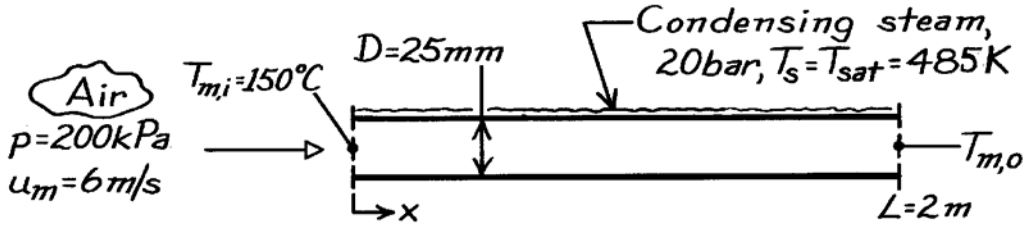
PROBLEM 8.52

KNOWN: Air at prescribed inlet temperature and mean velocity heated by condensing steam on its outer surface.

FIND: (a) Air outlet temperature, pressure drop and heat transfer rate and (b) Effect on parameters of part (a) if pressure were doubled.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) Negligible kinetic and potential energy changes, (3) Thermal resistance of tube wall and condensate film are negligible.

PROPERTIES: *Table A-4*, Air (assume $\overline{T}_m$ = 450 K, 1 atm = 101.3 kPa): ρ = 0.7740 kg/m^3, c_p = 1021 J/kg·K, μ = 250.7 × 10^{-7} N·s/m^2, k = 0.0373 W/m·K, Pr = $\mu c_p/k$ = 0.686. Note that only ρ is pressure dependent; i.e., $\rho \propto p$; *Table A-6*, Saturated water (20 bar): T_{sat} = T_s = 485 K.

ANALYSIS: (a) For constant wall temperature heating, from Eq. 8.41b,

$$\frac{T_s - T_{m,o}}{T_s - T_{m,i}} = \exp\left(-\frac{PL}{\dot{m}\, c_p}\overline{h}_i\right)$$

where P = πD. For the air flow, find the mass rate and Reynolds number,

$$\dot{m} = \rho A_c u_m = 0.7740\ \text{kg/m}^3\left(200\ \text{kPa}/101.3\ \text{kPa}\right)\left(\pi\left(0.025\ \text{m}\right)^2/4\right)\times 6\ \text{m/s}$$

$$\dot{m} = 4.501\times10^{-3}\text{kg/s}.$$

$$Re_D = \frac{4\dot{m}}{\mu\pi\ D} = \frac{4\times4.501\times10^{-3}\ \text{kg/s}}{250.7\times10^{-7}\ \text{N}\cdot\text{s/m}^2\times\pi\left(0.025\ \text{m}\right)} = 9.143\times10^3.$$

Using the Dittus-Boelter correlation for fully-developed turbulent flow,

$$Nu_D = 0.023Re^{4/5}\,Pr^{0.4} = 0.023\left(9.143\times10^3\right)^{4/5}\left(0.682\right)^{0.4} = 29.12$$

$$h_i = Nu\cdot k/D = 29.12\times0.0373\ \text{W/m}\cdot\text{K}/0.025\ \text{m} = 43.4\ \text{W/m}^2\cdot\text{K}.$$

Hence, the outlet temperature is

$$\frac{212 - T_{m,o}}{\left(212-150\right)^\circ C} = \exp\left[-\frac{\pi\left(0.025\ \text{m}\right)\times2\ \text{m}\times43.4\ \text{W/m}^2\cdot\text{K}}{4.501\times10^{-3}\ \text{kg/s}\times1021\ \text{J/kg}\cdot\text{K}}\right]$$

$$T_{m,o} = 198^\circ\text{C}.$$ <

Continued …

PROBLEM 8.52 (Cont.)

The pressure drop follows from Eqs. 8.21 and 8.22,

$$f = \left(0.790\ln(Re_D) - 1.64\right)^{-2} = \left(0.790\ln(9.143\times10^3) - 1.64\right)^{-2} = 0.0323$$

$$\Delta p = f\,\frac{\rho u_m^2}{2D}\,L$$

$$\Delta p = 0.0323\,\frac{0.7740\ \text{kg/m}^3\left(200/101.3\right)\left(6\ \text{m/s}\right)^2\times 2\ \text{m}}{2\times 0.025\ \text{m}} = 71.1\ \text{N/m}^2. \qquad <$$

The heat transfer rate is

$$q = \dot{m}\,c_p\left(T_{m,o} - T_{m,i}\right) = 4.501\times10^{-3}\ \text{kg/s}\times 1021\ \text{J/kg}\cdot\text{K}\left(198-150\right)\text{K} = 221\ \text{W}. \qquad <$$

(b) If the pressure were doubled, we can see from the above relations that $\dot{m} \propto p$ hence

$$\dot{m} = 2\dot{m}_o$$

$$Re_D = 2Re_{D,o},$$

since

$$h_i \propto \left(Re\right)^{4/5} \rightarrow \left(h_i / h_{i,o}\right) = 2^{4/5},$$

$$h_i = 1.74 h_{i,o}.$$

It follows that $T_{m,o}$ = 195°C, so that the effect on temperature is slight. However, the pressure drop increases by the factor 1.68 and the heat rate by the factor 1.88. In summary:

Parameter	p = 200 kPa Part (a)	p = 400 kPa Part (b)	Increase, %
$\dot{m}$, kg/s × 10^3	4.501	9.002	100
h_i, W/m^2·K	43.4	75.6	74
T_{mo} - $T_{m,i}$°C	48	45	-6
Δp, N/m^2	71.1	119	68
q, W	221	415	88

COMMENTS: (1) Note that $\overline{T}_m$ = (198 + 150)°C/2 = 447 K agrees well with the assumed value (450 K) used to evaluate the thermophysical properties.