Air Cooling: Natural Convection and Radiation

15-71C As the student watches the movie, the temperature of the electronic components in the VCR will keep increasing because of the blocked air passages. The VCR eventually may overheat and fail.

15-72C There is no natural convection in space because of the absence of gravity (and because of the absence of a medium outside). However, it can be cooled by radiation since radiation does not need a medium.

15-73C The openings on the side surfaces of a TV, VCR or other electronic enclosures provide passage ways for the cold air to enter and warm air to leave. If a TV or VCR is enclosed in a cabinet with no free space around, and if there is no other cooling process involved, the temperature of device will keep rising due to the heat generation in device, which may cause the device to fail eventually.

15-74C The magnitude of radiation, in general, is comparable to the magnitude of natural convection. Therefore, radiation heat transfer should be always considered in the analysis of natural convection cooled electronic equipment.

15-75C The effect of atmospheric pressure to heat transfer coefficient can be written as $h_{conv,P\,atm} = h_{conv,1\,atm}\sqrt{P}$ $(\mathrm{W/m^2.{}^\circ C})$ where P is the air pressure in atmosphere. Therefore, the greater the air pressure, the greater the heat transfer coefficient. The best and the worst orientation for heat transfer from a square surface are vertical and horizontal, respectively, since the former maximizes and the latter minimizes natural convection.

15-76C The view factor from surface 1 to surface 2 is the fraction of radiation which leaves surface 1 and strikes surface 2 directly. The magnitude of radiation heat transfer between two surfaces is proportional to the view factor. The larger the view factor, the larger the radiation exchange between the two surfaces.

15-77C Emissivity of a surface is the ratio of the radiation emitted by a surface at a specified temperature to the radiation emitted by a blackbody (which is the maximum amount) at the same temperature. The magnitude of radiation heat transfer between a surfaces and it surrounding surfaces is proportional to the emissivity. The larger the emissivity, the larger the radiation heat exchange between the two surfaces.

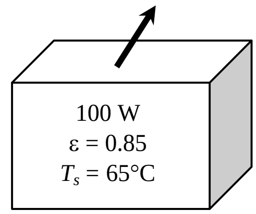
15-78C For most effective natural convection cooling of a PCB array, the PCB should be placed vertically to take advantage of natural convection currents which tend to rise naturally, and to minimize trapped air pockets. Placing the PCBs too close to each other tends to choke the flow because of the increased resistance. Therefore, the PCBs should be placed far from each other for effective heat transfer (A distance of about 2 cm between the PCBs turns out to be adequate for effective natural convection cooling.)

15-79C Radiation heat transfer from the components on the PCBs in an enclosure is negligible since the view of the components is largely blocked by other heat generating components at about the same temperature, and hot components face other hot surfaces instead of cooler surfaces.

15-80 The surface temperature of a sealed electronic box placed on top of a stand is not to exceed 65°C. It is to be determined if this box can be cooled by natural convection and radiation alone.

Assumptions **1** Steady operating conditions exist. **2** The local atmospheric pressure is 1 atm.

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



$$L = 0.2\text{ m}$$

$$A_{side} = (2)(0.5\text{ m} + 0.35\text{ m})(0.2\text{ m}) = 0.34\text{ m}^2$$

$$h_{conv,side} = 1.42\left(\frac{\Delta T}{L}\right)^{0.25} = 1.42\left(\frac{65-30}{0.2}\right)^{0.25} = 5.16\text{ W/m.°C}$$

$$\dot{Q}_{conv,side} = h_{conv,side}A_{side}(T_s - T_{fluid})$$
$$= (5.16\text{ W/m.°C})(0.34\text{ m}^2)(65-30)\text{°C} = 61.5\text{ W}$$

The heat transfer from the horizontal top surface by natural convection is

$$L = \frac{4A_{top}}{p} = \frac{4(0.5\text{ m})(0.35\text{m})}{(2)(0.5\text{ m} + 0.35\text{m})} = 0.41\text{m}$$

$$A_{top} = (0.5\text{ m})(0.35\text{ m}) = 0.175\text{ m}^2$$

$$h_{conv,top} = 1.32\left(\frac{\Delta T}{L}\right)^{0.25} = 1.32\left(\frac{65-30}{0.41}\right)^{0.25} = 4.01\text{W/m.°C}$$

$$\dot{Q}_{conv,top} = h_{conv,top}A_{top}(T_s - T_{fluid}) = (4.01\text{W/m.°C})(0.175\text{m}^2)(65-30)\text{°C} = 24.6\text{W}$$

The rate of heat transfer from the box by radiation is determined from

$$\dot{Q}_{rad} = \varepsilon A_s \sigma (T_s{}^4 - T_{surr}{}^4)$$
$$= (0.85)(0.34\text{ m}^2 + 0.175\text{ m}^2)(5.67\times10^{-8}\text{ W/m}^2\text{.K}^4)[(65+273\text{K})^4 - (30+273\text{K})^4] = 114.7\text{ W}$$

Then the total rate of heat transfer from the box becomes

$$\dot{Q}_{total} = \dot{Q}_{conv,side} + \dot{Q}_{conv,top} + \dot{Q}_{rad} = 61.5 + 24.6 + 114.7 = \mathbf{200.8\ W}$$

which is greater than 100 W. Therefore, this box can be cooled by combined natural convection and radiation.

15-81 The surface temperature of a sealed electronic box placed on top of a stand is not to exceed 65°C. It is to be determined if this box can be cooled by natural convection and radiation alone.

Assumptions **1** Steady operating conditions exist. **2** The local atmospheric pressure is 1 atm.

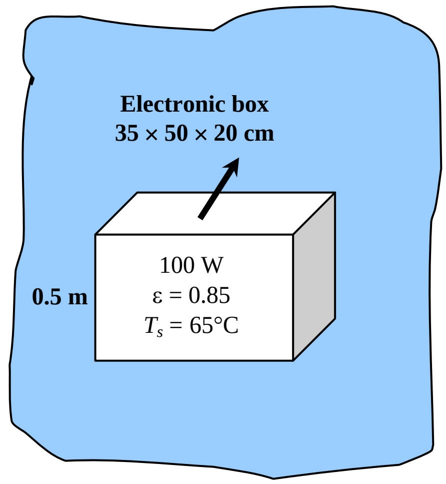
Analysis In given orientation, two side surfaces and the top surface will be vertical and other two side surfaces will be horizontal. Using Table 15-1, the heat transfer coefficient and the natural convection heat transfer from the vertical surfaces are determined to be

$$L = 0.5\text{ m}$$

$$A_{vertical} = (2\times0.2\times0.5 + 0.5\times0.35) = 0.375\text{ m}^2$$

$$h_{conv,vertical} = 1.42\left(\frac{\Delta T}{L}\right)^{0.25} = 1.42\left(\frac{65-30}{0.5}\right)^{0.25} = 4.107\text{ W/m.°C}$$

$$\dot{Q}_{conv,vertical} = h_{conv,vertical} A_{vertical}(T_s - T_{fluid})$$
$$= (4.107\text{ W/m.°C})(0.375\text{ m}^2)(65-30)\text{°C} = 53.9\text{ W}$$



The heat transfer from the horizontal top surface by natural convection is

$$A_{top} = (0.2\text{ m})(0.35\text{ m}) = 0.07\text{ m}^2$$

$$L = \frac{4A_{top}}{p} = \frac{(4)(0.07\text{ m}^2)}{(4)(0.2\text{ m} + 0.35\text{ m})} = 0.1273\text{m}$$

$$h_{conv,top} = 1.32\left(\frac{\Delta T}{L}\right)^{0.25} = 1.32\left(\frac{65-30}{0.1273}\right)^{0.25} = 5.4\text{ W/m.°C}$$

$$\dot{Q}_{conv,top} = h_{conv,top} A_{top}(T_s - T_{fluid})$$
$$= (5.4\text{ W/m.°C})(0.07\text{ m}^2)(65-30)\text{°C} = 13.2\text{ W}$$

The heat transfer from the horizontal top surface by natural convection is

$$h_{conv,bottom} = 0.59\left(\frac{\Delta T}{L}\right)^{0.25} = 0.59\left(\frac{65-30}{0.1273}\right)^{0.25} = 2.4\text{ W/m.°C}$$

$$\dot{Q}_{conv,bottom} = h_{conv,bottom} A_{bottom}(T_s - T_{fluid}) = (2.4\text{ W/m.°C})(0.07\text{ m}^2)(65-30)\text{°C} = 5.9\text{ W}$$

The rate of heat transfer from the box by radiation is determined from

$$\dot{Q}_{rad} = \varepsilon A_s \sigma(T_s^4 - T_{surr}^4)$$
$$= (0.85)(0.34\text{ m}^2 + 0.175\text{ m}^2)(5.67\times10^{-8}\text{ W/m}^2.\text{K}^4)[(65+273\text{K})^4 - (30+273\text{K})^4] = 114.7\text{ W}$$

Then the total rate of heat transfer from the box becomes

$$\dot{Q}_{total} = \dot{Q}_{conv,vertical} + \dot{Q}_{conv,top} + \dot{Q}_{conv,bottom} + \dot{Q}_{rad} = 53.9 + 13.2 + 5.9 + 114.7 = \mathbf{187.7\text{ W}}$$

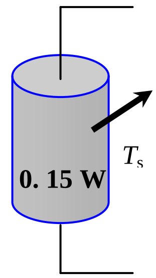
which is greater than 100 W. Therefore, this box can be cooled by combined natural convection and radiation.

15-82E A small cylindrical resistor mounted on a PCB is being cooled by natural convection and radiation. The surface temperature of the resistor is to be determined.

Assumptions **1** Steady operating conditions exist. **2** The local atmospheric pressure is 1 atm. **3** Radiation is negligible in this case since the resistor is surrounded by surfaces which are at about the same temperature, and the radiation heat transfer between two surfaces at the same temperature is zero. This leaves natural convection as the only mechanism of heat transfer from the resistor.

Analysis For components on a circuit board, the heat transfer coefficient relation from Table 15-1 is

$$h_{conv} = 0.50\left(\frac{T_s - T_{fluid}}{D}\right)^{0.25} \qquad (L = D)$$



Substituting it into the heat transfer relation to get

$$\dot{Q}_{conv} = h_{conv} A_s (T_s - T_{fluid})$$
$$= 0.50\left(\frac{T_s - T_{fluid}}{D}\right)^{0.25} A_s (T_s - T_{fluid})$$
$$= 0.50 A_s \frac{(T_s - T_{fluid})^{1.25}}{D^{0.25}}$$

Calculating surface area and substituting it into above equation for the surface temperature yields

$$A_s = 2\left(\frac{\pi D^2}{4}\right) + \pi DL = 2\left[\frac{\pi (0.15/12\text{ ft})^2}{4}\right] + \pi (0.15/12\text{ ft})(0.5/12\text{ft}) = 0.00188\text{ft}^2$$

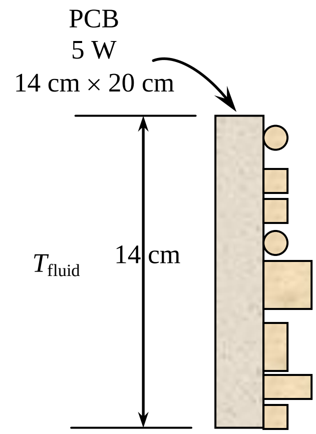
$$(0.15\text{ W} \times 3.41214\text{Btu/h.W}) = (0.50)(0.00188\text{ft}^2)\frac{(T_s - 130)^{1.25}}{(0.15/12\text{ft})^{0.25}} \longrightarrow T_s = \mathbf{194°F}$$

15-83 The surface temperature of a PCB is not to exceed 90°C. The maximum environment temperatures for safe operation at sea level and at 3,000 m altitude are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Radiation heat transfer is negligible since the PCB is surrounded by other PCBs at about the same temperature. **3** Heat transfer from the back surface of the PCB will be very small and thus negligible.

Analysis Using the simplified relation for a vertical orientation from Table 15-1, the natural convection heat transfer coefficient is determined to be

$$h_{conv} = 1.42\left(\frac{T_s - T_{fluid}}{L}\right)^{0.25}$$



Substituting it into the heat transfer relation to get

$$\begin{aligned}\dot{Q}_{conv} &= h_{conv} A_s (T_s - T_{fluid}) \\ &= 1.42\left(\frac{T_s - T_{fluid}}{L}\right)^{0.25} A_s (T_s - T_{fluid}) \\ &= 1.42 A_s \frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}\end{aligned}$$

Calculating surface area and characteristic length and substituting them into above equation for the surface temperature yields

$$L = 0.14\,\text{m}$$

$$A_s = (0.14\,\text{m})(0.2\,\text{m}) = 0.028\,\text{m}^2$$

$$5\,\text{W} = (1.42)(0.028\,\text{m}^2)\frac{(90 - T_{fluid})^{1.25}}{(0.14\,\text{m})^{0.25}} \longrightarrow T_{fluid} = \mathbf{57.7°C}$$

At an altitude of 3000 m, the atmospheric pressure is 70.12 kPa which is equivalent to

$$P = (70.12\ \text{kPa})\frac{1\ \text{atm}}{101.325\ \text{kPa}} = 0.692\ \text{atm}$$

Modifying the heat transfer relation for this pressure (by multiplying by the square root of it) yields

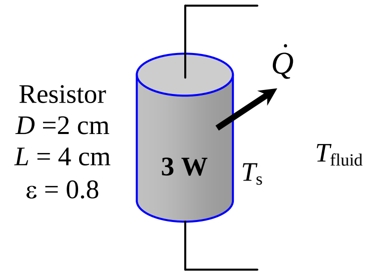
$$5\,\text{W} = (1.42)(0.028\,\text{m}^2)\frac{(90 - T_{fluid})^{1.25}}{(0.14\,\text{m})^{0.25}}\sqrt{0.692} \longrightarrow T_{fluid} = \mathbf{52.6°C}$$

15-84 A cylindrical electronic component is mounted on a board with its axis in the vertical direction. The average surface temperature of the component is to be determined.

Assumptions **1** Steady operating conditions exist. **2** The local atmospheric pressure is 1 atm.

Analysis The natural convection heat transfer coefficient for vertical orientation using Table 15-1 can be determined from

$$h_{conv} = 1.42\left(\frac{T_s - T_{fluid}}{L}\right)^{0.25}$$



Substituting it into the heat transfer relation gives

$$\begin{aligned}\dot{Q}_{conv} &= h_{conv} A_s (T_s - T_{fluid}) \\ &= 1.42\left(\frac{T_s - T_{fluid}}{L}\right)^{0.25} A_s (T_s - T_{fluid}) \\ &= 1.42 A_s \frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}\end{aligned}$$

The rate of heat transfer from the cylinder by radiation is

$$\dot{Q}_{rad} = \varepsilon A_s \sigma (T_s{}^4 - T_{surr}{}^4)$$

Then the total rate of heat transfer can be written as

$$\dot{Q}_{total} = \dot{Q}_{conv} + \dot{Q}_{rad} = 1.42 A_s \frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}} + \varepsilon A_s \sigma (T_s{}^4 - T_{surr}{}^4)$$

We will calculate total surface area of the cylindrical component including top and bottom surfaces, and assume the natural heat transfer coefficient to be the same throughout all surfaces of the component

$$A_s = 2\left(\frac{\pi D^2}{4}\right) + \pi D L = 2\left[\frac{\pi (0.02\,\text{m})^2}{4}\right] + \pi (0.02\,\text{m})(0.04\text{m}) = 0.00314\text{m}^2$$

Substituting

$$\begin{aligned}3\,\text{W} &= (1.42)(0.00314\text{m}^2)\frac{[T_s - (30+273\text{K})]^{1.25}}{(0.04\text{m})^{0.25}} \\ &\quad + (0.8)(0.00314\text{m}^2)(5.67\times10^{-8}\ \text{W/m}^2\text{K}^4)[T_s{}^4 - (20+273\text{K})^4]\end{aligned}$$

Solving for the surface temperature gives

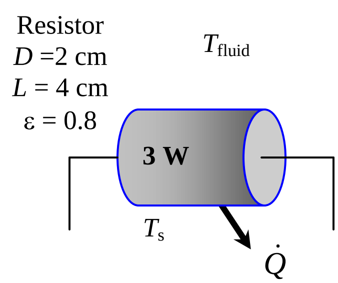
$$T_s = 363\text{K} = \mathbf{90^\circ C}$$

15-85 A cylindrical electronic component is mounted on a board with its axis in horizontal direction. The average surface temperature of the component is to be determined.

Assumptions **1** Steady operating conditions exist. **2** The local atmospheric pressure is 1 atm.

Analysis Since atmospheric pressure is not given, we assume it to be 1 atm. The natural convection heat transfer coefficient for horizontal orientation using Table 15-1 can be determined from

$$h_{conv} = 1.32\left(\frac{T_s - T_{fluid}}{D}\right)^{0.25}$$



Substituting it into the heat transfer relation to get

$$\dot{Q}_{conv} = h_{conv} A_s (T_s - T_{fluid})$$

$$= 1.32\left(\frac{T_s - T_{fluid}}{D}\right)^{0.25} A_s (T_s - T_{fluid})$$

$$= 1.32 A_s \frac{(T_s - T_{fluid})^{1.25}}{D^{0.25}}$$

The rate of heat transfer from the cylinder by radiation is

$$\dot{Q}_{rad} = \varepsilon A_s \sigma (T_s^{\ 4} - T_{surr}^{\ 4})$$

Then the total heat transfer can be written as

$$\dot{Q}_{total} = \dot{Q}_{conv} + \dot{Q}_{rad} = 1.32 A_s \frac{(T_s - T_{fluid})^{1.25}}{D^{0.25}} + \varepsilon A \sigma (T_s^{\ 4} - T_{surr}^{\ 4})$$

We will calculate total surface area of the cylindrical component including top and bottom surfaces, and assume the natural heat transfer coefficient to be the same throughout all surfaces of the component

$$A_s = 2\left(\frac{\pi D^2}{4}\right) + \pi DL = 2\left[\frac{\pi (0.02\text{ m})^2}{4}\right] + \pi (0.02\text{ m})(0.04\text{m}) = 0.00314\text{m}^2$$

Substituting,

$$3\text{ W} = (1.32)(0.00314\text{m}^2)\frac{[T_s - (30+273)\text{ K}]^{1.25}}{(0.02\text{m})^{0.25}}$$

$$+ (0.8)(0.00314\text{m}^2)(5.67\times 10^{-8}\text{ W/m}^2\text{K}^4)[T_s^{\ 4} - (20+273\text{K})^4]$$

Solving for the surface temperature gives

$$T_s = 361\text{K} = \mathbf{88°C}$$

15-86 "!PROBLEM 15-086"

```
"GIVEN"
D=0.02 "[m]"
L=0.04 "[m]"
Q_dot=3 "[W]"
epsilon=0.8 "parameter to be varied"
"T_ambient=30+273 [K], parameter to be varied"
T_surr=T_ambient-10

"ANALYSIS"
Q_dot=Q_dot_conv+Q_dot_rad
Q_dot_conv=h*A*(T_s-T_ambient)
h=1.42*((T_s-T_ambient)/L)^0.25
A=2*(pi*D^2)/4+pi*D*L
Q_dot_rad=epsilon*A*sigma*(T_s^4-T_surr^4)
sigma=5.67E-8 "[W/m^2-K^4]"
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ε	T_s [K]
0.1	391.6
0.15	388.4
0.2	385.4
0.25	382.6
0.3	380.1
0.35	377.7
0.4	375.5
0.45	373.4
0.5	371.4
0.55	369.5
0.6	367.8
0.65	366.1
0.7	364.5
0.75	363
0.8	361.5
0.85	360.2
0.9	358.9
0.95	357.6
1	356.4

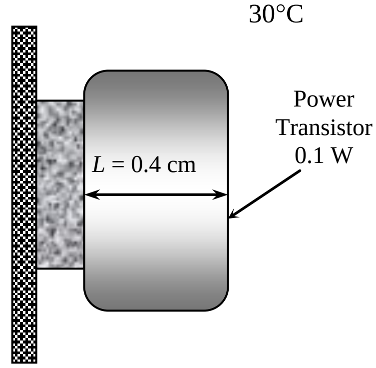
$T_{ambient}$ [K]	T_s [K]
288	349.6
289	350.4
290	351.2
291	352
292	352.8
293	353.6
294	354.4
295	355.2
296	356
297	356.8
298	357.6
299	358.4
300	359.2
301	360
302	360.7
303	361.5

304	362.3
305	363.1
306	363.9
307	364.7
308	365.5

15-87 A power transistor dissipating 0.1 W of power is considered. The heat flux on the surface of the transistor and the surface temperature of the transistor are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Heat is transferred uniformly from all surfaces of the transistor.

Analysis *(a)* The heat flux on the surface of the transistor is



$$A_s = 2\left(\frac{\pi D^2}{4}\right) + \pi DL$$

$$= 2\left[\frac{\pi(0.4\text{ cm})^2}{4}\right] + \pi(0.4\text{ cm})(0.4\text{cm}) = 0.754\text{cm}^2$$

$$\dot{q} = \frac{\dot{Q}}{A_s} = \frac{0.1\text{W}}{0.754\text{cm}^2} = 0.1326\text{W/cm}^2$$

(*b*) The surface temperature of the transistor is determined from Newton's law of cooling to be

$$\dot{q} = h_{combined}(T_s - T_{fluid})$$

$$T_s = T_{fluid} + \frac{\dot{q}}{h_{combined}} = 30°\text{C} + \frac{1326\text{W/m}^2}{18\text{W/m}^2.°\text{C}} = \mathbf{103.7°C}$$

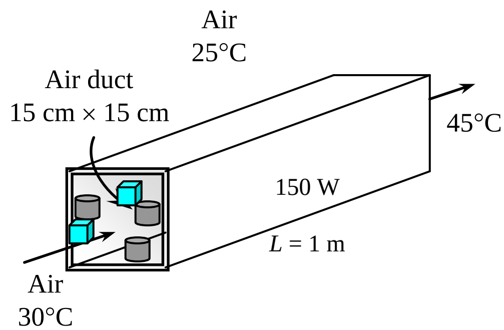
15-88 The components of an electronic equipment located in a horizontal duct with rectangular cross-section are cooled by forced air. The heat transfer from the outer surfaces of the duct by natural convection and the average temperature of the duct are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Radiation heat transfer from the outer surfaces is negligible.

Analysis (*a*) Using air properties at 300 K and 1 atm, the mass flow rate of air and the heat transfer rate by forced convection are determined to be

$$\dot{m} = \rho\dot{V} = (1.177\ \text{kg/m}^3)(0.4/60\ \text{m}^3/\text{s}) = 0.00785\ \text{kg/s}$$

$$\dot{Q}_{\substack{forced\\convection}} = \dot{m}C_p\Delta T = (0.00785\ \text{kg/s})(1005\ \text{J/kg.°C})(45-30)\text{°C} = 118.3\ \text{W}$$



Noting that radiation heat transfer is negligible, the rest of the 150 W heat generated must be dissipated by natural convection,

$$\dot{Q}_{\substack{natural\\convection}} = \dot{Q}_{total} - \dot{Q}_{\substack{forced\\convection}} = 150 - 118.3 = \mathbf{31.7\ W}$$

(*b*) The natural convection heat transfer from the vertical side surfaces of the duct is

$$A_{side} = 2\times(0.15\ \text{m})(1\ \text{m}) = 0.3\ \text{m}^2$$

$$h_{conv,side} = 1.42\left(\frac{\Delta T}{L}\right)^{0.25}$$

$$\dot{Q}_{conv,side} = h_{conv,side}A_{side}(T_s - T_{fluid}) = 1.42\left(\frac{(T_s - T_{fluid})}{L}\right)^{0.25} A_{side}(T_s - T_{fluid})$$

$$= 1.42A_{side}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}$$

Natural convection from the top and bottom surfaces of the duct is

$$L = \frac{4A_{top}}{p} = \frac{(4)(0.15\ \text{m})(1\ \text{m})}{(2)(0.15\ \text{m}+1\ \text{m})} = 0.26\ \text{m}, \quad A_{top} = (0.15\ \text{m})(1\ \text{m}) = 0.15\ \text{m}^2, \quad h_{conv,top} = 1.32\left(\frac{\Delta T}{L}\right)^{0.25}$$

$$\dot{Q}_{conv,top} = h_{conv,top}A_{top}(T_s - T_{fluid}) = 1.32\left(\frac{(T_s - T_{fluid})}{L}\right)^{0.25} A_{top}(T_s - T_{fluid}) = 1.32A_{top}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}$$

$$h_{conv,bottom} = 0.59\left(\frac{\Delta T}{L}\right)^{0.25}$$

$$\dot{Q}_{conv,bottom} = h_{conv,bot}A_{top}(T_s - T_{fluid}) = 0.59\left(\frac{(T_s - T_{fluid})}{L}\right)^{0.25} A_{bot}(T_s - T_{fluid}) = 0.59A_{bot}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}$$

Then the total heat transfer by natural convection becomes

$$\dot{Q}_{total,conv} = \dot{Q}_{conv,side} + \dot{Q}_{conv,top} + \dot{Q}_{conv,bottom}$$

$$\dot{Q}_{total,conv} = 1.42A_{side}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}} + 1.32A_{top}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}} + 0.59A_{bottom}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}$$

Substituting all known quantities with proper units gives the average temperature of the duct to be

$$31.7 = (1.42)(0.3)\frac{(T_s - 25)^{1.25}}{0.15^{0.25}} + (1.32)(0.15)\frac{(T_s - 25)^{1.25}}{0.26^{0.25}} + (0.59)(0.15)\frac{(T_s - 25)^{1.25}}{0.26^{0.25}}$$

$$31.7 = (1.086)(T_s - 25)^{1.25} \longrightarrow T_s = \mathbf{40°C}$$

15-89 The components of an electronic equipment located in a circular horizontal duct are cooled by forced air. The heat transfer from the outer surfaces of the duct by natural convection and the average temperature of the duct are to be determined.

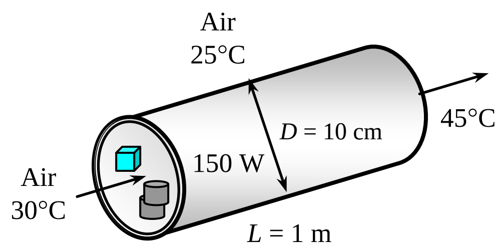
Assumptions **1** Steady operating conditions exist. **2** Radiation heat transfer from the outer surfaces is negligible.

Analysis (*a*) Using air properties at 300 K and 1 atm, the mass flow rate of air and the heat transfer rate by forced convection are determined to be

$$\dot{m} = \rho\dot{V} = (1.177\ \text{kg/m}^3)(0.4/60\ \text{m}^3/\text{s}) = 0.00785\ \text{kg/s}$$

$$\dot{Q}_{\substack{forced\\convection}} = \dot{m}C_p \Delta T = (0.00785\ \text{kg/s})(1005\ \text{J/kg.°C})(45-30)\text{°C} = 118.3\ \text{W}$$

Noting that radiation heat transfer is negligible, the rest of the 150 W heat generated must be dissipated by natural convection,



$$\dot{Q}_{\substack{natural\\convection}} = \dot{Q}_{total} - \dot{Q}_{\substack{forced\\convection}} = 150 - 118.3 = \mathbf{31.7\ W}$$

(*b*) The natural convection heat transfer from the circular duct is

$$L = D = 0.1\,\text{m}$$

$$A_s = 2\left(\frac{\pi D^2}{4}\right) + \pi DL = 2\left[\frac{\pi(0.1\,\text{m})^2}{4}\right] + \pi(0.1\,\text{m})(1\,\text{m}) = 0.33\,\text{m}^2$$

$$h_{conv} = 1.32\left(\frac{\Delta T}{D}\right)^{0.25}$$

$$\dot{Q}_{conv} = h_{conv}A(T_s - T_{fluid}) = 1.32\left(\frac{(T_s - T_{fluid})}{D}\right)^{0.25} A_s(T_s - T_{fluid})$$

$$= 1.32 A_s \frac{(T_s - T_{fluid})^{1.25}}{D^{0.25}}$$

Substituting all known quantities with proper units gives the average temperature of the duct to be

$$31.7\ \text{W} = (1.32)(0.33\,\text{m}^2)\frac{(T_s - 25)^{1.25}}{(0.1\,\text{m})^{0.25}} \longrightarrow T_s = \mathbf{44°C}$$

15-90 "!PROBLEM 15-090"

```
"GIVEN"
Q_dot_total=150 "[W]"
L=1 "[m]"
"side=0.15 [m],parameter to be varied"
T_in=30 "[C]"
T_out=45 "[C]"
V_dot=0.4 "[m^3/min], parameter to be varied"
T_ambient=25 "[C]"

"PROPERTIES"
rho=Density(air, T=T_ave, P=101.3)
C_p=CP(air, T=T_ave)*Convert(kJ/kg-C, J/kg-C)
T_ave=1/2*(T_in+T_out)

"ANALYSIS"
"(a)"
m_dot=rho*V_dot*Convert(m^3/min, m^3/s)
Q_dot_ForcedConv=m_dot*C_p*(T_out-T_in)
Q_dot_NaturalConv=Q_dot_total-Q_dot_ForcedConv
"(b)"
A_side=2*side*L
h_conv_side=1.42*((T_s-T_ambient)/L)^0.25
Q_dot_conv_side=h_conv_side*A_side*(T_s-T_ambient)
L_top=(4*A_top)/p_top
A_top=side*L
p_top=2*(side+L)
h_conv_top=1.32*((T_s-T_ambient)/L_top)^0.25
Q_dot_conv_top=h_conv_top*A_top*(T_s-T_ambient)
h_conv_bottom=0.59*((T_s-T_ambient)/L_top)^0.25
Q_dot_conv_bottom=h_conv_bottom*A_top*(T_s-T_ambient)
Q_dot_NaturalConv=Q_dot_conv_side+Q_dot_conv_top+Q_dot_conv_bottom
```

V [m^3/min]	$Q_{NaturalConv}$ [W]	T_s [C]
0.1	121.4	79.13
0.15	107.1	73.97
0.2	92.81	68.66
0.25	78.51	63.19
0.3	64.21	57.52
0.35	49.92	51.58
0.4	35.62	45.29
0.45	21.32	38.46
0.5	7.023	30.54

side [m]	$Q_{NaturalConv}$ [W]	T_s [C]
0.1	35.62	52.08
0.11	35.62	50.31
0.12	35.62	48.8
0.13	35.62	47.48
0.14	35.62	46.32
0.15	35.62	45.29
0.16	35.62	44.38
0.17	35.62	43.55
0.18	35.62	42.81
0.19	35.62	42.13

0.2	35.62	41.5

15-91 The components of an electronic equipment located in a horizontal duct with rectangular cross-section are cooled by forced air. The heat transfer from the outer surfaces of the duct by natural convection and the average temperature of the duct are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Radiation heat transfer from the outer surfaces is negligible.

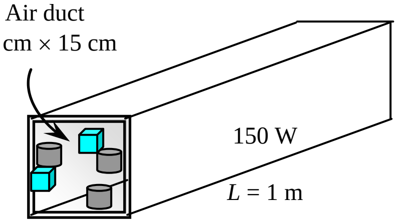
Analysis In this case the entire 150 W must be dissipated by natural convection from the outer surface of the duct. Natural convection from the vertical side surfaces of the duct can be expressed as

$$L = 0.15 \text{ m} \qquad A_{side} = 2\times(0.15\,\text{m})(1\,\text{m}) = 0.3\,\text{m}^2$$

$$h_{conv,side} = 1.42\left(\frac{\Delta T}{L}\right)^{0.25}$$

$$\dot{Q}_{conv,side} = h_{conv,side}A_{side}(T_s - T_{fluid}) = 1.42\left(\frac{(T_s - T_{fluid})}{L}\right)^{0.25} A_{side}(T_s - T_{fluid})$$

$$= 1.42A_{side}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}$$



Natural convection from the top surface of the duct is

$$L = \frac{4A_{top}}{p} = \frac{(4)(0.15\,\text{m})(1\,\text{m})}{(2)(0.15\,\text{m}+1\,\text{m})} = 0.26\,\text{m}$$

$$A_{top} = (0.15\,\text{m})(1\,\text{m}) = 0.15\,\text{m}^2$$

$$h_{conv,top} = 1.32\left(\frac{\Delta T}{L}\right)^{0.25}$$

$$\dot{Q}_{conv,top} = h_{conv,top}A_{top}(T_s - T_{fluid}) = 1.32\left(\frac{(T_s - T_{fluid})}{L}\right)^{0.25} A_{top}(T_s - T_{fluid})$$

$$= 1.32A_{top}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}$$

Natural convection from the bottom surface of the duct is

$$h_{conv,bottom} = 0.59\left(\frac{\Delta T}{L}\right)^{0.25}$$

$$\dot{Q}_{conv,bottom} = h_{conv,bottom}A_{top}(T_s - T_{fluid}) = 0.59\left(\frac{(T_s - T_{fluid})}{L}\right)^{0.25} A_{bottom}(T_s - T_{fluid})$$

$$= 0.59A_{bottom}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}$$

Then the total heat transfer by natural convection becomes

$$\dot{Q}_{total,conv} = \dot{Q}_{conv,side} + \dot{Q}_{conv,top} + \dot{Q}_{conv,bottom}$$

$$\dot{Q}_{total,conv} = 1.42A_{side}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}} + 1.32A_{top}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}} + 0.59A_{bottom}\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}$$

Substituting all known quantities with proper units gives the average temperature of the duct to be

$$150 = (1.42)(0.3)\frac{(T_s - 25)^{1.25}}{0.15^{0.25}} + (1.32)(0.15)\frac{(T_s - 25)^{1.25}}{0.26^{0.25}} + (0.59)(0.15)\frac{(T_s - 25)^{1.25}}{0.26^{0.25}}$$

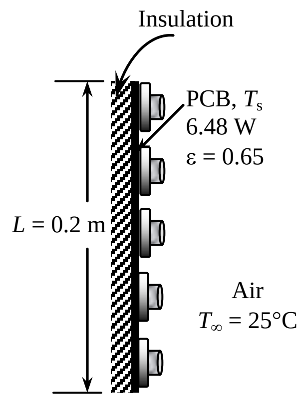
$$150 = (1.086)(T_s - 25)^{1.25} \longrightarrow T_s = \mathbf{77°C}$$

15-92 A wall-mounted circuit board containing 81 square chips is cooled by combined natural convection and radiation. The surface temperature of the chips is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Heat transfer from the back side of the circuit board is negligible. **3** Temperature of surrounding surfaces is the same as the air temperature. **3** The local atmospheric pressure is 1 atm.

Analysis The natural convection heat transfer coefficient for the vertical orientation of board can be determined from (Table 15-1)

$$h_{conv} = 1.42\left(\frac{T_s - T_{fluid}}{L}\right)^{0.25}$$



Substituting it relation into the heat transfer relation gives

$$\dot{Q}_{conv} = h_{conv}A_s(T_s - T_{fluid})$$
$$= 1.42\left(\frac{T_s - T_{fluid}}{L}\right)^{0.25} A(T_s - T_{fluid}) = 1.42A\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}$$

The rate of heat transfer from the board by radiation is

$$\dot{Q}_{rad} = \varepsilon A_s \sigma\left(T_s^{\ 4} - T_{surr}^{\ 4}\right)$$

Then the total heat transfer can be expressed as

$$\dot{Q}_{total} = \dot{Q}_{conv} + \dot{Q}_{rad} = 1.42A_s\frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}} + \varepsilon A_s\sigma(T_s^{\ 4} - T_{surr}^{\ 4})$$

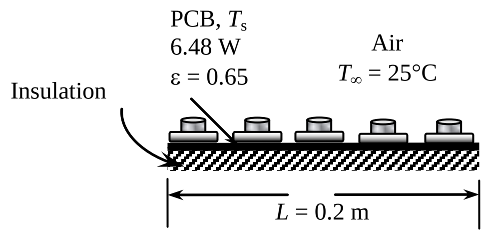
where $\dot{Q}_{total} = (0.08\,\text{W}) \times 81 = 6.48\,\text{W}$. Noting that the characteristic length is L = 0.2 m, calculating the surface area and substituting the known quantities into the above equation, the surface temperature is determined to be

$$L = 0.2\,\text{m}$$
$$A_s = (0.2\,\text{m})(0.2\,\text{m}) = 0.04\,\text{m}^2$$
$$6.48\,\text{W} = (2.44)(0.04\,\text{m}^2)\frac{[T_s - (25+273\,\text{K})]^{1.25}}{(0.2\,\text{m})^{0.25}}$$
$$+ (0.65)(0.04\,\text{m}^2)(5.67\times10^{-8}\,\text{W/m}^2\text{K}^4)\left[T_s^{\ 4} - (25+273\,\text{K})^4\right]$$
$$T_s = 312.3\,\text{K} = \mathbf{39.3^\circ C}$$

15-93 A horizontal circuit board containing 81 square chips is cooled by combined natural convection and radiation. The surface temperature of the chips is to be determined for two cases.

Assumptions **1** Steady operating conditions exist. **2** Heat transfer from the back side of the circuit board is negligible. **3** Temperature of surrounding surfaces is the same as the air temperature. **3** The local atmospheric pressure is 1 atm.

Analysis (*a*) The natural convection heat transfer coefficient for the horizontal orientation of board with chips facing up can be determined from (Table 15-1)



$$h_{conv} = 1.32\left(\frac{T_s - T_{fluid}}{L}\right)^{0.25}$$

Substituting it into the heat transfer relation gives

$$\dot{Q}_{conv} = h_{conv} A_s (T_s - T_{fluid})$$
$$= 1.32\left(\frac{T_s - T_{fluid}}{L}\right)^{0.25} A_s (T_s - T_{fluid}) = 1.32 A_s \frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}}$$

The rate of heat transfer from the board by radiation is

$$\dot{Q}_{rad} = \varepsilon A_s \sigma (T_s{}^4 - T_{surr}{}^4)$$

Then the total heat transfer can be written as

$$\dot{Q}_{total} = \dot{Q}_{conv} + \dot{Q}_{rad} = 1.32 A_s \frac{(T_s - T_{fluid})^{1.25}}{L^{0.25}} + \varepsilon A_s \sigma (T_s{}^4 - T_{surr}{}^4)$$

where $\dot{Q}_{total} = (0.08\text{ W}) \times 81 = 6.48\text{ W}$. Noting that the characteristic length is L = 0.2 m, calculating the surface area and substituting the known quantities into the above equation, the surface temperature is determined to be

$$L = \frac{4A_s}{p} = \frac{(4)(0.2\text{ m})(0.2\text{ m})}{(4)(0.2\text{m})} = 0.2\text{ m} \qquad A_s = (0.2\text{ m})(0.2\text{ m}) = 0.04\text{ m}^2$$

$$6.48\text{ W} = (1.32)(0.04\text{ m}^2)\frac{(T_s - (25+273)\text{K})^{1.25}}{(0.2\text{ m})^{0.25}}$$
$$+ (0.65)(0.04\text{ m}^2)(5.67\times10^{-8}\text{ W/m}^2\text{K}^4)[T_s{}^4 - (25+273\text{K})^4]$$
$$T_s = 317.2\text{ K} = \mathbf{44.2°C}$$

(*b*) The solution in this case (the chips are facing down instead of up) is identical to the one above, except we must replace the constant 1.32 in the heat transfer coefficient relation by 0.59. Then the surface temperature in this case becomes

$$6.48\text{ W} = (0.59)(0.04\text{ m}^2)\frac{(T_s - (25+273)\text{K})^{1.25}}{(0.2\text{ m})^{0.25}}$$
$$+ (0.65)(0.04\text{ m}^2)(5.67\times10^{-8}\text{ W/m}^2\text{K}^4)[T_s{}^4 - (25+273\text{K})^4]$$
$$T_s = 323.3\text{ K} = \mathbf{50.3°C}$$