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The complete (small-slope) solution to this problem is:

$$\eta = h \cos \theta = (\rho g V^2)^{1/3} \lambda, \text{ where } h = (V/\rho g)^{2/3} \cos \theta. \text{ Ans.}$$

The formula clearly satisfies the requirement that  $\eta = 0$  if  $\lambda = \infty$ . It requires "small slope" and therefore the contact angle should be in the range  $70^\circ < \theta < 110^\circ$ .

**1.69** A solid cylindrical needle of diameter  $d$ , length  $L$ , and density  $\rho_s$  may "float" on a liquid surface. Neglect buoyancy and assume a contact angle of  $0^\circ$ . Calculate the maximum diameter needle able to float on the surface.




**Solution:** The needle "dents" the surface downward and the surface tension forces are upward, as shown. If these tensions are nearly vertical, a vertical force balance gives:

$$\sum F_y = 0 = 2YL - \rho_s \frac{\pi d^2}{4} L, \text{ or: } d_{\max} = \sqrt{\frac{8Y}{\rho_s}}. \text{ Ans. (a)}$$

(b) Calculate  $d_{\max}$  for a steel needle ( $\rho_s = 7.84$ ) in water at  $20^\circ\text{C}$ . The formula becomes:

$$d_{\max} = \sqrt{\frac{8Y}{\rho_s}} = \sqrt{\frac{8(0.073 \text{ N/m})}{(7.84 \times 998 \text{ kg/m}^3)(9.81 \text{ m/s}^2)}} = 0.00156 \text{ m} = 1.6 \text{ mm}. \text{ Ans. (b)}$$

**1.70** Derive an expression for the capillary height change  $h$ , as shown, for a fluid of surface tension  $Y$  and contact angle  $\theta$  between two parallel plates  $W$  apart. Evaluate  $h$  for water at  $20^\circ\text{C}$  if  $W = 0.5$  mm.



**Solution:** With  $\theta$  the width of the plates into the paper, the capillary forces on each wall together balance the weight of water held above the reservoir free surface:

$$\rho g W h b = 2Y b \cos \theta, \text{ or: } h = \frac{2Y \cos \theta}{\rho g W}. \text{ Ans.}$$