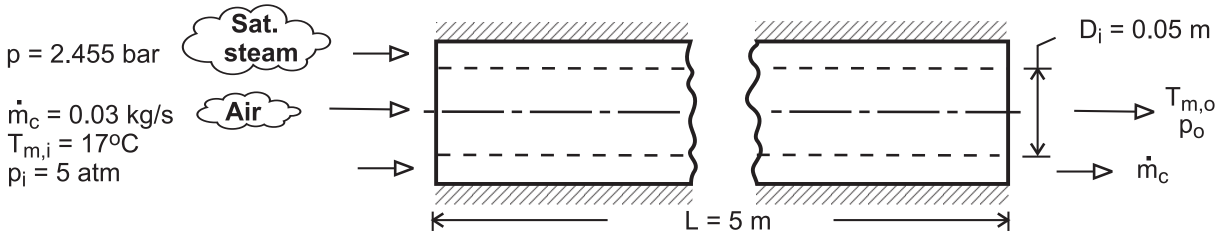
PROBLEM 8.38

KNOWN: Inlet temperature, pressure and flow rate of air. Tube diameter and length. Pressure of saturated steam.

FIND: Outlet temperature and pressure of air. Mass rate of steam condensation.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state, (2) Outer surface of annulus is adiabatic, (3)Ideal gas with negligible viscous dissipation and pressure variation, (4) Fully-developed flow throughout the tube, (5) Smooth tube surface, (6) Constant properties.

PROPERTIES: *Table A-4*, air $\left(\overline{T}_m \approx 325\,K,\ p = 5\,atm\right)$: $\rho = 5 \times \rho(1\,atm) = 5.391\,kg/m^3$,

$c_p = 1008\,J/kg\cdot K$, $\mu = 196.4 \times 10^{-7}\,N\cdot s/m^2$, $k = 0.0281\,W/m\cdot K$, $Pr = 0.703$. *Table A-6*, sat. steam (p = 2.455 bars): T_s = 400 K, h_{fg} = 2183 kJ/kg.

ANALYSIS: With a uniform surface temperature, the air outlet temperature is

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

With $Re_D = 4\dot{m}/\pi D_i\,\mu = 0.12\,kg/s/\pi(0.05m)196.4\times10^{-7}\,kg/s\cdot m = 38{,}980,$ the flow is turbulent, and the Dittus-Boelter correlation yields

$$\overline{h} \approx h_{fd} = \left(\frac{k}{D_i}\right)0.023\,Re_D^{4/5}\,Pr^{0.4} = \left(\frac{0.0281\,W/m\cdot K}{0.05m}\right)0.023(38{,}980)^{4/5}(0.703)^{0.4} = 52.8\,W/m^2\cdot K$$

$$T_{m,o} = 127°C - (110°C)\exp\left(-\frac{\pi\times0.05m\times5m\times52.8\,W/m^2\cdot K}{0.03\,kg/s\times1008\,J/kg\cdot K}\right) = 99°C \qquad <$$

The pressure drop is $\Delta p = f\left(\rho u_m^2/2D_i\right)L$, where, with $A_c = \pi D_i^2/4 = 1.963\times10^{-3}m^2$, $u_m = \dot{m}/\rho A_c$ $= 2.83\,m/s$, and with $Re_D = 38{,}980$, Eq. 8.21 gives f = $[0.790\ln(Re_D) - 1.64]^{-2}$ = 0.022. Hence,

$$\Delta p = 0.022\times5.391\,kg/m^3\,\frac{(2.83\,m/s)^2\,5m}{2\times0.05m} = 47.5\,N/m^2 = 4.7\times10^{-4}atm \qquad <$$

The rate of heat transfer to the air is

$$q = \dot{m}\,c_p\left(T_{m,o} - T_{m,i}\right) = 0.03\,kg/s\times1008\,J/kg\cdot K(82°C) = 2480\,W$$

and the rate of condensation is then

$$\dot{m}_c = \frac{q}{h_{fg}} = \frac{2480\,W}{2.183\times10^6\,J/kg} = 1.14\times10^{-3}kg/s \qquad <$$

COMMENTS: (1) With $\overline{T}_m = \left(T_{m,i} + T_{m,o}\right)/2 = 331\,K$, the initial estimate of 325 K is reasonable and iteration is not necessary. (2) For a steam flow rate of 0.01 kg/s, approximately 10% of the outflow would be in the form of saturated liquid, (3) With L/D_i = 100, it is reasonable to assume fully developed flow throughout the tube.