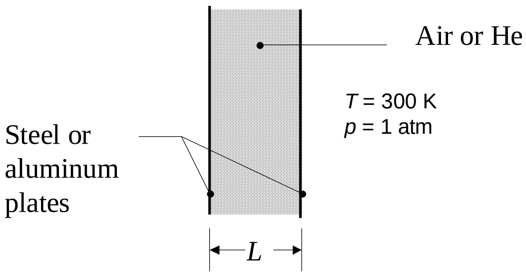
PROBLEM 3.174

KNOWN: Air or helium between steel and aluminum parallel plates, respectively. Gas temperature and pressure. Thermal accommodation coefficient values.

FIND: The separation distance, L, above which $R_{t,m\text{-}s}/R_{t,m\text{-}m}$ is less than 0.01 for (*a*) air and (*b*) helium.

SCHEMATIC:



ASSUMPTIONS: (1) Ideal gas behavior, (2) One-dimensional conduction.

PROPERTIES: Table A.4 (T = 300 K): Air; c_p = 1007 J/kg·K, k = 0.0263 W/m·K. He; c_p = 5193 J/kg·K, k = 0.170 W/m·K Figure 2.8: Air; $\mathcal{M}$ = 28.97 kg/kmol, $d = 0.372 \times 10^{-9}$ m. He; $\mathcal{M}$ = 4.003 kg/kmol, $d = 0.219 \times 10^{-9}$ m.

ANALYSIS:

(*a*) For air, the ideal gas constant, specific heat at constant volume, and ratio of specific heats are:

$$R = \frac{\mathcal{R}}{\mathcal{M}} = \frac{8.315 \text{ kJ/kmol}\cdot\text{K}}{28.97 \text{ kg/kmol}} = 0.287 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$c_v = c_p - R = 1.007\frac{\text{kJ}}{\text{kg}\cdot\text{K}} - 0.287\frac{\text{kJ}}{\text{kg}\cdot\text{K}} = 0.720\frac{\text{kJ}}{\text{kg}\cdot\text{K}}; \quad \gamma = \frac{c_p}{c_v} = \frac{1.007}{0.720} = 1.399$$

From Equation 2.11 the mean free path of air is

$$\lambda_{\text{mfp}} = \frac{k_B T}{\sqrt{2}\pi d^2 p} = \frac{1.381\times10^{-23} \text{ J/K}\times 300 \text{ K}}{\sqrt{2}\pi\left(0.372 \times 10^{-9} \text{ m}\right)^2\left(1.0133\times10^5 \text{ N/m}^2\right)} = 66.5\times10^{-9} \text{ m} = 66.5 \text{ nm}$$

From Section 3.9.1, the plate separation, L, is

$$L = \lambda_{\text{mfp}}\frac{R_{t,m-m}}{R_{t,m-s}}\left[\frac{2-\alpha_t}{\alpha_t}\right]\left[\frac{9\gamma-5}{\gamma+1}\right]$$

$$= 66.5\times10^{-9} \text{ m}\times100\times\left[\frac{2-0.92}{0.92}\right]\left[\frac{9\times1.399-5}{1.399+1}\right] = 2.47\times10^{-5} \text{ m} = 24.7 \ \mu\text{m}$$

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PROBLEM 3.174 (Cont.)

(*b*) For He, the ideal gas constant, specific heat at constant volume, and ratio of specific heats are:

$$R = \frac{\mathcal{R}}{\mathcal{M}} = \frac{8.315 \text{ kJ/kmol} \cdot \text{K}}{4.003 \text{ kg/kmol}} = 2.077 \ \frac{\text{kJ}}{\text{kg} \cdot \text{K}};$$

$$c_v = c_p - R = 5.193 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} - 2.077 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} = 3.116 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}; \quad \gamma = \frac{c_p}{c_v} = \frac{5.193}{3.116} = 1.667$$

The mean free path is

$$\lambda_{\text{mfp}} = \frac{k_B T}{\sqrt{2}\pi d^2 p} = \frac{1.381 \times 10^{-23} \text{ J/K} \times 300 \text{ K}}{\sqrt{2}\pi \left(0.219 \times 10^{-9} \text{ m}\right)^2 \left(1.0133 \times 10^5 \text{ N/m}^2\right)} = 1.919 \times 10^{-7} \text{ m} = 192 \text{ nm}$$

The plate separation, *L*, is

$$L = \lambda_{\text{mfp}} \frac{R_{t,m-m}}{R_{t,m-s}} \left[\frac{2-\alpha_t}{\alpha_t}\right] \left[\frac{9\gamma - 5}{\gamma + 1}\right]$$

$$= 1.919 \times 10^{-7} \text{ m} \times 100 \times \left[\frac{2-0.02}{0.02}\right] \left[\frac{9 \times 1.667 - 5}{1.667 + 1}\right] = 0.0071 \text{ m} = 7.1 \text{ mm}$$

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COMMENTS: The critical plate separation associated with helium is 7.1×10^{-3} m/ 24.7×10^{-6} m = 290 times greater than that for air. The thermal resistance associated with molecule-surface interactions can become significant for gases of small molecular diameter and for gas-surface material combinations that have a small thermal accommodation coefficient, even at relatively large plate separation distances (7.1 mm).