CHAPTER

15

COOLING OF ELECTRONIC EQUIPMENT

Electronic equipment has made its way into practically every aspect of modern life, from toys and appliances to high-power computers. The reliability of the electronics of a system is a major factor in the overall reliability of the system. Electronic components depend on the passage of electric current to perform their duties, and they become potential sites for excessive heating, since the current flow through a resistance is accompanied by heat generation. Continued miniaturization of electronic systems has resulted in a dramatic increase in the amount of heat generated per unit volume, comparable in magnitude to those encountered at nuclear reactors and the surface of the sun. Unless properly designed and controlled, high rates of heat generation result in high operating temperatures for electronic equipment, which jeopardizes its safety and reliability.

The failure rate of electronic equipment increases exponentially with temperature. Also, the high thermal stresses in the solder joints of electronic components mounted on circuit boards resulting from temperature variations are major causes of failure. Therefore, thermal control has become increasingly important in the design and operation of electronic equipment.

In this chapter, we discuss several cooling techniques commonly used in electronic equipment such as conduction cooling, natural convection and radiation cooling, forced-air cooling, liquid cooling, and immersion cooling. This chapter is intended to familiarize the reader with these techniques and put them into perspective. The reader interested in an in-depth coverage of any of these topics can consult numerous other sources available, such as those listed in the references.

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15–1 ■ INTRODUCTION AND HISTORY

The field of electronics deals with the construction and utilization of devices that involve current flow through a vacuum, a gas, or a semiconductor. This exciting field of science and engineering dates back to 1883, when Thomas Edison invented the vacuum diode. The **vacuum tube** served as the foundation of the electronics industry until the 1950s, and played a central role in the development of radio, TV, radar, and the digital computer. Of the several computers developed in this era, the largest and best known is the ENIAC (Electronic Numerical Integrator and Computer), which was built at the University of Pennsylvania in 1946. It had over 18,000 vacuum tubes and occupied a room 7 m × 14 m in size. It consumed a large amount of power, and its reliability was poor because of the high failure rate of the vacuum tubes.

The invention of the bipolar **transistor** in 1948 marked the beginning of a new era in the electronics industry and the obsolescence of vacuum tube technology. Transistor circuits performed the functions of the vacuum tubes with greater reliability, while occupying negligible space and consuming negligible power compared with vacuum tubes. The first transistors were made from germanium, which could not function properly at temperatures above 100°C. Soon they were replaced by silicon transistors, which could operate at much higher temperatures.

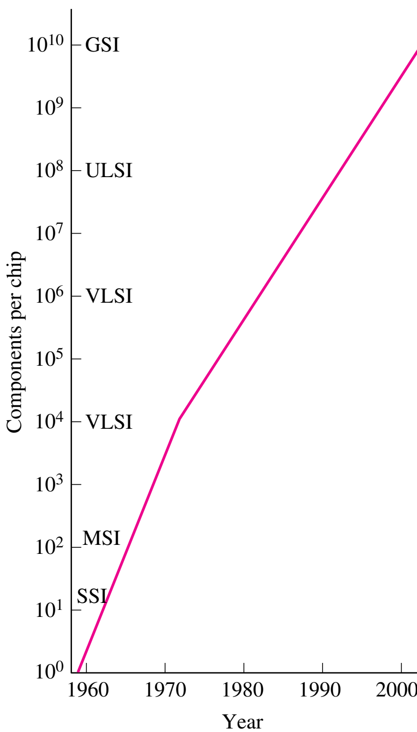


FIGURE 15–1
The increase in the number of components packed on a chip over the years.

The next turning point in electronics occurred in 1959 with the introduction of the **integrated circuits** (IC), where several components such as diodes, transistors, resistors, and capacitors are placed in a single chip. The number of components packed in a single chip has been increasing steadily since then at an amazing rate, as shown in Fig. 15–1. The continued miniaturization of electronic components has resulted in *medium-scale integration* (MSI) in the 1960s with 50 to 1000 components per chip, *large-scale integration* (LSI) in the 1970s with 1000 to 100,000 components per chip, and *very large-scale integration* (VLSI) in the 1980s with 100,000 to 10,000,000 components per chip. Today it is not unusual to have a chip 3 cm × 3 cm in size with several million components on it.

The development of the **microprocessor** in the early 1970s by the Intel Corporation marked yet another beginning in the electronics industry. The accompanying rapid development of large-capacity memory chips in this decade made it possible to introduce capable personal computers for use at work or at home at an affordable price. Electronics has made its way into practically everything from watches to household appliances to automobiles. Today it is difficult to imagine a new product that does not involve any electronic parts.

The current flow through a resistance is always accompanied by *heat generation* in the amount of I^2R, where I is the electric current and R is the resistance. When the transistor was first introduced, it was touted in the newspapers as a device that "produces no heat." This certainly was a fair statement, considering the huge amount of heat generated by vacuum tubes. Obviously, the little heat generated in the transistor was no match to that generated in its predecessor. But when thousands or even millions of such components are packed in a small volume, the heat generated increases to such high levels that its removal becomes a formidable task and a major concern for the safety and reliability of the electronic devices. The heat fluxes encountered in electronic devices range from less than 1 W/cm^2 to more than 100 W/cm^2.

Heat is generated in a resistive element for as long as current continues to flow through it. This creates a *heat build-up* and a subsequent *temperature rise* at and around the component. The temperature of the component will continue rising until the component is destroyed unless heat is transferred away from it. The temperature of the component will remain constant when the rate of heat removal from it equals the rate of heat generation.

Individual electronic components have *no moving parts,* and thus nothing to wear out with time. Therefore, they are inherently reliable, and it seems as if they can operate safely for many years. Indeed, this would be the case if components operated at room temperature. But electronic components are observed to fail under prolonged use at high temperatures. Possible causes of failure are *diffusion* in semiconductor materials, *chemical reactions,* and *creep* in the bonding materials, among other things. The failure rate of electronic devices increases almost *exponentially* with the operating temperature, as shown in Fig. 15–2. The cooler the electronic device operates, the more reliable it is. A rule of thumb is that the failure rate of electronic components is halved for each 10°C reduction in their junction temperature.

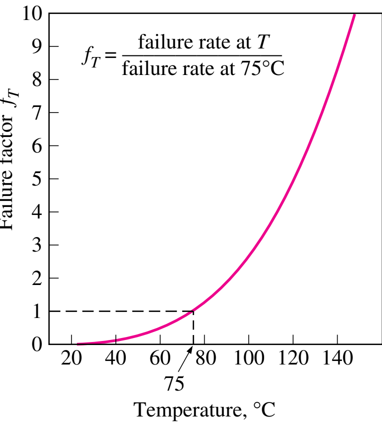


FIGURE 15–2
The increase in the failure rate of bipolar digital devices with temperature.
(From Ref. 15.)

15–2 ▪ MANUFACTURING OF ELECTRONIC EQUIPMENT

The narrow band where two different regions of a semiconductor (such as the p-type and n-type regions) come in contact is called a **junction**. A transistor, for example, involves two such junctions, and a diode, which is the simplest semiconductor device, is based on a single p-n junction. In heat transfer analysis, the circuitry of an electronic component through which electrons flow and thus heat is generated is also referred to as the junction. That is, junctions are the sites of heat generation and thus the hottest spots in a component. In silicon-based semiconductor devices, the junction temperature is limited to 125°C for safe operation. However, lower junction temperatures are desirable for extended life and lower maintenance costs. In a typical application, numerous electronic components, some smaller than 1 μm in size, are formed from a silicon wafer into a chip.

The Chip Carrier

The chip is housed in a **chip carrier** or substrate made of ceramic, plastic, or glass in order to protect its delicate circuitry from the detrimental effects of the environment. The chip carrier provides a rugged housing for the safe handling of the chip during the manufacturing process, as well as the connectors between the chip and the circuit board. The various components of the chip carrier are shown in Fig. 15–3. The chip is secured in the carrier by bonding it to the bottom surface. The thermal expansion coefficient of the *plastic* is about 20 times that of silicon. Therefore, bonding the silicon chip directly to the plastic case would result in such large thermal stresses that the reliability would be seriously jeopardized. To avoid this problem, a *lead frame* made of a copper alloy with a thermal expansion coefficient close to that of silicon is used as the bonding surface.

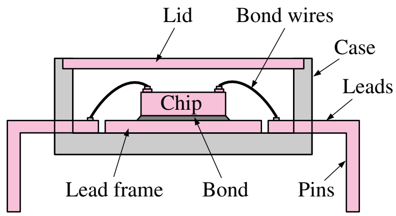


FIGURE 15–3
The components of a chip carrier.

The design of the chip carrier is the *first level* in the thermal control of electronic devices, since the transfer of heat from the chip to the chip carrier is the

first step in the dissipation of the heat generated on the chip. The heat generated on the chip is transferred to the case of the chip carrier by a combination of conduction, convection, and radiation. However, it is obvious from the figure that the common chip carrier is designed with the *electrical aspects* in mind, and little consideration is given to the *thermal aspects.* First of all, the cavity of the chip carrier is filled with a gas, which is a poor heat conductor, and the case is often made of materials that are also poor conductors of heat. This results in a relatively large thermal resistance between the chip and the case, called the **junction-to-case resistance**, and thus a large temperature difference. As a result, the temperature of the chip will be much higher than that of the case for a specified heat dissipation rate. The junction-to-case thermal resistance depends on the *geometry* and the *size* of the chip and the chip carrier as well as the material properties of the *bonding* and the *case.* It varies considerably from one device to another and ranges from about 10°C/W to more than 100°C/W.

Moisture in the cavity of the chip carrier is highly undesirable, since it causes corrosion on the wiring. Therefore, chip carriers are made of materials that prevent the entry of moisture by diffusion and are *hermetically sealed* in order to prevent the direct entry of moisture through cracks. Materials that outgas are also not permitted in the chip cavity, because such gases can also cause corrosion. In products with strict hermeticity requirements, the more expensive ceramic cases are used instead of the plastic ones.

A common type of chip carrier for high-power transistors is shown in Fig. 15–4. The transistor is formed on a small silicon chip housed in the disk-shaped cavity, and the I/O pins come out from the bottom. The case of the transistor carrier is usually attached directly to a flange, which provides a large surface area for heat dissipation and reduces the junction-to-case thermal resistance.

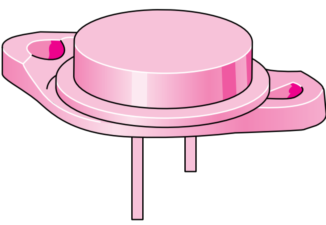


FIGURE 15–4
The chip carrier for a high-power transistor attached to a flange for enhanced heat transfer.

It is often desirable to house more than one chip in a single chip carrier. The result is a *hybrid* or *multichip package.* Hybrid packages house several chips, individual electronic components, and ordinary circuit elements connected to each other in a single chip carrier. The result is improved performance due to the shortening of the wiring lengths, and enhanced reliability. Lower cost would be an added benefit of multichip packages if they are produced in sufficiently large quantity.

EXAMPLE 15–1 Predicting the Junction Temperature of a Transistor

The temperature of the case of a power transistor that is dissipating 3 W is measured to be 50°C. If the junction-to-case resistance of this transistor is specified by the manufacturer to be 15°C/W, determine the temperature at the junction of the transistor.

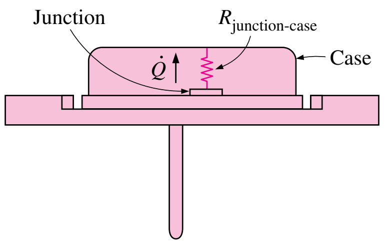


FIGURE 15–5
Schematic for Example 15–1.

SOLUTION The case temperature of a power transistor and the junction-to-case resistance are given. The junction temperature is to be determined.
Assumptions Steady operating conditions exist.
Analysis The schematic of the transistor is given in Fig. 15–5. The rate of heat transfer between the junction and the case in steady operation can be expressed as

$$\dot{Q} = \left(\frac{\Delta T}{R}\right)_{\text{junction-case}} = \frac{T_{\text{junction}} - T_{\text{case}}}{R_{\text{junction-case}}}$$

Then the junction temperature becomes

$$\begin{aligned} T_{\text{junction}} &= T_{\text{case}} + \dot{Q}R_{\text{junction-case}} \\ &= 50^\circ\text{C} + (3\text{ W})(15^\circ\text{C/W}) \\ &= \mathbf{95^\circ C} \end{aligned}$$

Therefore, the temperature of the transistor junction will be 95°C when its case is at 50°C.

EXAMPLE 15–2 **Determining the Junction-to-Case Thermal Resistance**

This experiment is conducted to determine the junction-to-case thermal resistance of an electronic component. Power is supplied to the component from a 15-V source, and the variations in the electric current and in the junction and the case temperatures with time are observed. When things are stabilized, the current is observed to be 0.1 A and the temperatures to be 80°C and 55°C at the junction and the case, respectively. Calculate the junction-to-case resistance of this component.

SOLUTION The power dissipated by an electronic component as well as the junction and case temperatures are measured. The junction-to-case resistance is to be determined.

Assumptions Steady operating conditions exist.

Analysis The schematic of the component is given in Fig. 15–6. The electric power consumed by this electronic component is

$$\dot{W}_e = \mathbf{V}I = (15\text{ V})(0.1\text{ A}) = 1.5\text{ W}$$

In steady operation, this is equivalent to the heat dissipated by the component. That is,

$$\dot{Q} = \left(\frac{\Delta T}{R}\right)_{\text{junction-case}} = \frac{T_{\text{junction}} - T_{\text{case}}}{R_{\text{junction-case}}} = 1.5\text{ W}$$

Then the junction-to-case resistance is determined to be

$$R_{\text{junction-case}} = \frac{T_{\text{junction}} - T_{\text{case}}}{\dot{Q}} = \frac{(80 - 55)^\circ\text{C}}{1.5\text{ W}} = \mathbf{16.7^\circ C/W}$$

Discussion Note that a temperature difference of 16.7°C will occur between the electronic circuitry and the case of the chip carrier for each W of power consumed by the component.

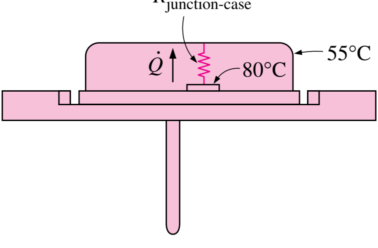


FIGURE 15–6
Schematic for Example 15–2.

Printed Circuit Boards

A printed circuit board (PCB) is a properly wired plane board made of polymers and glass–epoxy materials on which various electronic components such

as the ICs, diodes, transistors, resistors, and capacitors are mounted to perform a certain task, as shown in Fig. 15–7. The PCBs are commonly called *cards,* and they can be replaced easily during a repair. The PCBs are plane boards, usually 10 cm wide and 15 cm long and only a few millimeters thick, and they are not suitable for heavy components such as transformers. Usually a copper cladding is added on one or both sides of the board. The cladding on one side is subjected to an etching process to form wiring strips and attachment pads for the components. The power dissipated by a PCB usually ranges from 5 W to about 30 W.

A typical electronic system involves several layers of PCBs. The PCBs are usually cooled by direct contact with a fluid such as air flowing between the boards. But when the boards are placed in a hermetically sealed enclosure, they must be cooled by a cold plate (a heat exchanger) in contact with the edge of the boards. The *device-to-board edge thermal resistance* of a PCB is usually high (about 20 to 60°C/W) because of the small thickness of the board and the low thermal conductivity of the board material. In such cases, even a thin layer of copper cladding on one side of the board can decrease the device-to-board edge thermal resistance in the plane of the board and enhance heat transfer in that direction drastically.

In the thermal design of a PCB, it is important to pay particular attention to the components that are not tolerant of high temperatures, such as certain high-performance capacitors, and to ensure their safe operation. Often when one component on a PCB fails, the whole board fails and must be replaced.

Printed circuit boards come in three types: *single-sided, double-sided,* and *multilayer* boards. Each type has its own strengths and weaknesses. Single-sided PCBs have circuitry lines on one side of the board only and are suitable for low-density electronic devices (10 to 20 components). Double-sided PCBs

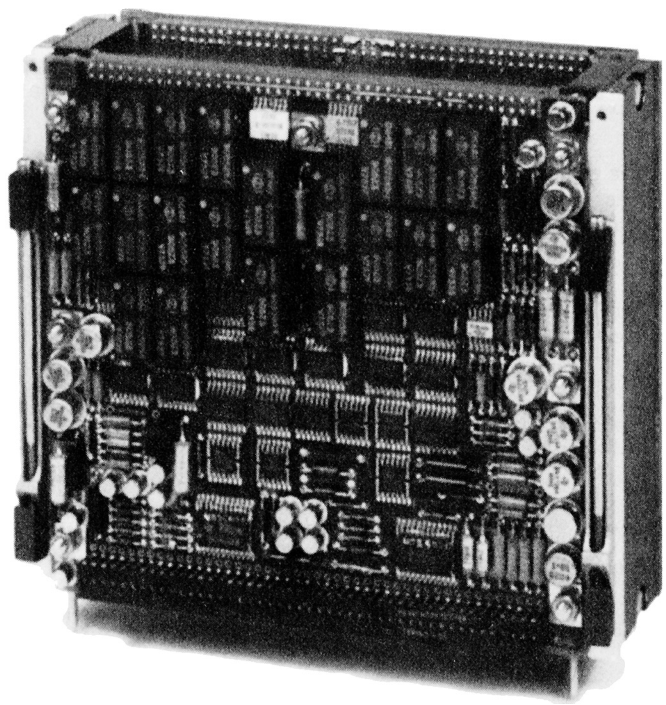


FIGURE 15–7
A printed circuit board (PCB) with a variety of components on it.
(Courtesy of Litton Systems, Inc.)

have circuits on both sides and are best suited for intermediate-density devices. Multilayer PCBs contain several layers of circuitry and are suitable for high-density devices. They are equivalent to several PCBs sandwiched together.

The single-sided PCB has the lowest cost, as expected, and it is easy to maintain, but it occupies a lot of space. The multilayer PCB, on the other hand, allows the placement of a large number of components in a three-dimensional configuration, but it has the highest initial cost and is difficult to repair. Also, temperatures are most likely to be the highest in multilayer PCBs.

In critical applications, the electronic components are placed on boards attached to a conductive metal, called the *heat frame,* that serves as a conduction path to the edge of the circuit board and thus to the cold plate for the heat generated in the components. Such boards are said to be *conduction-cooled.* The temperature of the components in this case will depend on the location of the components on the boards: it will be highest for the components in the middle and lowest for those near the edge, as shown in Fig. 15–8.

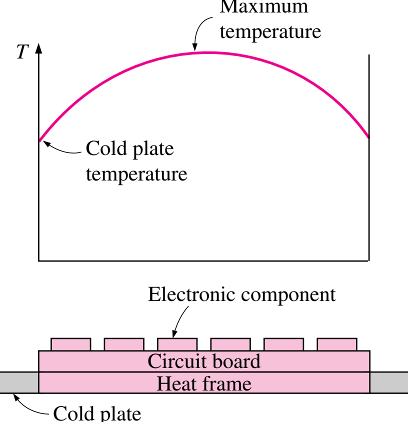


FIGURE 15–8
The path of heat flow in a conduction-cooled PCB and the temperature distribution.

Materials used in the fabrication of circuit boards should be (1) effective electrical insulators to prevent electrical breakdown and (2) good heat conductors to conduct away the heat generated. They should also have (3) high material strength to withstand forces and to maintain dimensional stability; (4) thermal expansion coefficients that closely match that of copper, to prevent cracking in the copper cladding during thermal cycling; (5) resistance to moisture absorption, since moisture can affect both mechanical and electrical properties and degrade performance; (6) stability in properties at temperature levels encountered in electronic applications; (7) ready availability and manufacturability; and, of course, (8) low cost. As you might have already guessed, no existing material has all of these desirable characteristics.

Glass–epoxy laminates made of an epoxy or polymide matrix reinforced by several layers of woven glass cloth are commonly used in the production of circuit boards. Polymide matrices are more expensive than epoxy but can withstand much higher temperatures. Polymer or polymide films are also used without reinforcement for flexible circuits.

The Enclosure

An electronic system is not complete without a rugged enclosure (a case or a cabinet) that will *house* the circuit boards and the necessary peripheral equipment and connectors, *protect* them from the detrimental effects of the environment, and *provide* a cooling mechanism (Fig. 15–9). In a small electronic system such as a personal computer, the enclosure can simply be an inexpensive box made of sheet metal with proper connectors and a small fan. But for a large system with several hundred PCBs, the design and construction of the enclosure are challenges for both electronic and thermal designers. An enclosure must provide *easy access* for service personnel so that they can identify and replace any defective parts easily and quickly in order to minimize down time, which can be very costly. But, at the same time, the enclosure must *prevent* any easy access by unauthorized people in order to protect the sensitive electronics from them as well as the people from possible electrical hazards. Electronic circuits are powered by low voltages (usually under 15 V), but the currents involved may be very high (sometimes a few hundred amperes).

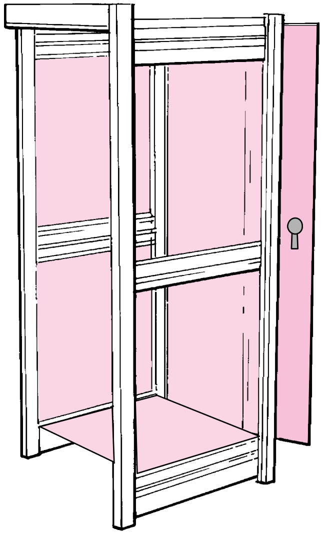


FIGURE 15–9
A cabinet-style enclosure.

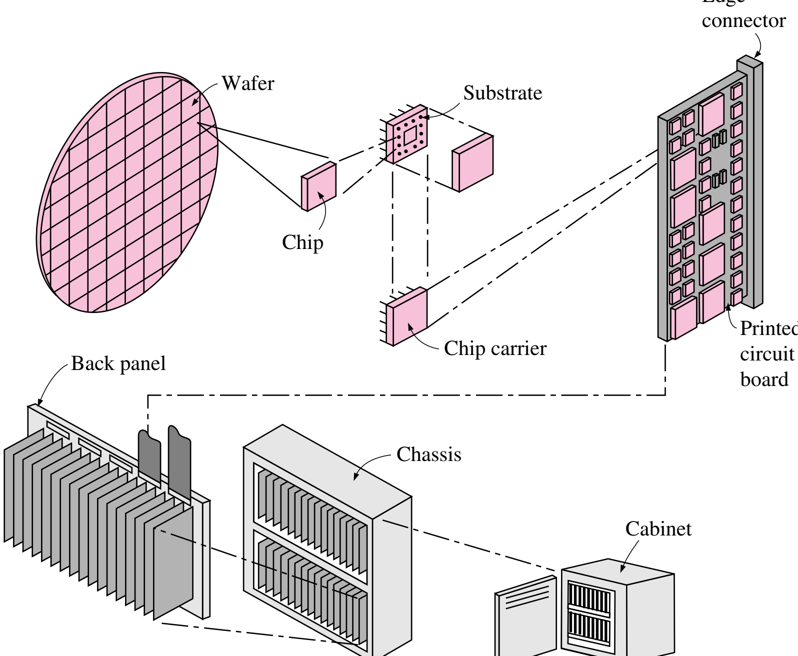


FIGURE 15–10
Different stages involved in the production of an electronic system.
(From Dally, 1990.)

Plug-in-type circuit boards make it very easy to replace a defective board and are commonly used in low-power electronic equipment. High-power circuit boards in large systems, however, are tightly attached to the racks of the cabinet with special brackets. A well-designed enclosure also includes switches, indicator lights, a screen to display messages and present information about the operation, and a key pad for user interface.

The printed circuit boards in a large system are plugged into a *back panel* through their edge connectors. The back panel supplies power to the PCBs and interconnects them to facilitate the passage of current from one board to another. The PCBs are assembled in an orderly manner in card racks or chassis. One or more such assemblies are housed in a *cabinet,* as shown in Fig. 15–10.

Electronic enclosures come in a wide variety of sizes and shapes. Sheet metals such as thin-gauge aluminum or steel sheets are commonly used in the production of enclosures. The thickness of the enclosure walls depends on the shock and vibration requirements. Enclosures made of thick metal sheets or by casting can meet these requirements, but at the expense of increased weight and cost.

Electronic boxes are sometimes sealed to prevent the fluid inside (usually air) from leaking out and the water vapor outside from leaking in. Sealing against moisture migration is very difficult because of the small size of the water molecule and the large vapor pressure outside the box relative to that within the box. Sealing adds to the size, weight, and cost of an electronic box, especially in space or high-altitude operation, since the box in this case must withstand the larger forces due to the higher pressure differential between inside and outside the box.

15–3 ▪ COOLING LOAD OF ELECTRONIC EQUIPMENT

The first step in the selection and design of a cooling system is the determination of the heat dissipation, which constitutes the *cooling load.* The easiest way to determine the power dissipation of electronic equipment is to measure the voltage applied **V** and the electric current I at the entrance of the electronic device under full-load conditions and to substitute them into the relation

$$\dot{W}_e = \mathbf{V}I = I^2R \qquad \text{(W)} \tag{15–1}$$

where $\dot{W}_e$ is the electric power consumption of the electronic device, which constitutes the *energy input* to the device.

The first law of thermodynamics requires that in *steady* operation the energy input into a system be equal to the energy output from the system. Considering that the only form of energy leaving the electronic device is heat generated as the current flows through resistive elements, we conclude that the heat dissipation or cooling load of an electronic device is equal to its power consumption. That is, $\dot{Q} = \dot{W}_e$, as shown in Fig. 15–11. The exception to this rule is equipment that outputs other forms of energy as well, such as the emitter tubes of a radar, radio, or TV installation emitting radiofrequency (RF) electromagnetic radiation. In such cases, the cooling load will be equal to the difference between the power consumption and the RF power emission. An equivalent but cumbersome way of determining the cooling load of an electronic device is to determine the heat dissipated by each component in the device and then to add them up.

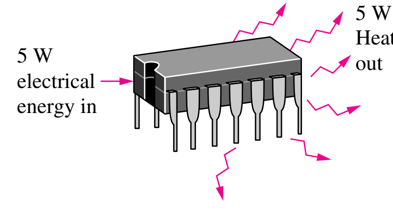


FIGURE 15–11
In the absence of other energy interactions, the heat output of an electronic device in steady operation is equal to the power input to the device.

The discovery of *superconductor* materials that can operate at room temperature will cause drastic changes in the design of electronic devices and cooling techniques, since such devices will generate hardly any heat. As a result, more components can be packed into a smaller volume, resulting in enhanced speed and reliability without having to resort to exotic cooling techniques.

Once the cooling load has been determined, it is common practice to inflate this number to leave some *safety margin,* or a "cushion," and to make some allowance for future growth. It is not uncommon to add another card to an existing system (such as adding a fax/modem card to a PC) to perform an additional task. But we should not go overboard in being conservative, since an *oversized* cooling system will cost more, occupy more space, be heavier, and consume more power. For example, there is no need to install a large and noisy fan in an electronic system just to be "safe" when a smaller one will do. For the same reason, there is no need to use an expensive and failure-prone liquid cooling system when air cooling is adequate. We should always keep in mind that the most desirable form of cooling is *natural convection cooling,* since it does not require any moving parts, and thus it is inherently reliable, quiet, and, best of all, free.

The cooling system of an electronic device must be designed considering the actual *field* operating conditions. In critical applications such as those in the military, the electronic device must undergo extensive testing to satisfy stringent requirements for safety and reliability. Several such codes exist to specify the minimum standards to be met in some applications.

The *duty cycle* is another important consideration in the design and selection of a cooling technique. The actual power dissipated by a device can be

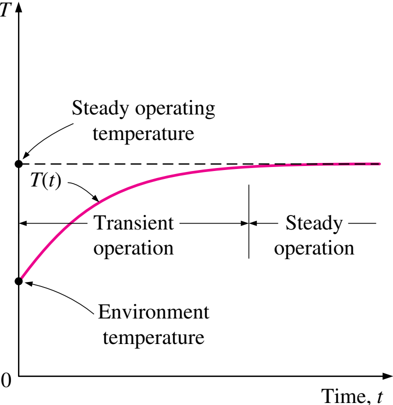


FIGURE 15–12
The temperature change of an electronic component with time as it reaches steady operating temperature after it is turned on.

much less than the rated power, depending on its duty cycle (the fraction of time it is on). A 5-W power transistor, for example, will dissipate an average of 2 W of power if it is active only 40 percent of the time. If the chip of this transistor is 1.5 mm wide, 1.5 mm high, and 0.1 mm thick, then the heat flux on the chip will be $(2\ \text{W})/(0.15\ \text{cm})^2 = 89\ \text{W/cm}^2$.

An electronic device that is not running is in *thermal equilibrium* with its surroundings, and thus is at the temperature of the surrounding medium. When the device is turned on, the temperature of the components and thus the device starts rising as a result of absorbing the heat generated. The temperature of the device stabilizes at some point when the heat generated equals the heat removed by the cooling mechanism. At this point, the device is said to have reached *steady* operating conditions. The warming-up period during which the component temperature rises is called the *transient* operation stage (Fig. 15–12).

Another thermal factor that undermines the reliability of electronic devices is the thermal stresses caused by *temperature cycling*. In an experimental study (see Hilbert and Kube, 1969), the failure rate of electronic devices subjected to deliberate temperature cycling of more than 20°C is observed to increase eightfold. *Shock* and *vibration* are other common causes of failure for electronic devices and should be considered in the design and manufacturing process for increased reliability.

Most electronic devices operate for long periods of time, and thus their cooling mechanism is designed for steady operation. But electronic devices in some applications never run long enough to reach steady operation. In such cases, it may be sufficient to use a limited cooling technique, such as thermal storage for a short period, or not to use one at all. Transient operation can also be caused by large swings in the environmental conditions. A common cooling technique for transient operation is to use a double-wall construction for the enclosure of the electronic equipment, with the space between the walls filled with a wax with a suitable melting temperature. As the wax melts, it absorbs a large amount of heat and thus delays overheating of the electronic components considerably. During off periods, the wax solidifies by rejecting heat to the environment.

15–4 ▪ THERMAL ENVIRONMENT

An important consideration in the selection of a cooling technique is the *environment* in which the electronic equipment is to operate. Simple *ventilation holes* on the case may be all we need for the cooling of low-power-density electronics such as a TV or a DVD player in a room, and a *fan* may be adequate for the safe operation of a home computer (Fig. 15–13). But the thermal control of the electronics of an *aircraft* will challenge thermal designers, since the environmental conditions in this case will swing from one extreme to another in a matter of minutes. The expected *duration of operation* in a hostile environment is also an important consideration in the design process. The thermal design of the electronics for an aircraft that cruises for hours each time it takes off will be quite different than that of a missile that has an operation time of a few minutes.

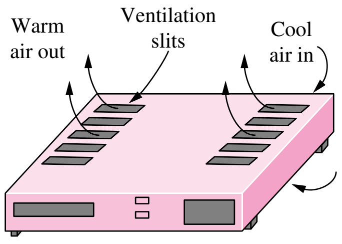


FIGURE 15–13
Strategically located ventilation holes are adequate to cool low-power electronics such as a TV or DVD player.

The thermal environment in *marine applications* is relatively stable, since the ultimate heat sink in this case is water with a temperature range of 0°C to 30°C. For *ground applications,* however, the ultimate heat sink is the atmospheric

air, whose temperature varies from −50°C at polar regions to +50°C in desert climates, and whose pressure ranges from about 70 kPa (0.69 atm) at 3000 m elevation to 107 kPa (1.06 atm) at 500 m below sea level. The combined convection and radiation heat transfer coefficient can range from 10 W/m² · °C in calm weather to 80 W/m² · °C in 100 km/h (62 mph) winds. Also, the surfaces of the devices facing the sun directly can be subjected to solar radiation heat flux of 1000 W/m² on a clear day.

In *airborne applications,* the thermal environment can change from 1 atm and 35°C on the ground to 19 kPa (0.2 atm) and −60°C at a typical cruising altitude of 12,000 m in minutes (Fig. 15–14). At supersonic velocities, the surface temperature of some part of the aircraft may rise 200°C above the environment temperature.

Electronic devices are rarely exposed to uncontrolled environmental conditions directly because of the wide variations in the environmental variables. Instead, a conditioned fluid such as air, water, or a dielectric fluid is used to serve as a local heat sink and as an intermediary between the electronic equipment and the environment, just like the air-conditioned air in a building providing thermal comfort to the human body. Conditioned air is the preferred cooling medium, since it is benign, readily available, and not prone to leakage. But its use is limited to equipment with low power densities, because of the low thermal conductivity of air. The thermal design of electronic equipment in military applications must comply with strict military standards in order to satisfy the utmost reliability requirements.

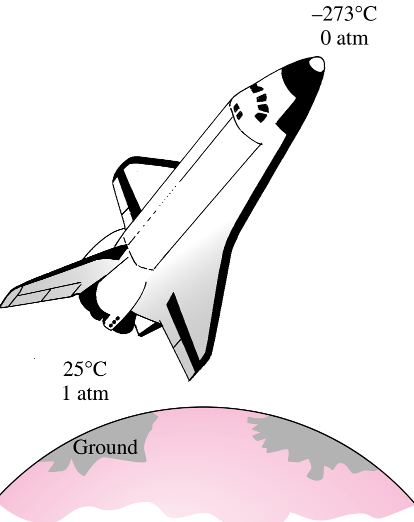


FIGURE 15–14
The thermal environment of a spacecraft changes drastically in a short time, and this complicates the thermal control of the electronics.

15–5 ▪ ELECTRONICS COOLING IN DIFFERENT APPLICATIONS

The cooling techniques used in the cooling of electronic equipment vary widely, depending on the particular application. Electronic equipment designed for *airborne applications* such as airplanes, satellites, space vehicles, and missiles offers challenges to designers because it must fit into odd-shaped spaces because of the curved shape of the bodies, yet be able to provide adequate paths for the flow of fluid and heat. Most such electronic equipment are cooled by forced convection using pressurized air bled off a compressor. This compressed air is usually at a high temperature, and thus it is cooled first by expanding it through a turbine. The moisture in the air is also removed before the air is routed to the electronic boxes. But the removal process may not be adequate under rainy conditions. Therefore, electronics in some cases are placed in sealed finned boxes that are externally cooled to eliminate any direct contact with electronic components.

The electronics of short-range *missiles* do not need any cooling because of their short cruising times (Fig. 15–15). The missiles reach their destinations before the electronics reach unsafe temperatures. Long-range missiles such as cruise missiles, however, may have a flight time of several hours. Therefore, they must utilize some form of cooling mechanism. The first thing that comes to mind is to use forced convection with the air that rams the missile by utilizing its large *dynamic pressure.* However, the *dynamic temperature* of air, which is the rise in the temperature of the air as a result of the ramming effect, may be more than 50°C at speeds close to the speed of sound (Fig. 15–16).

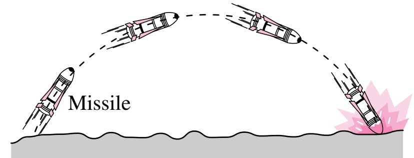


FIGURE 15–15
The electronics of short-range missiles may not need any cooling because of the short flight time involved.

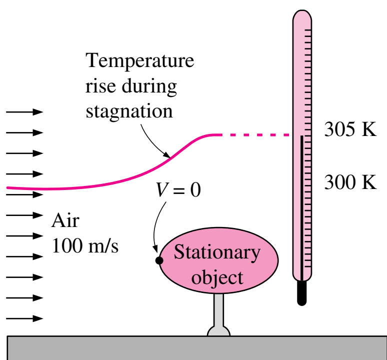


FIGURE 15–16
The temperature of a gas having a specific heat c_p flowing at a velocity of V rises by $V^2/2c_p$ when it is brought to a complete stop.

For example, at a speed of 320 m/s, the dynamic temperature of air is

$$T_{\text{dynamic}} = \frac{V^2}{2c_p} = \frac{(320 \text{ m/s})^2}{2(1007 \text{ J/kg} \cdot \text{°C})}\left(\frac{1 \text{ J/kg}}{1 \text{ m}^2/\text{s}^2}\right) = 51\text{°C} \qquad \textbf{(15–2)}$$

Therefore, the temperature of air at a velocity of 320 m/s and a temperature of 30°C will rise to 81°C as a result of the conversion of kinetic energy to internal energy. Air at such high temperatures is not suitable for use as a cooling medium. Instead, cruise missiles are often cooled by taking advantage of the cooling capacity of the large quantities of *liquid fuel* they carry. The electronics in this case are cooled by passing the fuel through the cold plate of the electronic enclosure as it flows toward the combustion chamber.

Electronic equipment in *space vehicles* is usually cooled by a liquid circulated through the components, where heat is picked up, and then through a space radiator, where the waste heat is radiated into deep space at about 0 K. Note that radiation is the only heat transfer mechanism for rejecting heat to the vacuum environment of space, and radiation exchange depends strongly on surface properties. Desirable radiation properties on surfaces can be obtained by special coatings and surface treatments. When electronics in sealed boxes are cooled by a liquid flowing through the outer surface of the electronics box, it is important to run a fan in the box to circulate the air, since there are no natural convection currents in space because of the absence of a gravity field.

Electronic equipment in *ships* and *submarines* is usually housed in rugged cabinets to protect it from vibrations and shock during stormy weather. Because of easy access to water, water-cooled heat exchangers are commonly used to cool shipboard electronics. This is usually done by cooling air in a closed- or open-loop air-to-water heat exchanger and forcing the cool air to the electronic cabinet by a fan. When forced-air cooling is used, it is important to establish a flow path for air such that no trapped hot-air pockets will be formed in the cabinets.

Communication systems located at remote locations offer challenges to thermal designers because of the extreme conditions under which they operate. These electronic systems operate for long periods of time under adverse conditions such as rain, snow, high winds, solar radiation, high altitude, high humidity, and extremely high or low temperatures. Large communication systems are housed in specially built shelters. Sometimes it is necessary to air-condition these shelters to safely dissipate the large quantities of heat dissipated by the electronics of communication systems.

Electronic components used in high-power *microwave equipment* such as radars generate enormous amounts of heat because of the low conversion efficiency of electrical energy to microwave energy. Klystron tubes of high-power radar systems where radio-frequency energy is generated can yield local heat fluxes as high as 2000 W/cm^2, which is close to one-third of the heat flux on the sun's surface. The safe and reliable dissipation of these high heat fluxes usually requires the immersion of such equipment in a suitable dielectric fluid that can remove large quantities of heat by boiling.

The manufacturers of electronic devices usually specify the *rate of heat dissipation* and the *maximum allowable component temperature* for reliable operation. These two numbers help us determine the cooling techniques that are suitable for the device under consideration.

The heat fluxes attainable at specified temperature differences are plotted in Fig. 15–17 for some common heat transfer mechanisms. When the power

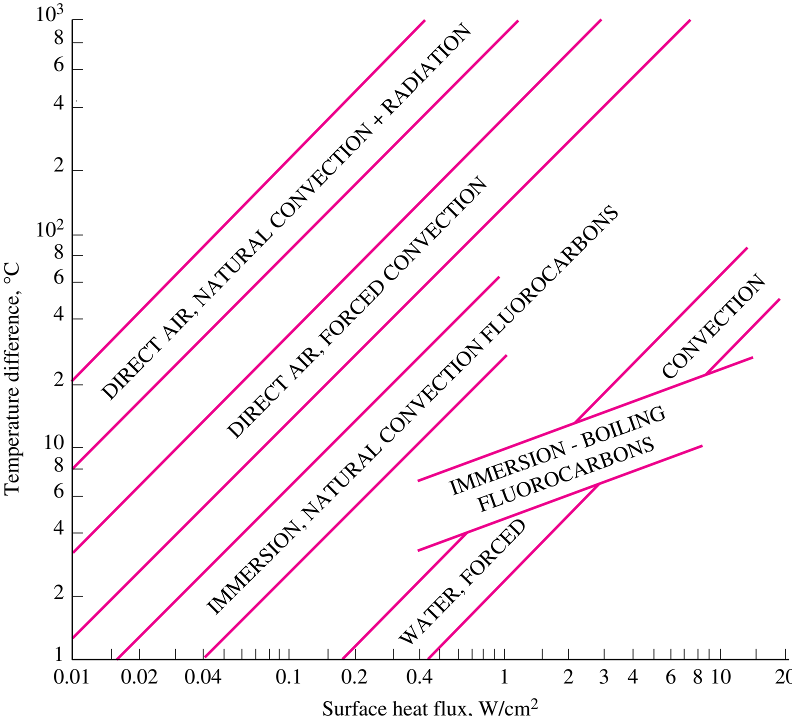


FIGURE 15–17
Heat fluxes that can be attained at specified temperature differences with various heat transfer mechanisms and fluids.
(From Kraus and Bar-Cohen, 1983, p. 22; reproduced with permission.)

rating of a device or component is given, the heat flux is determined by dividing the power rating by the exposed surface area of the device or component. Then suitable heat transfer mechanisms can be determined from Fig. 15–17 from the requirement that the temperature difference between the surface of the device and the surrounding medium not exceed the allowable maximum value. For example, a heat flux of 0.5 W/cm^2 for an electronic component would result in a temperature difference of about 500°C between the component surface and the surrounding air if natural convection in air is used. Considering that the maximum allowable temperature difference is typically under 80°C, the natural convection cooling of this component in air is out of the question. But forced convection with air is a viable option if using a fan is acceptable. Note that at heat fluxes greater than 1 W/cm^2, even forced convection with air will be inadequate, and we must use a sufficiently large heat sink or switch to a different cooling fluid such as water. Forced convection with water can be used effectively for cooling electronic components with high heat fluxes. Also note that dielectric liquids such as fluorochemicals can remove high heat fluxes by immersing the component directly in them.

15–6 ▪ CONDUCTION COOLING

Heat is *generated* in electronic components whenever electric current flows through them. The generated heat causes the temperature of the components to rise, and the resulting temperature difference drives the heat away from the components through a path of *least thermal resistance.* The temperature of the components stabilizes when the heat dissipated equals the heat generated. In order to minimize the temperature rise of the components, *effective heat transfer*

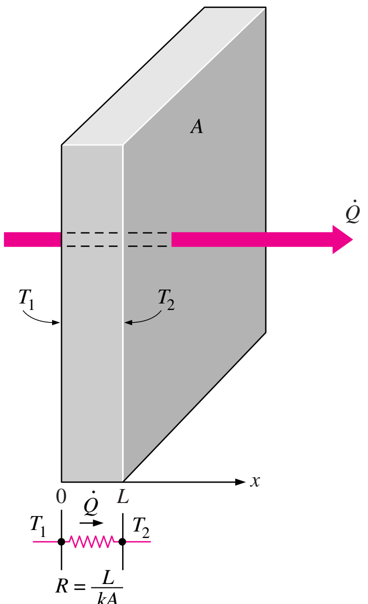


FIGURE 15–18
The thermal resistance of a medium is proportional to its length in the direction of heat transfer, and inversely proportional to its heat transfer surface area and thermal conductivity.

paths must be established between the components and the ultimate heat sink, which is usually the atmospheric air.

The selection of a cooling mechanism for electronic equipment depends on the *magnitude* of the heat generated, *reliability* requirements, *environmental* conditions, and *cost.* For low-cost electronic equipment, inexpensive cooling mechanisms such as natural or forced convection with air as the cooling medium are commonly used. For high-cost, high-performance electronic equipment, however, it is often necessary to resort to expensive and complicated cooling techniques.

Conduction cooling is based on the *diffusion* of heat through a solid, liquid, or gas as a result of molecular interactions in the absence of any bulk fluid motion. Steady *one-dimensional* heat conduction through a plane medium of thickness L, heat transfer surface area A, and thermal conductivity k is given by (Fig. 15–18).

$$\dot{Q} = kA\frac{\Delta T}{L} = \frac{\Delta T}{R} \qquad \text{(W)} \tag{15–3}$$

where

$$R = \frac{L}{kA} = \frac{\text{Length}}{\text{Thermal conductivity} \times \text{Heat transfer area}} \tag{15–4}$$

is the *thermal resistance* of the medium and ΔT is the temperature difference across the medium. Note that this is analogous to the *electric current* being equal to the potential difference divided by the electrical resistance.

The thermal resistance concept enables us to solve heat transfer problems in an analogous manner to electric circuit problems using the thermal resistance network, as discussed in Chapter 3. When the rate of heat conduction $\dot{Q}$ is known, the temperature drop along a medium whose thermal resistance is R is simply determined from

$$\Delta T = \dot{Q}R \qquad (°\text{C}) \tag{15–5}$$

Therefore, the greatest temperature drops along the path of heat conduction will occur across portions of the heat flow path with the largest thermal resistances.

Conduction in Chip Carriers

The conduction analysis of an electronic device starts with the *circuitry* or *junction* of a chip, which is the site of *heat generation.* In order to understand the heat transfer mechanisms at the chip level, consider the DIP (dual in-line package) type chip carrier shown in Fig. 15–19.

The heat generated at the junction spreads throughout the chip and is conducted across the *thickness* of the chip. The spread of heat from the junction to the body of the chip is three-dimensional in nature, but can be approximated as one-dimensional by adding a *constriction thermal resistance* to the thermal resistance network. For a small heat generation area of diameter d on a considerably larger body, the constriction resistance is given by

$$R_{\text{constriction}} = \frac{1}{\sqrt{\pi}dk} \qquad (°\text{C/W}) \tag{15–6}$$

where k is the thermal conductivity of the larger body.

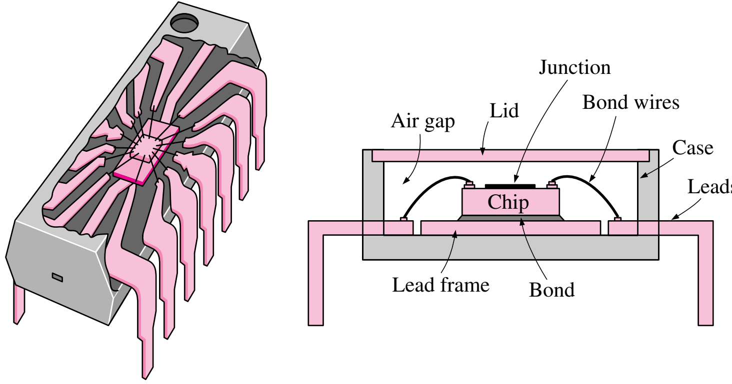


FIGURE 15–19
The schematic for the internal geometry and the cross-sectional view of a DIP (dual in-line package) type electronic device with 14 leads.

The chip is attached to the lead frame with a highly conductive *bonding material* that provides a low-resistance path for heat flow from the chip to the lead frame. There is no metal connection between the *lead frame* and the *leads,* since this would short-circuit the entire chip. Therefore, heat flow from the lead frame to the leads is through the dielectric case material such as *plastic* or *ceramic.* Heat is then transported outside the electronic device through the leads.

When solving a heat transfer problem, it is often necessary to make some simplifying assumptions regarding the *primary* heat flow path and the magnitudes of heat transfer in other directions (Fig. 15–20). In the chip carrier discussed above, for example, heat transfer through the top is disregarded since it is very small because of the large thermal resistance of the stagnant air space between the chip and the lid. Heat transfer from the base of the electronic device is also considered to be negligible because of the low thermal conductivity of the case material and the lack of effective convection on the base surface.

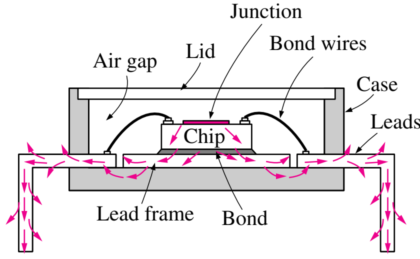


FIGURE 15–20
Heat generated at the junction of an electronic device flows through the path of least resistance.

EXAMPLE 15–3 Analysis of Heat Conduction in a Chip

A chip is dissipating 0.6 W of power in a DIP with 12 pin leads. The materials and the dimensions of various sections of this electronic device are as given in the table below. If the temperature of the leads is 40°C, estimate the temperature at the junction of the chip.

Section and Material	Thermal Conductivity, W/m · °C	Thickness, mm	Heat Transfer Surface Area
Junction constriction	—	—	diameter 0.4 mm
Silicon chip	120†	0.4	3 mm × 3 mm
Eutectic bond	296	0.03	3 mm × 3 mm
Copper lead frame	386	0.25	3 mm × 3 mm
Plastic separator	1	0.2	12 × 1 mm × 0.25 mm
Copper leads	386	5	12 × 1 mm × 0.25 mm

†The thermal conductivity of silicon varies greatly with temperature from 153.5 W/m · °C at 27°C to 113.7 W/m · °C at 100°C, and the value 120 W/m · °C reflects the anticipation that the temperature of the silicon chip will be close to 100°C.

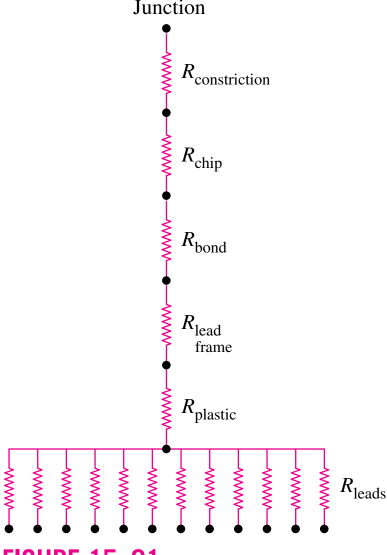


FIGURE 15–21
Thermal resistance network for the electronic device considered in Example 15–3.

SOLUTION The dimensions and power dissipation of a chip are given. The junction temperature of the chip is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Heat transfer through various components is one-dimensional. **3** Heat transfer through the air gap and the lid on top of the chip is negligible because of the very large thermal resistance involved along this path.

Analysis The geometry of the device is as shown in Fig. 15–20. We take the primary heat flow path to be the chip, the eutectic bond, the lead frame, the plastic insulator, and the 12 leads. When the constriction resistance between the junction and the chip is considered, the thermal resistance network for this problem becomes as shown in Fig. 15–21.

The various thermal resistances on the path of primary heat flow are determined as follows.

$$R_{\text{constriction}} = \frac{1}{\sqrt{\pi}dk} = \frac{1}{\sqrt{\pi}(0.4 \times 10^{-3}\text{ m})(120\text{ W/m}\cdot{}^\circ\text{C})} = 11.75^\circ\text{C/W}$$

$$R_{\text{chip}} = \left(\frac{L}{kA}\right)_{\text{chip}} = \frac{0.4 \times 10^{-3}\text{ m}}{(120\text{ W/m}\cdot{}^\circ\text{C})(9 \times 10^{-6}\text{ m}^2)} = 0.37^\circ\text{C/W}$$

$$R_{\text{bond}} = \left(\frac{L}{kA}\right)_{\text{bond}} = \frac{0.03 \times 10^{-3}\text{ m}}{(296\text{ W/m}\cdot{}^\circ\text{C})(9 \times 10^{-6}\text{ m}^2)} = 0.01^\circ\text{C/W}$$

$$R_{\text{lead frame}} = \left(\frac{L}{kA}\right)_{\text{lead frame}} = \frac{0.25 \times 10^{-3}\text{ m}}{(386\text{ W/m}\cdot{}^\circ\text{C})(9 \times 10^{-6}\text{ m}^2)} = 0.07^\circ\text{C/W}$$

$$R_{\text{plastic}} = \left(\frac{L}{kA}\right)_{\text{plastic}} = \frac{0.2 \times 10^{-3}\text{ m}}{(1\text{ W/m}\cdot{}^\circ\text{C})(12 \times 0.25 \times 10^{-6}\text{ m}^2)} = 66.67^\circ\text{C/W}$$

$$R_{\text{leads}} = \left(\frac{L}{kA}\right)_{\text{leads}} = \frac{5 \times 10^{-3}\text{ m}}{(386\text{ W/m}\cdot{}^\circ\text{C})(12 \times 0.25 \times 10^{-6}\text{ m}^2)} = 4.32^\circ\text{C/W}$$

Note that for heat transfer purposes, all 12 leads can be considered as a single lead whose cross-sectional area is 12 times as large. The alternative is to find the resistance of a single lead and to calculate the equivalent resistance for 12 such resistances connected in parallel. Both approaches give the same result.

All the resistances determined here are in series. Thus the total thermal resistance between the junction and the leads is determined by simply adding them up:

$$\begin{aligned} R_{\text{total}} = R_{\text{junction-lead}} &= R_{\text{constriction}} + R_{\text{chip}} + R_{\text{bond}} + R_{\text{lead frame}} + R_{\text{plastic}} + R_{\text{leads}} \\ &= (11.75 + 0.37 + 0.01 + 0.07 + 66.67 + 4.32)^\circ\text{C/W} \\ &= 83.19^\circ\text{C/W} \end{aligned}$$

Heat transfer through the chip can be expressed as

$$\dot{Q} = \left(\frac{\Delta T}{R}\right)_{\text{junction-leads}} = \frac{T_{\text{junction}} - T_{\text{leads}}}{R_{\text{junction-leads}}}$$

Solving for T_{junction} and substituting the given values, the junction temperature is determined to be

$$T_{\text{junction}} = T_{\text{leads}} + \dot{Q}R_{\text{junction-leads}} = 40^\circ\text{C} + (0.6\text{ W})(83.19^\circ\text{C/W}) = \mathbf{89.9^\circ C}$$

Note that the plastic layer between the lead frame and the leads accounts for 66.67/83.19 = 80 percent of the total thermal resistance and thus the

80 percent of the temperature drop (0.6 × 66.67 = 40°C) between the junction and the leads. In other words, the temperature of the junction would be just 89.9 − 40 = 49.9°C if the thermal resistance of the plastic was eliminated.

Discussion The simplified analysis given here points out that any attempt to reduce the thermal resistance in the chip carrier and thus improve the heat flow path should start with the plastic layer. We also notice from the magnitudes of individual resistances that some sections, such as the eutectic bond and the lead frame, have negligible thermal resistances, and any attempt to improve them further will have practically no effect on the junction temperature of the chip.

The analytical determination of the junction-to-case thermal resistance of an electronic device can be rather complicated and can involve considerable uncertainty, as already shown. Therefore, the manufacturers of electronic devices usually determine this value *experimentally* and list it as part of their product description. When the thermal resistance is known, the *temperature difference* between the junction and the outer surface of the device can be determined from

$$\Delta T_{\text{junction-case}} = T_{\text{junction}} - T_{\text{case}} = \dot{Q}R_{\text{junction-case}} \qquad (^\circ\text{C}) \tag{15–7}$$

where $\dot{Q}$ is the power consumed by the device.

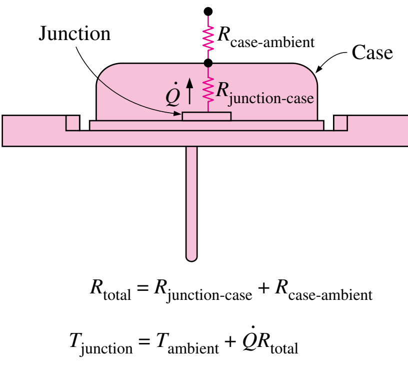
The determination of the *actual junction temperature* depends on the ambient temperature T_{ambient} as well as the thermal resistance $R_{\text{case-ambient}}$ between the case and the ambient (Fig. 15–22). The magnitude of this resistance depends on the type of ambient (such as air or water) and the fluid velocity. The two thermal resistances discussed above are in series, and the total resistance between the junction and the ambient is determined by simply adding them up:

$$R_{\text{total}} = R_{\text{junction-ambient}} = R_{\text{junction-case}} + R_{\text{case-ambient}} \qquad (^\circ\text{C/W}) \tag{15–8}$$

Many manufacturers of electronic devices go the extra step and list the *total resistance* between the junction and the ambient for various chip configurations and ambient conditions likely to be encountered. Once the total thermal resistance is available, the *junction temperature* corresponding to the specified power consumption (or heat dissipation rate) of $\dot{Q}$ is determined from

$$T_{\text{junction}} = T_{\text{ambient}} + \dot{Q}R_{\text{junction-ambient}} \qquad (^\circ\text{C}) \tag{15–9}$$

A typical chart for the total junction-to-ambient thermal resistance for a single DIP-type electronic device mounted on a circuit board is given in Fig. 15–23 for various air velocities and lead numbers. The values at the intersections of the curves and the vertical axis represent the thermal resistances corresponding to *natural convection* conditions (zero air velocity). Note that the thermal resistance and thus the junction temperature decrease with increasing air velocity and the number of leads extending from the electronic device, as expected.



$R_{\text{total}} = R_{\text{junction-case}} + R_{\text{case-ambient}}$

$T_{\text{junction}} = T_{\text{ambient}} + \dot{Q}R_{\text{total}}$

FIGURE 15–22
The junction temperature of a chip depends on the external case-to-ambient thermal resistance as well as the internal junction-to-case resistance.

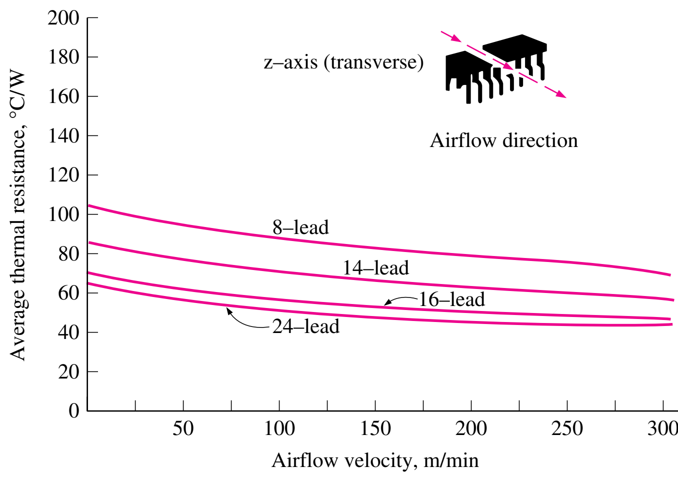


FIGURE 15–23
Total thermal resistance between the junction of a plastic DIP device mounted on a circuit board and the ambient air as a function of the air velocity and the number of leads
(Courtesy of Motorola Semiconductor Products, Inc.)

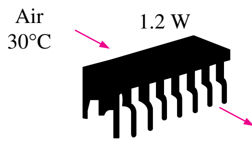


FIGURE 15–24
Schematic for Example 15–4.

EXAMPLE 15–4 Predicting the Junction Temperature of a Device

A fan blows air at 30°C at a velocity of 200 m/min over a 1.2-W plastic DIP with 16 leads mounted on a PCB, as shown in Fig. 15–24. Using data from Fig. 15–23, determine the junction temperature of the electronic device. What would the junction temperature be if the fan were to fail?

SOLUTION A plastic DIP with 16 leads is cooled by forced air. Using data supplied by the manufacturer, the junction temperature is to be determined.

Assumptions Steady operating conditions exist.

Analysis The junction-to-ambient thermal resistance of the device with 16 leads corresponding to an air velocity of 200 m/min is determined from Fig. 15–23 to be

$$R_{\text{junction-ambient}} = 55°\text{C/W}$$

Then the junction temperature can be determined from Eq. 15–9 to be

$$T_{\text{junction}} = T_{\text{ambient}} + \dot{Q}R_{\text{junction-ambient}} = 30°\text{C} + (1.2\text{ W})(55°\text{C/W}) = \mathbf{96°C}$$

When the fan fails, the airflow velocity over the device will be zero. The total thermal resistance in this case is determined from the same chart by reading the value at the intersection of the curve and the vertical axis to be

$$R_{\text{junction-ambient}} = 70°\text{C/W}$$

which gives

$$T_{\text{junction}} = T_{\text{ambient}} + \dot{Q}R_{\text{junction-ambient}} = 30°\text{C} + (1.2\text{ W})(70°\text{C/W}) = \mathbf{114°C}$$

Discussion Note that the temperature of the junction will rise by 18°C when the fan fails. Of course, this analysis assumes the temperature of the surrounding air still to be 30°C, which may no longer be the case. Any increase in the ambient temperature as a result of inadequate airflow will reflect on the junction temperature, which will seriously jeopardize the safety of the electronic device.

Conduction in Printed Circuit Boards

Heat-generating electronic devices are commonly mounted on thin rectangular *boards,* usually 10 cm × 15 cm in size, made of electrically insulating materials such as *glass–epoxy laminates,* which are also poor conductors of heat. The resulting printed circuit boards are usually cooled by blowing air or passing a dielectric liquid through them. In such cases, the components on the PCBs are cooled directly, and we are not concerned about heat conduction along the PCBs. But in some critical applications such as those encountered in the military, the PCBs are contained in *sealed enclosures,* and the boards provide the only effective heat path between the components and the heat sink attached to the sealed enclosure. In such cases, heat transfer from the side faces of the PCBs is negligible, and the heat generated in the components must be *conducted* along the PCB toward its edges, which are clamped to cold plates for removing the heat externally.

Heat transfer along a PCB is complicated in nature because of the multidimensional effects and nonuniform heat generation on the surfaces. We can still obtain sufficiently accurate results by using the thermal resistance network in one or more dimensions.

Copper or aluminum *cladding, heat frames,* or *cores* are commonly used to enhance heat conduction along the PCBs. The thickness of the copper cladding on the PCB is usually expressed in terms of *ounces of copper,* which is the thickness of 1-ft^2 copper sheet made of one ounce of copper. An ounce of copper is equivalent to 0.03556-mm (1.4-mil) thickness of a copper layer.

When analyzing heat conduction along a PCB with *copper* (or aluminum) *cladding* on one or both sides, often the question arises whether heat transfer along the epoxy laminate can be ignored relative to that along the copper layer, since the thermal conductivity of copper is about 1500 times that of epoxy. The answer depends on the relative cross-sectional areas of each layer, since heat conduction is proportional to the cross-sectional area as well as the thermal conductivity.

Consider a copper-cladded PCB of width w and length L, across which the temperature difference is ΔT, as shown in Fig. 15–25. Assuming heat conduction is along the length L only and heat conduction in other dimensions is negligible, the rate of heat conduction along this PCB is the sum of the heat conduction along the *epoxy board* and the *copper* layer and is expressed as

$$\begin{aligned}\dot{Q}_{\text{PCB}} &= \dot{Q}_{\text{epoxy}} + \dot{Q}_{\text{copper}} = \left(kA\,\frac{\Delta T}{L}\right)_{\text{epoxy}} + \left(kA\,\frac{\Delta T}{L}\right)_{\text{copper}} \\ &= [(kA)_{\text{epoxy}} + (kA)_{\text{copper}}]\,\frac{\Delta T}{L} \\ &= [(kt)_{\text{epoxy}} + (kt)_{\text{copper}}]\,\frac{w\Delta T}{L}\end{aligned} \tag{15–10}$$

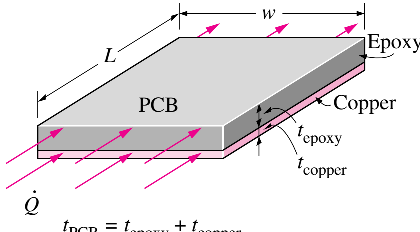


FIGURE 15–25
Schematic of a copper-cladded epoxy board and heat conduction along it.

where t denotes the thickness. Therefore, the relative magnitudes of heat conduction along the two layers depend on the relative magnitudes of the thermal conductivity–thickness product kt of the layer. Therefore, if the kt product of the copper is 100 times that of epoxy, then neglecting heat conduction along the epoxy board will involve an error of just 1 percent, which is negligible.

We can also define an **effective thermal conductivity** for metal-cladded PCBs as

$$k_{eff} = \frac{(kt)_{epoxy} + (kt)_{copper}}{t_{epoxy} + t_{copper}} \qquad (W/m \cdot °C) \qquad (15\text{–}11)$$

so that the rate of heat conduction along the PCB can be expressed as

$$\dot{Q}_{PCB} = k_{eff}(t_{epoxy} + t_{copper})\frac{w\Delta T}{L} = k_{eff}\,A_{PCB}\frac{\Delta T}{L} \qquad (W) \qquad (15\text{–}12)$$

where $A_{PCB} = w(t_{epoxy} + t_{copper})$ is the area normal to the direction of heat transfer. When there are holes or discontinuities along the copper cladding, the above analysis needs to be modified to account for their effect.

EXAMPLE 15–5 Heat Conduction along a PCB with Copper Cladding

Heat is to be conducted along a PCB with copper cladding on one side. The PCB is 10 cm long and 10 cm wide, and the thickness of the copper and epoxy layers are 0.04 mm and 0.16 mm, respectively, as shown in Fig. 15–26. Disregarding heat transfer from side surfaces, determine the percentages of heat conduction along the copper (k = 386 W/m · °C) and epoxy (k = 0.26 W/m · °C) layers. Also, determine the effective thermal conductivity of the PCB.

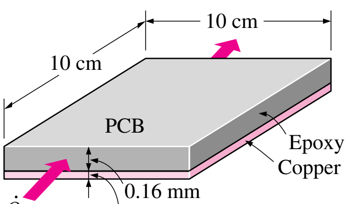


FIGURE 15–26
Schematic for Example 15–5.

SOLUTION A PCB with copper cladding is given. The percentages of heat conduction along the copper and epoxy layers as well as the effective thermal conductivity of the PCB are to be determined.

Assumptions **1** Heat conduction along the PCB is one-dimensional since heat transfer from side surfaces is negligible. **2** The thermal properties of epoxy and copper layers are constant.

Analysis The length and width of both layers are the same, and so is the temperature difference across each layer. Heat conduction along a layer is proportional to the thermal conductivity–thickness product kt, which is determined for each layer and the entire PCB to be

$$(kt)_{copper} = (386\ W/m \cdot °C)(0.04 \times 10^{-3}\ m) = 15.44 \times 10^{-3}\ W/°C$$
$$(kt)_{epoxy} = (0.26\ W/m \cdot °C)(0.16 \times 10^{-3}\ m) = 0.04 \times 10^{-3}\ W/°C$$
$$(kt)_{PCB} = (kt)_{copper} + (kt)_{epoxy} = (15.44 + 0.04) \times 10^{-3}\ m = 15.48 \times 10^{-3}\ W/°C$$

Therefore, heat conduction along the epoxy board will constitute

$$f = \frac{(kt)_{epoxy}}{(kt)_{PCB}} = \frac{0.04 \times 10^{-3}\ W/°C}{15.48 \times 10^{-3}\ W/°C} = 0.0026$$

or 0.26 percent of the thermal conduction along the PCB, which is negligible. Therefore, heat conduction along the epoxy layer in this case can be disregarded without any reservations.

The effective thermal conductivity of the board is determined from Eq. 15–11 to be

$$k_{eff} = \frac{(kt)_{epoxy} + (kt)_{copper}}{t_{epoxy} + t_{copper}} = \frac{(15.44 + 0.04) \times 10^{-3}\ W/°C}{(0.16 + 0.04) \times 10^{-3}\ m} = \mathbf{77.4\ W/m \cdot °C}$$

That is, the entire PCB can be treated as a 0.20-mm-thick single homogeneous layer whose thermal conductivity is 77.4 W/m · °C for heat transfer along its length.

Discussion Note that a very thin layer of copper cladding on a PCB improves heat conduction along the PCB drastically, and thus it is commonly used in conduction-cooled electronic devices.

Heat Frames

In applications where direct cooling of circuit boards by passing air or a dielectric liquid over the electronic components is not allowed, and the junction temperatures are to be maintained relatively low to meet strict safety requirements, a thick *heat frame* is used instead of a thin layer of copper cladding. This is especially the case for multilayer PCBs that are packed with high-power output chips.

The schematic of a PCB that is conduction-cooled via a heat frame is shown in Fig. 15–27. Heat generated in the chips is conducted through the circuit board, through the epoxy adhesive, to the center of the heat frame, along the heat frame, and to a heat sink or cold plate, where heat is externally removed.

The heat frame provides a low-resistance path for the flow of heat from the circuit board to the heat sink. The thicker the heat frame, the lower the thermal resistance, and thus the smaller the temperature difference between the center and the ends of the heat frame. When the heat load is evenly distributed on the PCB, there will be thermal symmetry about the centerline, and the temperature distribution along the heat frame and the PCB will be *parabolic* in nature, with the chips in the middle of the PCB (farthest away from the edges) operating at the highest temperatures and the chips near the edges operating at the lowest temperatures. Also, when the PCB is cooled from two edges, heat generated in the left half of the PCB will flow toward the left edge and heat generated in the right half will flow toward the right edge of the heat frame. But when the PCB is cooled from all four edges, the heat transfer along the heat frame as well as the resistance network will be two-dimensional.

When a heat frame is used, heat conduction in the epoxy layer of the PCB is through its *thickness* instead of along its length. The epoxy layer in this case offers a much smaller resistance to heat flow because of the short distance involved. This resistance can be made even smaller by drilling holes in the epoxy and filling them with copper, as shown in Fig. 15–28. These copper fillings are usually 1 mm in diameter and their centers are a few millimeters apart. Such highly conductive fillings provide easy passageways for heat from one side of the PCB to the other and result in considerable reduction in the thermal resistance of the board along its thickness, as shown in Examples 15–6, 15–7, and 15–8.

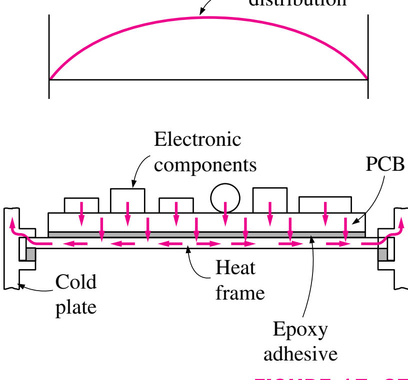


FIGURE 15–27
Conduction cooling of a printed circuit board with a heat frame, and the typical temperature distribution along the frame.

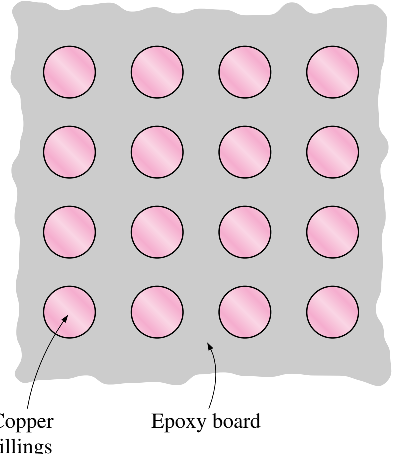


FIGURE 15–28
Planting the epoxy board with copper fillings decreases the thermal resistance across its thickness considerably.

EXAMPLE 15–6 Thermal Resistance of an Epoxy Glass Board

Consider a 10-cm × 15-cm glass–epoxy laminate (k = 0.26 W/m · °C) whose thickness is 0.8 mm, as shown in Fig. 15–29. Determine the thermal resistance of this epoxy layer for heat flow (*a*) along the 15-cm-long side and (*b*) across its thickness.

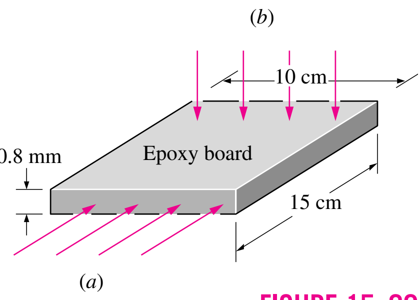


FIGURE 15–29
Schematic for Example 15–6.

SOLUTION The dimensions of an epoxy–glass laminate are given. The thermal resistances for heat flow along the layers and across the thickness are to be determined.

Assumptions **1** Heat conduction in the laminate is one-dimensional in either case. **2** Thermal properties of the laminate are constant.

Analysis The thermal resistance of a plane parallel medium in the direction of heat conduction is given by

$$R = \frac{L}{kA}$$

where L is the length in the direction of heat flow, k is the thermal conductivity, and A is the area normal to the direction of heat conduction. Substituting the given values, the thermal resistances of the board for both cases are determined to be

$$(a) \qquad R_{\text{along length}} = \left(\frac{L}{kA}\right)_{\text{along length}} = \frac{0.15 \text{ m}}{(0.26 \text{ W/m} \cdot {}^\circ\text{C})(0.1 \text{ m})(0.8 \times 10^{-3} \text{ m})} = \mathbf{7212^\circ C/W}$$

$$(b) \qquad R_{\text{across thickness}} = \left(\frac{L}{kA}\right)_{\text{across thickness}} = \frac{0.8 \times 10^{-3} \text{ m}}{(0.26 \text{ W/m} \cdot {}^\circ\text{C})(0.1 \text{ m})(0.15 \text{ m})} = \mathbf{0.21^\circ C/W}$$

Discussion Note that heat conduction at a rate of 1 W along this PCB would cause a temperature difference of 7212°C across a length of 15 cm. But the same rate of heat conduction would cause a temperature difference of only 0.21°C across the thickness of the epoxy board.

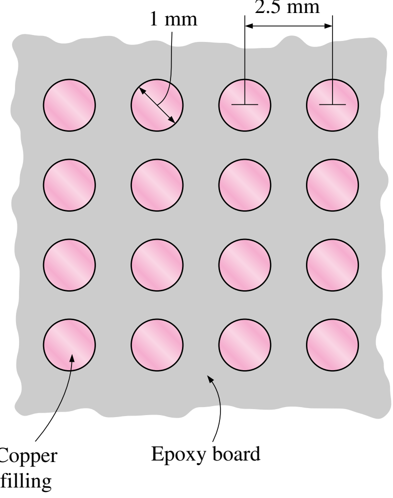


FIGURE 15–30
Schematic for Example 15–7.

EXAMPLE 15–7 Planting Cylindrical Copper Fillings in an Epoxy Board

Reconsider the 10-cm × 15-cm glass–epoxy laminate (k = 0.26 W/m · °C) of thickness 0.8 mm discussed in Example 15–6. In order to reduce the thermal resistance across its thickness from the current value of 0.21°C/W, cylindrical copper fillings (k = 386 W/m · °C) of 1-mm diameter are to be planted throughout the board with a center-to-center distance of 2.5 mm, as shown in Fig. 15–30. Determine the new value of the thermal resistance of the epoxy board for heat conduction across its thickness as a result of this modification.

SOLUTION Cylindrical copper fillings are planted throughout an epoxy glass board. The thermal resistance of the board across its thickness is to be determined.

Assumptions **1** Heat conduction along the board is one-dimensional. **2** Thermal properties of the board are constant.

Analysis Heat flow through the thickness of the board in this case will take place partly through the copper fillings and partly through the epoxy in parallel paths. The thickness of both materials is the same and is given to be 0.8 mm.

But we also need to know the surface area of each material before we can determine the thermal resistances.

It is stated that the distance between the centers of the copper fillings is 2.5 mm. That is, there is only one 1-mm-diameter copper filling in every 2.5-mm × 2.5-mm square section of the board. The number of such squares and thus the number of copper fillings on the board are

$$n = \frac{\text{Area of the board}}{\text{Area of one square}} = \frac{(100 \text{ mm})(150 \text{ mm})}{(2.5 \text{ mm})(2.5 \text{ mm})} = 2400$$

Then the surface areas of the copper fillings and the remaining epoxy layer become

$$A_{\text{copper}} = n\frac{\pi D^2}{4} = (2400)\frac{\pi(1 \times 10^{-3} \text{ m})^2}{4} = 0.001885 \text{ m}^2$$

$$A_{\text{total}} = (\text{Length})(\text{Width}) = (0.1 \text{ m})(0.15 \text{ m}) = 0.015 \text{ m}^2$$

$$A_{\text{epoxy}} = A_{\text{total}} - A_{\text{copper}} = (0.015 - 0.001885) \text{ m}^2 = 0.013115 \text{ m}^2$$

The thermal resistance of each material is

$$R_{\text{copper}} = \left(\frac{L}{kA}\right)_{\text{copper}} = \frac{0.8 \times 10^{-3} \text{ m}}{(386 \text{ W/m} \cdot {}^\circ\text{C})(0.001885 \text{ m}^2)} = 0.0011^\circ\text{C/W}$$

$$R_{\text{epoxy}} = \left(\frac{L}{kA}\right)_{\text{epoxy}} = \frac{0.8 \times 10^{-3} \text{ m}}{(0.26 \text{ W/m} \cdot {}^\circ\text{C})(0.013115 \text{ m}^2)} = 0.2346^\circ\text{C/W}$$

Noting that these two resistances are in parallel, the equivalent thermal resistance of the entire board is determined from

$$\frac{1}{R_{\text{board}}} = \frac{1}{R_{\text{copper}}} + \frac{1}{R_{\text{epoxy}}} = \frac{1}{0.0011^\circ\text{C/W}} + \frac{1}{0.2346^\circ\text{C/W}}$$

which gives

$$R_{\text{board}} = \mathbf{0.00109^\circ C/W}$$

Discussion Note that the thermal resistance of the epoxy board has dropped from 0.21°C/W by a factor of almost 200 to just 0.00109°C/W as a result of implanting 1-mm-diameter copper fillings into it. Therefore, implanting copper pins into the epoxy laminate has virtually eliminated the thermal resistance of the epoxy across its thickness.

EXAMPLE 15–8 Conduction Cooling of PCBs by a Heat Frame

A 10-cm × 12-cm circuit board dissipating 24 W of heat is to be conduction-cooled by a 1.2-mm-thick copper heat frame ($k = 386$ W/m · °C) 10 cm × 14 cm in size. The epoxy laminate ($k = 0.26$ W/m · °C) has a thickness of 0.8 mm and is attached to the heat frame with conductive epoxy adhesive ($k = 1.8$ W/m · °C) of 0.13-mm thickness, as shown in Fig. 15–31. The PCB is attached to a heat sink by clamping a 5-mm-wide portion of the edge to the heat sink from both ends. The temperature of the heat frame at this point is 20°C. Heat is uniformly generated on the PCB at a rate of 2 W per 1-cm × 10-cm strip. Considering only one-half of the PCB board because of symmetry, determine the

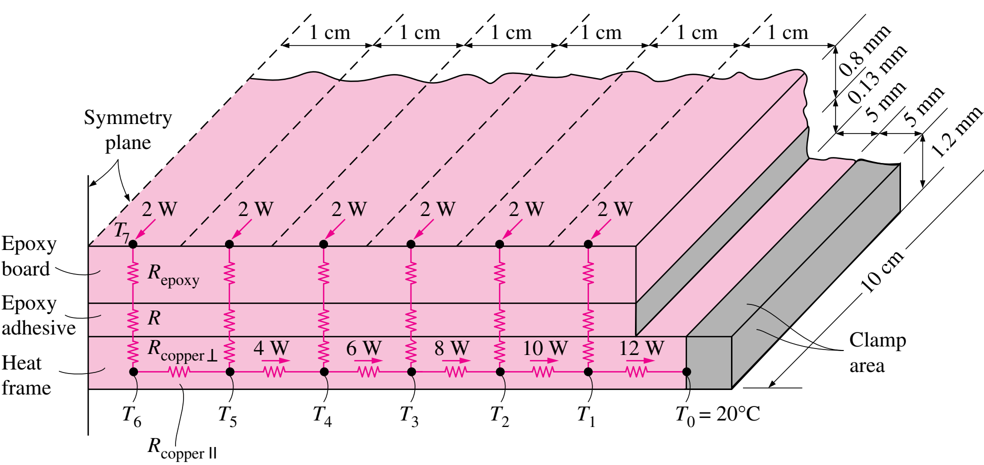


FIGURE 15–31
The schematic and thermal resistance network for Example 15–8.

maximum temperature on the PCB and the temperature distribution along the heat frame.

SOLUTION A circuit board with uniform heat generation is to be conduction-cooled by a copper heat frame. Temperature distribution along the heat frame and the maximum temperature 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 heat frame to the heat sink.

Analysis The PCB under consideration possesses thermal symmetry about the centerline. Therefore, the heat generated on the left half of the PCB is conducted to the left heat sink, and the heat generated on the right half is conducted to the right heat sink. Thus we need to consider only half of the board in the analysis.

The maximum temperature will occur at a location furthest away from the heat sinks, which is the symmetry line. Therefore, the temperature of the electronic components located at the center of the PCB will be the highest, and their reliability will be the lowest.

Heat generated in the components on each strip is conducted through the epoxy layer underneath. Heat is then conducted across the epoxy adhesive and to the middle of the copper heat frame. Finally, heat is conducted along the heat frame to the heat sink.

The thermal resistance network associated with heat flow in the right half of the PCB is also shown in Fig. 15–31. Note that all vertical resistances are identical and are equal to the sum of the three resistances in series. Also note that heat conduction toward the heat sink is assumed to be predominantly along the heat frame, and conduction along the epoxy adhesive is considered to be negligible. This assumption is quite reasonable, since the conductivity–thickness product of the heat frame is much larger than those of the other two layers.

The properties and dimensions of various sections of the PCB are summarized in this table.

Section and Material	Thermal Conductivity, W/m · °C	Thickness, mm	Heat Transfer Surface Area
Epoxy board	0.26	0.8	10 mm × 100 mm
Epoxy adhesive	1.8	0.13	10 mm × 100 mm
Copper heat frame, ⊥ (normal to frame)	386	0.6	10 mm × 100 mm
Copper heat frame, ∥ (along the frame)	386	10	1.2 mm × 100 mm

Using the values in the table, the various thermal resistances are determined to be

$$R_{\text{epoxy}} = \left(\frac{L}{kA}\right)_{\text{epoxy}} = \frac{0.8 \times 10^{-3}\text{ m}}{(0.26\text{ W/m}\cdot{}^\circ\text{C})(0.01\text{ m} \times 0.1\text{ m})} = 3.077^\circ\text{C/W}$$

$$R_{\text{adhesive}} = \left(\frac{L}{kA}\right)_{\text{adhesive}} = \frac{0.13 \times 10^{-3}\text{ m}}{(1.8\text{ W/m}\cdot{}^\circ\text{C})(0.01\text{ m} \times 0.1\text{ m})} = 0.072^\circ\text{C/W}$$

$$R_{\text{copper},\perp} = \left(\frac{L}{kA}\right)_{\text{copper},\perp} = \frac{0.6 \times 10^{-3}\text{ m}}{(386\text{ W/m}\cdot{}^\circ\text{C})(0.01\text{ m} \times 0.1\text{ m})} = 0.002^\circ\text{C/W}$$

$$R_{\text{frame}} = R_{\text{copper},\parallel} = \left(\frac{L}{kA}\right)_{\text{copper},\parallel} = \frac{0.01\text{ m}}{(386\text{ W/m}\cdot{}^\circ\text{C})(0.0012\text{ m} \times 0.1\text{ m})}$$
$$= 0.216^\circ\text{C/W}$$

The combined resistance between the electronic components on each strip and the heat frame can be determined, by adding the three resistances in series, to be

$$R_{\text{vertical}} = R_{\text{epoxy}} + R_{\text{adhesive}} + R_{\text{copper},\perp}$$
$$= (3.077 + 0.072 + 0.002)^\circ\text{C/W}$$
$$= 3.151^\circ\text{C/W}$$

The various temperatures along the heat frame can be determined from the relation

$$\Delta T = T_{\text{high}} - T_{\text{low}} = \dot{Q}R$$

where R is the thermal resistance between two specified points, $\dot{Q}$ is the heat transfer rate through that resistance, and ΔT is the temperature difference across that resistance.

The temperature at the location where the heat frame is clamped to the heat sink is given as $T_0 = 20^\circ$C. Noting that the entire 12 W of heat generated on the right half of the PCB must pass through the last thermal resistance adjacent to the heat sink, the temperature T_1 can be determined from

$$T_1 = T_0 + \dot{Q}_{1\text{–}0}R_{1\text{–}0} = 20^\circ\text{C} + (12\text{ W})(0.216^\circ\text{C/W}) = \mathbf{22.59^\circ C}$$

Following the same line of reasoning, the temperatures at specified locations along the heat frame are determined to be

$$T_2 = T_1 + \dot{Q}_{2\text{–}1}R_{2\text{–}1} = 22.59^\circ\text{C} + (10\text{ W})(0.216^\circ\text{C/W}) = \mathbf{24.75^\circ C}$$
$$T_3 = T_2 + \dot{Q}_{3\text{–}2}R_{3\text{–}2} = 24.75^\circ\text{C} + (8\text{ W})(0.216^\circ\text{C/W}) = \mathbf{26.48^\circ C}$$
$$T_4 = T_3 + \dot{Q}_{4\text{–}3}R_{4\text{–}3} = 26.48^\circ\text{C} + (6\text{ W})(0.216^\circ\text{C/W}) = \mathbf{27.78^\circ C}$$
$$T_5 = T_4 + \dot{Q}_{5\text{–}4}R_{5\text{–}4} = 27.78^\circ\text{C} + (4\text{ W})(0.216^\circ\text{C/W}) = \mathbf{28.64^\circ C}$$
$$T_6 = T_5 + \dot{Q}_{6\text{–}5}R_{6\text{–}5} = 28.64^\circ\text{C} + (2\text{ W})(0.216^\circ\text{C/W}) = \mathbf{29.07^\circ C}$$

Finally, T_7, which is the maximum temperature on the PCB, is determined from

$$T_7 = T_6 + \dot{Q}_{\text{vertical}} R_{\text{vertical}} = 29.07°\text{C} + (2\text{ W})(3.151°\text{C/W}) = \mathbf{35.37°C}$$

Discussion The maximum temperature difference between the PCB and the heat sink is only 15.37°C, which is very impressive considering that the PCB has no direct contact with the cooling medium. The junction temperatures in this case can be determined by calculating the temperature difference between the junction and the leads of the chip carrier at the point of contact to the PCB and adding 35.37°C to it. The maximum temperature rise of 15.37°C can be reduced, if necessary, by using a thicker heat frame.

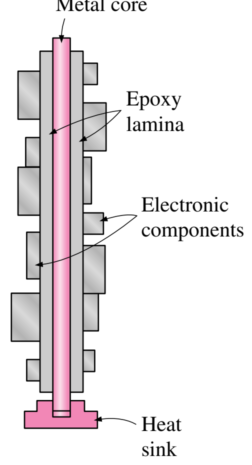


FIGURE 15–32
A two-sided printed circuit board with a metal core for conduction cooling.

Conduction cooling can also be used when electronic components are mounted on *both sides* of the PCB by using a copper or aluminum core plate in the middle of the PCB, as shown in Fig. 15–32. The heat load in this case will be twice that of a PCB that has components on one side only. Again, heat generated in the components will be conducted through the thickness of the epoxy layer to the *metal core,* which serves as a *channel* for effective heat removal. The thickness of the core is selected such that the maximum component temperatures remain below specified values to meet a prescribed reliability criterion.

The thermal expansion coefficients of aluminum and copper are about twice as large as that of the glass–epoxy. This large difference in *thermal expansion coefficients* can cause *warping* on the PCBs if the epoxy and the metal are not bonded properly. One way of avoiding warping is to use PCBs with components on both sides, as discussed. Extreme care should be exercised during the bonding and curing process when components are mounted on only one side of the PCB.

The Thermal Conduction Module (TCM)

The heat flux for logic chips has been increasing steadily as a result of the increasing circuit density in the chips. For example, the peak flux at the chip level has increased from 2 W/cm^2 on IBM System 370 to 20 W/cm^2 on IBM System 3081, which was introduced in the early 1980s. The conventional forced-air cooling technique used in earlier machines was inadequate for removing such high heat fluxes, and it was necessary to develop a new and more effective cooling technique. The result was the **thermal conduction** module, shown in Fig. 15–33. The TCM was different from previous chip packaging designs in that it incorporated both electrical and thermal considerations in early stages of chip design. Previously, a chip would be designed primarily by electrical designers, and the thermal designer would be told to come up with a cooling scheme for the chip. That approach resulted in unnecessarily high junction temperatures, and reduced reliability, since the thermal designer had no direct access to the chip. The TCM reflects a new philosophy in electronic packaging in that the thermal and electrical aspects are given equal treatment in the design process, and a successful thermal design starts at the chip level.

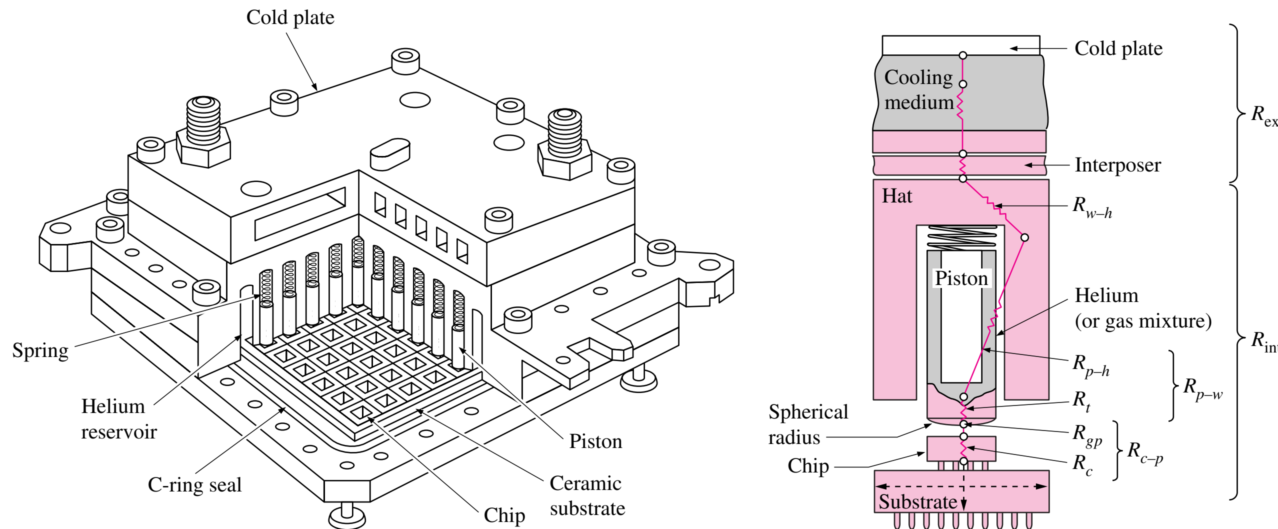


FIGURE 15–33

Cutaway view of the thermal conduction module (TCM), and the thermal resistance network between a single chip and the cooling fluid.

(Courtesy of IBM Corporation.)

In the TCM, one side of the chip is reserved for electrical connections and the other side for heat rejection. The chip is cooled by direct contact to the cooling system to minimize the junction-to-case thermal resistance.

The TCM houses 100 to 118 logic chips, which are bonded to a multilayer ceramic substrate 90 mm × 90 mm in size with solder balls, which also provide the electrical connections between the chips and the substrate. Each chip dissipates about 4 W of power. The heat flow path from the chip to the metal casing is provided by a *piston,* which is pressed against the back surface of the chip by a spring. The tip of the piston is slightly curved to ensure good thermal contact even when the chip is tilted or misaligned.

Heat conduction between the chip and the piston occurs primarily through the gas space between the chip and the piston because of the limited contact area between them. To maximize heat conduction through the gas, the air in the TCM cavity is evacuated and is replaced by helium gas, whose thermal conductivity is about six times that of air. Heat is then conducted through the piston, across the surrounding helium gas layer, through the module housing, and finally to the cooling water circulating through the cold plate attached to the top surface of the TCM.

The total *internal thermal resistance* R_{int} of the TCM is about 8°C/W, which is rather impressive. This means that the temperature difference between the chip surface and the outer surface of the housing of the module will be only 24°C for a 3-W chip. The *external thermal resistance* R_{ext} between the housing of the module and the cooling fluid is usually comparable in magnitude to R_{int}. Also, the thermal resistance between the junction and the surface of the chip can be taken to be 1°C/W.

The compact design of the TCM significantly reduces the *distance* between the chips, and thus the signal transmission time between the chips. This, in turn, increases the *operating speed* of the electronic device.

EXAMPLE 15–9 Cooling of Chips by the Thermal Conduction Module

Consider a thermal conduction module with 100 chips, each dissipating 3 W of power. The module is cooled by water at 25°C flowing through the cold plate on top of the module. The thermal resistances in the path of heat flow are R_{chip} = 1°C/W between the junction and the surface of the chip, R_{int} = 8°C/W between the surface of the chip and the outer surface of the thermal conduction module, and R_{ext} = 6°C/W between the outer surface of the module and the cooling water. Determine the junction temperature of the chip.

SOLUTION A thermal conduction module TCM with 100 chips is cooled by water. The junction temperature of the chip is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Heat transfer through various components is one-dimensional.

Analysis Because of symmetry, we will consider only one of the chips in our analysis. The thermal resistance network for heat flow is given in Fig. 15–34. Noting that all resistances are in series, the total thermal resistance between the junction and the cooling water is

$$R_{total} = R_{junction\text{-}water} = R_{chip} + R_{int} + R_{ext} = (1 + 8 + 6)\text{°C/W} = 15\text{°C/W}$$

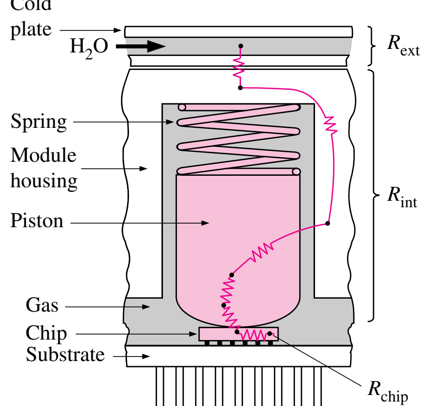


FIGURE 15–34
Thermal resistance network for Example 15–9.

Noting that the total power dissipated by the chip is 3 W and the water temperature is 25°C, the junction temperature of the chip in steady operation can be determined from

$$\dot{Q} = \left(\frac{\Delta T}{R}\right)_{junction\text{-}water} = \frac{T_{junction} - T_{water}}{R_{junction\text{-}water}}$$

Solving for $T_{junction}$ and substituting the specified values gives

$$T_{junction} = T_{water} + \dot{Q}R_{junction\text{-}water} = 25\text{°C} + (3\text{ W})(15\text{°C/W}) = \mathbf{70°C}$$

Therefore, the circuits of the chip will operate at about 70°C, which is considered to be a safe operating temperature for silicon chips.

Cold plates are usually made of metal plates with fluid channels running through them, or copper tubes attached to them by brazing. Heat transferred to the cold plate is conducted to the tubes, and from the tubes to the fluid flowing through them. The heat carried away by the fluid is finally dissipated to the ambient in a heat exchanger.

15–7 ▪ AIR COOLING: NATURAL CONVECTION AND RADIATION

Low-power electronic systems are conveniently cooled by *natural convection* and *radiation.* Natural convection cooling is very desirable, since it does not involve any fans that may break down.

Natural convection is based on the *fluid motion* caused by the density differences in a fluid due to a temperature difference. A fluid expands when heated and becomes less dense. In a gravitational field, this lighter fluid rises and initiates a motion in the fluid called *natural convection currents* (Fig. 15–35). Natural convection cooling is most effective when the path of the fluid is relatively free of obstacles, which tend to slow down the fluid, and is least effective when the fluid has to pass through narrow flow passages and over many obstacles.

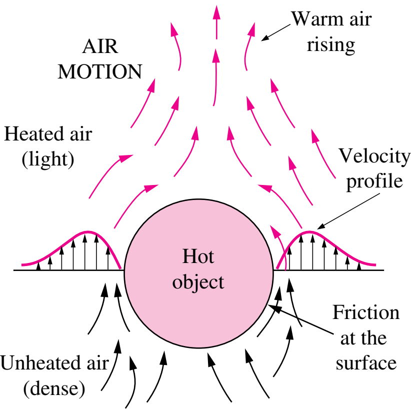


FIGURE 15–35
Natural convection currents around a hot object in air.

The magnitude of the natural convection heat transfer between a surface and a fluid is directly related to the *flow rate* of the fluid. The higher the flow rate, the higher the heat transfer rate. In natural convection, no blowers are used and therefore the flow rate cannot be controlled externally. The flow rate in this case is established by the dynamic balance of *buoyancy* and *friction.* The *larger* the temperature difference between the fluid adjacent to a hot surface and the fluid away from it, the *larger* the buoyancy force, and the *stronger* the natural convection currents, and thus the *higher* the heat transfer rate. Also, whenever two bodies in contact move relative to each other, a *friction force* develops at the contact surface in the direction opposite to that of the motion. This opposing force slows down the fluid, and thus reduces the flow rate of the fluid. Under steady conditions, the airflow rate driven by buoyancy is established at the point where these two effects *balance* each other. The friction force increases as more and more solid surfaces are introduced, seriously disrupting the fluid flow and heat transfer.

Electronic components or PCBs placed in *enclosures* such as a TV or DVD player are cooled by natural convection by providing a sufficient number of *vents* on the case to enable the cool air to enter and the heated air to leave the case freely, as shown in Fig. 15–36. From the heat transfer point of view, the vents should be as large as possible to minimize the flow resistance and should be located at the bottom of the case for air entering and at the top for air leaving. But equipment and human safety requirements dictate that the vents should be quite narrow to discourage unintended entry into the box. Also, concern about human habits such as putting a cup of coffee on the closest flat surface make it very risky to place vents on the top surface. The narrow clearance allowed under the case also offers resistance to airflow. Therefore, vents on the enclosures of natural convection–cooled electronic equipment are usually placed at the *lower section* of the side or back surfaces for air inlet and at the *upper section* of those surfaces for air exit.

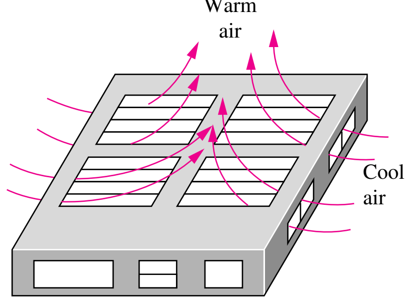


FIGURE 15–36
Natural convection cooling of electronic components in an enclosure with air vents.

The heat transfer from a surface at temperature T_s to a fluid at temperature T_{fluid} by convection is expressed as

$$\dot{Q}_{\text{conv}} = h_{\text{conv}} A_s \Delta T = h_{\text{conv}} A_s (T_s - T_{\text{fluid}}) \qquad \text{(W)} \qquad \textbf{(15–13)}$$

where h_{conv} is the convection heat transfer coefficient and A_s is the heat transfer surface area. The value of h_{conv} depends on the geometry of the surface and the type of fluid flow, among other things.

Natural convection currents start out as *laminar* (smooth and orderly) and turn *turbulent* when the dimension of the body and the temperature difference between the hot surface and the fluid are large. For air, the flow remains laminar when the temperature differences involved are less than 100°C and the characteristic length of the body is less than 0.5 m, which is almost always the

case in electronic equipment. Therefore, the airflow in the analysis of electronic equipment can be assumed to be laminar.

The natural convection heat transfer coefficient for laminar flow of *air* at atmospheric pressure is given by a simplified relation of the form

$$h_{\text{conv}} = K\left(\frac{\Delta T}{L_c}\right)^{0.25} \qquad (\text{W/m}^2 \cdot {}^\circ\text{C}) \qquad \textbf{(15–14)}$$

where $\Delta T = T_s - T_{\text{fluid}}$ is the temperature difference between the surface and the fluid, L_c is the characteristic length (the length of the body along the heat flow path), and K is a constant whose value depends on the *geometry* and *orientation* of the body.

The heat transfer coefficient relations are given in Table 15–1 for some common geometries encountered in electronic equipment in both SI and English unit systems. Once h_{conv} has been determined from one of these relations, the rate of heat transfer can be determined from Eq. 15–13. The relations in Table 15–1 can also be used at pressures other than 1 atm by multiplying them by $\sqrt{P}$, where P is the *air pressure* in *atm* (1 atm = 101.325 kPa = 14.696 psia). That is,

$$h_{\text{conv}, P\text{ atm}} = h_{\text{conv, 1 atm}}\sqrt{P} \qquad (\text{W/m}^2 \cdot {}^\circ\text{C}) \qquad \textbf{(15–15)}$$

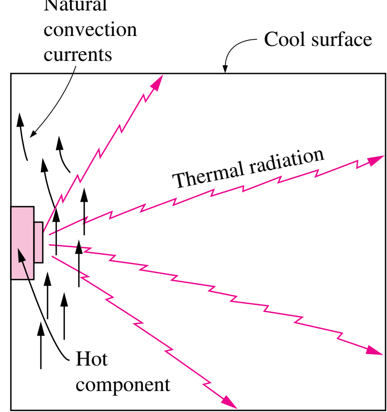


FIGURE 15–37
Simultaneous natural convection heat transfer to air and radiation heat transfer to the surrounding surfaces from a hot electronic component mounted on the wall of an enclosure.

When hot surfaces are surrounded by cooler surfaces such as the walls and ceilings of a room or just the sky, the surfaces are also cooled by *radiation,* as shown in Fig. 15–37. The magnitude of radiation heat transfer, in general, is comparable to the magnitude of natural convection heat transfer. This is especially the case for surfaces whose emissivity is close to *unity,* such as plastics and painted surfaces (regardless of color). Radiation heat transfer is negligible for *polished metals* because of their very low emissivity and for bodies surrounded by surfaces at about the same temperature.

Radiation heat transfer between a surface at temperature T_s completely surrounded by a much larger surface at temperature T_{surr} can be expressed as

$$\dot{Q}_{\text{rad}} = \varepsilon A_s \sigma (T_s^4 - T_{\text{surr}}^4) \qquad (\text{W}) \qquad \textbf{(15–16)}$$

where ε is the emissivity of the surface, A_s is the heat transfer surface area, and σ is the Stefan–Boltzmann constant, whose value is $\sigma = 5.67 \times 10^{-8}$ W/m$^2 \cdot$ K^4 = 0.1714×10^{-8} Btu/h $\cdot$ ft$^2 \cdot$ R^4. Here, both temperatures must be expressed in K or R. Also, if the hot surface analyzed has only a partial view of the surrounding cooler surface at T_{surr}, the result obtained from Eq. 15–16 must be multiplied by a *view factor,* which is the fraction of the view of the hot surface blocked by the cooler surface. The value of the view factor ranges from 0 (the hot surface has no direct view of the cooler surface) to 1 (the hot surface is completely surrounded by the cooler surface). In preliminary analysis, the surface is usually assumed to be completely surrounded by a single hypothetical surface whose temperature is the equivalent average temperature of the surrounding surfaces.

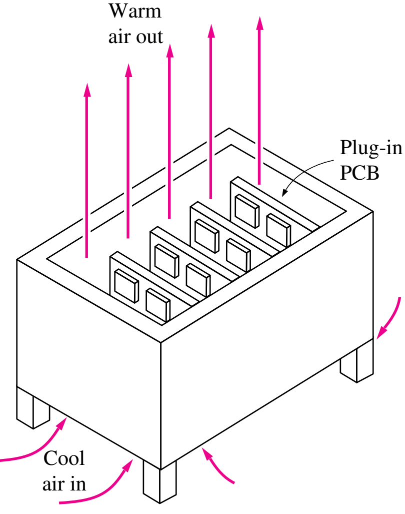


FIGURE 15–38
A chassis with an array of vertically oriented PCBs cooled by natural convection.

Arrays of low-power PCBs are often cooled by natural convection by mounting them within a chassis with adequate openings at the top and at the bottom to facilitate airflow, as shown in Fig. 15–38. The air between the PCBs rises when heated by the electronic components and is replaced by the cooler air entering from below. This initiates the natural convection flow through the

TABLE 15–1

Simplified relations for natural convection heat transfer coefficients for various geometries in air at atmospheric pressure for laminar flow conditions

Geometry	*Natural Convection Heat Transfer Coefficient* W/m² · °C (ΔT in °C, L or D in m)	Btu/h · ft² · °F (ΔT in °F, L or D in ft)
Vertical plate or cylinder	$h_{conv} = 1.42\left(\frac{\Delta T}{L}\right)^{0.25}$	$h_{conv} = 0.29\left(\frac{\Delta T}{L}\right)^{0.25}$
Horizontal cylinder	$h_{conv} = 1.32\left(\frac{\Delta T}{D}\right)^{0.25}$	$h_{conv} = 0.27\left(\frac{\Delta T}{D}\right)^{0.25}$
Horizontal plate ($L_c = 4A/p$, where A is surface area and p is perimeter) (*a*) Hot surface facing up	$h_{conv} = 1.32\left(\frac{\Delta T}{L_c}\right)^{0.25}$	$h_{conv} = 0.27\left(\frac{\Delta T}{L_c}\right)^{0.25}$
(*b*) Hot surface facing down	$h_{conv} = 0.59\left(\frac{\Delta T}{L_c}\right)^{0.25}$	$h_{conv} = 0.12\left(\frac{\Delta T}{L_c}\right)^{0.25}$
Components on a circuit board	$h_{conv} = 2.44\left(\frac{\Delta T}{L_c}\right)^{0.25}$	$h_{conv} = 0.50\left(\frac{\Delta T}{L_c}\right)^{0.25}$
Small components or wires in free air	$h_{conv} = 3.53\left(\frac{\Delta T}{L}\right)^{0.25}$	$h_{conv} = 0.72\left(\frac{\Delta T}{L}\right)^{0.25}$
Sphere	$h_{conv} = 1.92\left(\frac{\Delta T}{D}\right)^{0.25}$	$h_{conv} = 0.39\left(\frac{\Delta T}{D}\right)^{0.25}$

(From Refs. 4 and 5.)

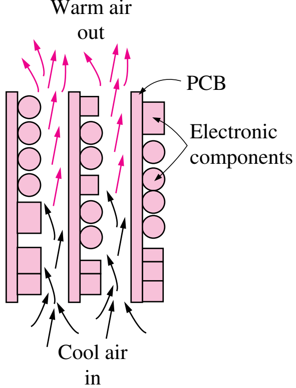


FIGURE 15–39
The PCBs in a chassis must be oriented vertically and spaced adequately to maximize heat transfer by natural convection.

parallel flow passages formed by the PCBs. The PCBs must be placed *vertically* to take advantage of natural convection currents and to minimize trapped air pockets (Fig. 15–39). Placing the PCBs too far from each other wastes valuable cabinet space, and placing them too close tends to "choke" the flow because of the increased resistance. Therefore, there should be an optimum spacing between the PCBs. It turns out that a distance of about 2 cm between the PCBs provides adequate air flow for effective natural convection cooling.

In the heat transfer analysis of PCBs, *radiation* heat transfer is *disregarded*, since the view of the components is largely *blocked* by other heat-generating components. As a result, hot components face other hot surfaces instead of a cooler surface. The exceptions are the two PCBs at the ends of the chassis that view the cooler side surfaces. Therefore, it is wise to mount any high-power components on the PCBs facing the walls of the chassis to take advantage of the additional cooling provided by radiation.

Circuit boards that dissipate up to about 5 W of power (or that have a power density of about 0.02 W/cm^2) can be cooled effectively by natural convection. Heat transfer from PCBs can be analyzed by treating them as rectangular plates with uniformly distributed heat sources on one side, and insulated on the other side, since heat transfer from the back surfaces of the PCBs is usually small. For PCBs with electronic components mounted on both sides, the rate of heat transfer and the heat transfer surface area will be twice as large.

It should be remembered that natural convection currents occur only in *gravitational fields.* Therefore, there can be no heat transfer in space by natural convection. This will also be the case when the air passageways are blocked and hot air cannot rise. In such cases, there will be no air motion, and heat transfer through the air will be by convection.

The heat transfer from hot surfaces by natural convection and radiation can be enhanced by attaching fins to the surfaces. The heat transfer in this case can best be determined by using the data supplied by the manufacturers, as discussed in Chapter 3, especially for complex geometries.

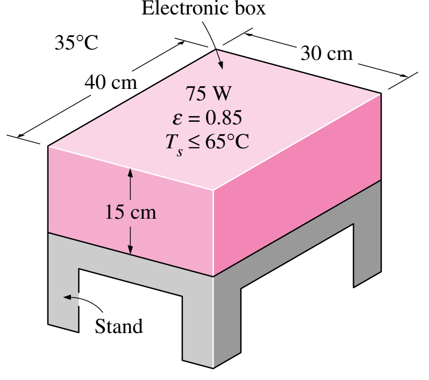


FIGURE 15–40
Schematic for Example 15–10.

EXAMPLE 15–10 Cooling of a Sealed Electronic Box

Consider a sealed electronic box whose dimensions are 15 cm × 30 cm × 40 cm placed on top of a stand in a room at 35°C, as shown in Fig. 15–40. The box is painted, and the emissivity of its outer surface is 0.85. If the electronic components in the box dissipate 75 W of power and the outer surface temperature of the box is not to exceed 65°C, determine if this box can be cooled by natural convection and radiation alone. Assume the heat transfer from the bottom surface of the box to the stand to be negligible.

SOLUTION 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** The box is located at sea level so that the local atmospheric pressure is 1 atm. **2** The temperature of the surrounding surfaces is the same as the air temperature in the room.

Analysis The sealed electronic box will lose heat from the top and the side surfaces by natural convection and radiation. All four side surfaces of the box

can be treated as 0.15-m-high vertical surfaces. Then the natural convection heat transfer from these surfaces is determined to be

$$L = 0.15 \text{ m}$$
$$A_{\text{side}} = (2 \times 0.4 \text{ m} + 2 \times 0.3 \text{ m})(0.15 \text{ m}) = 0.21 \text{ m}^2$$
$$h_{\text{conv, side}} = \left(\frac{\Delta T}{L}\right)^{0.25} = 1.42\left(\frac{65 - 35}{0.15}\right)^{0.25} = 5.34 \text{ W/m}^2 \cdot {}^\circ\text{C}$$
$$\begin{aligned}\dot{Q}_{\text{conv, side}} &= h_{\text{conv, side}} A_{\text{side}}(T_s - T_{\text{fluid}}) \\ &= (5.34 \text{ W/m}^2 \cdot {}^\circ\text{C})(0.21 \text{ m}^2)(65 - 35)^\circ\text{C} \\ &= 33.6 \text{ W}\end{aligned}$$

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

$$L_c = \frac{4A_{\text{top}}}{p} = \frac{4(0.3 \text{ m})(0.4 \text{ m})}{2(0.3 + 0.4) \text{ m}} = 0.34 \text{ m}$$
$$A_{\text{top}} = (0.3 \text{ m})(0.4 \text{ m}) = 0.12 \text{ m}^2$$
$$h_{\text{conv, top}} = 1.32\left(\frac{\Delta T}{L_c}\right)^{0.25} = 1.32\left(\frac{65 - 35}{0.34}\right)^{0.25} = 4.05 \text{ W/m}^2 \cdot {}^\circ\text{C}$$
$$\begin{aligned}\dot{Q}_{\text{conv, top}} &= h_{\text{conv, top}} A_{\text{top}}(T_s - T_{\text{fluid}}) \\ &= (4.05 \text{ W/m}^2 \cdot {}^\circ\text{C})(0.12 \text{ m}^2)(65 - 35)^\circ\text{C} \\ &= 14.6 \text{ W}\end{aligned}$$

Therefore, the natural convection heat transfer from the entire box is

$$\dot{Q}_{\text{conv}} = \dot{Q}_{\text{conv, side}} + \dot{Q}_{\text{conv, top}} = 33.6 + 14.6 = 48.2 \text{ W}$$

The box is completely surrounded by the surfaces of the room, and it is stated that the temperature of the surfaces facing the box is equal to the air temperature in the room. Then the rate of heat transfer from the box by radiation can be determined from

$$\begin{aligned}\dot{Q}_{\text{rad}} &= \varepsilon A_s \sigma(T_s^4 - T_{\text{surr}}^4) \\ &= 0.85[(0.21 + 0.12) \text{ m}^2](5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4) \\ &\quad \times [(65 + 273)^4 - (35 + 273)^4]\text{K}^4 \\ &= 64.5 \text{ W}\end{aligned}$$

Note that we must use absolute temperatures in radiation calculations. Then the total heat transfer from the box is simply

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = 48.2 + 64.5 = \mathbf{112.7 \text{ W}}$$

which is greater than 75 W. Therefore, this box can be cooled by combined natural convection and radiation, and there is no need to install any fans. There is even some safety margin left for occasions when the air temperature rises above 35°C.

EXAMPLE 15–11 Cooling of a Component by Natural Convection

A 0.2-W small cylindrical resistor mounted on a PCB is 1 cm long and has a diameter of 0.3 cm, as shown in Fig. 15–41. The view of the resistor is largely

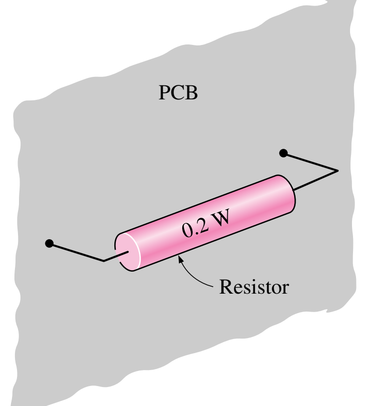


FIGURE 15–41
Schematic for Example 15–11.

blocked by the PCB facing it, and the heat transfer from the connecting wires is negligible. The air is free to flow through the parallel flow passages between the PCBs. If the air temperature at the vicinity of the resistor is 50°C, determine the surface temperature of the resistor.

SOLUTION 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 device is located at sea level so that the local atmospheric pressure is 1 atm. **3** Radiation is negligible in this case since the resistor is surrounded by surfaces that are at about the same temperature, and the net 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 Using the relation for components on a circuit board from Table 15–1, the natural convection heat transfer coefficient for this cylindrical component can be determined from

$$h_{\text{conv}} = 2.44\left(\frac{T_s - T_{\text{fluid}}}{D}\right)^{0.25}$$

where the diameter $D = 0.003$ m, which is the length in the heat flow path, is the characteristic length. We cannot determine h_{conv} yet since we do not know the surface temperature of the component and thus ΔT. But we can substitute this relation into the heat transfer relation to get

$$\dot{Q}_{\text{conv}} = h_{\text{conv}} A_s(T_s - T_{\text{fluid}}) = 2.44\left(\frac{T_s - T_{\text{fluid}}}{D}\right)^{0.25} A_s(T_s - T_{\text{fluid}})$$
$$= 2.44A_s\left(\frac{T_s - T_{\text{fluid}}}{D}\right)^{1.25}$$

The heat transfer surface area of the component is

$$A_s = 2 \times \tfrac{1}{4}\pi D^2 + \pi DL = 2 \times \tfrac{1}{4}\pi(0.3\text{ cm})^2 + \pi(0.3\text{ cm})(1\text{ cm}) = 1.084\text{ cm}^2$$

Substituting this and other known quantities in proper units (W for $\dot{Q}$, °C for T, m^2 for A, and m for D) into this equation and solving for T_s yields

$$0.2 = 2.44(1.084 \times 10^{-4})\frac{(T_s - 50)^{1.25}}{0.003^{0.25}} \longrightarrow T_s = \mathbf{113°C}$$

Therefore, the surface temperature of the resistor on the PCB will be 113°C, which is considered to be a safe operating temperature for the resistors. Note that blowing air to the circuit board will lower this temperature considerably as a result of increasing the convection heat transfer coefficient and decreasing the air temperature at the vicinity of the components due to the larger flow rate of air.

20 cm
15 cm
7 W
PCB

FIGURE 15–42
Schematic for Example 15–12.

EXAMPLE 15–12 Cooling of a PCB in a Box by Natural Convection

A 15-cm × 20-cm PCB has electronic components on one side, dissipating a total of 7 W, as shown in Fig. 15–42. The PCB is mounted in a rack vertically together with other PCBs. If the surface temperature of the components is not

to exceed 100°C, determine the maximum temperature of the environment in which this PCB can operate safely at sea level. What would your answer be if this rack is located at a location at 4000 m altitude where the atmospheric pressure is 61.66 kPa?

SOLUTION The surface temperature of a PCB is not to exceed 100°C. The maximum environment temperatures for safe operaton at sea level and at 4000 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 The entire heat load of the PCB is dissipated to the ambient air by natural convection from its front surface, which can be treated as a vertical flat plate.

Using the simplified relation for a vertical surface from Table 15–1, the natural convection heat transfer coefficient for this PCB can be determined from

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

The characteristic length in this case is the height ($L = 0.15$ m) of the PCB, which is the length in the path of heat flow. We cannot determine h_{conv} yet, since we do not know the ambient temperature and thus ΔT. But we can substitute this relation into the heat transfer relation to get

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

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

The heat transfer surface area of the PCB is

$$A_s = \text{(Width)(Height)} = (0.2 \text{ m})(0.15 \text{ m}) = 0.03 \text{ m}^2$$

Substituting this and other known quantities in proper units (W for $\dot{Q}$, °C for T, m^2 for A_s, and m for L) into this equation and solving for T_{fluid} yields

$$7 = 1.42(0.03)\frac{(100 - T_{fluid})^{1.25}}{0.15^{0.25}} \longrightarrow T_{fluid} = \mathbf{59.5°C}$$

Therefore, the PCB will operate safely in environments with temperatures up to 59.5°C by relying solely on natural convection.

At an altitude of 4000 m, the atmospheric pressure is 61.66 kPa, which is equivalent to

$$P = (61.66 \text{ kPa})\frac{1 \text{ atm}}{101.325 \text{ kPa}} = 0.609 \text{ atm}$$

The heat transfer coefficient in this case is obtained by multiplying the value at sea level by $\sqrt{P}$, where P is in atm. Substituting

$$7 = 1.42(0.03)\frac{(100 - T_{fluid})^{1.25}}{0.15^{0.25}}\sqrt{0.609} \longrightarrow T_{fluid} = \mathbf{50.6°C}$$

which is about 10°C lower than the value obtained at 1 atm pressure. Therefore, the effect of altitude on convection should be considered in high-altitude applications.

15–8 ▪ AIR COOLING: FORCED CONVECTION

We mentioned earlier that convection heat transfer between a solid surface and a fluid is proportional to the velocity of the fluid. The *higher* the velocity, the *larger* the flow rate and the *higher* the heat transfer rate. The fluid velocities associated with natural convection currents are naturally low, and thus natural convection cooling is limited to low-power electronic systems.

When natural convection cooling is not adequate, we simply add a *fan* and blow air through the enclosure that houses the electronic components. In other words, we resort to *forced convection* in order to enhance the velocity and thus the flow rate of the fluid as well as the heat transfer. By doing so, we can increase the heat transfer coefficient by a factor of up to about 10, depending on the size of the fan. This means we can remove heat at much higher rates for a specified temperature difference between the components and the air, or we can reduce the surface temperature of the components considerably for a specified power dissipation.

The *radiation* heat transfer in forced-convection-cooled electronic systems is usually disregarded for two reasons. First, forced convection heat transfer is usually much larger than that due to radiation, and the consideration of radiation causes no significant change in the results. Second, the electronic components and circuit boards in convection-cooled systems are mounted so close to each other that a component is almost entirely surrounded by other components at about the same high temperature. That is, the components have hardly any direct view of a cooler surface. This results in little or no radiation heat transfer from the components. The components near the edges of circuit boards with a large view of a cooler surface may benefit somewhat from the additional cooling by radiation, and it is a good design practice to reserve those spots for high-power components to have a thermally balanced system.

When heat transfer from the outer surface of the enclosure of the electronic equipment is negligible, the amount of heat absorbed by the air becomes equal to the amount of heat rejected (or power dissipated) by the electronic components in the enclosure, and can be expressed as (Fig. 15–43)

$$\dot{Q} = \dot{m}c_p(T_{out} - T_{in}) \quad \text{(W)} \tag{15–17}$$

where $\dot{Q}$ is the rate of heat transfer to the air; c_p is the specific heat of air; T_{in} and T_{out} are the average temperatures of air at the inlet and exit of the enclosure, respectively; and $\dot{m}$ is the mass flow rate of air.

Note that for a specified mass flow rate and power dissipation, the *temperature rise* of air, $T_{out} - T_{in}$, remains constant as it flows through the enclosure. Therefore, the higher the inlet temperature of the air, the higher the exit temperature, and thus the higher the surface temperature of the components. It is considered a good design practice to limit the temperature rise of air to 10°C and the maximum exit temperature of air to 70°C. In a properly designed forced-air-cooled system, this results in a maximum component surface temperature of under 100°C.

The mass flow rate of air required for cooling an electronic box depends on the temperature of air available for cooling. In cool environments, such as an air-conditioned room, a smaller flow rate will be adequate. However, in hot environments, we may need to use a larger flow rate to avoid overheating the components and the potential problems associated with it.

Power consumed:
$\dot{W}_{electric} = \dot{Q}_{absorbed} = \dot{m}c_p(T_{out} - T_{in})$

FIGURE 15–43
In steady operation, the heat absorbed by air per unit time as it flows through an electronic box is equal to the power consumed by the electronic components in the box.

Forced convection is covered in detail in a separate chapter. For those who skipped that chapter because of time limitations, here we present a brief review of basic concepts and relations.

The fluid flow over a body such as a transistor is called **external flow**, and flow through a confined space such as inside a tube or through the parallel passage area between two circuit boards in an enclosure is called **internal flow** (Fig. 15–44). Both types of flow are encountered in a typical electronic system.

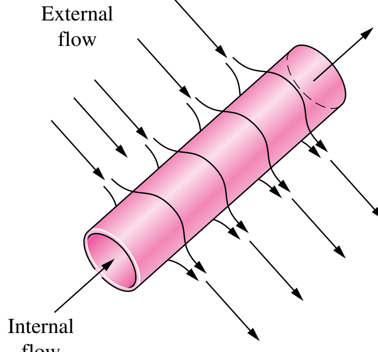


FIGURE 15–44
Internal flow through a circular tube and external flow over it.

Fluid flow is also categorized as being **laminar** (smooth and streamlined) or **turbulent** (intense eddy currents and random motion of chunks of fluid). Turbulent flow is desirable in heat transfer applications since it results in a much larger heat transfer coefficient. But it also comes with a much larger friction coefficient, which requires a much larger fan (or pump for liquids).

Numerous experimental studies have shown that turbulence tends to occur at larger velocities, during flow over larger bodies or flow through larger channels, and with fluids having smaller viscosities. These effects are combined into the dimensionless **Reynolds number**, defined as

$$\text{Re} = \frac{VL_c}{\nu} \qquad \textbf{(15–18)}$$

where

V = velocity of the fluid (*free-stream* velocity for external flow and *average* velocity for internal flow), m/s

L_c = characteristic length of the geometry (the length the fluid flows over in external flow, and the equivalent diameter in internal flow), m

$\nu = \mu/\rho$ = kinematic viscosity of the fluid, m^2/s

The Reynolds number at which the flow changes from laminar to turbulent is called the *critical Reynolds number,* whose value is 2300 for internal flow, 500,000 for flow over a flat plate, and 200,000 for flow over a cylinder or sphere.

The *equivalent* (or *hydraulic*) diameter for internal flow is defined as

$$D_h = \frac{4A_c}{p} \qquad \text{(m)} \qquad \textbf{(15–19)}$$

where A_c is the cross-sectional area of the flow passage and p is the perimeter. Note that for a circular pipe, the hydraulic diameter is equivalent to the ordinary diameter.

The convection heat transfer is expressed by *Newton's law of cooling* as

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_{\text{fluid}}) \qquad \text{(W)} \qquad \textbf{(15–20)}$$

where

h = average convection heat transfer coefficient, $W/m^2 \cdot °C$

A_s = heat transfer surface area, m^2

T_s = temperature of the surface, °C

T_{fluid} = temperature of the fluid sufficiently far from the surface for *external* flow, and average temperature of the fluid at a specified location in *internal* flow, °C

When the heat load is distributed uniformly on the surfaces with a constant heat flux $\dot{q}$, the total rate of heat transfer can also be expressed as $\dot{Q} = \dot{q}A_s$.

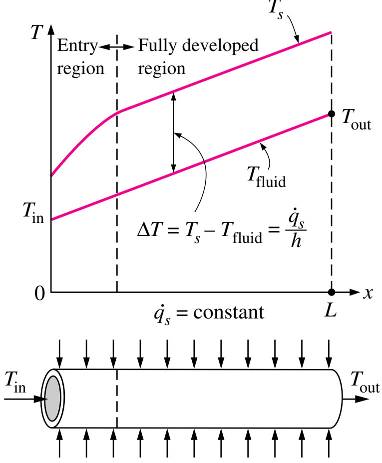


FIGURE 15–45
Under constant heat flux conditions, the surface and fluid temperatures increase linearly, but their difference remains constant in the fully developed region.

In *fully developed flow* through a pipe or duct (i.e., when the entrance effects are negligible) subjected to constant heat flux on the surfaces, the convection heat transfer coefficient h remains *constant.* In this case, both the surface temperature T_s and the fluid temperature T_{fluid} increase *linearly,* as shown in Fig. 15–45, but the difference between them, $T_s - T_{fluid}$, remains *constant.* Then the *temperature rise* of the surface above the fluid temperature can be determined from Eq. 15–20 to be

$$\Delta T_{\text{rise, surface}} = T_s - T_{\text{fluid}} = \frac{\dot{Q}_{\text{conv}}}{hA_s} \qquad (°\text{C}) \tag{15–21}$$

Note that the temperature rise of the surface is inversely proportional to the convection heat transfer coefficient. Therefore, the greater the convection coefficient, the lower the surface temperature of the electronic components.

When the exit temperature of the fluid, T_{out}, is known, the highest surface temperature that will occur at the end of the flow channel can be determined from Eq. 15–21 to be

$$T_{s,\text{ max}} = T_{\text{fluid, max}} + \frac{\dot{Q}}{hA_s} = T_{\text{out}} + \frac{\dot{Q}}{hA_s} \qquad (°\text{C}) \tag{15–22}$$

If this temperature is within the safe range, then we don't need to worry about temperatures at other locations. But if it is not, it may be necessary to use a larger fan to increase the flow rate of the fluid.

In convection analysis, the convection heat transfer coefficient h is usually expressed in terms of the dimensionless **Nusselt number** Nu as

$$h = \frac{k}{D}\text{Nu} \qquad (\text{W/m}^2 \cdot °\text{C}) \tag{15–23}$$

where k is the thermal conductivity of the fluid and D is the characteristic length of the geometry. Relations for the average Nusselt number based on experimental data are given in Table 15–2 for external flow and in Table 15–3 for laminar ($\text{Re} < 2300$) internal flow under a uniform heat flux condition, which is closely approximated by electronic equipment. For *turbulent flow* ($\text{Re} > 10{,}000$) through smooth tubes and channels, the Nusselt number can be determined from the Dittus–Boelter correlation,

$$\text{Nu} = 0.023\ \text{Re}^{0.8}\text{Pr}^{0.4} \tag{15–24}$$

for any geometry. Here Pr is the dimensionless **Prandtl number**, and its value is about 0.7 for air at room temperature.

The fluid properties in the above relations are to be evaluated at the *bulk mean fluid temperature* $T_{avg} = \frac{1}{2}(T_{in} + T_{out})$ for internal flow, which is the arithmetic average of the mean fluid temperatures at the inlet and the exit of the tube, and at the *film temperature* $T_{film} = \frac{1}{2}(T_s + T_{fluid})$ for external flow, which is the arithmetic average of the surface temperature and free-stream temperature of the fluid.

The relations in Table 15–3 for internal flow assume fully developed flow over the entire flow section, and disregard the heat transfer enhancement effects of the development region at the entrance. Therefore, the results obtained from these relations are on the conservative side. We don't mind this much, however, since it is common practice in engineering design to have some safety margin to fall back to "just in case," as long as it does not result in a grossly overdesigned system. Also, it may sometimes be necessary to do

TABLE 15–2

Empirical correlations for the average Nusselt number for forced convection over a flat plate and circular and noncircular cylinders in cross flow

Cross-section of the cylinder	Fluid	Range of Re	Nusselt number
Circle (D)	Gas or liquid	0.4–4 4–40 40–4000 4000–40,000 40,000–400,000	$Nu = 0.989\ Re^{0.330}Pr^{1/3}$ $Nu = 0.911\ Re^{0.385}Pr^{1/3}$ $Nu = 0.683\ Re^{0.466}Pr^{1/3}$ $Nu = 0.193\ Re^{0.618}Pr^{1/3}$ $Nu = 0.027\ Re^{0.805}Pr^{1/3}$
Square (a, a)	Gas	5000–100,000	$Nu = 0.102\ Re^{0.675}Pr^{1/3}$
Square (tilted 45°)	Gas	5000–100,000	$Nu = 0.246\ Re^{0.588}Pr^{1/3}$
Flat plate (L)	Gas or liquid	$0–5 \times 10^5$ $5 \times 10^5–10^7$	$Nu = 0.664\ Re^{1/2}Pr^{1/3}$ $Nu = (0.037\ Re^{4/5} - 871)Pr^{1/3}$
Vertical plate (L)	Gas	4000–15,000	$Nu = 0.228\ Re^{0.731}Pr^{1/3}$

[From Jakob (1949) and Zukauskas (1972)]

TABLE 15–3

Nusselt number of fully developed laminar flow in circular tubes and rectangular channels

Cross-section of the tube	Aspect ratio	Nusselt number
Circle (D)	—	4.36
Square	—	3.61
Rectangle (a, b)	a/b	
	1	3.61
	2	4.12
	3	4.79
	4	5.33
	6	6.05
	8	6.49
	∞	8.24

some local analysis for critical components with small surface areas to assure reliability and to incorporate solutions to local problems such as attaching heat sinks to high power components.

Fan Selection

Air can be supplied to electronic equipment by one or several fans. Although the air is free and abundant, the fans are not. Therefore, a few words about the fan selection are in order.

A fan at a fixed speed (or fixed rpm) will deliver a fixed volume of air regardless of the altitude and pressure. But the mass flow rate of air will be less at *high altitude* as a result of the lower density of air. For example, the atmospheric

pressure of air drops by more than 50 percent at an altitude of 6000 m from its value at sea level. This means that the fan will deliver *half* as much air mass at this altitude at the same rpm and temperature, and thus the temperature rise of air cooling will double. This may create serious reliability problems and catastrophic failures of electronic equipment if proper precautions are not taken. *Variable-speed fans* that automatically increase speed when the air density decreases are available to avoid such problems. Expensive electronic systems are usually equipped with thermal cutoff switches to prevent overheating due to inadequate airflow rate or the failure of the cooling fan.

Fans draw in not only cooling air but also all kinds of *contaminants* that are present in the air, such as lint, dust, moisture, and even oil. If unattended, these contaminants can pile up on the components and plug up narrow passageways, causing overheating. It should be remembered that the dust that settles on the electronic components acts as an insulation layer that makes it very difficult for the heat generated in the component to escape. To minimize the contamination problem, air filters are commonly used. It is good practice to use the largest air filter practical to minimize the pressure drop of air and to maximize the dust capacity.

Often the question arises about whether to place the fan at the inlet or the exit of an electronic box. The generally preferred location is the *inlet.* A fan placed at the inlet draws air in and pressurizes the electronic box and prevents air infiltration into the box from cracks or other openings. Having only one location for air inlet makes it practical to install a filter at the inlet to clean the air from all the dust and dirt before they enter the box. This allows the electronic system to operate in a *clean* environment. Also, a fan placed at the inlet handles cooler and thus *denser* air, which results in a higher mass flow rate for the same volume flow rate or rpm. Since the fan is always subjected to cool air, this has the added benefit that it increased the reliability and extends the life of the fan. The major disadvantage associated with having a fan mounted at the inlet is that the *heat* generated by the fan and its motor is picked up by air on its way into the box, which adds to the heat load of the system.

When the fan is placed at the *exit,* the heat generated by the fan and its motor is immediately discarded to the atmosphere without getting blown first into the electronic box. However, a fan at the exit creates a *vacuum* inside the box, which draws air into the box through inlet vents as well as any cracks and openings (Fig. 15–46). Therefore, the air is difficult to filter, and the dirt and dust that collect on the components undermine the reliability of the system.

Exhaust
fan
Air outlet
Electronic
box
Crack
Air inlet

FIGURE 15–46
A fan placed at the exit of an electronic box draws in air as well as contaminants in the air through cracks.

There are several types of fans available on the market for cooling electronic equipment, and the right choice depends on the situation on hand. There are two primary considerations in the selection of the fan: the *static pressure head* of the system, which is the total resistance an electronic system offers to air as it passes through, and the *volume flow rate* of the air. *Axial fans* are simple, small, light, and inexpensive, and they can deliver a large flow rate. However, they are suitable for systems with relatively small pressure heads. Also, axial fans usually run at very high speeds, and thus they are noisy. The *radial* or *centrifugal fans,* on the other hand, can deliver moderate flow rates to systems with high-static pressure heads at relatively low speeds. But they are larger, heavier, more complex, and more expensive than axial fans.

The performance of a fan is represented by a set of curves called the *characteristic curves,* which are provided by fan manufacturers to help engineers

with the selection of fans. A typical static pressure head curve for a fan is given in Fig. 15–47 together with a typical system flow resistance curve plotted against the flow rate of air. Note that a fan creates the *highest* pressure head at *zero* flow rate. This corresponds to the limiting case of blocked exit vents of the enclosure. The flow rate increases with decreasing static head and reaches its maximum value when the fan meets no flow resistance.

Any electronic enclosure will offer some resistance to flow. The system resistance curve is *parabolic* in shape, and the pressure or head loss due to this resistance is nearly proportional to the *square* of the flow rate. The fan must overcome this resistance to maintain flow through the enclosure. The design of a forced convection cooling system requires the determination of the total system resistance characteristic curve. This curve can be generated accurately by measuring the static pressure drop at different flow rates. It can also be determined approximately by evaluating the pressure drops.

A fan will operate at the *point* where the fan static head curve and the system resistance curve *intersect.* Note that a fan will deliver a higher flow rate to a system with a low flow resistance. The required airflow rate for a system can be determined from heat transfer requirements alone, using the *design heat load* of the system and the *allowable temperature rise* of air. Then the flow resistance of the system at this flow rate can be determined analytically or experimentally. Knowing the flow rate and the needed pressure head, it is easy to select a fan from manufacturers' catalogs that will meet both of these requirements.

Below we present some general guidelines associated with the forced-air cooling of electronic systems.

1. Before deciding on forced-air cooling, check to see if *natural convection* cooling is adequate. If it is, which may be the case for low-power systems, incorporate it and avoid all the problems associated with fans such as cost, power consumption, noise, complexity, maintenance, and possible failure.
2. Select a fan that is neither too small nor too large. An *undersized* fan may cause the electronic system to overheat and fail. An *oversized* fan will definitely provide adequate cooling, but it will needlessly be larger and more expensive and will consume more power.
3. If the temperature rise of air due to the power consumed by the motor of the fan is acceptable, mount the fan at the *inlet* of the box to pressurize the box and filter the air to keep dirt and dust out (Fig. 15–48).
4. Position and size the air exit vents so that there is *adequate airflow* throughout the entire box. More air can be directed to a certain area by enlarging the size of the vent at that area. The total exit areas should be at least as large as the inlet flow area to avoid the choking of the airflow, which may result in a reduced airflow rate.
5. Place the most critical electronic components near the *entrance,* where the air is coolest. Place the non-critical components that consume a lot of power near the exit (Fig. 15–49).
6. Arrange the circuit boards and the electronic components in the box such that the *resistance* of the box to airflow is *minimized* and thus the flow rate of air through the box is maximized for the same fan speed. Make sure that no hot air pockets are formed during operation.

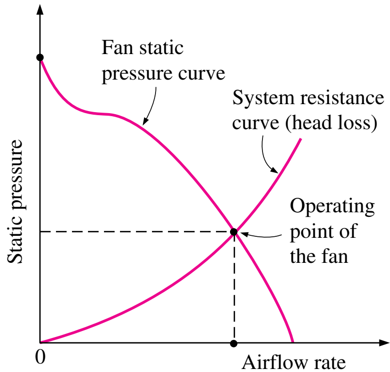


FIGURE 15–47
The airflow rate a fan delivers into an electronic enclosure depends on the flow resistance of that system as well as the variation of the static head of the fan with flow rate.

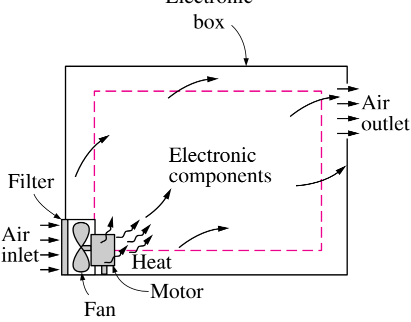


FIGURE 15–48
Installing the fan at the inlet keeps the dirt and dust out, but the heat generated by the fan motor in.

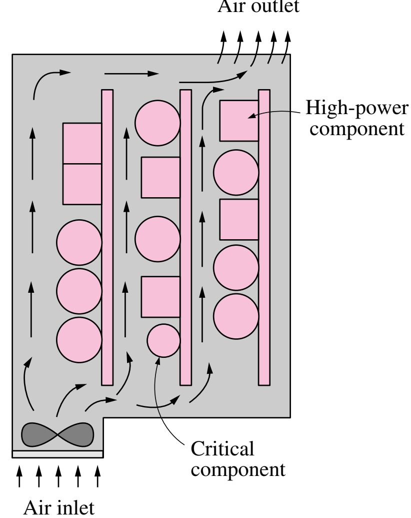


FIGURE 15–49
Sensitive components should be located near the inlet and high-power components near the exit.

7. Consider the effect of *altitude* in high-altitude applications.
8. Try to avoid any flow sections that increase the flow resistance of the systems, such as unnecessary corners, sharp turns, sudden expansions and contractions, and very high velocities (greater than 7 m/s), since the flow resistance is nearly proportional to the flow rate. Also, avoid very low velocities since these result in a poor heat transfer performance and allow the dirt and the dust in the air to settle on the components.
9. Arrange the system such that *natural convection* helps forced convection instead of hurting it. For example, mount the PCBs vertically, and blow the air from the bottom toward the top instead of the other way around.
10. When the design calls for the use of two or more fans, a decision needs to be made about mounting the fans in parallel or in series. Fans mounted in *series* will boost the pressure head available and are best suited for systems with a high flow resistance. Fans connected in *parallel* will increase the flow rate of air and are best suited for systems with small flow resistance.

Cooling Personal Computers

The introduction of the 4004 chip, the first general-purpose microprocessor, by the Intel Corporation in the early 1970s marked the beginning of the electronics era in consumer goods, from calculators and washing machines to personal computers. The microprocessor, which is the "brain" of the personal computer, is basically a DIP-type LSE package that incorporates a central processing unit (CPU), memory, and some input/output capabilities.

A typical desktop personal computer consists of a few circuit boards plugged into a mother board, which houses the microprocessor and the memory chips, as well as the network of interconnections enclosed in a formed sheet metal chassis, which also houses the disk and CD-ROM and DVD drives. Connected to this "magic" box are the monitor, a keyboard, a printer, and other auxiliary equipment (Fig. 15–50). The PCBs are normally mounted vertically on a mother board, since this facilitates better cooling.

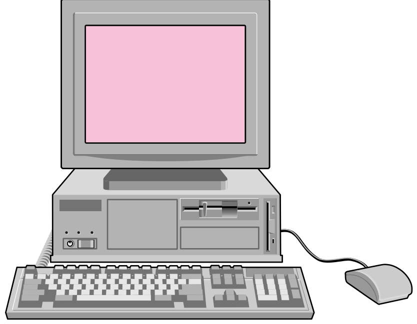


FIGURE 15–50
A desktop personal computer with monitor and keyboard.

A small and quiet fan is usually mounted to the rear or side of the chassis to cool the electronic components. There are also louvers and openings on the side surfaces to facilitate air circulation. Such openings are not placed on the top surface, since many users would block them by putting books or other things there, which will jeopardize safety, and a coffee or soda spill can cause major damage to the system.

EXAMPLE 15–13 Forced-Air Cooling of a Hollow-Core PCB

Some strict specifications of electronic equipment require that the cooling air not come into direct contact with the electronic components, in order to protect them from exposure to the contaminants in the air. In such cases, heat generated in the components on a PCB must be conducted a long way to the walls of the enclosure through a metal core strip or a heat frame attached to the PCB. An alternative solution is the *hollow-core PCB,* which is basically a narrow duct of rectangular cross section made of thin glass–epoxy board with electronic components mounted on both sides, as shown in Fig. 15–51. Heat generated in the

components is conducted to the hollow core through a thin layer of epoxy board and is then removed by the cooling air flowing through the core. Effective sealing is provided to prevent air leakage into the component chamber.

Consider a hollow-core PCB 12 cm high and 18 cm long, dissipating a total of 40 W. The width of the air gap between the two sides of the PCB is 0.3 cm. The cooling air enters the core at 20°C at a rate of 0.72 L/s. Assuming the heat generated to be uniformly distributed over the two side surfaces of the PCB, determine (*a*) the temperature at which the air leaves the hollow core and (*b*) the highest temperature on the inner surface of the core.

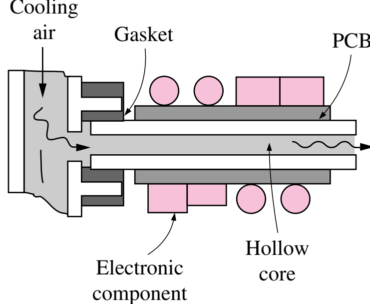


FIGURE 15–51
The hollow-core PCB discussed in Example 15–13.

SOLUTION A hollow-core PCB is cooled by forced air. The outlet temperature of air and the highest surface temperature are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The inner surfaces of the duct are smooth. **3** Air is an ideal gas. **4** Operation is at sea level and thus the atmospheric pressure is 1 atm. **5** The entire heat generated in electronic components is removed by the air flowing through the hollow core.

Properties The temperature of air varies as it flows through the core, and so do its properties. We will perform the calculations using property values at 40°C from Table A–15 since the air enters at 20°C and its temperature will increase.

$$\rho = 1.127 \text{ kg/m}^3 \qquad k = 0.02662 \text{ W/m}\cdot{}^\circ\text{C}$$
$$c_p = 1007 \text{ J/kg}\cdot{}^\circ\text{C} \qquad \nu = 1.702 \times 10^{-5} \text{ m}^2\text{/s}$$
$$\text{Pr} = 0.7255$$

After we calculate the exit temperature of air, we can repeat the calculations, if necessary, using properties at the average temperature.

Analysis The cross-sectional area of the channel and its hydraulic diameter are

$$A_c = (\text{Height})(\text{Width}) = (0.12 \text{ m})(0.003 \text{ m}) = 3.6 \times 10^{-4} \text{ m}^2$$
$$D_h = \frac{4A_c}{p} = \frac{4 \times (3.6 \times 10^{-4} \text{ m}^3)}{2 \times (0.12 + 0.003) \text{ m}} = 0.005854 \text{ m}$$

The average velocity and the mass flow rate of air are

$$V = \frac{\dot{V}}{A_c} = \frac{0.72 \times 10^{-3} \text{ m}^2\text{/s}}{3.6 \times 10^{-4} \text{ m}^2} = 2.0 \text{ m/s}$$
$$\dot{m} = \rho\dot{V} = (1.127 \text{ kg/m}^3)(0.72 \times 10^{-3} \text{ m}^3\text{/s}) = 0.8114 \times 10^{-3} \text{ kg/s}$$

(*a*) The temperature of air at the exit of the hollow core can be determined from

$$\dot{Q} = \dot{m}c_p(T_{\text{out}} - T_{\text{in}})$$

Solving for T_{out} and substituting the given values, we obtain

$$T_{\text{out}} = T_{\text{in}} + \frac{\dot{Q}}{\dot{m}c_p} = 20^\circ\text{C} + \frac{40 \text{ J/s}}{(0.8114 \times 10^{-3} \text{ kg/s})(1007 \text{ J/kg}\cdot{}^\circ\text{C})} = \mathbf{69.0^\circ C}$$

The average air temperature is (20 + 69)/2 = 44.5°C, which is sufficiently close to the assumed value of 40°C. Therefore, there is no need to repeat the calculations.

(*b*) The surface temperature of the channel at any location can be determined from

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_{\text{fluid}})$$

where the heat transfer surface area is

$$A_s = 2A_{\text{side}} = 2(\text{Height})(\text{Length}) = 2(0.12\text{ m})(0.18\text{ m}) = 0.0432\text{ m}^2$$

To determine the convection heat transfer coefficient, we first need to calculate the Reynolds number:

$$\text{Re} = \frac{VD_h}{\nu} = \frac{(2\text{ m/s})(0.005854\text{ m})}{1.702 \times 10^{-5}\text{ m}^2/\text{s}} = 688 < 2300$$

Therefore, the flow is laminar, and, assuming fully developed flow, the Nusselt number for the airflow in this rectangular cross section corresponding to the aspect ratio $a/b = (12\text{ cm})/(0.3\text{ cm}) = 40 \approx \infty$ is determined from Table 15–3 to be

$$\text{Nu} = 8.24$$

and thus

$$h = \frac{k}{D_h}\text{Nu} = \frac{0.02662\text{ W/m}\cdot{}^\circ\text{C}}{0.005854\text{ m}}(8.24) = 37.5\text{ W/m}^2\cdot{}^\circ\text{C}$$

Then the surface temperature of the hollow core near the exit becomes

$$T_{s,\max} = T_{\text{out}} + \frac{\dot{Q}}{hA_s} = 69.0^\circ\text{C} + \frac{40\text{ W}}{(37.5\text{ W/m}^2\cdot{}^\circ\text{C})(0.0432\text{ m}^2)} = \mathbf{93.7^\circ C}$$

Discussion Note that the temperature difference between the surface and the air at the exit of the hollow core is 24.7°C. This temperature difference between the air and the surface remains at that value throughout the core, since the heat generated on the side surfaces is uniform and the convection heat transfer coefficient is constant. Therefore, the surface temperature of the core at the inlet will be 20°C + 24.7°C = 44.7°C. In reality, however, this temperature will be somewhat lower because of the entrance effects, which affect heat transfer favorably. The fully developed flow assumption gives somewhat conservative results but is commonly used in practice because it provides considerable simplification in calculations.

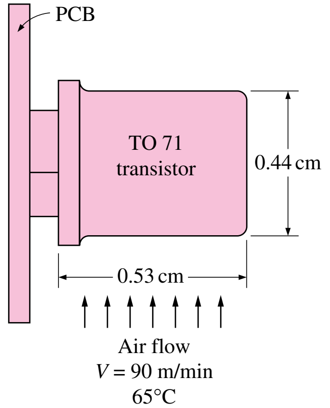


FIGURE 15–52
Schematic for Example 15–14.

EXAMPLE 15–14 Forced-Air Cooling of a Transistor Mounted on a PCB

A TO 71 transistor with a height of 0.53 cm and a diameter of 0.44 cm is mounted on a circuit board, as shown in Fig. 15–52. The transistor is cooled by air flowing over it at a velocity of 90 m/min. If the air temperature is 65°C and the transistor case temperature is not to exceed 95°C, determine the amount of power this transistor can dissipate safely.

SOLUTION A transistor mounted on a circuit board is cooled by air flowing over it. The power dissipated when its case temperature is 90°C is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Air is an ideal gas. **3** Operation is at sea level and thus the atmospheric pressure is 1 atm.

Properties The properties of air at 1 atm pressure and the film temperature of $T_f = (T_s + T_{\text{fluid}})/2 = (95 + 65)/2 = 80^\circ\text{C}$ are

$$\rho = 0.9994 \text{ kg/m}^3 \qquad k = 0.02953 \text{ W/m} \cdot {}^\circ\text{C}$$
$$c_p = 1008 \text{ J/kg} \cdot {}^\circ\text{C} \qquad \nu = 2.097 \times 10^{-5} \text{ m}^2\text{/s}$$
$$\text{Pr} = 0.7154$$

Analysis The transistor is cooled by forced convection through its cylindrical surface as well as its flat top and bottom surfaces. The characteristic length for flow over a cylinder is the diameter $D = 0.0044$ m. Then the Reynolds number becomes

$$\text{Re} = \frac{VD}{\nu} = \frac{(90/60 \text{ m/s})(0.0044 \text{ m})}{2.097 \times 10^{-5} \text{ m}^2\text{/s}} = 315$$

which falls into the range 40 to 4000. Using the corresponding relation from Table 15–2 for the Nusselt number, we obtain

$$\text{Nu} = 0.683 \text{ Re}^{0.466} \text{ Pr}^{1/3} = 0.683(315)^{0.466}(0.7154)^{1/3} = 8.91$$

and

$$h = \frac{k}{D}\text{Nu} = \frac{0.02953 \text{ W/m} \cdot {}^\circ\text{C}}{0.0044 \text{ m}}(8.91) = 59.8 \text{ W/m}^2 \cdot {}^\circ\text{C}$$

Also,

$$A_{\text{cyl}} = \pi DL = \pi(0.0044 \text{ m})(0.0053 \text{ m}) = 0.7326 \times 10^{-4} \text{ m}^2$$

Then the rate of heat transfer from the cylindrical surface becomes

$$\dot{Q}_{\text{cyl}} = hA_{\text{cyl}}(T_s - T_{\text{fluid}})$$
$$= (59.8 \text{ W/m}^2 \cdot {}^\circ\text{C})(0.7326 \times 10^{-4} \text{ m}^2)(95 - 65){}^\circ\text{C} = 0.131 \text{ W}$$

We now repeat the calculations for the top and bottom surfaces of the transistor, which can be treated as flat plates of length $L = 0.0044$ m in the flow direction (which is the diameter), and, using the proper relation from Table 15–2,

$$\text{Re} = \frac{VL}{\nu} = \frac{(90/60 \text{ m/s})(0.0044 \text{ m})}{2.097 \times 10^{-5} \text{ m}^2\text{/s}} = 315$$
$$\text{Nu} = 0.664 \text{ Re}^{1/2}\text{Pr}^{1/3} = 0.664(315)^{1/2}(0.7154)^{1/3} = 10.5$$

and

$$h = \frac{k}{D}\text{Nu} = \frac{0.02953 \text{ W/m} \cdot {}^\circ\text{C}}{0.0044 \text{ m}}(10.5) = 70.7 \text{ W/m}^2 \cdot {}^\circ\text{C}$$

Also,

$$A_{\text{flat}} = A_{\text{top}} + A_{\text{bottom}} = 2 \times \tfrac{1}{4}\pi D^2 = 2 \times \tfrac{1}{4}\pi(0.0044 \text{ m})^2 = 0.3041 \times 10^{-4} \text{ m}^2$$
$$\dot{Q}_{\text{flat}} = hA_{\text{flat}}(T_s - T_{\text{fluid}}) = (70.7 \text{ W/m}^2 \cdot {}^\circ\text{C})(0.3041 \times 10^{-4} \text{ m}^2)(95 - 65){}^\circ\text{C}$$
$$= 0.065 \text{ W}$$

Therefore, the total rate of heat that can be dissipated from all surfaces of the transistor is

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{cyl}} + \dot{Q}_{\text{flat}} = (0.131 + 0.065) \text{ W} = \mathbf{0.196 \text{ W}}$$

which seems to be low. This value can be increased considerably by attaching a heat sink to the transistor to enhance the heat transfer surface area and thus heat transfer, or by increasing the air velocity, which will increase the heat transfer coefficient.

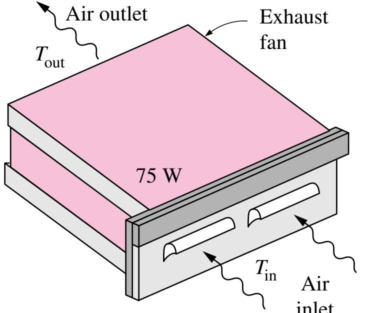


FIGURE 15–53
Schematic for Example 15–15.

EXAMPLE 15–15 Choosing a Fan to Cool a Computer

The desktop computer shown in Fig. 15–53 is to be cooled by a fan. The electronics of the computer consume 75 W of power under full-load conditions. The computer is to operate in environments at temperatures up to 40°C and at elevations up to 2000 m, where the atmospheric pressure is 79.50 kPa. The exit temperature of air is not to exceed 70°C to meet reliability requirements. Also, the average velocity of air is not to exceed 75 m/min at the exit of the computer case, where the fan is installed, to keep the noise level down. Determine the flow rate of the fan that needs to be installed and the diameter of the casing of the fan.

SOLUTION A desktop computer is to be cooled by a fan safely in hot environments and high elevations. The airflow rate of the fan and the diameter of the casing are to be determined.
Assumptions **1** Steady operation under worst conditions is considered. **2** Air is an ideal gas.
Properties The specific heat of air at the average temperature of (40 + 70)/2 = 55°C is 1007 J/kg · °C.
Analysis We need to determine the flow rate of air for the worst-case scenario. Therefore, we assume the inlet temperature of air to be 40°C and the atmospheric pressure to be 79.50 kPa and disregard any heat transfer from the outer surfaces of the computer case. Note that any direct heat loss from the computer case will provide a safety margin in the design.

Noting that all the heat dissipated by the electronic components is absorbed by air, the required mass flow rate of air to absorb heat at a rate of 75 W can be determined from

$$\dot{Q} = \dot{m}c_p(T_{out} - T_{in})$$

Solving for $\dot{m}$ and substituting the given values, we obtain

$$\dot{m} = \frac{\dot{Q}}{c_p(T_{out} - T_{in})} = \frac{75 \text{ J/s}}{(1007 \text{ J/kg} \cdot {}^\circ\text{C})(70 - 40)^\circ\text{C}}$$
$$= 0.00248 \text{ kg/s} = 0.148 \text{ kg/min}$$

In the worst case, the exhaust fan will handle air at 70°C. Then the density of air entering the fan and the volume flow rate become

$$\rho = \frac{P}{RT} = \frac{79.50 \text{ kPa}}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(70 + 273) \text{ K}} = 0.8076 \text{ kg/m}^3$$

$$\dot{V} = \frac{\dot{m}}{\rho} = \frac{0.148 \text{ kg/min}}{0.8076 \text{ kg/m}^2} = \mathbf{0.183\ m^3/min}$$

Therefore, the fan must be able to provide a flow rate of 0.183 m^3/min or 6.5 cfm (cubic feet per minute). Note that if the fan were installed at the inlet instead of the exit, then we would need to determine the flow rate using the density of air at the inlet temperature of 40°C, and we would need to add the power consumed by the motor of the fan to the heat load of 75 W. The result may be a slightly smaller or larger fan, depending on which effect dominates.

For an average velocity of 75 m/min, the diameter of the duct in which the fan is installed can be determined from

$$\dot{V} = A_cV = \frac{1}{4}\pi D^2 V$$

Solving for D and substituting the known values, we obtain

$$D = \sqrt{\frac{4\dot{V}}{\pi V}} = \sqrt{\frac{4 \times 0.183 \text{ m}^3/\text{min}}{\pi(7.5 \text{ m/min})}} = 0.176 \text{ m} = \mathbf{17.6 \text{ cm}}$$

Therefore, a fan with a casing diameter of 17.6 cm and a flow rate of 0.183 m^3/min will meet the design requirements.

EXAMPLE 15–16 Cooling of a Computer by a Fan

A computer cooled by a fan contains six PCBs, each dissipating 15 W of power, as shown in Fig. 15–54. The height of the PCBs is 15 cm and the length is 20 cm. The clearance between the tips of the components on the PCB and the back surface of the adjacent PCB is 0.4 cm. The cooling air is supplied by a 20-W fan mounted at the inlet. If the temperature rise of air as it flows through the case of the computer is not to exceed 10°C, determine (*a*) the flow rate of the air the fan needs to deliver, (*b*) the fraction of the temperature rise of air due to the heat generated by the fan and its motor, and (*c*) the highest allowable inlet air temperature if the surface temperature of the components is not to exceed 90°C anywhere in the system.

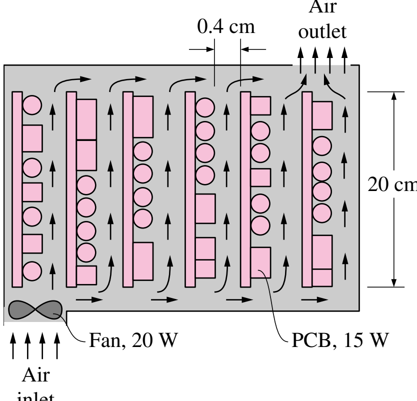


FIGURE 15–54
Schematic of the computer discussed in Example 15–16.

SOLUTION A computer cooled by a fan, and the temperature rise of air is limited to 10°C. The flow rate of the air, the fraction of the temperature rise of air caused by the fan and its motor, and maximum allowable air inlet temperature are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Air is an ideal gas. **3** The computer is located at sea level so that the local atmospheric pressure is 1 atm. **4** The entire heat generated by the electronic components is removed by air flowing through the opening between the PCBs. **5** The entire power consumed by the fan motor is transferred as heat to the cooling air. This is a conservative approach since the fan and its motor are usually mounted to the chassis of the electronic system, and some of the heat generated in the motor may be conducted to the chassis through the mounting brackets.

Properties We use properties of air at 30°C since the air enters at room temperature, and the temperature rise of air is limited to just 10°C.(Table A–15)

$$\rho = 1.164 \text{ kg/m}^3 \qquad k = 0.02588 \text{ W/m}\cdot{}^\circ\text{C}$$
$$c_p = 1007 \text{ J/kg}\cdot{}^\circ\text{C} \qquad \nu = 1.608 \times 10^{-5} \text{ m}^2/\text{s}$$
$$\text{Pr} = 0.7282$$

Analysis Because of symmetry, we consider the flow area between the two adjacent PCBs only. We assume the flow rate of air through all six channels to be identical, and to be equal to one-sixth of the total flow rate.

(a) Noting that the temperature rise of air is limited to 10°C and that the power consumed by the fan is also absorbed by the air, the total mass flow rate of air through the computer can be determined from

$$\dot{Q} = \dot{m}c_p(T_{\text{out}} - T_{\text{in}})$$

Solving for $\dot{m}$ and substituting the given values, we obtain

$$\dot{m} = \frac{\dot{Q}}{c_p(T_{\text{out}} - T_{\text{in}})} = \frac{(6 \times 15 + 20) \text{ J/s}}{(1007 \text{ J/kg}\cdot{}^\circ\text{C})(10^\circ\text{C})} = 0.01092 \text{ kg/s}$$

Then the volume flow rate of air and the air velocity become

$$\dot{V} = \frac{\dot{m}}{\rho} = \frac{0.01092 \text{ kg/s}}{1.164 \text{ kg/m}^3} = 0.009381 \text{ m}^3\text{/s} = \mathbf{0.563 \text{ m}^3\text{/min}}$$

$$V = \frac{\dot{V}}{A_c} = \frac{0.009381 \text{ m}^3\text{/s}}{(0.15 \times 0.004)} = 2.606 \text{ m/s}$$

Therefore, the fan needs to supply air at a rate of 0.563 m^3/min, or about 20 cfm.

(*b*) The temperature rise of air due to the power consumed by the fan motor can be determined by assuming the entire 20 W of power consumed by the motor to be transferred to air as heat:

$$\Delta T_{\text{air, rise}} = \frac{\dot{Q}_{fan}}{\dot{m}c_p} = \frac{20 \text{ J/s}}{(0.01092 \text{ kg/s})(1007 \text{ J/kg} \cdot °\text{C})} = \mathbf{1.8°C}$$

Therefore, 18 percent of the temperature rise of air is due to the heat generated by the fan motor. Note that the fraction of the power consumed by the fan is also 18 percent of the total, as expected.

(*c*) The surface temperature of the channel at any location can be determined from

$$\dot{q}_{\text{conv}} = \dot{Q}_{\text{conv}}/A_s = h(T_s - T_{\text{fluid}})$$

where the heat transfer surface area is

$$A_s = A_{\text{side}} = (\text{Height})(\text{Length}) = (0.15 \text{ m})(0.20 \text{ m}) = 0.03 \text{ m}^2$$

To determine the convection heat transfer coefficient, we first need to calculate the Reynolds number. The cross-sectional area of the channel and its hydraulic diameter are

$$A_c = (\text{Height})(\text{Width}) = (0.15 \text{ m})(0.004 \text{ m}) = 6 \times 10^{-4} \text{ m}^2$$

$$D_h = \frac{4A_c}{p} = \frac{4 \times (6 \times 10^{-4} \text{ m}^2)}{2 \times (0.15 + 0.004) \text{ m}} = 0.007792 \text{ m}$$

Then the Reynolds number becomes

$$\text{Re} = \frac{VD_h}{\nu} = \frac{(2.606 \text{ m/s})(0.007792 \text{ m})}{1.608 \times 10^{-5} \text{ m}^2\text{/s}} = 1263 < 2300$$

Therefore, the flow is laminar, and, assuming fully developed flow, the Nusselt number for the airflow in this rectangular cross-section corresponding to the aspect ratio a/b = (15 cm)/(0.4 cm) = 37.5 ≈ ∞ is determined from Table 15–3 to be

$$\text{Nu} = 8.24$$

and thus

$$h = \frac{k}{D_h}\text{Nu} = \frac{0.02588 \text{ W/m} \cdot °\text{C}}{0.007792 \text{ m}}(8.24) = 27.4 \text{ W/m}^2 \cdot °\text{C}$$

Disregarding the entrance effects, the temperature difference between the surface of the PCB and the air anywhere along the channel is determined to be

$$T_s - T_{\text{fluid}} = \left(\frac{\dot{q}}{h}\right)_{\text{PCB}} = \frac{(15\ \text{W})/(0.03\ \text{m}^2)}{27.4\ \text{W/m}^2\cdot{}^\circ\text{C}} = 18.3^\circ\text{C}$$

That is, the surface temperature of the components on the PCB will be 18.3°C higher than the temperature of air passing by.

The highest air and component temperatures will occur at the exit. Therefore, in the limiting case, the component surface temperature at the exit will be 90°C. The air temperature at the exit in this case will be

$$T_{\text{out, max}} = T_{s,\text{ max}} - \Delta T_{\text{rise}} = 90^\circ\text{C} - 18.3^\circ\text{C} = 71.7^\circ\text{C}$$

Noting that the air experiences a temperature rise of 10°C between the inlet and the exit, the inlet temperature of air is

$$T_{\text{in, max}} = T_{\text{out, max}} - 10^\circ\text{C} = (71.7 - 10)^\circ\text{C} = \mathbf{61.7^\circ C}$$

This is the highest allowable air inlet temperature if the surface temperature of the components is not to exceed 90°C anywhere in the system.

It should be noted that the analysis presented above is approximate since we have made some simplifying assumptions. However, the accuracy of the results obtained is usually adequate for engineering purposes.

15–9 ▪ LIQUID COOLING

Liquids normally have much higher thermal conductivities than gases, and thus much higher heat transfer coefficients associated with them. Therefore, liquid cooling is far more effective than gas cooling. However, liquid cooling comes with its own risks and potential problems, such as leakage, corrosion, extra weight, and condensation. Therefore, liquid cooling is reserved for applications involving power densities that are too high for safe dissipation by air cooling.

Liquid cooling systems can be classified as **direct cooling** and **indirect cooling** systems. In *direct cooling* systems, the electronic components are in direct contact with the liquid, and thus the heat generated in the components is transferred directly to the liquid. In *indirect cooling* systems, however, there is no direct contact with the components. The heat generated in this case is first transferred to a medium such as a *cold plate* before it is carried away by the liquid. Liquid cooling systems are also classified as *closed-loop* and *open-loop* systems, depending on whether the liquid is discarded or recirculated after it is heated. In open-loop systems, tap water flows through the cooling system and is discarded into a drain after it is heated. The heated liquid in closed-loop systems is cooled in a heat exchanger and recirculated through the system. Closed-loop systems facilitate better temperature control while conserving water.

The electronic components in direct cooling systems are usually completely immersed in the liquid. The heat transfer from the components to the liquid can be by natural or forced convection or *boiling,* depending on the temperature levels involved and the properties of the fluids. Immersion cooling of electronic devices usually involves boiling and thus very high heat transfer coefficients, as discussed in the next section. Note that only *dielectric fluids* can be used in immersion or direct liquid cooling. This limitation immediately excludes water from consideration as a prospective fluid in immersion cooling.

Fluorocarbon fluids such as FC75 are well suited for direct cooling and are commonly used in such applications.

Indirect liquid cooling systems of electronic devices operate just like the cooling system of a *car engine,* where the water (actually a mixture of water and ethylene glycol) circulates through the passages around the cylinders of the engine block, absorbing heat generated in the cylinders by combustion. The heated water is then routed by the water pump to the radiator, where it is cooled by air blown through the radiator coils by the cooling fan. The cooled water is then rerouted to the engine to transfer more heat. To appreciate the effectiveness of the cooling system of a car engine, it will suffice to say that the temperatures encountered in the engine cylinders are typically much higher than the melting temperatures of the engine blocks.

In an electronic system, the heat is generated in the *components* instead of the combustion chambers. The components in this case are mounted on a metal plate made of a highly conducting material such as copper or aluminum. The metal plate is cooled by circulating a cooling fluid through tubes attached to it, as shown in Fig. 15–55. The heated liquid is then cooled in a heat exchanger, usually by air (or sea water in marine applications), and is recirculated by a pump through the tubes. The expansion and storage tank accommodates any expansions and contractions of the cooling liquid due to temperature variations while acting as a liquid reservoir.

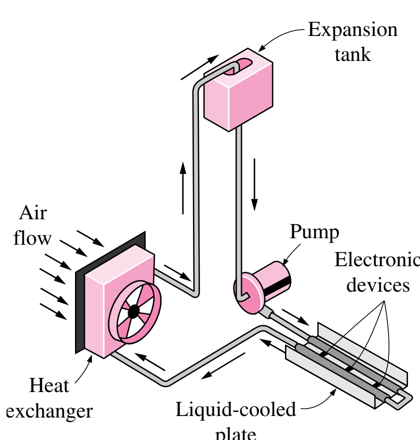


FIGURE 15–55
Schematic of an indirect liquid cooling system.

The liquids used in the cooling of electronic equipment must meet several requirements, depending on the specific application. Desirable characteristics of cooling liquids include *high thermal conductivity* (yields high heat transfer coefficients), *high specific heat* (requires smaller mass flow rate), *low viscosity* (causes a smaller pressure drop, and thus requires a smaller pump), *high surface tension* (less likely to cause leakage problems), *high dielectric strength* (a must in direct liquid cooling), *chemical inertness* (does not react with surfaces with which it comes into contact), *chemical stability* (does not decompose under prolonged use), *nontoxic* (safe for personnel to handle), *low freezing and high boiling points* (extends the useful temperature range), and *low cost.* Different fluids may be selected in different applications because of the different priorities set in the selection process.

The heat sinks or cold plates of an electronic enclosure are usually cooled by *water* by passing it through channels made for this purpose or through tubes attached to the cold plate. High heat removal rates can be achieved by circulating water through these channels or tubes. In high-performance systems, a *refrigerant* can be used in place of water to keep the temperature of the heat sink at subzero temperatures and thus reduce the junction temperatures of the electronic components proportionately. The heat transfer and pressure drop calculations in liquid cooling systems can be performed using appropriate relations.

Liquid cooling can be used effectively to cool clusters of electronic devices attached to a tubed metal plate (or heat sink), as shown in Fig. 15–56. Here 12 TO-3 cases, each dissipating up to 150 W of power, are mounted on a heat sink equipped with tubes on the back side through which a liquid flows. The thermal resistance between the case of the devices and the liquid is minimized in this case, since the electronic devices are mounted directly over the cooling lines. The case-to-liquid thermal resistance depends on the spacing between the devices, the quality of the thermal contact between the devices and the plate, the thickness of the plate, and the flow rate of the liquid, among other

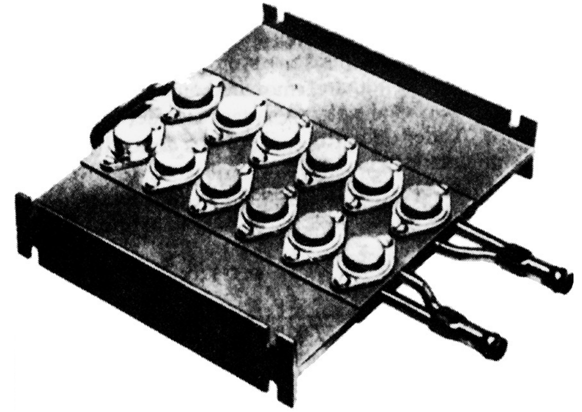


FIGURE 15–56
Liquid cooling of TO-3 packages placed on top of the coolant line.
(Courtesy of Wakefield Engineering.)

things. The tubed metal plate shown is 15.2 cm × 18 cm × 2.5 cm in size and is capable of dissipating up to 2 kW of power.

The thermal resistance network of a liquid cooling system is shown in Fig. 15–57. The junction temperatures of silicon-based electronic devices are usually limited to 125°C. The *junction-to-case* thermal resistance of a device is provided by the manufacturer. The *case-to-liquid* thermal resistance can be determined experimentally by measuring the temperatures of the case and the liquid, and dividing the difference by the total power dissipated. The *liquid-to-air* thermal resistance at the heat exchanger can be determined in a similar manner. That is,

$$R_{\text{case-liquid}} = \frac{T_{\text{case}} - T_{\text{liquid, device}}}{\dot{Q}} \qquad (°\text{C/W}) \qquad (15\text{–}25)$$
$$R_{\text{liquid-air}} = \frac{T_{\text{liquid, hx}} - T_{\text{air, in}}}{\dot{Q}}$$

where $T_{\text{liquid, device}}$ and $T_{\text{liquid, hx}}$ are the inlet temperatures of the liquid to the electronic device and the heat exchanger, respectively. The required mass flow rate of the liquid corresponding to a specified temperature rise of the liquid as it flows through the electronic systems can be determined from Eq. 15–17.

Electronic components mounted on liquid-cooled metal plates should be provided with good thermal contact in order to minimize the thermal resistance between the components and the plate. The thermal resistance can be minimized by applying silicone grease or beryllium oxide to the contact surfaces and fastening the components tightly to the metal plate. The liquid cooling of a cold plate with a large number of high-power components attached to it is illustrated in Example 15–17.

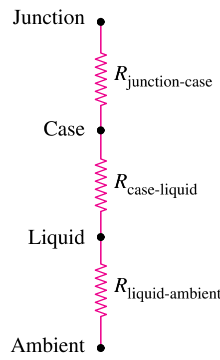


FIGURE 15–57
Thermal resistance network for a liquid-cooled electronic device.

EXAMPLE 15–17 Cooling of Power Transistors on a Cold Plate by Water

A cold plate that supports 20 power transistors, each dissipating 40 W, is to be cooled with water, as shown in Fig. 15–58. Half of the transistors are attached to the back side of the cold plate. It is specified that the temperature rise of the water is not to exceed 3°C and the velocity of water is to remain under 1 m/s. Assuming that 20 percent of the heat generated is dissipated from the

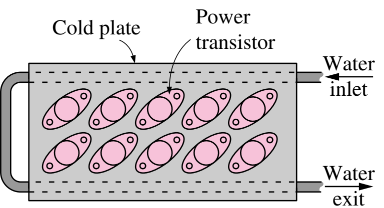


FIGURE 15–58
Schematic for Example 15–17.

components to the surroundings by convection and radiation, and the remaining 80 percent is removed by the cooling water, determine the mass flow rate of water needed and the diameter of the pipe to satisfy the restriction imposed on the flow velocity. Also, determine the case temperature of the devices if the total case-to-liquid thermal resistance is 0.030°C/W and the water enters the cold plate at 35°C.

SOLUTION A cold plate is to be cooled by water. The mass flow rate of water, the diameter of the pipe, and the case temperature of the transistors are to be determined.

Assumptions **1** Steady operating conditions exist. **2** About 20 percent of the heat generated is dissipated from the components to the surroundings by convection and radiation.

Properties The properties of water at room temperature are $\rho = 1000$ kg/m^3 and $c_p = 4180$ J/kg · °C.

Analysis Noting that each of the 20 transistors dissipates 40 W of power and 80 percent of this power must be removed by the water, the amount of heat that must be removed by the water is

$$\dot{Q} = (20 \text{ transistors})(40 \text{ W/transistor})(0.80) = 640 \text{ W}$$

In order to limit the temperature rise of the water to 3°C, the mass flow rate of water must be no less than

$$\dot{m} = \frac{\dot{Q}}{c_p \Delta T_{\text{rise}}} = \frac{640 \text{ J/s}}{(4180 \text{ J/kg} \cdot \text{°C})(3\text{°C})} = 0.051 \text{ kg/s} = \mathbf{3.06 \text{ kg/min}}$$

The mass flow rate of a fluid through a circular pipe can be expressed as

$$\dot{m} = \rho A_c V = \rho \frac{\pi D^2}{4} V$$

Then the diameter of the pipe to maintain the velocity of water under 1 m/s is determined to be

$$D = \sqrt{\frac{4\dot{m}}{\pi \rho V}} = \sqrt{\frac{4(0.051 \text{ kg/s})}{\pi(1000 \text{ kg/m}^3)(1 \text{ m/s})}} = 0.0081 \text{ m} = \mathbf{0.81 \text{ cm}}$$

Noting that the total case-to-liquid thermal resistance is 0.030°C/W and the water enters the cold plate at 35°C, the case temperature of the devices is determined from Eq. 15–25 to be

$$T_{\text{case}} = T_{\text{liquid, device}} + \dot{Q}R_{\text{case-liquid}} = 35\text{°C} + (640 \text{ W})(0.03\text{°C/W}) = \mathbf{54.2\text{°C}}$$

The junction temperature of the device can be determined similarly by using the junction-to-case thermal resistance of the device supplied by the manufacturer.

15–10 ▪ IMMERSION COOLING

High-power electronic components can be cooled effectively by immersing them in a *dielectric liquid* and taking advantage of the very high heat transfer coefficients associated with boiling. Immersion cooling has been used since the 1940s in the cooling of electronic equipment, but for many years its

use was largely limited to the electronics of high-power radar systems. The miniaturization of electronic equipment and the resulting high heat fluxes brought about renewed interest in immersion cooling, which had been largely viewed as an exotic cooling technique.

You will recall from thermodynamics that, at a specified pressure, a fluid boils isothermally at the corresponding saturation temperature. A large amount of heat is absorbed during the boiling process, essentially in an isothermal manner. Therefore, immersion cooling also provides a constant-temperature bath for the electronic components and eliminates hot spots effectively.

The simplest type of immersion cooling system involves an *external reservoir* that supplies liquid continually to the electronic enclosure. The vapor generated inside is simply allowed to escape to the atmosphere, as shown in Fig. 15–59. A pressure relief valve on the vapor vent line keeps the pressure and thus the temperature inside at the preset value, just like the petcock of a pressure cooker. Note that without a pressure relief valve, the pressure inside the enclosure would be atmospheric pressure and the temperature would have to be the boiling temperature of the fluid at the atmospheric pressure.

The **open-loop**-type immersion cooling system described here is simple, but there are several impracticalities associated with it. First of all, it is heavy and bulky because of the presence of an external liquid reservoir, and the fluid lost through evaporation needs to be replenished continually, which adds to the cost. Further, the release of the vapor into the atmosphere greatly limits the fluids that can be used in such a system. Therefore, the use of open-loop immersion systems is limited to applications that involve occasional use and thus have a light duty cycle.

More sophisticated immersion cooling systems operate in a **closed loop** in that the vapor is condensed and returned to the electronic enclosure instead of being purged to the atmosphere. Schematics of two such systems are given in Fig. 15–60. The first system involves a condenser *external* to the electronics

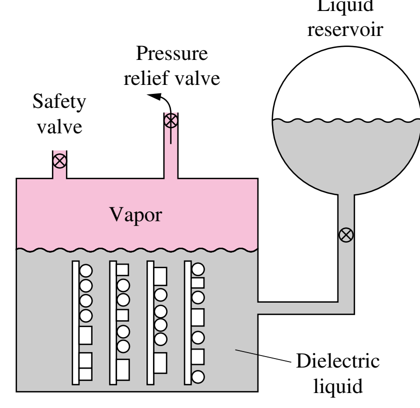


FIGURE 15–59
A simple open-loop immersion cooling system.

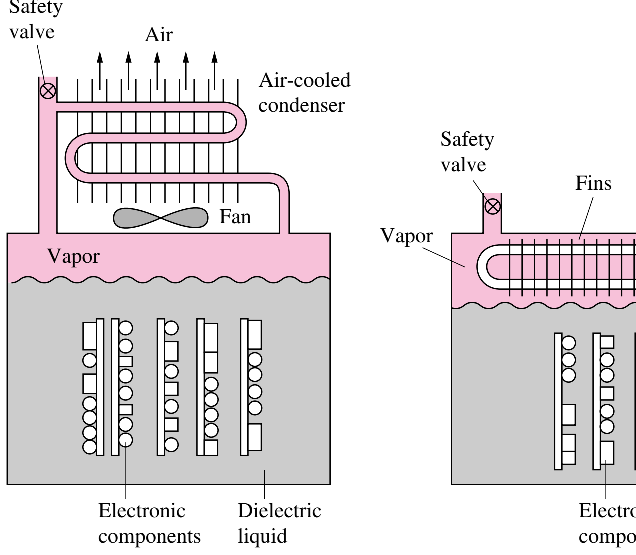


FIGURE 15–60
The schematics of two closed-loop immersion cooling systems.

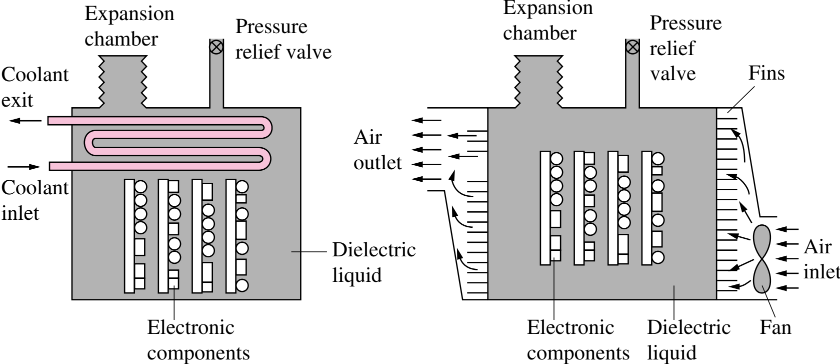


FIGURE 15–61
The schematics of two all-liquid immersion cooling systems.

enclosure, and the vapor leaving the enclosure is cooled by a cooling fluid such as air or water outside the enclosure. The condensate is returned to the enclosure for reuse. The condenser in the second system is actually *submerged* in the electronic enclosure and is part of the electronic system. The cooling fluid in this case circulates through the condenser tube, removing heat from the vapor. The vapor that condenses drips on top of the liquid in the enclosure and continues to recirculate.

The performance of closed-loop immersion cooling systems is most susceptible to the presence of *noncondensable gases* such as air in the vapor space. An increase of 0.5 percent of air by mass in the vapor can cause the condensation heat transfer coefficient to drop by a factor of up to 5. Therefore, the fluid used in immersion cooling systems should be degassed as much as practical, and care should be taken during the filling process to avoid introducing any air into the system.

The problems associated with the condensation process and noncondensable gases can be avoided by *submerging* the condenser (actually, heat exchanger tubes in this case) in the *liquid* instead of the vapor in the electronic enclosure, as shown in Fig. 15–61*a*. The cooling fluid, such as water, circulating through the tubes absorbs heat from the dielectric liquid at the top portion of the enclosure and subcools it. The liquid in contact with the electronic components is heated and may even be vaporized as a result of absorbing heat from the components. But these vapor bubbles collapse as they move up, as a result of transferring heat to the cooler liquid with which they come in contact. This system can still remove heat at high rates from the surfaces of electronic components in an isothermal manner by utilizing the boiling process, but its overall capacity is limited by the rate of heat that can be removed by the external cooling fluid in a *liquid-to-liquid* heat exchanger. Noting that the heat transfer coefficients associated with forced convection are far less than those associated with condensation, this all-liquid immersion cooling system is not suitable for electronic boxes with very high power dissipation rates per unit volume.

A step further in the all-liquid immersion cooling systems is to remove the heat from the dielectric liquid directly from the *outer surface* of the electronics enclosure, as shown in Fig. 15–61*b*. In this case, the dielectric liquid inside

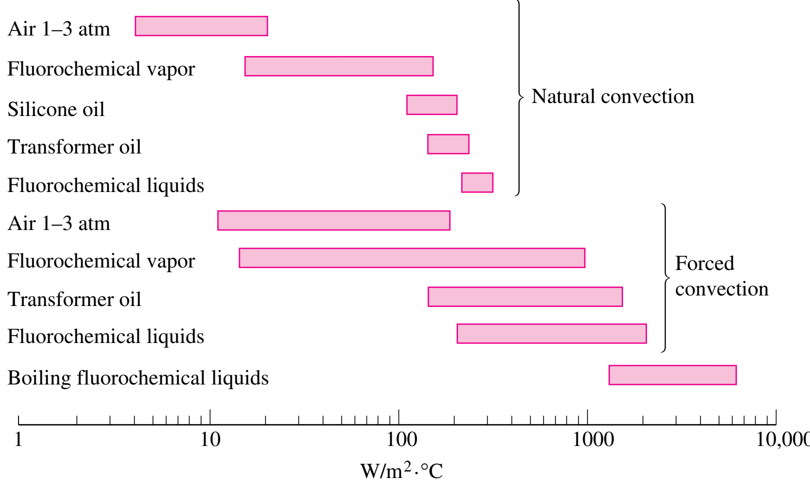


FIGURE 15–62
Typical heat transfer coefficients for various dielectric fluids.
(From Hwang and Moran, 1981.)

the sealed enclosure is heated as a result of absorbing the heat dissipated by the electronic components. The heat is then transferred to the walls of the enclosure, where it is removed by external means. This immersion cooling technique is the most reliable of all since it does not involve any penetration into the electronics enclosure and the components reside in a completely sealed liquid environment. However, the use of this system is limited to applications that involve moderate power dissipation rates. The heat dissipation is limited by the ability of the system to reject the heat from the outer surface of the enclosure. To enhance this ability, the outer surfaces of the enclosures are often *finned,* especially when the enclosure is cooled by air.

Typical ranges of heat transfer coefficients for various dielectric fluids suitable for use in the cooling of electronic equipment are given in Fig. 15–62 for natural convection, forced convection, and boiling. Note that extremely high heat transfer coefficients (from about 1500 to 6000 W/m^2 · °C) can be attained with the boiling of *fluorocarbon fluids* such as FC78 and FC86 manufactured by the 3M company. Fluorocarbon fluids, not to be confused with the ozone-destroying fluorochloro fluids, are found to be very suitable for immersion cooling of electronic equipment. They have boiling points ranging from 30°C to 174°C and freezing points below −50°C. They are nonflammable, chemically inert, and highly compatible with materials used in electronic equipment.

Experimental results for the power dissipation of a chip having a heat transfer area of 0.457 cm^2 and its substrate during immersion cooling in an FC86 bath are given in Fig. 15–63. The FC86 liquid is maintained at a bulk temperature of 5°C during the experiments by the use of a heat exchanger. Heat transfer from the chip is by *natural convection* in regime A–B, and *bubble formation* and thus boiling begins in regime B–C. Note that the chip surface temperature suddenly drops with the onset of *boiling* because of the high heat transfer coefficients associated with boiling. Heat transfer is by nucleate boiling in regime C–D, and very high heat transfer rates can be achieved in this regime with relatively small temperature differences.

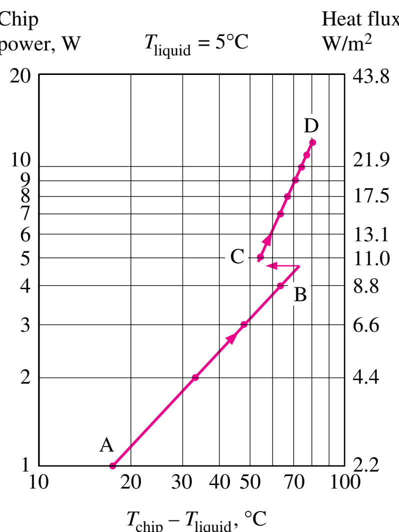


FIGURE 15–63
Heat transfer from a chip immersed in the fluorocarbon fluid FC86.
(From Hwang and Moran, 1981.)

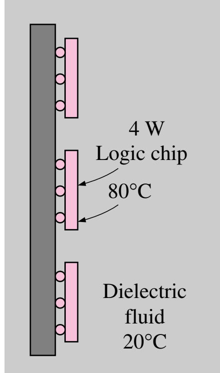


FIGURE 15–64
Schematic for Example 15–18.

EXAMPLE 15–18 Immersion Cooling of a Logic Chip

A logic chip used in an IBM 3081 computer dissipates 4 W of power and has a heat transfer surface area of 0.279 cm^2, as shown in Fig. 15–64. If the surface of the chip is to be maintained at 80°C while being cooled by immersion in a dielectric fluid at 20°C, determine the necessary heat transfer coefficient and the type of cooling mechanism that needs to be used to achieve that heat transfer coefficient.

SOLUTION A logic chip is to be cooled by immersion in a dielectric fluid. The minimum heat transfer coefficient and the type of cooling mechanism are to be determined.

Assumptions Steady operating conditions exist.

Analysis The average heat transfer coefficient over the surface of the chip can be determined from Newton's law of cooling,

$$\dot{Q} = hA_s(T_{\text{chip}} - T_{\text{fluid}})$$

Solving for h and substituting the given values, the convection heat transfer coefficient is determined to be

$$h = \frac{\dot{Q}}{A_s(T_{\text{chip}} - T_{\text{fluid}})} = \frac{4\text{ W}}{(0.279 \times 10^{-4}\text{ m}^2)(80 - 20)°\text{C}} = \mathbf{2390\ W/m^2 \cdot °C}$$

which is rather high. Examination of Figure 15–62 reveals that we can obtain such high heat transfer coefficients with the boiling of fluorocarbon fluids. Therefore, a suitable cooling technique in this case is immersion cooling in such a fluid. A viable alternative to immersion cooling is the thermal conduction module discussed earlier.

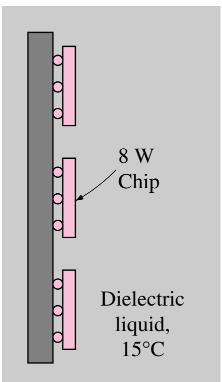


FIGURE 15–65
Schematic for Example 15–19.

EXAMPLE 15–19 Cooling of a Chip by Boiling

An 8-W chip having a surface area of 0.6 cm^2 is cooled by immersing it into FC86 liquid that is maintained at a temperature of 15°C, as shown in Fig. 15–65. Using the boiling curve in Fig. 15–63, estimate the temperature of the chip surface.

SOLUTION A chip is cooled by boiling in a dielectric fluid. The surface temperature of the chip is to be determined.

Assumptions The boiling curve in Fig. 15–63 is prepared for a chip having a surface area of 0.457 cm^2 being cooled in FC86 maintained at 5°C. The chart can be used for similar cases with reasonable accuracy.

Analysis The heat flux is

$$\dot{q} = \frac{\dot{Q}}{A_s} = \frac{8\text{ W}}{0.6\text{ cm}^2} = 13.3\text{ W/cm}^2$$

Corresponding to this value on the chart is $T_{\text{chip}} - T_{\text{fluid}} = 60°\text{C}$. Therefore,

$$T_{\text{chip}} = T_{\text{fluid}} + 60 = 15 + 60 = \mathbf{75°C}$$

That is, the surface of this 8-W chip will be at 75°C as it is cooled by boiling in the dielectric fluid FC86.

A liquid-based cooling system brings with it the possibility of leakage and associated reliability concerns. Therefore, the consideration of immersion cooling should be limited to applications that require precise temperature control and those that involve heat dissipation rates that are too high for effective removal by conduction or air cooling.

SUMMARY

Electric current flow through a resistance is always accompanied by heat generation, and the essence of thermal design is the safe removal of this internally generated heat by providing an effective path for heat flow from electronic components to the surrounding medium. In this chapter, we have discussed several *cooling techniques* commonly used in electronic equipment, such as conduction cooling, natural convection and radiation cooling, forced-air convection cooling, liquid cooling, immersion cooling, and heat pipes.

In a chip carrier, heat generated at the junction is conducted along the thickness of the chip, the bonding material, the lead frame, the case material, and the leads. The *junction-to-case thermal resistance* $R_{\text{junction-case}}$ represents the total resistance to heat transfer between the junction of a component and its case. This resistance should be as low as possible to minimize the temperature rise of the junction above the case temperature. The epoxy board used in PCBs is a poor heat conductor, and so it is necessary to use copper cladding or to attach the PCB to a heat frame in conduction-cooled systems.

Low-power electronic systems can be cooled effectively with natural convection and radiation. The heat transfer from a surface at temperature T_s to a fluid at temperature T_{fluid} by *convection* is expressed as

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_{\text{fluid}})$$

where h is the convection heat transfer coefficient and A_s is the heat transfer surface area. The natural convection heat transfer coefficient for laminar flow of air at atmospheric pressure is given by a simplified relation of the form

$$h = K\left(\frac{\Delta T}{L_c}\right)^{0.25}$$

where $\Delta T = T_s - T_{\text{fluid}}$ is the temperature difference between the surface and the fluid, L_c is the characteristic length (the length of the body along the heat flow path), and K is a constant, whose value is given in Table 15–1. The relations in Table 15–1 can also be used at pressures other than 1 atm by multiplying them by $\sqrt{P}$, where P is the air pressure in atm.

Radiation heat transfer between a surface at temperature T_s completely surrounded by a much larger surface at temperature T_{surr} can be expressed as

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

where ε is the emissivity of the surface, A_s is the heat transfer surface area, and σ is the Stefan–Boltzmann constant, whose value is $\sigma = 5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4 = 0.1714 \times 10^{-8}\ \text{Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$.

Fluid flow over a body such as a transistor is called *external flow,* and flow through a confined space such as inside a tube or through the parallel passage area between two circuit boards in an enclosure is called *internal flow.* Fluid flow is also categorized as being *laminar* or *turbulent,* depending on the value of the Reynolds number. In convection analysis, the convection heat transfer coefficient is usually expressed in terms of the dimensionless *Nusselt number* Nu as

$$h = \frac{k}{D}\text{Nu}$$

where k is thermal conductivity of the fluid and D is the characteristic length of the geometry. Relations for the average Nusselt number based on experimental data are given in Table 15–2 for external flow and in Table 15–3 for laminar internal flow under the uniform heat flux condition, which is closely approximated by electronic equipment. In forced-air-cooled systems, the heat transfer can also be expressed as

$$\dot{Q} = \dot{m}c_p(T_{\text{out}} - T_{\text{in}})$$

where $\dot{Q}$ is the rate of heat transfer to the air; c_p is the specific heat of air; T_{in} and T_{out} are the average temperatures of air at the inlet and exit of the enclosure, respectively; and $\dot{m}$ is the mass flow rate of air.

The heat transfer coefficients associated with liquids are usually an order of magnitude higher than those associated with gases. Liquid cooling systems can be classified as *direct cooling* and *indirect cooling* systems. In direct cooling systems, the electronic components are in direct contact with the liquid, and thus the heat generated in the components is transferred directly to the liquid. In indirect cooling systems, however, there is no direct contact with the components. Liquid cooling systems are also classified as *closed-loop* and *open-loop* systems, depending on whether the liquid is discharged or recirculated after it is heated. Only *dielectric fluids* can be used in immersion or direct liquid cooling.

High-power electronic components can be cooled effectively by immersing them in a *dielectric liquid* and taking advantage of the very high heat transfer coefficients associated with boiling. The simplest type of immersion cooling system involves an

external reservoir that supplies liquid continually to the electronic enclosure. This *open-loop-type* immersion cooling system is simple but often impractical. Immersion cooling systems usually operate in a *closed loop,* in that the vapor is condensed and returned to the electronic enclosure instead of being purged to the atmosphere.

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PROBLEMS*

Introduction and History

15–1C What invention started the electronic age? Why did the invention of the transistor mark the beginning of a revolution in that age?

15–2C What is an integrated circuit? What is its significance in the electronics era? What do the initials MSI, LSI, and VLSI stand for?

15–3C When electric current I passes through an electrical element having a resistance R, why is heat generated in the element? How is the amount of heat generation determined?

15–4C Consider a TV that is wrapped in the blankets from all sides except its screen. Explain what will happen when the TV is turned on and kept on for a long time, and why. What will happen if the TV is kept on for a few minutes only?

15–5C Consider an incandescent light bulb that is completely wrapped in a towel. Explain what will happen when the light is turned on and kept on. (P.S. Do not try this at home!)

15–6C A businessman ties a large cloth advertisement banner in front of his car such that it completely blocks the airflow to the radiator. What do you think will happen when he starts the car and goes on a trip?

*Problems designated by a "C" are concept questions, and students are encouraged to answer them all. Problems designated by an "E" are in English units, and the SI users can ignore them.

15–7C Which is more likely to break: a car or a TV? Why?

15–8C Why do electronic components fail under prolonged use at high temperatures?

15–9 The temperature of the case of a power transistor that is dissipating 12 W is measured to be 60°C. If the junction-to-case thermal resistance of this transistor is specified by the manufacturer to be 5°C/W, determine the junction temperature of the transistor. *Answer:* 120°C

15–10 Power is supplied to an electronic component from a 12-V source, and the variation in the electric current, the junction temperature, and the case temperatures with time are observed. When everything is stabilized, the current is observed to be 0.15 A and the temperatures to be 80°C and 55°C at the junction and the case, respectively. Calculate the junction-to-case thermal resistance of this component.

15–11 A logic chip used in a computer dissipates 6 W of power in an environment at 55°C and has a heat transfer surface area of 0.32 cm^2. Assuming the heat transfer from the surface to be uniform, determine (*a*) the amount of heat this chip dissipates during an 8-h work day, in kWh, and (*b*) the heat flux on the surface of the chip, in W/cm^2.

15–12 A 15-cm × 20-cm circuit board houses 90 closely spaced logic chips, each dissipating 0.1 W, on its surface. If the heat transfer from the back surface of the board is negligible, determine (*a*) the amount of heat this circuit board dissipates during a 10-h period, in kWh, and (*b*) the heat flux on the surface of the circuit board, in W/cm^2.

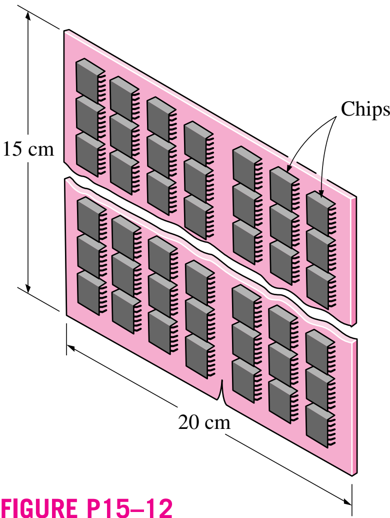

FIGURE P15–12

15–13E A resistor on a circuit board has a total thermal resistance of 130°F/W. If the temperature of the resistor is not to exceed 360°F, determine the power at which it can operate safely in an ambient at 120°F.

15–14 Consider a 0.1-kΩ resistor whose surface-to-ambient thermal resistance is 300°C/W. If the voltage drop across the resistor is 7.5 V and its surface temperature is not to exceed 150°C, determine the power at which it can operate safely in an ambient at 30°C. *Answer:* 0.4 W

15–15 Reconsider Prob. 15–14. Using EES (or other) software, plot the power at which the resistor can operate safely as a function of the ambient temperature as the temperature varies from 20ºC to 40ºC, and discuss the results.

Manufacturing of Electronic Equipment

15–16C Why is a chip in a chip carrier bonded to a lead frame instead of the plastic case of the chip carrier?

15–17C Draw a schematic of a chip carrier, and explain how heat is transferred from the chip to the medium outside of the chip carrier.

15–18C What does the junction-to-case thermal resistance represent? On what does it depend for a chip carrier?

15–19C What is a hybrid chip carrier? What are the advantages of hybrid electronic packages?

15–20C What is a PCB? Of what is the board of a PCB made? What does the "device-to-PCB edge" thermal resistance in conduction-cooled systems represent? Why is this resistance relatively high?

15–21C What are the three types of printed circuit boards? What are the advantages and disadvantages of each type?

15–22C What are the desirable characteristics of the materials used in the fabrication of the circuit boards?

15–23C What is an electronic enclosure? What is the primary function of the enclosure of an electronic system? Of what materials are the enclosures made?

Cooling Load of Electronic Equipment and Thermal Environment

15–24C Consider an electronics box that consumes 120 W of power when plugged in. How is the heating load of this box determined?

15–25C Why is the development of superconducting materials generating so much excitement among designers of electronic equipment?

15–26C How is the duty cycle of an electronic system defined? How does the duty cycle affect the design and selection of a cooling technique for a system?

15–27C What is temperature cycling? How does it affect the reliability of electronic equipment?

15–28C What is the ultimate heat sink for (*a*) a TV, (*b*) an airplane, and (*c*) a ship? For each case, what is the range of temperature variation of the ambient?

15–29C What is the ultimate heat sink for (*a*) a DVD player, (*b*) a spacecraft, and (*c*) a communication system on top of a mountain? For each case, what is the range of temperature variation of the ambient?

Electronics Cooling in Different Applications

15–30C How are the electronics of short-range and long-range missiles cooled?

15–31C What is dynamic temperature? What causes it? How is it determined? At what velocities is it significant?

15–32C How are the electronics of a ship or submarine cooled?

15–33C How are the electronics of the communication systems at remote areas cooled?

15–34C How are the electronics of high-power microwave equipment such as radars cooled?

15–35C How are the electronics of a space vehicle cooled?

15–36 Consider an airplane cruising in the air at a temperature of −25°C at a velocity of 850 km/h. Determine the temperature rise of air at the nose of the airplane as a result of the ramming effect of the air.

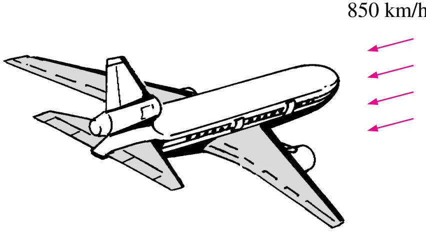

FIGURE P15–36

15–37 The temperature of air in high winds is measured by a thermometer to be 12°C. Determine the true temperature of air if the wind velocity is 90 km/h. *Answer:* 11.7°C

15–38 Reconsider Prob. 15–37. Using EES (or other) software, plot the true temperature of air as a function of the wind velocity as the velocity varies from 20 km/h to 120 km/h, and discuss the results.

15–39 Air at 25°C is flowing in a channel at a velocity of (*a*) 1, (*b*) 10, (*c*) 100, and (*d*) 1000 m/s. Determine the temperature that a stationary probe inserted into the channel will read for each case.

15–40 An electronic device dissipates 2 W of power and has a surface area of 5 cm^2. If the surface temperature of the device is not to exceed the ambient temperature by more than 50°C, determine a suitable cooling technique for this device. Use Figure 15–17.

15–41E A stand-alone circuit board, 6 in × 8 in in size, dissipates 20 W of power. The surface temperature of the board is not to exceed 165°F in an 85°F environment. Using Fig. 15–17 as a guide, select a suitable cooling mechanism.

Conduction Cooling

15–42C What are the major considerations in the selection of a cooling technique for electronic equipment?

15–43C What is thermal resistance? To what is it analogous in electrical circuits? Can thermal resistance networks be analyzed like electrical circuits? Explain.

15–44C If the rate of heat conduction through a medium and the thermal resistance of the medium are known, how can the temperature difference between the two sides of the medium be determined?

15–45C Consider a wire of electrical resistance R, length L, and cross-sectional area A through which electric current I is flowing. How is the voltage drop across the wire determined? What happens to the voltage drop when L is doubled while I is held constant?

Now consider heat conduction at a rate of $\dot{Q}$ through the same wire having a thermal resistance of R. How is the temperature drop across the wire determined? What happens to the temperature drop when L is doubled while $\dot{Q}$ is held constant?

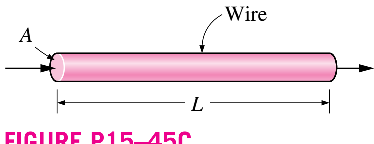

FIGURE P15–45C

15–46C What is a heat frame? How does it enhance heat transfer along a PCB? Which components on a PCB attached to a heat frame operate at the highest temperatures: those at the middle of the PCB or those near the edge?

15–47C What is constriction resistance in heat flow? To what is it analogous in fluid flow through tubes and electric current flow in wires?

15–48C What does the junction-to-case thermal resistance of an electronic component represent? In practice, how is this value determined? How can the junction temperature of a component be determined when the case temperature, the power dissipation of the component, and the junction-to-case thermal resistance are known?

15–49C What does the case-to-ambient thermal resistance of an electronic component represent? In practice, how is this value determined? How can the case temperature of a component be determined when the ambient temperature, the power dissipation of the component, and the case-to-ambient thermal resistance are known?

15–50C Consider an electronic component whose junction-to-case thermal resistance $R_{\text{junction-case}}$ is provided by the manufacturer and whose case-to-ambient thermal resistance $R_{\text{case-ambient}}$ is determined by the thermal designer. When the power dissipation of the component and the ambient temperature are known, explain how the junction temperature can be determined. When $R_{\text{junction-case}}$ is greater than $R_{\text{case-ambient}}$, will the case temperature be closer to the junction or ambient temperature?

15–51C Why is the rate of heat conduction along a PCB very low? How can heat conduction from the mid-parts of a PCB to

its outer edges be improved? How can heat conduction across the thickness of the PCB be improved?

15–52C Why is the warping of epoxy boards that are copper cladded on one side a major concern? What is the cause of this warping? How can the warping of PCBs be avoided?

15–53C Why did the thermal conduction module receive so much attention from thermal designers of electronic equipment? How does the design of TCM differ from traditional chip carrier design? Why is the cavity in the TCM filled with helium instead of air?

15–54 Consider a chip dissipating 0.8 W of power in a DIP with 18 pin leads. The materials and the dimensions of various sections of this electronic device are given in the table. If the temperature of the leads is 50°C, estimate the temperature at the junction of the chip.

Section and Material	Thermal Conductivity, W/m · °C	Thickness, mm	Heat Transfer Surface Area
Junction constriction	—	—	Diameter 0.5 mm
Silicon chip	120	0.5	4 mm × 4 mm
Eutectic bond	296	0.05	4 mm × 4 mm
Copper lead frame	386	0.25	4 mm × 4 mm
Plastic separator	1	0.3	18 × 1 mm × 0.25 mm
Copper leads	386	6	18 × 1 mm × 0.25 mm

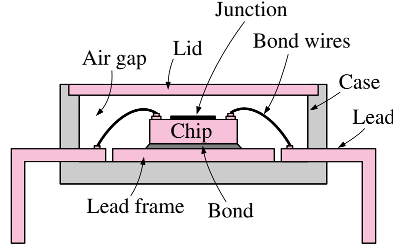

FIGURE P15–54

15–55 A fan blows air at 25°C over a 2-W plastic DIP with 16 leads mounted on a PCB at a velocity of 300 m/min. Using data from Fig. 15–23, determine the junction temperature of the electronic device. What would the junction temperature be if the fan were to fail?

15–56 Heat is to be conducted along a PCB with copper cladding on one side. The PCB is 12 cm long and 12 cm wide, and the thicknesses of the copper and epoxy layers are 0.06 mm and 0.5 mm, respectively. Disregarding heat transfer from the side surfaces, determine the percentages of heat conduction along the copper (k = 386 W/m · °C) and epoxy (k = 0.26 W/m · °C) layers. Also, determine the effective thermal conductivity of the PCB.

Answers: 0.6 percent, 99.4 percent, 41.6 W/m · °C

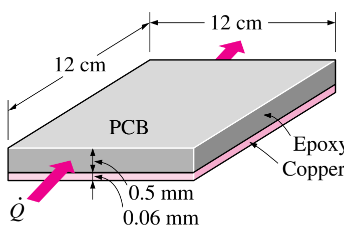

FIGURE P15–56

15–57 Reconsider Prob. 15–56. Using EES (or other) software, investigate the effect of the thickness of the copper layer on the percentage of heat conducted along the copper layer and the effective thermal conductivity of the PCB. Let the thickness vary from 0.02 mm to 0.10 mm. Plot the percentage of heat conducted along the copper layer and the effective thermal conductivity as a function of the thickness of the copper layer, and discuss the results.

15–58 The heat generated in the circuitry on the surface of a silicon chip (k = 130 W/m · °C) is conducted to the ceramic substrate to which it is attached. The chip is 6 mm × 6 mm in size and 0.5-mm thick and dissipates 3 W of power. Determine the temperature difference between the front and back surfaces of the chip in steady operation.

15–59E Consider a 6-in × 7-in glass–epoxy laminate (k = 0.15 Btu/h · ft · °F) whose thickness is 0.05 in. Determine the thermal resistance of this epoxy layer for heat flow (a) along the 7-in-long side and (b) across its thickness.

15–60 Consider a 15-cm × 18-cm glass–epoxy laminate (k = 0.26 W/m · °C) whose thickness is 1.4 mm. In order to reduce the thermal resistance across its thickness, cylindrical copper fillings (k = 386 W/m · °C) of diameter 1 mm are to be planted throughout the board with a center-to-center distance of 3 mm. Determine the new value of the thermal resistance of the epoxy board for heat conduction across its thickness as a result of this modification.

15–61 Reconsider Prob. 15–60. Using EES (or other) software, investigate the effects of the thermal conductivity and the diameter of the filling material on the thermal resistance of the epoxy board. Let the thermal conductivity vary from 10 W/m · 0°C to 400 W/m · 0°C and the diameter from 0.5 mm to 2.0 mm. Plot the thermal resistance as

functions of the thermal conductivity and the diameter, and discuss the results.

15–62 A 12-cm × 15-cm circuit board dissipating 45 W of heat is to be conduction-cooled by a 1.5-mm-thick copper heat frame (k = 386 W/m · °C) 12 cm × 17 cm in size. The epoxy laminate (k = 0.26 W/m · °C) has a thickness of 2 mm and is attached to the heat frame with conductive epoxy adhesive (k = 1.8 W/m · °C) of thickness 0.12 mm. The PCB is attached to a heat sink by clamping a 5-mm-wide portion of the edge to the heat sink from both ends. The temperature of the heat frame at this point is 30°C. Heat is uniformly generated on the PCB at a rate of 3 W per 1-cm × 12-cm strip. Considering only one-half of the PCB board because of symmetry, determine the maximum surface temperature on the PCB and the temperature distribution along the heat frame.

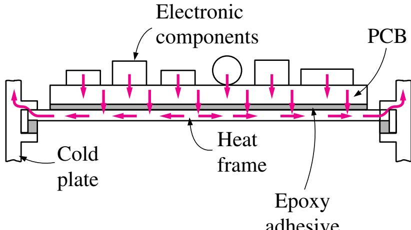

FIGURE P15–62

15–63 Consider a 15-cm × 20-cm double-sided circuit board dissipating a total of 30 W of heat. The board consists of a 3-mm-thick epoxy layer (k = 0.26 W/m · °C) with 1-mm-diameter aluminum wires (k = 237 W/m · °C) inserted along the 20-cm-long direction, as shown in Fig. P15–63. The distance between the centers of the aluminum wires is 2 mm. The circuit board is attached to a heat sink from both ends, and the temperature of the board at both ends is 30°C. Heat is considered to be uniformly generated on both sides of the epoxy layer of the PCB. Considering only a portion of the PCB because of symmetry, determine the magnitude and location of the maximum temperature that occurs in the PCB. *Answer:* 88.7°C

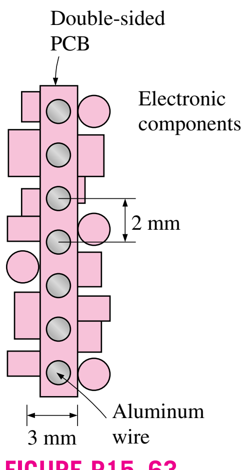

FIGURE P15–63

15–64 Repeat Prob. 15–63, replacing the aluminum wires by copper wires (k = 386 W/m · °C).

15–65 Repeat Prob. 15–63 for a center-to-center distance of 4 mm instead of 2 mm between the wires.

15–66 Consider a thermal conduction module with 80 chips, each dissipating 4 W of power. The module is cooled by water at 18°C flowing through the cold plate on top of the module. The thermal resistances in the path of heat flow are R_{chip} = 12°C/W between the junction and the surface of the chip, R_{int} = 9°C/W between the surface of the chip and the outer surface of the thermal conduction module, and R_{ext} = 7°C/W between the outer surface of the module and the cooling water. Determine the junction temperature of the chip.

15–67 Consider a 0.3-mm-thick epoxy board (k = 0.26 W/m · °C) that is 15 cm × 20 cm in size. Now a 0.1-mm-thick layer of copper (k = 386 W/m · °C) is attached to the back surface of the PCB. Determine the effective thermal conductivity of the PCB along its 20-cm-long side. What fraction of the heat conducted along that side is conducted through copper?

15–68 A 0.5-mm-thick copper plate (k = 386 W/m · °C) is sandwiched between two 3-mm-thick epoxy boards (k = 0.26 W/m · °C) that are 12 cm × 18 cm in size. Determine the effective thermal conductivity of the PCB along its 18-cm-long side. What fraction of the heat conducted along that side is conducted through copper?

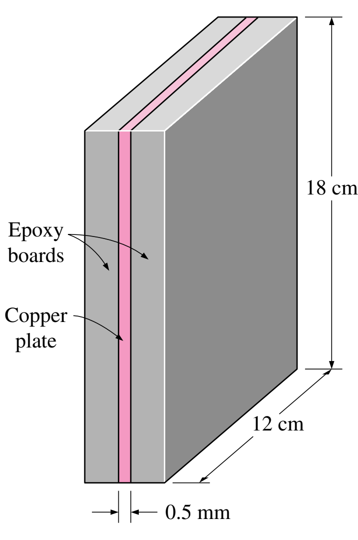

FIGURE P15–68

15–69E A 6-in × 8-in × 0.06-in copper heat frame is used to conduct 20 W of heat generated in a PCB along the

8-in-long side toward the ends. Determine the temperature difference between the midsection and either end of the heat frame. *Answer:* 12.8°F

15–70 A 12-W power transistor is cooled by mounting it on an aluminum bracket (k = 237 W/m · °C) that is attached to a liquid-cooled plate by 0.2-mm-thick epoxy adhesive (k = 1.8 W/m · °C), as shown in Fig. P15–70. The thermal resistance of the plastic washer is given as 2.5°C/W. Preliminary calculations show that about 20 percent of the heat is dissipated by convection and radiation, and the rest is conducted to the liquid-cooled plate. If the temperature of the cold plate is 50°C, determine the temperature of the transistor case.

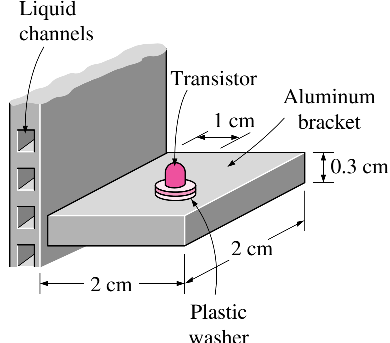

FIGURE P15–70

Air Cooling: Natural Convection and Radiation

15–71C A student puts his books on top of a DVD player, completely blocking the air vents on the top surface. What do you think will happen as the student watches a rented movie played by that DVD player?

15–72C Can a low-power electronic system in space be cooled by natural convection? Can it be cooled by radiation? Explain.

15–73C Why are there several openings on the various surfaces of a TV, DVD player, and other electronic enclosures? What happens if a TV or DVD player is enclosed in a cabinet with no free air space around?

15–74C Why should radiation heat transfer always be considered in the analysis of natural convection–cooled electronic equipment?

15–75C How does atmospheric pressure affect natural convection heat transfer? What are the best and worst orientations for heat transfer from a square surface?

15–76C What is view factor? How does it affect radiation heat transfer between two surfaces?

15–77C What is emissivity? How does it affect radiation heat transfer between two surfaces?

15–78C For most effective natural convection cooling of a PCB array, should the PCBs be placed horizontally or vertically? Should they be placed close to each other or far from each other?

15–79C Why is radiation heat transfer from the components on the PCBs in an enclosure negligible?

15–80 Consider a sealed 20-cm-high electronic box whose base dimensions are 35 cm × 50 cm that is placed on top of a stand in a room at 30°C. The emissivity of the outer surface of the box is 0.85. If the electronic components in the box dissipate a total of 100 W of power and the outer surface temperature of the box is not to exceed 65°C, determine if this box can be cooled by natural convection and radiation alone. Assume the heat transfer from the bottom surface of the box to the stand to be negligible, and the temperature of the surrounding surfaces to be the same as the air temperature of the room.

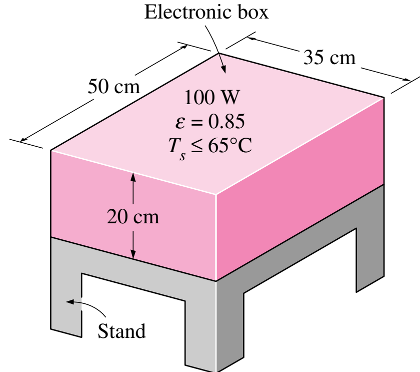

FIGURE P15–80

15–81 Repeat Prob. 15–80, assuming the box is mounted on a wall instead of a stand such that it is 0.5 m high. Again, assume heat transfer from the bottom surface to the wall to be negligible.

15–82E A 0.15-W small cylindrical resistor mounted on a circuit board is 0.5 in long and has a diameter of 0.15 in. The view of the resistor is largely blocked by the circuit board facing it, and the heat transfer from the connecting wires is negligible. The air is free to flow through the parallel flow passages between the PCBs as a result of natural convection currents. If the air temperature in the vicinity of the resistor is 130°F, determine the surface temperature of the resistor.
Answer: 194°F

15–83 A 14-cm × 20-cm PCB has electronic components on one side, dissipating a total of 7 W. The PCB is mounted in a rack vertically (height 14 cm) together with other PCBs (Fig. P15–83 on the next page). If the surface temperature of the components is not to exceed 90°C, determine the maximum temperature of the environment in which this PCB can operate safely at sea level. What would your answer be if this rack is located at a location at 3000 m altitude where the atmospheric pressure is 70.12 kPa?

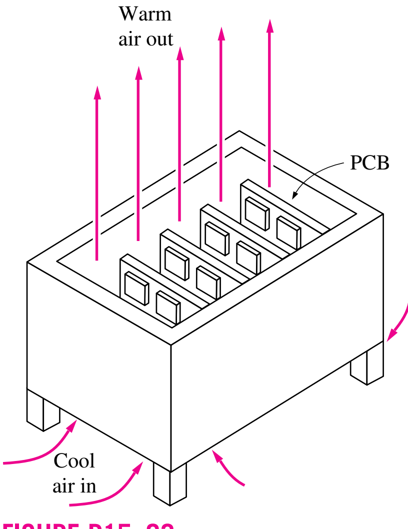

FIGURE P15–83

15–84 A cylindrical electronic component whose diameter is 2 cm and length is 4 cm is mounted on a board with its axis in the vertical direction and is dissipating 3 W of power. The emissivity of the surface of the component is 0.8, and the temperature of the ambient air is 30°C. Assuming the temperature of the surrounding surfaces to be 20°C, determine the average surface temperature of the component under combined natural convection and radiation cooling.

15–85 Repeat Prob. 15–84, assuming the component is oriented horizontally.

15–86 Reconsider Prob. 15–84. Using EES (or other) software, investigate the effects of surface emissivity and ambient temperature on the average surface temperature of the component. Let the emissivity vary from 0.1 to 1.0 and the ambient temperature from 15ºC to 35ºC. Take the temperature of the surrounding surfaces to be 10ºC smaller than the ambient air temperature. Plot the average surface temperature as functions of the emissivity and the ambient air temperature, and discuss the results.

15–87 Consider a power transistor that dissipates 0.1 W of power in an environment at 30°C. The transistor is 0.4 cm long and has a diameter of 0.4 cm. Assuming heat to be transferred uniformly from all surfaces, determine (*a*) the heat flux on the surface of the transistor, in W/cm^2, and (*b*) the surface temperature of the transistor for a combined convection and radiation heat transfer coefficient of 18 W/m$^2 \cdot$ °C.

15–88 The components of an electronic system dissipating 150 W are located in a 1-m-long horizontal duct whose cross section is 15 cm × 15 cm. The components in the duct are cooled by forced air, which enters at 30°C at a rate of 0.4 m^3/min and leaves at 45°C. The surfaces of the sheet metal duct are not painted, and thus radiation heat transfer from the outer surfaces is negligible. If the ambient air temperature is 25°C, determine (*a*) the heat transfer from the outer surfaces of the duct to the ambient air by natural convection and (*b*) the average temperature of the duct. *Answers*: (*a*) 31.7 W, (*b*) 40°C

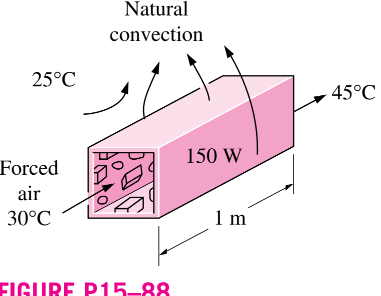

FIGURE P15–88

15–89 Repeat Prob. 15–88 for a circular horizontal duct of diameter 10 cm.

15–90 Reconsider Prob. 15–88. Using EES (or other) software, investigate the effects of the volume flow rate of air and the side-length of the duct on heat transfer by natural convection and the average temperature of the duct. Let the flow rate vary from 0.1 m^3/min to 0.5 m^3/min, and the side-length from 10 cm to 20 cm. Plot the heat transfer rate by natural convection and the average duct temperature as functions of flow rate and side-length, and discuss the results.

15–91 Repeat Prob. 15–88, assuming that the fan fails and thus the entire heat generated inside the duct must be rejected to the ambient air by natural convection from the outer surfaces of the duct.

15–92 A 20-cm × 20-cm circuit board containing 81 square chips on one side is to be cooled by combined natural convection

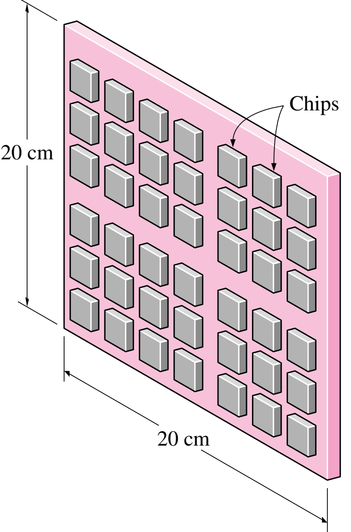

FIGURE P15–92

and radiation by mounting it on a vertical surface in a room at 25°C. Each chip dissipates 0.08 W of power, and the emissivity of the chip surfaces is 0.65. Assuming the heat transfer from the back side of the circuit board to be negligible and the temperature of the surrounding surfaces to be the same as the air temperature of the room, determine the surface temperature of the chips.

15–93 Repeat Prob. 15–92, assuming the circuit board to be positioned horizontally with (*a*) chips facing up and (*b*) chips facing down.

Air Cooling: Forced Convection

15–94C Why is radiation heat transfer in forced-air-cooled systems disregarded?

15–95C If an electronic system can be cooled adequately by either natural convection or forced-air convection, which would you prefer? Why?

15–96C Why is forced convection cooling much more effective than natural convection cooling?

15–97C Consider a forced-air-cooled electronic system dissipating a fixed amount of power. How will increasing the flow rate of air affect the surface temperature of the components? Explain. How will it affect the exit temperature of the air?

15–98C To what do internal and external flow refer in forced convection cooling? Give an example of a forced-air-cooled electronic system that involves both types of flow.

15–99C For a specified power dissipation and air inlet temperature, how does the convection heat transfer coefficient affect the surface temperature of the electronic components? Explain.

15–100C How does high altitude affect forced convection heat transfer? How would you modify your forced-air cooling system to operate at high altitudes safely?

15–101C What are the advantages and disadvantages of placing the cooling fan at the inlet or at the exit of an electronic box?

15–102C How is the volume flow rate of air in a forced-air-cooled electronic system that has a constant-speed fan established? If a few more PCBs are added to the box while keeping the fan speed constant, will the flow rate of air through the system change? Explain.

15–103C What happens if we attempt to cool an electronic system with an undersized fan? What about if we do that with an oversized fan?

15–104 Consider a hollow-core PCB that is 15 cm high and 20 cm long, dissipating a total of 30 W. The width of the air gap in the middle of the PCB is 0.25 cm. The cooling air enters the core at 30°C at a rate of 1 L/s. Assuming the heat generated to be uniformly distributed over the two side surfaces of the PCB, determine (*a*) the temperature at which the air leaves the hollow core and (*b*) the highest temperature on the inner surface of the core. *Answers:* (*a*) 56.4°C, (*b*) 67.6°C

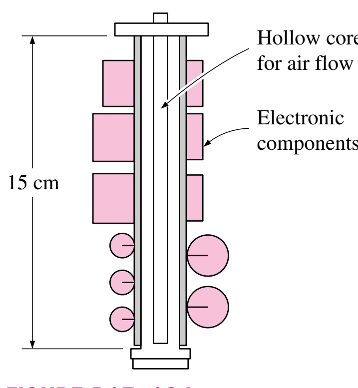

FIGURE P15–104

15–105 Repeat Prob. 15–104 for a hollow-core PCB dissipating 45 W.

15–106 Reconsider Prob. 15–104. Using EES (or other) software, investigate the effects of the power rating of the PCB and the volume flow rate of the air on the exit temperature of the air and the maximum temperature on the inner surface of the core. Let the power vary from 20 W to 60 W and the flow rate from 0.5 L/s to 2.5 L/s. Plot the air exit temperature and the maximum surface temperature of the core as functions of power and flow rate, and discuss the results.

15–107E A transistor with a height of 0.25 in and a diameter of 0.2 in is mounted on a circuit board. The transistor is cooled by air flowing over it at a velocity of 400 ft/min. If the air temperature is 140°F and the transistor case temperature is not to exceed 175°F, determine the amount of power this transistor can dissipate safely. *Answer:* 0.15 W

15–108 A desktop computer is to be cooled by a fan. The electronic components of the computer consume 75 W of power under full-load conditions. The computer is to operate in environments at temperatures up to 45°C and at elevations up to 3400 m where the atmospheric pressure is 66.63 kPa. The exit temperature of air is not to exceed 60°C to meet reliability requirements. Also, the average velocity of air is not to exceed 110 m/min at the exit of the computer case, where the fan is installed to keep the noise level down. Determine the flow rate of the fan that needs to be installed and the diameter of the casing of the fan.

15–109 Repeat Prob. 15–108 for a computer that consumes 100 W of power.

15–110 A computer cooled by a fan contains eight PCBs, each dissipating 12 W of power. The height of the PCBs is 12 cm and the length is 18 cm. The clearance between the tips of the components on the PCB and the back surface of the

adjacent PCB is 0.3 cm. The cooling air is supplied by a 15-W fan mounted at the inlet. If the temperature rise of air as it flows through the case of the computer is not to exceed 15°C, determine (*a*) the flow rate of the air that the fan needs to deliver, (*b*) the fraction of the temperature rise of air due to the heat generated by the fan and its motor, and (*c*) the highest allowable inlet air temperature if the surface temperature of the components is not to exceed 90°C anywhere in the system.

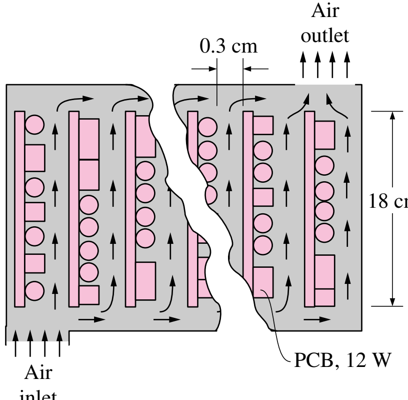

FIGURE P15–110

15–111 An array of power transistors, each dissipating 2 W of power, is to be cooled by mounting them on a 20-cm × 20-cm square aluminum plate and blowing air over the plate with a fan at 30°C with a velocity of 3 m/s. The average temperature of the plate is not to exceed 60°C. Assuming the heat transfer from the back side of the plate to be negligible, determine the number of transistors that can be placed on this plate. *Answer:* 9

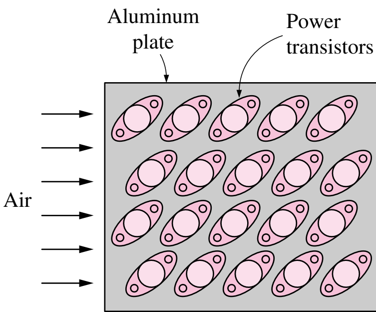

FIGURE P15–111

15–112 Repeat Prob. 15–111 for a location at an elevation of 1610 m where the atmospheric pressure is 83.4 kPa.

15–113 Reconsider Prob. 15–111. Using EES (or other) software, investigate the effects of air velocity and the maximum plate temperature on the number of transistors. Let the air velocity vary from 1 m/s to 8 m/s and the maximum plate temperature from 40ºC to 80ºC. Plot the number of transistors as functions of air velocity and maximum plate temperature, and discuss the results.

15–114 An enclosure contains an array of circuit boards, 15 cm high and 20 cm long. The clearance between the tips of the components on the PCB and the back surface of the adjacent PCB is 0.3 cm. Each circuit board contains 75 square chips on one side, each dissipating 0.15 W of power. Air enters the space between the boards through the 0.3-cm × 15-cm cross section at 40°C with a velocity of 300 m/min. Assuming the heat transfer from the back side of the circuit board to be negligible, determine the exit temperature of the air and the highest surface temperature of the chips.

15–115 The components of an electronic system dissipating 120 W are located in a 1-m-long horizontal duct whose cross section is 20 cm × 20 cm. The components in the duct are cooled by forced air, which enters at 30°C at a rate of 0.5 m^3/min. Assuming 80 percent of the heat generated inside is transferred to air flowing through the duct and the remaining 20 percent is lost through the outer surfaces of the duct, determine (*a*) the exit temperature of air and (*b*) the highest component surface temperature in the duct.

15–116 Repeat Prob. 15–115 for a circular horizontal duct of diameter 10 cm.

Liquid Cooling

15–117C If an electronic system can be cooled adequately by either forced-air cooling or liquid cooling, which one would you prefer? Why?

15–118C Explain how direct and indirect liquid cooling systems differ from each other.

15–119C Explain how closed-loop and open-loop liquid cooling systems operate.

15–120C What are the properties of a liquid ideally suited for cooling electronic equipment?

15–121 A cold plate that supports 10 power transistors, each dissipating 40 W, is to be cooled with water. It is specified that the temperature rise of the water not exceed 4°C and the velocity of water remain under 0.5 m/s. Assuming 25 percent of the heat generated is dissipated from the components to the surroundings by convection and radiation, and the remaining 75 percent is removed by the cooling water, determine the mass

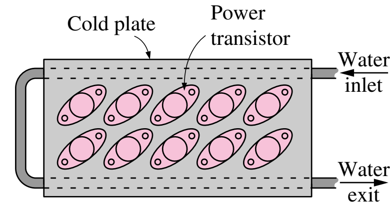

FIGURE P15–121

flow rate of water needed and the diameter of the pipe to satisfy the restriction imposed on the flow velocity. Also, determine the case temperature of the devices if the total case-to-liquid thermal resistance is 0.04°C/W and the water enters the cold plate at 25°C.

15–122 Reconsider Prob. 15–121. Using EES (or other) software, investigate the effect of the maximum temperature rise of the water on the mass flow rate of water, the diameter of the pipe, and the case temperature. Let the maximum temperature rise vary from 1ºC to 10ºC. Plot the mass flow rate, the diameter, and the case temperature as a function of the temperature rise, and discuss the results.

15–123E Water enters the tubes of a cold plate at 95°F with an average velocity of 60 ft/min and leaves at 105°F. The diameter of the tubes is 0.25 in. Assuming 15 percent of the heat generated is dissipated from the components to the surroundings by convection and radiation, and the remaining 85 percent is removed by the cooling water, determine the amount of heat generated by the electronic devices mounted on the cold plate. *Answer:* 263 W

15–124 A sealed electronic box is to be cooled by tap water flowing through channels on two of its sides. It is specified that the temperature rise of the water not exceed 3°C. The power dissipation of the box is 2 kW, which is removed entirely by water. If the box operates 24 h a day, 365 days a year, determine the mass flow rate of water flowing through the box and the amount of cooling water used per year.

15–125 Repeat Prob. 15–124 for a power dissipation of 3 kW.

Immersion Cooling

15–126C What are the desirable characteristics of a liquid used in immersion cooling of electronic devices?

15–127C How does an open-loop immersion cooling system operate? How does it differ from closed-loop cooling systems?

15–128C How do immersion cooling systems with internal and external cooling differ? Why are externally cooled systems limited to relatively low-power applications?

15–129C Why is boiling heat transfer used in the cooling of very high-power electronic devices instead of forced air or liquid cooling?

15–130 A logic chip used in a computer dissipates 4 W of power and has a heat transfer surface area of 0.3 cm^2. If the surface of the chip is to be maintained at 70°C while being cooled by immersion in a dielectric fluid at 20°C, determine the necessary heat transfer coefficient and the type of cooling mechanism that needs to be used to achieve that heat transfer coefficient.

15–131 A 6-W chip having a surface area of 0.5 cm^2 is cooled by immersing it into FC86 liquid that is maintained at a temperature of 25°C. Using the boiling curve in Fig. 15–63, estimate the temperature of the chip surface. *Answer:* 82°C

15–132 A logic chip cooled by immersing it in a dielectric liquid dissipates 3.5 W of power in an environment at 50°C and has a heat transfer surface area of 0.8 cm^2. The surface temperature of the chip is measured to be 95°C. Assuming the heat transfer from the surface to be uniform, determine (*a*) the heat flux on the surface of the chip, in W/cm^2, (*b*) the heat transfer coefficient on the surface of the chip, in W/m^2 · °C, and (*c*) the thermal resistance between the surface of the chip and the cooling medium, in °C/W.

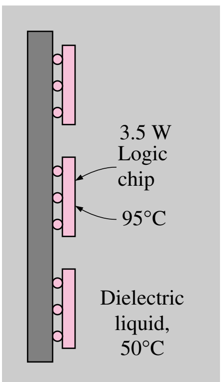

FIGURE P15–132

15–133 Reconsider Prob. 15–132. Using EES (or other) software, investigate the effect of chip power on the heat flux, the heat transfer coefficient, and the convection resistance on chip surface. Let the power vary from 2 W to 10 W. Plot the heat flux, the heat transfer coefficient, and the thermal resistance as a function of power dissipated, and discuss the results.

15–134 A computer chip dissipates 5 W of power and has a heat transfer surface area of 0.4 cm^2. If the surface of the chip is to be maintained at 55°C while being cooled by immersion in a dielectric fluid at 10°C, determine the necessary heat transfer coefficient and the type of cooling mechanism that needs to be used to achieve that heat transfer coefficient.

15–135 A 3-W chip having a surface area of 0.2 cm^2 is cooled by immersing it into FC86 liquid that is maintained at a temperature of 45°C. Using the boiling curve in Fig. 15–63, estimate the temperature of the chip surface. *Answer:* 108°C

15–136 A logic chip having a surface area of 0.3 cm^2 is to be cooled by immersing it into FC86 liquid that is maintained at a temperature of 35°C. The surface temperature of the chip is not to exceed 60°C. Using the boiling curve in Fig. 15–63, estimate the maximum power that the chip can dissipate safely.

15–137 A 2-kW electronic device that has a surface area of 120 cm^2 is to be cooled by immersing it in a dielectric fluid with a boiling temperature of 60°C contained in a 1-m × 1-m × 1-m

cubic enclosure. Noting that the combined natural convection and the radiation heat transfer coefficients in air are typically about 10 W/m^2 · °C, determine if the heat generated inside can be dissipated to the ambient air at 20°C by natural convection and radiation. If it cannot, explain what modification you could make to allow natural convection cooling.

Also, determine the heat transfer coefficients at the surface of the electronic device for a surface temperature of 80°C. Assume the liquid temperature remains constant at 60°C throughout the enclosure.

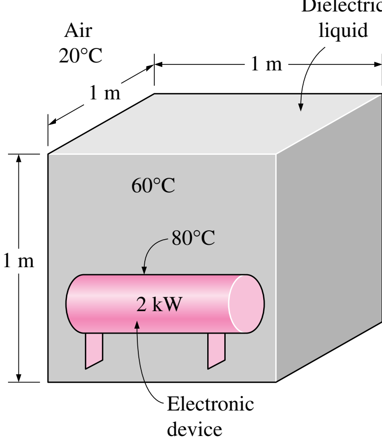

FIGURE P15–137

Review Problems

15–138C Several power transistors are to be cooled by mounting them on a water-cooled metal plate. The total power dissipation, the mass flow rate of water through the tube, and the water inlet temperature are fixed. Explain what you would do for the most effective cooling of the transistors.

15–139C Consider heat conduction along a vertical copper bar whose sides are insulated. One person claims that the bar should be oriented such that the hot end is at the bottom and the cold end is at the top for better heat transfer, since heat rises. Another person claims that it makes no differences to heat conduction whether heat is conducted downward or upward, and thus the orientation of the bar is irrelevant. With which person do you agree?

15–140 Consider a 15-cm × 15-cm multilayer circuit board dissipating 22.5 W of heat. The board consists of four layers of 0.1-mm-thick copper (k = 386 W/m · °C) and three layers of 0.5-mm-thick glass-epoxy (k = 0.26 W/m · °C) sandwiched together, as shown in Fig. P15–140. The circuit board is attached to a heat sink from both ends, and the temperature of the board at those ends is 35°C. Heat is considered to be uniformly generated in the epoxy layers of the PCB at a rate of 0.5 W per 1-cm × 15-cm epoxy laminate strip (or 1.5 W per 1-cm × 15-cm strip of the board). Considering only a portion of the PCB because of symmetry, determine the magnitude and location of the maximum temperature that occurs in the PCB. Assume heat transfer from the top and bottom faces of the PCB to be negligible. *Answer:* 55.5°C

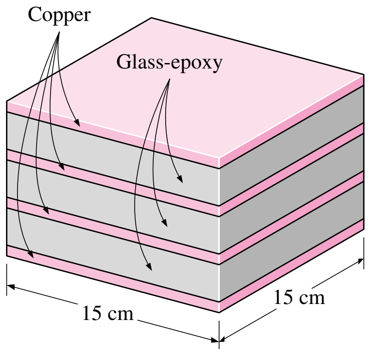

FIGURE P15–140

15–141 Repeat Prob. 15–140, assuming that the board consists of a single 1.5-mm-thick layer of glass-epoxy, with no copper layers.

15–142 The components of an electronic system that is dissipating 150 W are located in a 1-m-long horizontal duct whose cross section is 10 cm × 10 cm. The components in the duct are cooled by forced air, which enters at 30°C and 50 m/min and leaves at 45°C. The surfaces of the sheet metal duct are not painted, and so radiation heat transfer from the outer surfaces is negligible. If the ambient air temperature is 30°C, determine (a) the heat transfer from the outer surfaces of the duct to the ambient air by natural convection, (b) the average temperature of the duct, and (c) the highest component surface temperature in the duct.

15–143 Two 10-W power transistors are cooled by mounting them on the two sides of an aluminum bracket (k = 237 W/m · °C) that is attached to a liquid-cooled plate by 0.2-mm-thick epoxy adhesive (k = 1.8 W/m · °C), as shown in Fig. P15–143. The thermal resistance of each plastic washer is

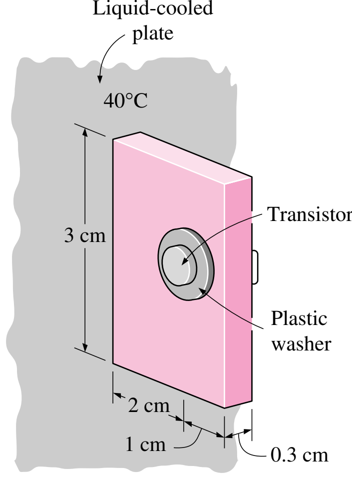

FIGURE P15–143

given as 2°C/W, and the temperature of the cold plate is 40°C. The surface of the aluminum plate is untreated, and thus radiation heat transfer from it is negligible because of the low emissivity of aluminum surfaces. Disregarding heat transfer from the 0.3-cm-wide edges of the aluminum plate, determine the surface temperature of the transistor case. Also, determine the fraction of heat dissipation to the ambient air by natural convection and to the cold plate by conduction. Take the ambient temperature to be 25°C.

15–144E A fan blows air at 70°F and a velocity of 500 ft/min over a 1.5-W plastic DIP with 24 leads mounted on a PCB. Using data from Fig. 15–23, determine the junction temperature of the electronic device. What would the junction temperature be if the fan were to fail?

15–145 A 15-cm × 18-cm double-sided circuit board dissipating a total of 18 W of heat is to be conduction-cooled by a 1.2-mm-thick aluminum core plate (k = 237 W/m · °C) sandwiched between two epoxy laminates (k = 0.26 W/m · °C). Each epoxy layer has a thickness of 0.5 mm and is attached to the aluminum core plate with conductive epoxy adhesive (k = 1.8 W/m · °C) of thickness 0.1 mm. Heat is uniformly generated on each side of the PCB at a rate of 0.5 W per 1-cm × 15-cm epoxy laminate strip. All of the heat is conducted along the 18-cm side since the PCB is cooled along the two 15-cm-long edges. Considering only part of the PCB board because of symmetry, determine the maximum temperature rise across the 9-cm distance between the center and the sides of the PCB. *Answer:* 10.1°C

15–146 Ten power transistors, each dissipating 2 W, are attached to a 7-cm × 7-cm × 0.2-cm aluminum plate with a square cutout in the middle in a symmetrical arrangement, as shown in Fig. P15–146. The aluminum plate is cooled from two sides by liquid at 40°C. If 70 percent of the heat generated by the transistors is estimated to be conducted through the aluminum plate, determine the temperature rise across the 1-cm-wide section of the aluminum plate between the transistors and the heat sink.

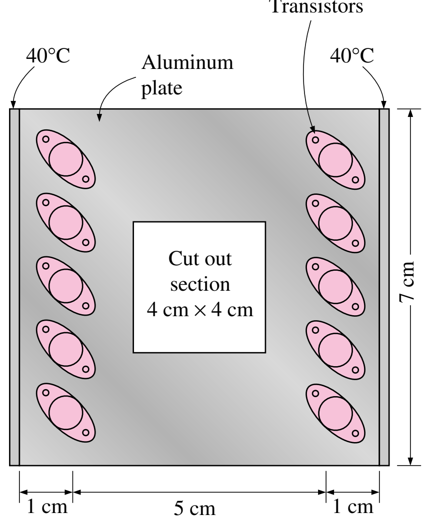

FIGURE P15–146

15–147 The components of an electronic system are located in a 1.2-m-long horizontal duct whose cross section is 10 cm × 20 cm. The components in the duct are not allowed to come into direct contact with cooling air, and so are cooled by air flowing over the duct at 30°C with a velocity of 250 m/min. The duct is oriented such that air strikes the 10-cm-high side of the duct normally. If the surface temperature of the duct is not to exceed 60°C, determine the total power rating of the electronic devices that can be mounted in the duct. What would your answer be if the duct is oriented such that air strikes the 20-cm-high side normally? *Answers:* 481 W, 384 W

15–148 Repeat Prob. 15–147 for a location at an altitude of 5000 m, where the atmospheric pressure is 54.05 kPa.

15–149E A computer that consumes 65 W of power is cooled by a fan blowing air into the computer enclosure. The dimensions of the computer case are 6 in × 20 in × 24 in, and all surfaces of the case are exposed to the ambient, except for the base surface. Temperature measurements indicate that the case is at an average temperature of 95°F when the ambient temperature and the temperature of the surrounding walls are 80°F. If the emissivity of the outer surface of the case is 0.85, determine the fraction of heat lost from the outer surfaces of the computer case.

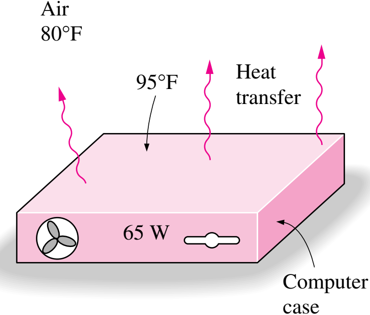

FIGURE P15–149E

Computer, Design, and Essay Problems

15–150 Bring an electronic device that is cooled by heat sinking to class and discuss how the heat sink enhances heat transfer.

15–151 Obtain a catalog from a heat sink manufacturer and select a heat sink model that can cool a 10-W power transistor safely under (*a*) natural convection and radiation and (*b*) forced convection conditions.

15–152 Take the cover off a PC or another electronic box and identify the individual sections and components. Also, identify the cooling mechanisms involved and discuss how the current design facilitates effective cooling.