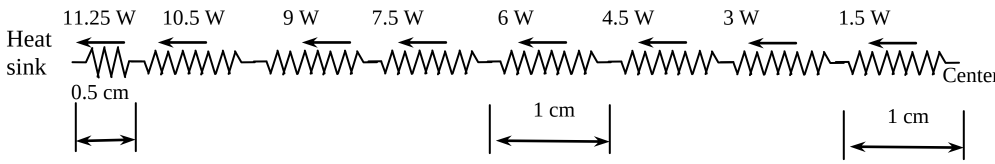
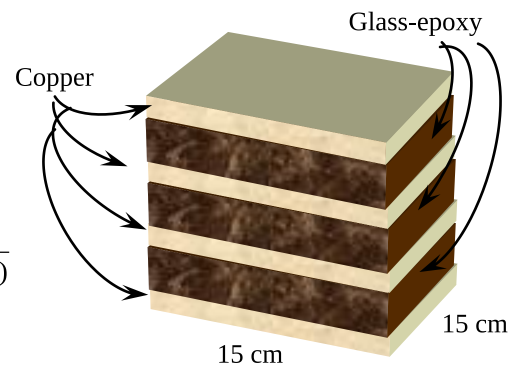
15-140 A multilayer circuit board consisting of four layers of copper and three layers of glass-epoxy sandwiched together is considered. The magnitude and location of the maximum temperature that occurs in the PCB are to be determined.

Assumptions **1** Steady operating conditions exist **2** Thermal properties are constant. **3** There is no direct heat dissipation from the surface of the PCB, and thus all the heat generated is conducted by the PCB to the heat sink.



Analysis The effective thermal conductivity of the board is determined from



$$(k_1 t_1)_{copper} = 4[(386\ \text{W/m.°C})(0.0001\text{m})] = 0.1544\ \text{W/°C}$$

$$(k_2 t_2)_{epoxy} = 3[(0.26\ \text{W/m.°C})(0.0005\text{m})] = 0.00039\ \text{W/°C}$$

$$k_{eff} = \frac{(k_1 t_1)_{copper} + (k_2 t_2)_{epoxy}}{t_1 + t_2} = \frac{(0.1544 + 0.00039)\ \text{W/°C}}{4(0.0001\text{m}) + 3(0.0005\text{m})}$$
$$= 81.5\ \text{W/m.°C}$$

The maximum temperature will occur in the middle of the board which is farthest away from the heat sink. We consider half of the board because of symmetry, and divide the region in 1-cm thick strips, starting at the mid-plane. Then from Fourier's law, the temperature difference across a strip can be determined from

$$\dot{Q} = k_{eff} A \frac{\Delta T}{L} \longrightarrow \Delta T = \frac{\dot{Q}L}{k_{eff} A}$$

where L = 1 cm = 0.01 m (except it is 0.5 cm for the strip attached to the heat sink), and the heat transfer area for all the strips is

$$A = (0.15\ \text{m})[4(0.0001\ \text{m}) + 3(0.0005\ \text{m})] = 0.000285\ \text{m}^2$$

Then the temperature at the center of the board is determined by adding the temperature differences across all the strips as

$$\Delta T_{\text{center-heat sink}} = \sum \frac{\dot{Q}L}{k_{eff} A} = \frac{(\dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{Q}_4 + \dot{Q}_5 + \dot{Q}_6 + \dot{Q}_7 + \dot{Q}_8 / 2)L}{k_{eff} A}$$

$$= \frac{(1.5 + 3 + 4.5 + 6 + 7.5 + 9 + 10.5 + 11.25/2\ \text{W})(0.01\ \text{m})}{(81.5\ \text{W/m.°C})(0.000285\ \text{m}^2)} = 20.5\text{°C}$$

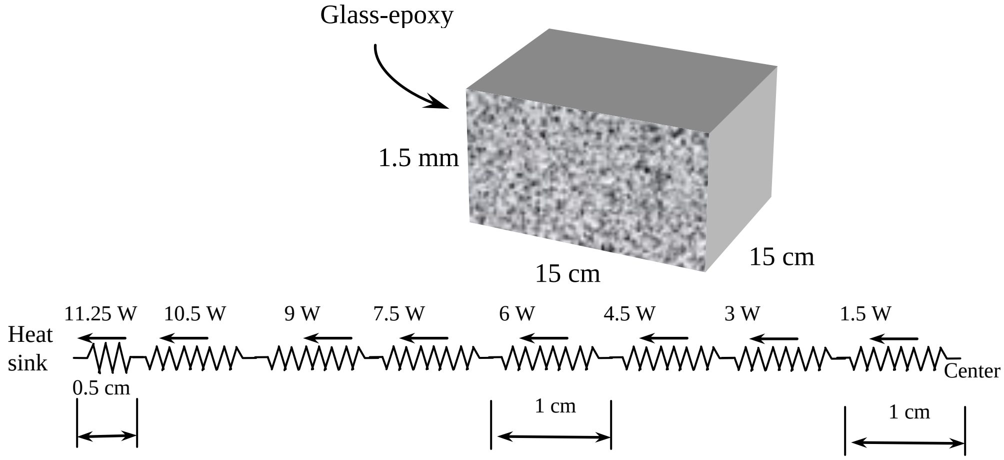
and $$T_{\text{center}} = T_{\text{heat sink}} + \Delta T_{\text{center-heat sink}} = 35\text{°C} + 20.5\text{°C} = \mathbf{55.5°C}$$

Discussion This problem can also be solved approximately by using the "average" heat transfer rate for the entire half board, and treating it as a constant. The heat transfer rate in each half changes from 0 at the center to 22.5/2 = 11.25 W at the heat sink, with an average of 11.25/2 = 5.625 W. Then the center temperature becomes

$$\dot{Q}_{ave} \cong k_{eff} A \frac{T_1 - T_2}{L} \longrightarrow T_{\text{center}} \cong T_{\text{heat sink}} + \frac{\dot{Q}_{ave} L}{k_{eff} A} = 35\text{°C} + \frac{(5.625\ \text{W})(0.075\ \text{m})}{(81.5\ \text{W/m.°C})(0.000285\ \text{m}^2)} = \mathbf{53.2°C}$$

15-141 A circuit board consisting of a single layer of glass-epoxy is considered. The magnitude and location of the maximum temperature that occurs in the PCB are to be determined.

Assumptions **1** Steady operating conditions exist **2** Thermal properties are constant. **3** There is no direct heat dissipation from the surface of the PCB, and thus all the heat generated is conducted by the PCB to the heat sink.



Analysis In this case the board consists of a 1.5-mm thick layer of epoxy. Again the maximum temperature will occur in the middle of the board which is farthest away from the heat sink. We consider half of the board because of symmetry, and divide the region in 1-cm thick strips, starting at the mid-plane. Then from Fourier's law, the temperature difference across a strip can be determined from

$$\dot{Q} = k_{eff} A \frac{\Delta T}{L} \longrightarrow \Delta T = \frac{\dot{Q} L}{k_{eff} A}$$

where L = 1 cm = 0.01 m (except it is 0.5 cm for the strip attached to the heat sink), and the heat transfer area for all the strips is

$$A = (0.15 \text{ m})(0.0015 \text{ m}) = 0.000225 \text{ m}^2$$

Then the temperature at the center of the board is determined by adding the temperature differences across all the strips as

$$\Delta T_{\text{center-heat sink}} = \sum \frac{\dot{Q} L}{k_{eff} A} = \frac{(\dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{Q}_4 + \dot{Q}_5 + \dot{Q}_6 + \dot{Q}_7 + \dot{Q}_8 / 2) L}{k_{eff} A}$$

$$= \frac{(1.5 + 3 + 4.5 + 6 + 7.5 + 9 + 10.5 + 11.25/2 \text{ W})(0.01 \text{ m})}{(0.26 \text{ W/m.°C})(0.000225 \text{ m}^2)} = 8141\text{°C}$$

and $$T_{\text{center}} = T_{\text{heat sink}} + \Delta T_{\text{center-heat sink}} = 35\text{°C} + 8141\text{°C} = \mathbf{8176\text{°C}}$$

Discussion This problem can also be solved approximately by using the "average" heat transfer rate for the entire half board, and treating it as a constant. The heat transfer rate in each half changes from 0 at the center to 22.5/2 = 11.25 W at the heat sink, with an average of 11.25/2 = 5.625 W. Then the center temperature becomes

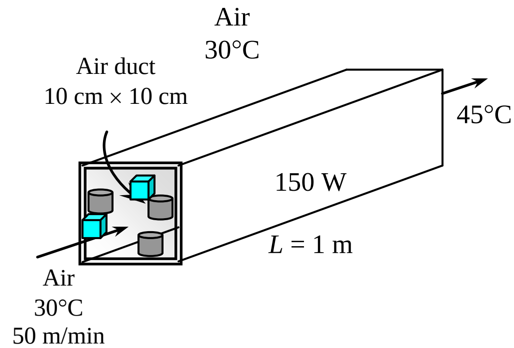
$$\dot{Q}_{ave} \cong k_{eff} A \frac{T_1 - T_2}{L} \longrightarrow T_{\text{center}} \cong T_{\text{heat sink}} + \frac{\dot{Q}_{ave} L}{k_{eff} A} = 35\text{°C} + \frac{(5.625 \text{ W})(0.075 \text{ m})}{(0.26 \text{ W/m.°C})(0.000225 \text{ m}^2)} = \mathbf{7247\text{°C}}$$

15-142 The components of an electronic system located in a horizontal duct of rectangular cross-section are cooled by forced air flowing through the duct. The heat transfer from the outer surfaces of the duct by natural convection, the average temperature of the duct and the highest component surface temperature in the duct are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Air is an ideal gas. **3** The local atmospheric pressure is 1 atm.

Properties We use the properties of air at (30+45)/2 = 37.5°C are (Table A-15)

$$\rho = 1.136\ \text{kg/m}^3$$
$$C_p = 1007\ \text{J/kg.°C}$$
$$\text{Pr} = 0.726$$
$$k = 0.0264\ \text{W/m.°C}$$
$$\nu = 1.68\times10^{-5}\ \text{m}^2/\text{s}$$



Analysis (*a*) The volume and the mass flow rates of air are

$$\dot{V} = A_c\mathbf{V} = (0.1\text{m})(0.1\text{m})(50/60\text{m/s}) = 0.008333\text{m}^3/\text{s}$$
$$\dot{m} = \rho\dot{V} = (1.136\,\text{kg/m}^3)(0.008333\text{m}^3/\text{s}) = 0.009466\text{kg/s}$$

The rate of heat transfer to the air flowing through the duct is

$$\dot{Q}_{forced\,conv} = \dot{m}C_p(T_{in} - T_{out}) = (0.009466\text{kg/s})(1007\,\text{J/kg.°C})(45 - 30)\text{°C} = 143.0\,\text{W}$$

Then the rate of heat loss from the outer surfaces of the duct to the ambient air by natural convection becomes

$$\dot{Q}_{conv} = \dot{Q}_{total} - \dot{Q}_{forced\,conv} = 150\,\text{W} - 143\,\text{W} = \mathbf{57\ W}$$

(*b*) The average surface temperature can be determined from

$$\dot{Q}_{conv} = hA_s(T_{s,duct} - T_{\substack{ambient\\air}})$$

But we first need to determine convection heat transfer coefficient. Using the Nusselt number relation from Table 15-2,

$$A_s = (4)(0.1\,\text{m})(1\,\text{m}) = 0.4\,\text{m}^2$$
$$\text{Re} = \frac{\mathbf{V}D_h}{\nu} = \frac{(50/60\,\text{m/s})(0.1\text{m})}{1.68\times10^{-5}\ \text{m}^2/\text{s}} = 4960$$
$$Nu = 0.102\,\text{Re}^{0.675}\,\text{Pr}^{1/3} = (0.102)(4960)^{0.675}(0.726)^{1/3} = 28.6$$
$$h = \frac{k}{D_h}Nu = \frac{0.0264\,\text{W/m.°C}}{0.1\,\text{m}}(28.6) = 7.56\,\text{W/m}^2.\text{°C}$$

Then the average surface temperature of the duct becomes

$$\dot{Q}_{conv} = hA_s(T_s - T_{ambient}) \longrightarrow T_s = T_{ambient} + \frac{\dot{Q}_{conv}}{hA_s} = 30\text{°C} + \frac{57\,\text{W}}{(7.56\,\text{W/m}^2.\text{°C})(0.4\,\text{m}^2)} = \mathbf{48.9°C}$$

(*c*) The highest component surface temperature will occur at the exit of the duct. From Newton's law relation at the exit,

$$\dot{q}_{conv} = h(T_{s,\max} - T_{air,exit}) \longrightarrow T_{s,\max} = T_{air,exit} + \frac{\dot{Q}_{conv}/A_s}{h} = 45\text{°C} + \frac{57\,\text{W}}{(7.56\,\text{W/m}^2.\text{°C})(0.4\,\text{m}^2)} = \mathbf{63.8°C}$$

15-143 Two power transistors are cooled by mounting them on the two sides of an aluminum bracket that is attached to a liquid-cooled plate. The temperature of the transistor case and the fraction of heat dissipation to the ambient air by natural convection and to the cold plate by conduction are to be determined.

Assumptions **1** Steady operating conditions exist **2** Conduction heat transfer is one-dimensional. **3** We assume the ambient temperature is 25°C.

Analysis The rate of heat transfer by conduction is

$$\dot{Q}_{conduction} = (0.80)(12\text{ W}) = 9.6\text{ W}$$

Assuming heat conduction in the plate to be one-dimensional for simplicity, the thermal resistance of the aluminum plate and epoxy adhesive are

$$R_{aluminum} = \frac{L}{kA} = \frac{0.02\text{ m}}{(237\text{ W/m.}^\circ\text{C})(0.003\text{ m})(0.03\text{ m})} = 0.938^\circ\text{C/W}$$

$$R_{epoxy} = \frac{L}{kA} = \frac{0.0002\text{ m}}{(1.8\text{ W/m.}^\circ\text{C})(0.003\text{ m})(0.03\text{ m})} = 1.235^\circ\text{C/W}$$

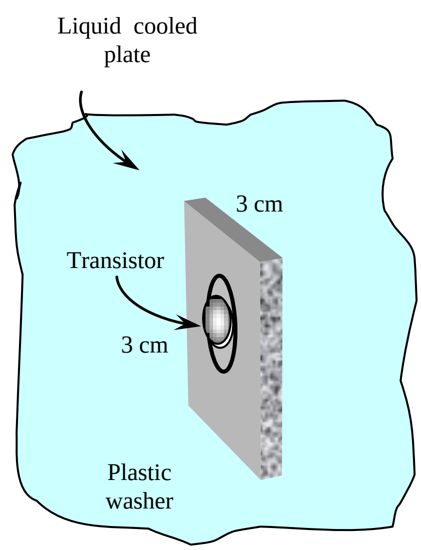
The total thermal resistance of the plate and the epoxy is

$$R_{plate+epoxy} = R_{epoxy} + R_{plate} = 1.235 + 0.938 = 2.173^\circ\text{C/W}$$

Heat generated by the transistors is conducted to the plate, and then it is dissipated to the cold plate by conduction, and to the ambient air by convection. Denoting the plate temperature where the transistors are connected as $T_{s,max}$ and using the heat transfer coefficient relation from Table 15-1 for a vertical plate, the total heat transfer from the plate can be expressed as

$$\dot{Q}_{total} = \dot{Q}_{cond} + \dot{Q}_{conv} = \frac{\Delta T_{plate}}{R_{plate+epoxy}} + hA_{side}(T_{s,ave} - T_{air})$$

$$= \frac{T_{s,\max} - T_{cold\ plate}}{R_{plate+epoxy}} + 1.42\left(\frac{(T_{s,ave} - T_{air})}{L}\right)^{0.25} A_{side}(T_{s,\max} - T_{air})$$



where $T_{s,\ ave}$ = ($T_{s,\ max}$ + $T_{cold\ plate}$)/2, L 0.03 m, and A_{side} = 2(0.03 m)(0.03 m) = 0.00018 m^2. Substituting the known quantities gives

$$20\text{ W} = \frac{T_{s,\max} - 40}{2.173^\circ\text{C/W}} + 1.42(0.00018)\frac{[(T_{s,\max} + 40)/2 - 25]^{1.25}}{(0.03)^{0.25}}$$

Solving for $T_{s,\ max}$ gives

$$T_{s,\ max} = 83.3^\circ\text{C}$$

Then the rate of heat transfer by natural convection becomes

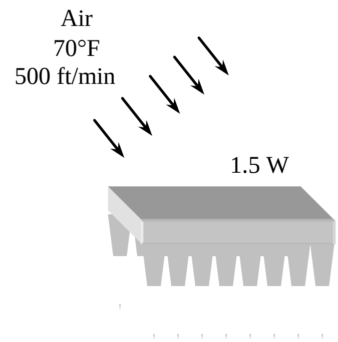
$$\dot{Q}_{conv} = 1.42(0.00018)\frac{[(83.3 + 40)/2 - 25]^{1.25}}{(0.03)^{0.25}} = 0.055\text{ W}$$

which is 0.055/20 = 0.00275 or **0.3%** of the total heat dissipated. The remaining **99.7%** of the heat is transferred by conduction. Therefore, heat transfer by natural convection is negligible. Then the surface temperature of the transistor case becomes

$$T_{\text{case}} = T_{\text{s,max}} + \dot{Q}R_{\text{plastic washer}} = 83.3^\circ\text{C} + (10\text{ W})(2^\circ\text{C/W}) = \mathbf{103.3^\circ C}$$

15-144E A plastic DIP with 24 leads is cooled by forced air. Using data supplied by the manufacturer, the junction temperature is to be determined for two cases.

Assumptions Steady operating conditions exist.



Analysis The junction-to-ambient thermal resistance of the device with 24 leads corresponding to an air velocity of 500 × 0.3048 = 152.4 m/min is determined from Fig. 15-23 to be

$$R_{junction-ambient} = 50\ °\text{C/W} = (50 \times 1.8) + 32 = 122\ °\text{F/W}$$

Then the junction temperature becomes

$$\dot{Q} = \frac{T_{junction} - T_{ambient}}{R_{junction-ambient}} \longrightarrow T_{junction} = T_{ambient} + \dot{Q}R_{junction-ambient}$$

$$= 70°\text{F} + (1.5\,\text{W})(122°\text{F/W}) = \mathbf{253°F}$$

When the fan fails the total thermal resistance is determined from Fig. 15-23 by reading the value at the intersection of the curve at the vertical axis to be

$$R_{junction-ambient} = 66\ °\text{C/W} = (66 \times 1.8) + 32 = 150.8\ °\text{F/W}$$

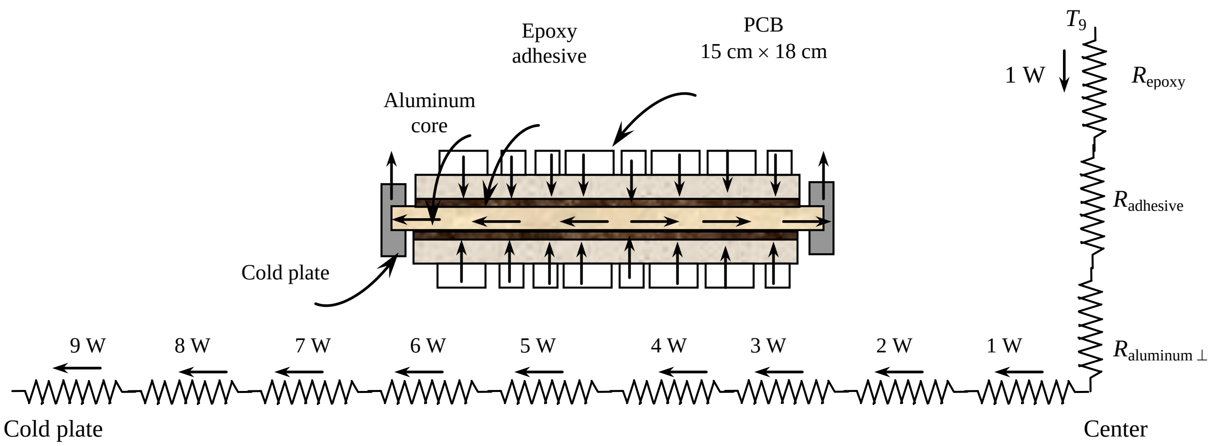
which yields

$$\dot{Q} = \frac{T_{junction} - T_{ambient}}{R_{junction-ambient}} \longrightarrow T_{junction} = T_{ambient} + \dot{Q}R_{junction-ambient}$$

$$= 70°\text{F} + (1.5\,\text{W})(150.8°\text{F/W}) = \mathbf{296°F}$$

15-145 A circuit board is to be conduction-cooled by aluminum core plate sandwiched between two epoxy laminates. The maximum temperature rise between the center and the sides of the PCB is to be determined.

Assumptions **1** Steady operating conditions exist **2** Thermal properties are constant. **3** There is no direct heat dissipation from the surface of the PCB., and thus all the heat generated is conducted by the PCB to the heat sink.



Analysis Using the half thickness of the aluminum frame because of symmetry, the thermal resistances against heat flow in the vertical direction for a 1-cm wide strip are

$$R_{\text{aluminum},\perp} = \frac{L}{kA} = \frac{0.0006\text{ m}}{(237\text{ W/m.°C})(0.01\text{ m})(0.15\text{ m})} = 0.00169\text{ °C/W}$$

$$R_{\text{epoxy}} = \frac{L}{kA} = \frac{0.0005\text{ m}}{(0.26\text{ W/m.°C})(0.01\text{ m})(0.15\text{ m})} = 1.28205\text{ °C/W}$$

$$R_{\text{adhesive}} = \frac{L}{kA} = \frac{0.0001\text{ m}}{(1.8\text{ W/m.°C})(0.01\text{ m})(0.15\text{ m})} = 0.03703\text{ °C/W}$$

$$R_{\text{vertical}} = R_{\text{aluminum},\perp} + R_{\text{epoxy}} + R_{\text{adhesive}} = 0.00169 + 1.28205 + 0.03704 = 1.321\text{ °C/W}$$

We assume heat conduction along the epoxy and adhesive in the horizontal direction to be negligible, and heat to be conduction to the heat sink along the aluminum frame. The thermal resistance of the aluminum frame against heat conduction in the horizontal direction for a 1-cm long strip is

$$R_{\text{frame}} = R_{\text{aluminum},\parallel} = \frac{L}{kA} = \frac{0.01\text{ m}}{(237\text{ W/m.°C})(0.0012\text{ m})(0.18\text{ m})} = 0.1953\text{ °C/W}$$

The temperature difference across a strip is determined from

$$\Delta T = \dot{Q}R_{\text{aluminum},\parallel}$$

The maximum temperature rise across the 9 cm distance between the center and the sides of the board is determined by adding the temperature differences across all the strips as

$$\Delta T_{\text{horizontal}} = \sum \dot{Q}R_{\text{aluminum},\parallel} = (\dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{Q}_4 + \dot{Q}_5 + \dot{Q}_6 + \dot{Q}_7 + \dot{Q}_8 2)R_{\text{aluminum},\parallel}$$
$$= (1+2+3+4+5+6+7+8+9\text{ W})(0.1953\text{ °C/W}) = 8.8\text{°C}$$

The temperature difference between the center of the aluminum core and the outer surface of the PCB is determined similarly to be

$$\Delta T_{\text{vertical}} = \sum \dot{Q}R_{\text{vertical},\perp} = (1\text{ W})(1.321\text{ °C/W}) = 1.3\text{°C}$$

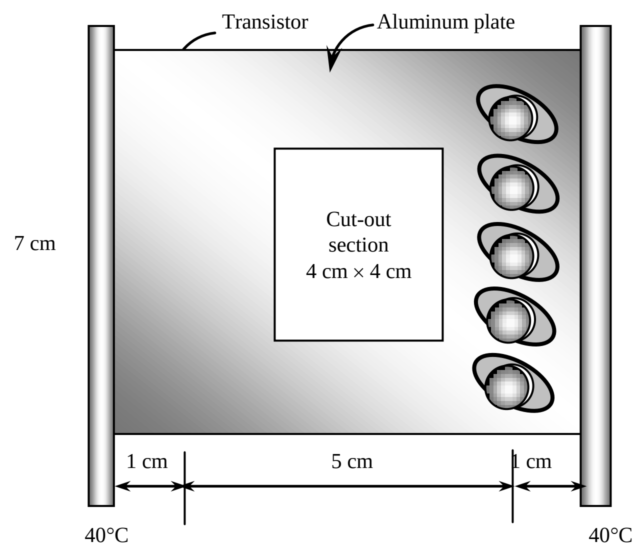
Then the maximum temperature rise across the 9-cm distance between the center and the sides of the PCB becomes

$$\Delta T_{\max} = \Delta T_{\text{horizontal}} + \Delta T_{\text{vertical}} = 8.8 + 1.3 = \mathbf{10.1°C}$$

15-146 Ten power transistors attached to an aluminum plate are cooled from two sides of the plate by liquid. The temperature rise between the transistors and the heat sink is to be determined.

Assumptions **1** Steady operating conditions exist **2** Thermal properties are constant.

Analysis We consider only half of the plate because of symmetry. It is stated that 70% of the heat generated is conducted through the aluminum plate, and this heat will be conducted across the 1-cm wide section between the transistors and the cooled edge of the plate. (Note that the mid section of the plate will essentially be isothermal and thus there will be no significant heat transfer towards the midsection). The rate of heat conduction to each side is of the plate is



$$\dot{Q}_{\text{cond,1-side}} = 0.70 \times (10\text{ W}) = 7\text{ W}$$

Then the temperature rise across the 1-cm wide section of the plate can be determined from

$$\dot{Q}_{\text{cond. 1-side}} = kA\frac{(\Delta T)_{\text{plate}}}{L}$$

Solving for $(\Delta T)_{\text{plate}}$ and substituting gives

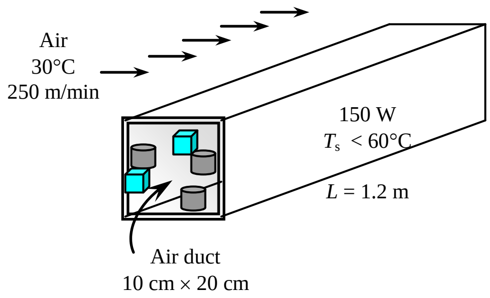
$$(\Delta T)_{\text{plate}} = \frac{\dot{Q}_{\text{cond.1-side}} L}{kA} = \frac{(7\text{ W})(0.01\text{m})}{(237\text{ W/m.°C})(0.07 \times 0.002\text{ m}^2)} = \mathbf{2.1°C}$$

15-147 The components of an electronic system located in a horizontal duct are cooled by air flowing over the duct. The total power rating of the electronic devices that can be mounted in the duct is to be determined for two cases.

Assumptions **1** Steady operating conditions exist **2** Thermal properties of air are constant. **3** The local atmospheric pressure is 1 atm.

Properties The properties of air at the film temperature of (30+60)/2 = 45°C are (Table A-15)

$$\Pr = 0.724$$
$$k = 0.0270 \text{ W/m.°C}$$
$$\nu = 1.75\times10^{-5} \text{ m}^2/\text{s}$$



Analysis The surface area of the duct is

$$A_s = 2\{[(1.2\text{ m})(0.1\text{m})] + [(1.2\text{ m})(0.2\text{m})]\} = 0.72\text{m}^2$$

The duct is oriented such that air strikes the 10 cm high side normally. Using the Nusselt number relation from Table 15-2 for a 10-cm by 10-cm cross-section square as an approximation, the heat transfer coefficient is determined to be

$$\text{Re} = \frac{\mathbf{V}D}{\nu} = \frac{(250/60\text{ m/s})(0.1\text{m})}{1.75\times10^{-5}\text{ m}^2/\text{s}} = 23{,}810$$

$$Nu = 0.102\,\text{Re}^{0.675}\,\Pr^{1/3} = (0.102)(23{,}810)^{0.675}(0.724)^{1/3} = 82.4$$

$$h = \frac{k}{D_h}Nu = \frac{0.0270\text{ W/m.°C}}{0.1\text{ m}}(82.4) = 22.3\text{ W/m}^2\text{.°C}$$

Then the heat transfer rate (and thus the power rating of the components inside) in this orientation is determined from

$$\dot{Q} = hA_s(T_s - T_{fluid}) = (22.3\text{W/m}^2\text{.°C})(0.72\text{ m}^2)(60\text{-}30)\text{°C} = \mathbf{481\ W}$$

We now consider the duct oriented such that air strikes the 20 cm high side normally. Using the Nusselt number relation from Table 15-2 for a 20-cm by 20-cm cross-section square as an approximation, the heat transfer coefficient is determined to be

$$\text{Re} = \frac{\mathbf{V}D}{\nu} = \frac{(250/60\text{ m/s})(0.2\text{ m})}{1.75\times10^{-5}\text{ m}^2/\text{s}} = 47{,}619$$

$$Nu = 0.102\,\text{Re}^{0.675}\,\Pr^{1/3} = (0.102)(47{,}619)^{0.675}(0.724)^{1/3} = 131.6$$

$$h = \frac{k}{D_h}Nu = \frac{0.0270\text{ W/m.°C}}{0.2\text{ m}}(131.6) = 17.8\text{ W/m}^2\text{.°C}$$

Then the heat transfer rate (and thus the power rating of the components inside) in this orientation is determined from

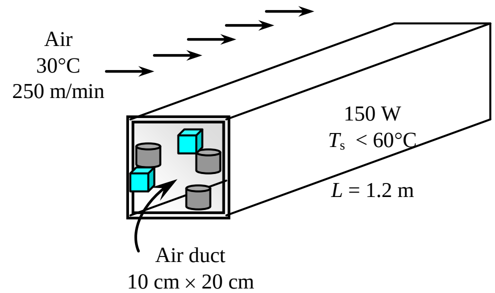
$$\dot{Q} = hA_s(T_s - T_{fluid}) = (17.8\text{W/m}^2\text{.°C})(0.72\text{ m}^2)(60\text{-}30)\text{°C} = \mathbf{384\ W}$$

15-148 The components of an electronic system located in a horizontal duct are cooled by air flowing over the duct. The total power rating of the electronic devices that can be mounted in the duct is to be determined for two cases.

Assumptions **1** Steady operating conditions exist **2** Thermal properties of air are constant. **3** The local atmospheric pressure is 1 atm.

Properties The properties of air at the film temperature of (30+60)/2 = 45°C and 54.05 kPa are (Table A-15)

$$\Pr = 0.724$$
$$k = 0.0270\ \text{W/m.°C}$$
$$\nu = \frac{1.75\times10^{-5}\ \text{m}^2/\text{s}}{54.05/101325} = 3.28\times10^{-5}\ \text{m}^2/\text{s}$$



Analysis The surface area of the duct is

$$A_s = 2\{[(1.2\ \text{m})(0.1\text{m})] + [(1.2\ \text{m})(0.2\ \text{m})]\} = 0.72\ \text{m}^2$$

The duct is oriented such that air strikes the 10 cm high side normally. Using the Nusselt number relation from Table 15-2 for a 10-cm by 10-cm cross-section square as an approximation, the heat transfer coefficient is determined to be

$$\text{Re} = \frac{\mathbf{V}D}{\nu} = \frac{(250/60\ \text{m/s})(0.1\text{m})}{3.28\times10^{-5}\ \text{m}^2/\text{s}} = 12{,}703$$

$$Nu = 0.102\,\text{Re}^{0.675}\,\Pr^{1/3} = (0.102)(12{,}703)^{0.675}(0.724)^{1/3} = 53.9$$

$$h = \frac{k}{D_h}Nu = \frac{0.0270\ \text{W/m.°C}}{0.1\ \text{m}}(53.9) = 14.6\ \text{W/m}^2.\text{°C}$$

Then the heat transfer rate (and thus the power rating of the components inside) in this orientation is determined from

$$\dot{Q} = hA_s(T_s - T_{fluid}) = (14.6\ \text{W/m}^2.\text{°C})(0.72\ \text{m}^2)(60-30)\text{°C} = \mathbf{315\ W}$$

We now consider the duct oriented such that air strikes the 20 cm high side normally. Using the Nusselt number relation from Table 15-2 for a 20-cm by 20-cm cross-section square as an approximation, the heat transfer coefficient is determined to be

$$\text{Re} = \frac{\mathbf{V}D}{\nu} = \frac{(250/60\ \text{m/s})(0.2\ \text{m})}{3.28\times10^{-5}\ \text{m}^2/\text{s}} = 25{,}407$$

$$Nu = 0.102\,\text{Re}^{0.675}\,\Pr^{1/3} = (0.102)(25{,}407)^{0.675}(0.724)^{1/3} = 86.1$$

$$h = \frac{k}{D_h}Nu = \frac{0.0270\ \text{W/m.°C}}{0.2\ \text{m}}(86.1) = 11.6\ \text{W/m}^2.\text{°C}$$

Then the heat transfer rate (and thus the power rating of the components inside) in this orientation is determined from

$$\dot{Q} = hA_s(T_s - T_{fluid}) = (11.6\ \text{W/m}^2.\text{°C})(0.72\ \text{m}^2)(60-30)\text{°C} = \mathbf{251\ W}$$

15-149E A computer is cooled by a fan blowing air into the computer enclosure. The fraction of heat lost from the outer surfaces of the computer case is to be determined.

Assumptions **1** Steady operating conditions exist **2** Thermal properties of air are constant. **3** The local atmospheric pressure is 1 atm.

Analysis Using the proper relation from Table 15-1, the heat transfer coefficient and the rate of natural convection heat transfer from the vertical side surfaces are determined to be

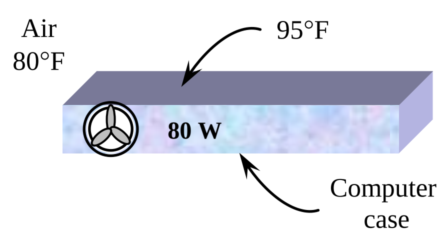
$$L = \frac{6}{12}\text{ ft}$$

$$A_{side} = (2)\left(\frac{20}{12}\text{ ft} + \frac{24}{12}\text{ ft}\right)\left(\frac{6}{12}\text{ ft}\right) = 3.67\text{ ft}^2$$

$$h_{conv,side} = 1.42\left(\frac{\Delta T}{L}\right)^{0.25} = 1.42\left(\frac{95-80}{6/12}\right)^{0.25} = 3.32\text{ Btu/h.ft}^2.°\text{F}$$

$$\dot{Q}_{conv,side} = h_{conv,side}A_{side}(T_s - T_{fluid}) = (3.32\text{ Btu/h.ft}^2.°\text{F})(3.67\text{ ft}^2)(95-80)°\text{F} = 182.9\text{ Btu/h}$$

Similarly, the rate of heat transfer from the horizontal top surface by natural convection is determined to be



$$L = \frac{4A_{top}}{p} = \frac{4\left(\frac{20}{12}\text{ ft}\right)\left(\frac{24}{12}\text{ ft}\right)}{2\left[\left(\frac{20}{12}\text{ ft}\right)+\left(\frac{24}{12}\text{ ft}\right)\right]} = 1.82\text{ ft}$$

$$A_{top} = \left(\frac{20}{12}\text{ ft}\right)\left(\frac{24}{12}\text{ ft}\right) = 3.33\text{ ft}^2$$

$$h_{conv,top} = 1.32\left(\frac{\Delta T}{L}\right)^{0.25} = 1.32\left(\frac{95-80}{1.82}\right)^{0.25} = 2.24\text{ Btu/h.ft}^2.°\text{F}$$

$$\dot{Q}_{conv,top} = h_{conv,top}A_{top}(T_s - T_{fluid}) = (2.24\text{ Btu/h.ft}^2.°\text{F})(3.33\text{ft}^2)(95-80)°\text{F} = 111.7\text{ Btu/h}$$

The rate of heat transfer from the outer surfaces of the computer case by radiation is

$$\begin{aligned}\dot{Q}_{rad} &= \varepsilon A_s\sigma(T_s^{\,4} - T_{surr}^{\,4}) \\ &= (0.85)(3.67\text{ ft}^2 + 3.33\text{ ft}^2)(0.1714\text{ Btu/h.ft}^2.\text{R}^4)[(95+460\text{ R})^4 - (80+273\text{R})^4] \\ &= 100.4\text{ Btu/h}\end{aligned}$$

Then the total rate of heat transfer from the outer surfaces of the computer case becomes

$$\dot{Q}_{total} = \dot{Q}_{conv,side} + \dot{Q}_{conv,top} + \dot{Q}_{rad} = 182.9 + 111.7 + 100.4 = 395\text{ Btu/h}$$

Therefore, the fraction of the heat loss from the outer surfaces of the computer case is

$$f = \frac{(395/3.41214)\text{ W}}{170\text{ W}} = 0.68 = \mathbf{68\%}$$

15-150 . . . 15-152 Design and Essay Problems
