropriate mean pressure between ① and ② for purposes of estimating the density can be taken as 14.06 or (as done here, with a trifling change in the answer) slightly less — say 14.0 psia.

$$p_A = \frac{M_A P}{R T} = \frac{28.8 \times 14.0}{10.73 \times (460 + 25)} = 0.0775 \frac{\text{lbm}}{\text{ft}^3}$$

↑
Average for January

Change in Pressure $p_2 - p_1 = -p_A g (z_2 - z_1)$

Change in Barometer Reading $H_2 - H_1 = \frac{p_2 - p_1}{\rho_M g} = -\frac{p_A (z_2 - z_1)}{\rho_M}$

$$H_2 - H_1 = - \frac{0.0775 (950 - 700) \times 12}{13.57 \times 62.4} = -0.27 \text{ in}$$

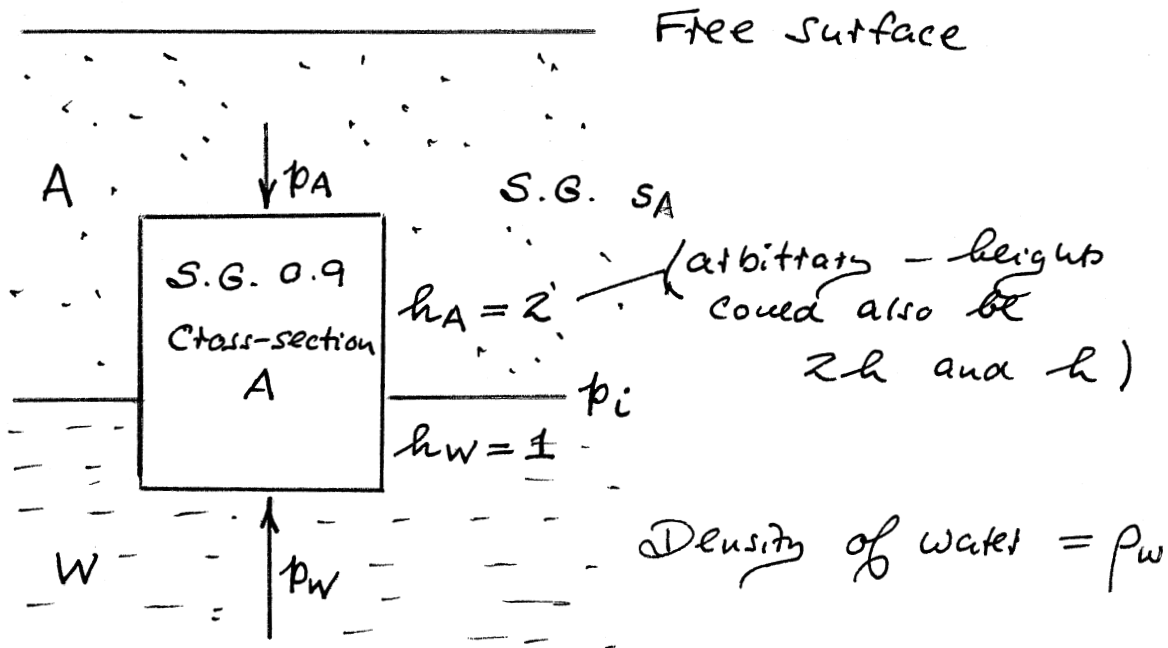
Hence $H_2 = H_1 - 0.27 = 28.57 - 0.27 = \underline{\underline{28.3 \text{ in Hg}}}$

Pressure $p_2 = \rho_M g H_2 = \frac{13.57 \times 62.4 \times 32.2 \times 28.3}{32.2 \times 144 \times 12}$

$$p_2 = \underline{\underline{13.87 \text{ psia}}} \quad \frac{\text{lbm}}{\text{ft}^3} \frac{\text{ft}}{\text{sec}^2} \text{ in} \frac{\text{lbf sec}^2 \text{ ft}^2 \text{ ft}}{\text{lbm ft in}^2 \text{ in}}$$

1.9

Two-Layer Buoyancy



Method 1

Weight displaced
(upwards buoyant force)

$$\rho_w A g (1 + 2 s_A)$$

Weight of
cylinder downwards

$$= 0.9 \rho_w A 3 g$$

$$\underline{\underline{s_A = 0.85}}$$

Method 2 Force balance on cylinder \downarrow

$$p_A A + 0.9 \rho_w A 3 g - p_W A = 0$$

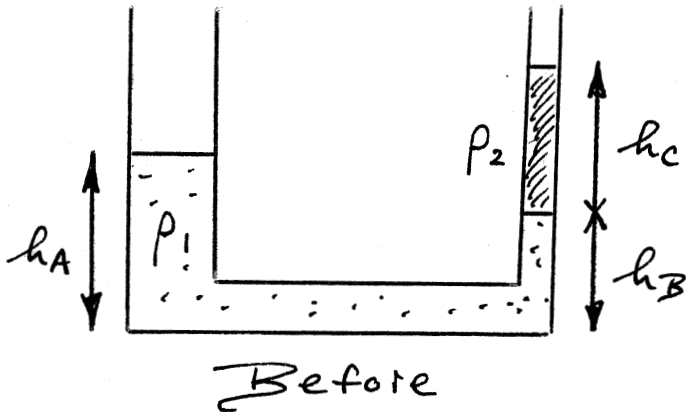
weight

$$p_i - 2 s_A \rho_w g + 2.7 \rho_w g - (p_i + \rho_w g) = 0$$

$$\underline{\underline{s_A = 0.85}}$$

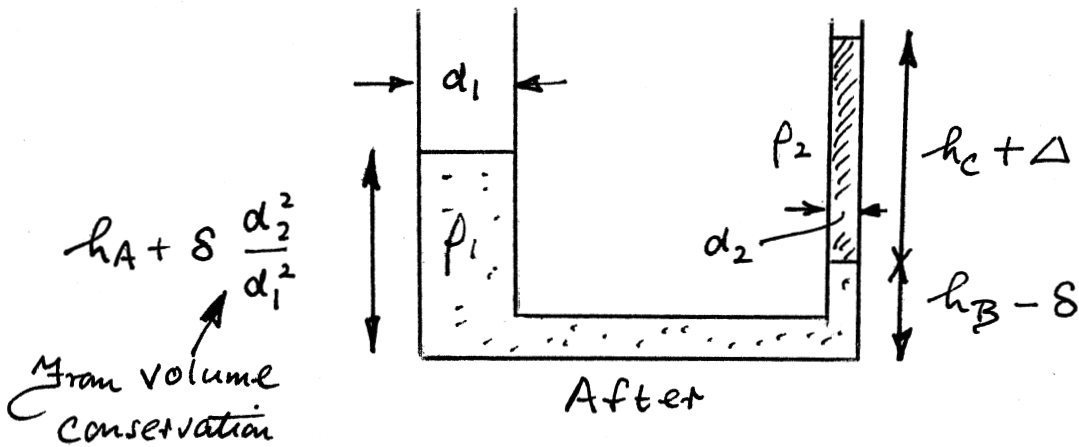
1.10-1

Differential Manometer



$$\rho_1 (h_A - h_B) = \rho_2 h_c \quad (1)$$

Now add Δ to h_c and let h_B decline by δ



$$\rho_1 \left(h_A + \delta \frac{d_2^2}{d_1^2} - (h_B - \delta) \right) = \rho_2 (h_c + \Delta) \quad (2)$$

Subtract (1) from (2)

$$\rho_1 \delta \left(\frac{d_2^2}{d_1^2} + 1 \right) = \rho_2 \Delta = \rho_2 \frac{v_2}{\frac{\pi d_2^2}{4}} \quad (3)$$

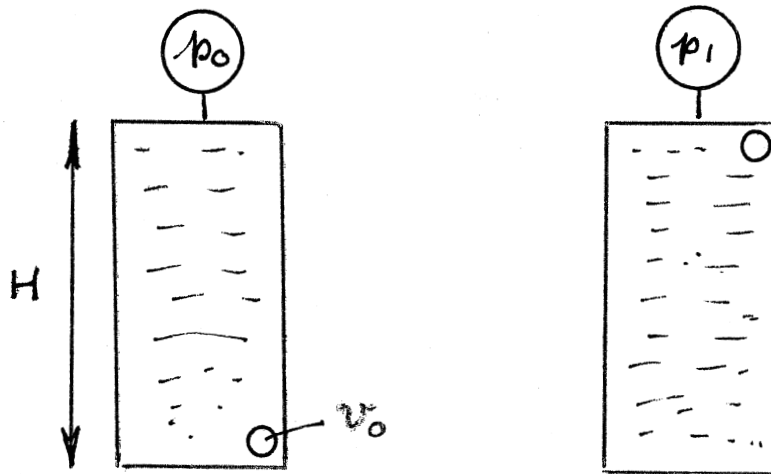
Equation (3) gives δ as a function of v_2 , and also enables ρ_2 to be found by observing the value of δ .

1.10 - 2

Solution for δ gives:

$$\delta = \frac{\rho_2}{\rho_1} \frac{4v_2}{\pi d_2^2} \left(\frac{d_1^2}{d_1^2 + d_2^2} \right)$$

Ascending Bubble



Since the cylinder and oil volumes don't change, the bubble volume must remain constant at v_0 .

But

$$pV_0 = nRT$$

Therefore, since T is constant, p within the bubble does not change. Hence

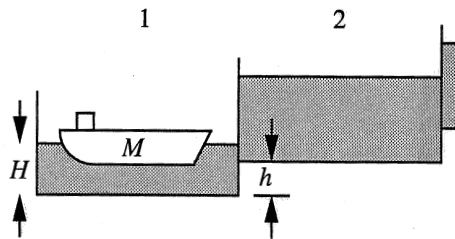
$$p = \underbrace{p_0 + \rho g H}_{\text{Before}} = \underbrace{p_1}_{\text{After}}$$

Thus
$$p_1 = p_0 + \rho g H$$

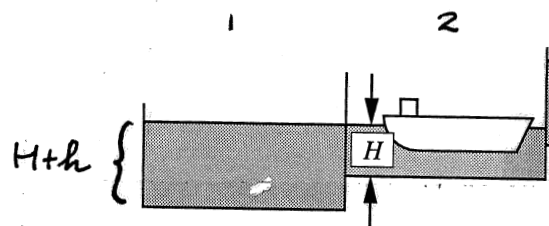
Ship Passing Through Locks

Uphill The ship must increase its elevation by an amount h as it passes from lock 1 to lock 2. Consider the water in lock 1 before and after;

Before



After



$$\begin{aligned} \text{Mass of water in lock} \\ = \rho A H - M \end{aligned}$$

$$\begin{aligned} \text{Mass of water in lock} \\ = \rho A (H+h) \end{aligned}$$

From Archimedes law, the ship displaces a mass M of water

Hence mass of water to be supplied to lock 1 is

$$\rho A (H+h) - (\rho A H - M) = \rho A h + M$$

Downhill A similar analysis gives the water loss from a lock as

$$\begin{aligned} \underbrace{\rho A H - M}_{\text{mass at start}} - \underbrace{\rho A (H-h)}_{\text{mass at end (note that final depth of water in lock is } H-h)} = \rho A h - M \end{aligned}$$

Total water supply

(i) Uphill only: $\rho A h + M$ (depends on M)

(ii) Up and down: $\rho A h + M + \rho A h - M = 2\rho A h$
(independent of M)

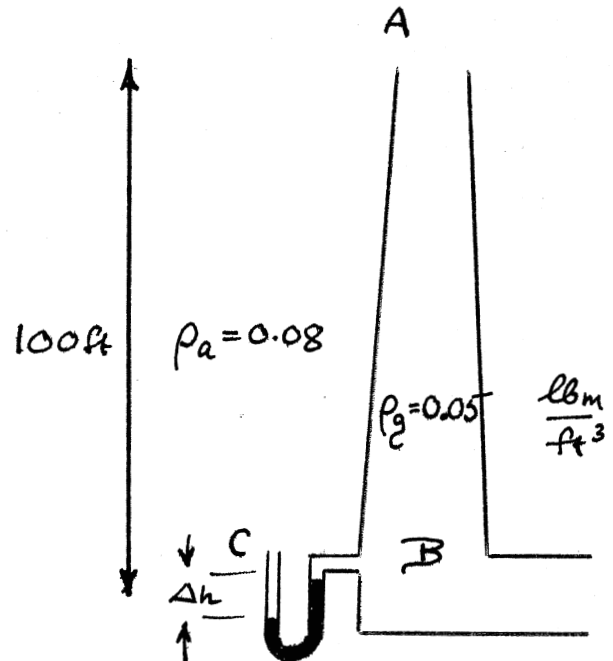
1.13

Furnace Stack

Start from point A
and consider hydro-
static increase of
pressure in both cases:

$$p_B = p_A + \rho_g g H$$

$$p_C = p_A + \rho_a g H$$



Hence $p_C = p_B + \underbrace{(\rho_a - \rho_g) g H}_{\text{positive}}$

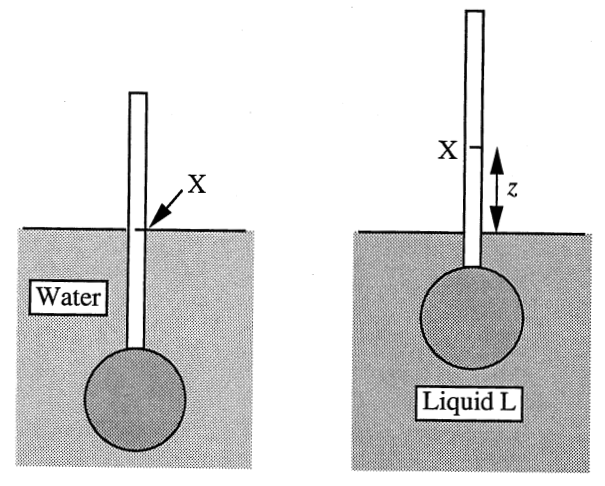
Hence the water moves up in the right-hand leg by Δh given by

$$\rho_w g \Delta h = (\rho_a - \rho_g) g H$$

$$\Delta h = \frac{\rho_a - \rho_g}{\rho_w} H = \frac{(0.08 - 0.05) \times 100 \times 12}{62.4} = \underline{\underline{0.58 \text{ in.}}}$$

1.14

Hydrometer



Since the same weight (that of the hydrometer) is supported by the displaced liquid in both cases:

$$Mg = V \rho_w g = (V - Az) \rho_w s g$$

↑
Density of water

mass of hydrometer

Cancellation of $\rho_w g$ and solution for s gives

$$s = \frac{1}{1 - \frac{Az}{V}}$$
