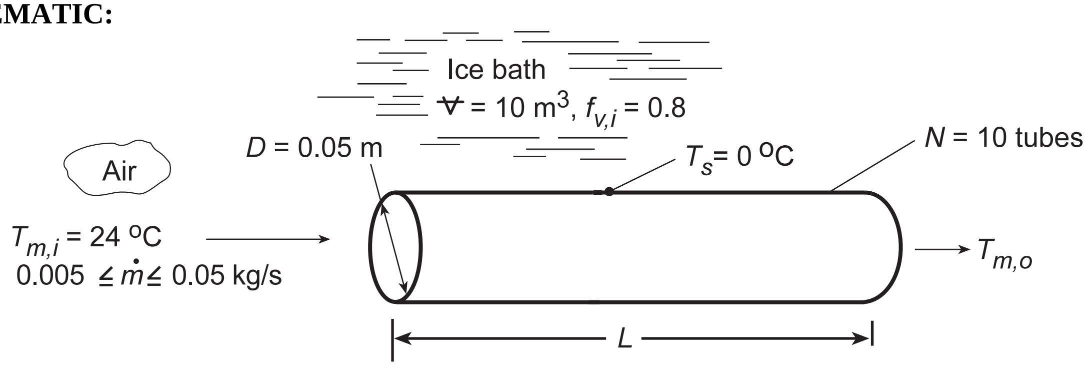
PROBLEM 8.33

KNOWN: Diameter and surface temperature of ten tubes in an ice bath. Inlet temperature and flowrate per tube. Volume (∀) of container and initial volume fraction, $f_{v,i}$, of ice.

FIND: (a) Tube length required to achieve a prescribed air outlet temperature $T_{m,o}$ and time to completely melt the ice, (b) Effect of mass flowrate on $T_{m,o}$ and suitable design and operating conditions.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state, (2) Ideal gas with negligible viscous dissipation and pressure variation, (3) Constant properties, (4) Fully developed flow throughout each tube, (5) Negligible tube wall thermal resistance.

PROPERTIES: *Table A.4*, air (assume $\overline{T}_m$ = 292 K): c_p = 1007 J/kg·K, $\mu = 180.6 \times 10^{-7}$ N·s/m², k = 0.0257 W/m·K, Pr = 0.709; Ice: ρ = 920 kg/m³, $h_{sf} = 3.34 \times 10^5$ J/kg.

ANALYSIS: (a) With $Re_D = 4\dot{m}/\pi D\mu = 4(0.01\text{ kg/s})/\pi(0.05\text{ m})180.6 \times 10^{-7}\text{ N·s/m}^2 = 14{,}100$ for $\dot{m}$ = 0.01 kg/s, the flow is turbulent, and from Eq. 8.60,

$$\overline{Nu}_D = Nu_D = 0.023 Re_D^{0.8} Pr^{0.3} = 0.023(14{,}100)^{0.8}(0.709)^{0.3} = 43.3$$

$$\overline{h} = \overline{Nu}_D(k/D) = 43.3(0.0257\,\text{W/m}\cdot\text{K}/0.05\,\text{m}) = 22.2\,\text{W/m}^2\cdot\text{K}$$

With $T_{m,o}$ = 14°C, the tube length may be obtained from Eq. 8.41b,

$$\frac{T_s - T_{m,o}}{T_s - T_{m,i}} = \frac{-14}{-24} = \exp\left(-\frac{\pi D L \overline{h}}{\dot{m} c_p}\right) = \exp\left[-\frac{\pi(0.05\,\text{m})(22.2\,\text{W/m}^2\cdot\text{K})L}{0.01\,\text{kg/s}(1007\,\text{J/kg}\cdot\text{K})}\right]$$

L = 1.56 m <

The time required to completely melt the ice may be obtained from an energy balance of the form,

$$(-q)t = f_{v,i}\forall(\rho h_{sf})$$

where $q = N\dot{m}c_p(T_{m,i} - T_{m,o}) = 10(0.01\,\text{kg/s})1007\,\text{J/kg}\cdot\text{K}(10\,\text{K}) = 1007\,\text{W}$. Hence,

$$t = \frac{0.8(10\,\text{m}^3)(920\,\text{kg/m}^3)3.34\times10^5\,\text{J/kg}}{1007\,\text{W}} = 2.44\times10^6\,\text{s} = 28.3\,\text{days}$$ <

(b) Using the appropriate IHT Correlations and Properties Tool Pads, the following results were obtained.

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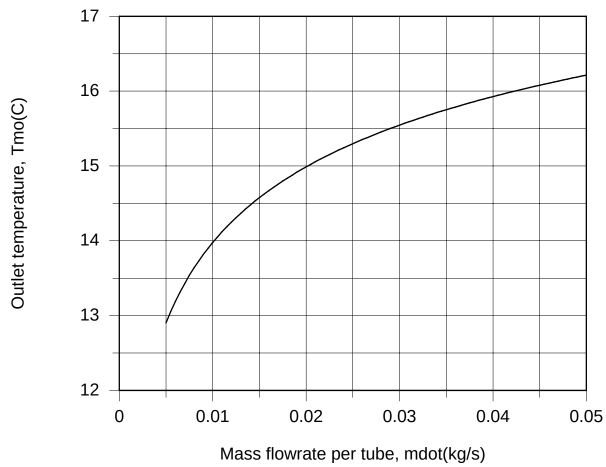
PROBLEM 8.33 (Cont.)



Although heat extraction from the air passing through each tube increases with increasing flowrate, the increase is not in proportion to the change in $\dot{m}$ and the temperature difference ($T_{m,i}$ - $T_{m,o}$) decreases. If 0.05 kg/s of air is routed through a single tube, the outlet temperature of $T_{m,o}$ = 16.2°C slightly exceeds the desired value of 16°C. The prescribed value could be achieved by slightly increasing the tube length. However, in the interest of reducing pressure drop requirements, it would be better to operate at a lower flowrate per tube. If, for example, air is routed through four of the tubes at 0.01 kg/s per tube and the discharge is mixed with 0.01 kg/s of the available air at 24°C, the desired result would be achieved.

COMMENTS: Since the flow is turbulent and L/D = 31, the assumption of fully developed flow throughout a tube is marginal and the foregoing analysis overestimates the discharge temperature.