

less expensive) condenser. Therefore, dropwise condensation is the preferred mode of condensation in heat transfer applications.

The challenge in dropwise condensation is not to achieve it, but rather, to *sustain* it for prolonged periods of time. Dropwise condensation is achieved by *adding* a promoting chemical into the vapor, *treating* the surface with a promoter chemical, or *coating* the surface with a polymer such as teflon or a noble metal such as gold, silver, rhodium, palladium, or platinum. The *promoters* used include various waxes and fatty acids such as oleic, stearic, and linoic acids. They lose their effectiveness after a while, however, because of fouling, oxidation, and the removal of the promoter from the surface. It is possible to sustain dropwise condensation for over a year by the combined effects of surface coating and periodic injection of the promoter into the vapor. However, any gain in heat transfer must be weighed against the cost associated with sustaining dropwise condensation.

Dropwise condensation has been studied experimentally for a number of surface–fluid combinations. Of these, the studies on the condensation of steam on copper surfaces has attracted the most attention because of their widespread use in steam power plants. P. Griffith (1983) recommends these simple correlations for dropwise condensation of *steam on copper surfaces*:

$$h_{\text{dropwise}} = \begin{cases} 51,104 + 2044T_{\text{sat}}, & 22^{\circ}\text{C} < T_{\text{sat}} < 100^{\circ}\text{C} \\ 255,310 & T_{\text{sat}} > 100^{\circ}\text{C} \end{cases} \quad \begin{matrix} (10-36) \\ (10-37) \end{matrix}$$

where T_{sat} is in $^{\circ}\text{C}$ and the heat transfer coefficient h_{dropwise} is in $\text{W/m}^2 \cdot ^{\circ}\text{C}$.

The very high heat transfer coefficients achievable with dropwise condensation are of little significance if the material of the condensing surface is not a good conductor like copper or if the thermal resistance on the other side of the surface is too large. In steady operation, heat transfer from one medium to another depends on the sum of the thermal resistances on the path of heat flow, and a large thermal resistance may overshadow all others and dominate the heat transfer process. In such cases, improving the accuracy of a small resistance (such as one due to condensation or boiling) makes hardly any difference in overall heat transfer calculations.

TOPIC OF SPECIAL INTEREST*

Heat Pipes

A **heat pipe** is a simple device with no moving parts that can transfer large quantities of heat over fairly large distances essentially at a constant temperature without requiring any power input. A heat pipe is basically a sealed slender tube containing a wick structure lined on the inner surface and a small amount of fluid such as water at the saturated state, as shown in Figure 10–36. It is composed of three sections: the *evaporator* section at one end, where heat is absorbed and the fluid is vaporized; a *condenser* section at the other end, where the vapor is condensed and heat is rejected; and the *adiabatic* section in between, where the vapor and the liquid phases of the fluid flow in opposite directions through the core and the wick,

*This section can be skipped without a loss in continuity.

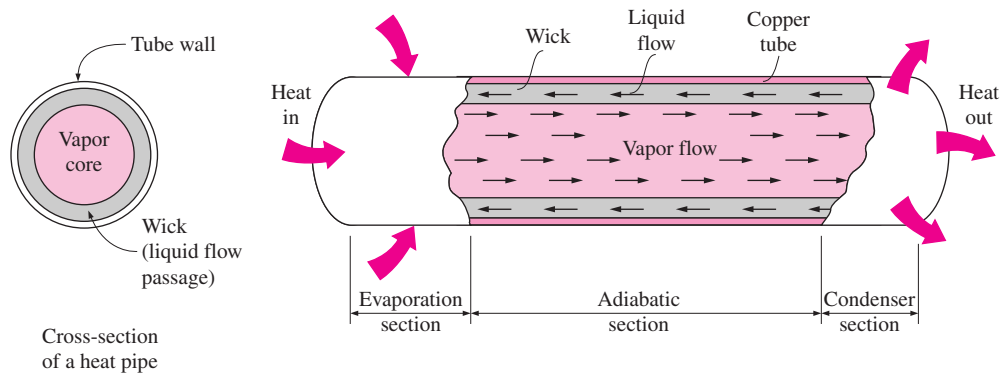


FIGURE 10-36

Schematic and operation of a heat pipe.

respectively, to complete the cycle with no significant heat transfer between the fluid and the surrounding medium.

The *type of fluid* and the *operating pressure* inside the heat pipe depend on the *operating temperature* of the heat pipe. For example, the critical- and triple-point temperatures of water are 0.01°C and 374.1°C , respectively. Therefore, water can undergo a liquid-to-vapor or vapor-to-liquid phase change process in this temperature range only, and thus it will not be a suitable fluid for applications involving temperatures beyond this range. Furthermore, water will undergo a phase-change process at a specified temperature only if its pressure equals the saturation pressure at that temperature. For example, if a heat pipe with water as the working fluid is designed to remove heat at 70°C , the pressure inside the heat pipe must be maintained at 31.2 kPa, which is the boiling pressure of water at this temperature. Note that this value is well below the atmospheric pressure of 101 kPa, and thus the heat pipe will operate in a vacuum environment in this case. If the pressure inside is maintained at the local atmospheric pressure instead, heat transfer would result in an increase in the temperature of the water instead of evaporation.

Although water is a suitable fluid to use in the moderate temperature range encountered in electronic equipment, several other fluids can be used in the construction of heat pipes to enable them to be used in cryogenic as well as high-temperature applications. The suitable temperature ranges for some common heat pipe fluids are given in Table 10-5. Note that the overall temperature range extends from almost absolute zero for cryogenic fluids such as helium to over 1600°C for liquid metals such as lithium. The ultimate temperature limits for a fluid are the *triple-* and *critical-point* temperatures. However, a narrower temperature range is used in practice to avoid the extreme pressures and low heats of vaporization that occur near the critical point. Other desirable characteristics of the candidate fluids are having a high surface tension to enhance the capillary effect and being compatible with the wick material, as well as being readily available, chemically stable, nontoxic, and inexpensive.

The concept of heat pipe was originally conceived by R. S. Gaugler of the General Motors Corporation, who filed a patent application for it in

TABLE 10-5

Suitable temperature ranges for
some fluids used in heat pipes

Fluid	Temperature Range, $^{\circ}\text{C}$
Helium	-271 to -268
Hydrogen	-259 to -240
Neon	-248 to -230
Nitrogen	-210 to -150
Methane	-182 to -82
Ammonia	-78 to -130
Water	5 to 230
Mercury	200 to 500
Cesium	400 to 1000
Sodium	500 to 1200
Lithium	850 to 1600

1942. However, it did not receive much attention until 1962, when it was suggested for use in space applications. Since then, heat pipes have found a wide range of applications, including the cooling of electronic equipment.

The Operation of a Heat Pipe

The operation of a heat pipe is based on the following physical principles:

- At a specified pressure, a liquid will vaporize or a vapor will condense at a certain temperature, called the *saturation temperature*. Thus, fixing the pressure inside a heat pipe fixes the temperature at which phase change will occur.
- At a specified pressure or temperature, the amount of heat *absorbed* as a unit mass of liquid vaporizes is equal to the amount of heat *rejected* as that vapor condenses.
- The capillary pressure developed in a wick will move a liquid in the wick even *against* the gravitational field as a result of the capillary effect.
- A fluid in a channel flows in the direction of *decreasing pressure*.

Initially, the *wick* of the heat pipe is saturated with liquid and the *core section* is filled with vapor. When the evaporator end of the heat pipe is brought into contact with a hot surface or is placed into a hot environment, heat will transfer into the heat pipe. Being at a saturated state, the liquid in the evaporator end of the heat pipe will *vaporize* as a result of this heat transfer, causing the vapor pressure there to rise. This resulting pressure difference drives the vapor through the core of the heat pipe from the evaporator toward the condenser section. The condenser end of the heat pipe is in a cooler environment, and thus its surface is slightly cooler. The vapor that comes into contact with this cooler surface *condenses*, releasing the heat a vaporization, which is rejected to the surrounding medium. The liquid then returns to the evaporator end of the heat pipe through the wick as a result of *capillary action* in the wick, completing the cycle. As a result, heat is absorbed at one end of the heat pipe and is rejected at the other end, with the fluid inside serving as a transport medium for heat.

The boiling and condensation processes are associated with extremely high heat transfer coefficients, and thus it is natural to expect the heat pipe to be a very effective heat transfer device, since its operation is based on alternative boiling and condensation of the working fluid. Indeed, heat pipes have effective conductivities *several hundred times* that of copper or silver. That is, replacing a copper bar between two mediums at different temperatures by a heat pipe of equal size can increase the rate of heat transfer between those two mediums by several hundred times. A simple heat pipe with water as the working fluid has an effective thermal conductivity of the order of $100,000 \text{ W/m} \cdot ^\circ\text{C}$ compared with about $400 \text{ W/m} \cdot ^\circ\text{C}$ for copper. For a heat pipe, it is not unusual to have an effective conductivity of $400,000 \text{ W/m} \cdot ^\circ\text{C}$, which is 1000 times that of copper. A 15-cm-long, 0.6-cm-diameter horizontal cylindrical heat pipe with water inside, for example, can transfer heat at a rate of 300 W. Therefore, heat pipes are preferred in some critical applications, despite their high initial cost.

There is a small pressure difference between the evaporator and condenser ends, and thus a small temperature difference between the two ends of the heat pipe. This temperature difference is usually between 1°C and 5°C.

The Construction of a Heat Pipe

The wick of a heat pipe provides the means for the return of the liquid to the evaporator. Therefore, the structure of the wick has a strong effect on the performance of a heat pipe, and the design and construction of the wick are the most critical aspects of the manufacturing process.

The wicks are often made of porous ceramic or woven stainless wire mesh. They can also be made together with the tube by extruding axial grooves along its inner surface, but this approach presents manufacturing difficulties.

The performance of a wick depends on its structure. The characteristics of a wick can be changed by changing the *size* and the *number* of the pores per unit volume and the *continuity* of the passageway. Liquid motion in the wick depends on the dynamic balance between two opposing effects: the *capillary pressure*, which creates the suction effect to draw the liquid, and the *internal resistance to flow* as a result of friction between the mesh surfaces and the liquid. A small pore size increases the capillary action, since the capillary pressure is inversely proportional to the effective capillary radius of the mesh. But decreasing the pore size and thus the capillary radius also increases the friction force opposing the motion. Therefore, the core size of the mesh should be reduced so long as the increase in capillary force is greater than the increase in the friction force.

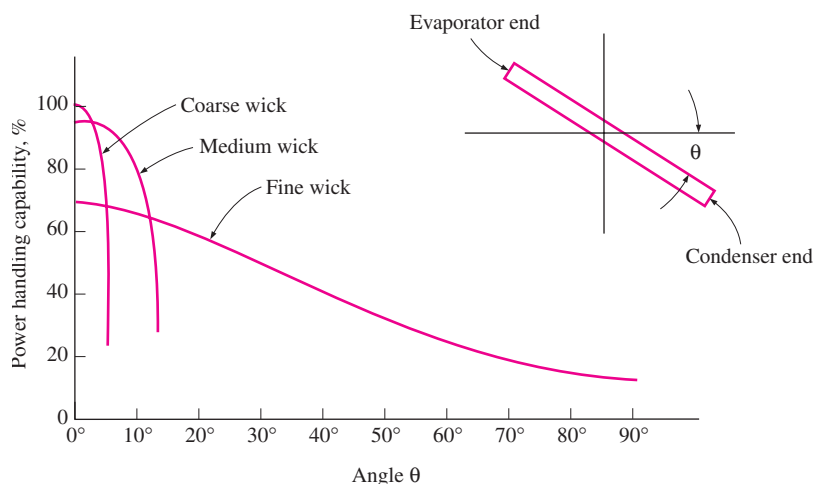
Note that the *optimum pore size* will be different for different fluids and different orientations of the heat pipe. An improperly designed wick will result in an inadequate liquid supply and eventual failure of the heat pipe.

Capillary action permits the heat pipe to operate in any orientation in a gravity field. However, the performance of a heat pipe will be best when the capillary and gravity forces act in the same direction (evaporator end down) and will be worst when these two forces act in opposite directions (evaporator end up). Gravity does not affect the capillary force when the heat pipe is in the horizontal position. The heat removal capacity of a horizontal heat pipe can be *doubled* by installing it vertically with evaporator end down so that gravity helps the capillary action. In the opposite case, vertical orientation with evaporator end up, the performance declines considerably relative the horizontal case since the capillary force in this case must work against the gravity force.

Most heat pipes are cylindrical in shape. However, they can be manufactured in a variety of shapes involving 90° bends, S-turns, or spirals. They can also be made as a flat layer with a thickness of about 0.3 cm. Flat heat pipes are very suitable for cooling high-power-output (say, 50 W or greater) PCBs. In this case, flat heat pipes are attached directly to the back surface of the PCB, and they absorb and transfer the heat to the edges. Cooling fins are usually attached to the condenser end of the heat pipe to improve its effectiveness and to eliminate a bottleneck in the path of heat flow from the components to the environment when the ultimate heat sink is the ambient air.

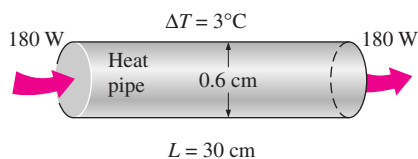
FIGURE 10–37

Variation of the heat removal capacity of a heat pipe with tilt angle from the horizontal when the liquid flows in the wick against gravity (from Steinberg, Ref. 18).

**TABLE 10–6**

Typical heat removal capacity of various heat pipes

Outside Diameter, cm (in.)	Length, cm (in.)	Heat Removal Rate, W
0.64($\frac{1}{4}$)	15.2(6)	300
	30.5(12)	175
	45.7(18)	150
0.95($\frac{3}{8}$)	15.2(6)	500
	30.5(12)	375
	45.7(18)	350
1.27($\frac{1}{2}$)	15.2(6)	700
	30.5(12)	575
	45.7(18)	550

**FIGURE 10–38**

Schematic for Example 10–8.

The decline in the performance of a 122-cm-long water heat pipe with the tilt angle from the horizontal is shown in Figure 10–37 for heat pipes with coarse, medium, and fine wicks. Note that for the horizontal case, the heat pipe with a coarse wick performs best, but the performance drops off sharply as the evaporator end is raised from the horizontal. The heat pipe with a fine wick does not perform as well in the horizontal position but maintains its level of performance greatly at tilted positions. It is clear from this figure that heat pipes that work against gravity must be equipped with *fine* wicks. The heat removal capacities of various heat pipes are given in Table 10–6.

A major concern about the performance of a heat pipe is degradation with time. Some heat pipes have failed within just a few months after they are put into operation. The major cause of degradation appears to be *contamination* that occurs during the sealing of the ends of the heat pipe tube and affects the vapor pressure. This form of contamination has been minimized by electron beam welding in clean rooms. Contamination of the wick prior to installation in the tube is another cause of degradation. Cleanliness of the wick is essential for its reliable operation for a long time. Heat pipes usually undergo extensive testing and quality control process before they are put into actual use.

An important consideration in the design of heat pipes is the compatibility of the materials used for the tube, wick, and fluid. Otherwise, reaction between the incompatible materials produces noncondensable gases, which degrade the performance of the heat pipe. For example, the reaction between stainless steel and water in some early heat pipes generated hydrogen gas, which destroyed the heat pipe.

EXAMPLE 10–8 Replacing a Heat Pipe by a Copper Rod

A 30-cm-long cylindrical heat pipe having a diameter of 0.6 cm is dissipating heat at a rate of 180 W, with a temperature difference of 3°C across the heat pipe, as shown in Figure 10–38. If we were to use a 30-cm-long copper rod in-

stead to remove heat at the same rate, determine the diameter and the mass of the copper rod that needs to be installed.

SOLUTION A cylindrical heat pipe dissipates heat at a specified rate. The diameter and mass of a copper rod that can conduct heat at the same rate are to be determined.

Assumptions Steady operating conditions exist.

Properties The properties of copper at room temperature are $\rho = 8950 \text{ kg/m}^3$ and $k = 386 \text{ W/m} \cdot ^\circ\text{C}$.

Analysis The rate of heat transfer $\dot{Q}$ through the copper rod can be expressed as

$$\dot{Q} = kA \frac{\Delta T}{L}$$

where k is the thermal conductivity, L is the length, and ΔT is the temperature difference across the copper bar. Solving for the cross-sectional area A and substituting the specified values gives

$$A = \frac{L}{k\Delta T} \dot{Q} = \frac{0.3 \text{ m}}{(386 \text{ W/m} \cdot ^\circ\text{C})(3^\circ\text{C})} (180 \text{ W}) = 0.04663 \text{ m}^2 = 466.3 \text{ cm}^2$$

Then the diameter and the mass of the copper rod become

$$A = \frac{1}{4}\pi D^2 \longrightarrow D = \sqrt{4A/\pi} = \sqrt{4(466.3 \text{ cm}^2)/\pi} = \mathbf{24.4 \text{ cm}}$$

$$m = \rho V = \rho AL = (8950 \text{ kg/m}^3)(0.04663 \text{ m}^2)(0.3 \text{ m}) = \mathbf{125.2 \text{ kg}}$$

Therefore, the diameter of the copper rod needs to be almost 25 times that of the heat pipe to transfer heat at the same rate. Also, the rod would have a mass of 125.2 kg, which is impossible for an average person to lift.

SUMMARY

Boiling occurs when a liquid is in contact with a surface maintained at a temperature T_s sufficiently above the saturation temperature T_{sat} of the liquid. Boiling is classified as *pool boiling* or *flow boiling* depending on the presence of bulk fluid motion. Boiling is called *pool boiling* in the absence of bulk fluid flow and *flow boiling* (or *forced convection boiling*) in its presence. Pool and flow boiling are further classified as *subcooled boiling* and *saturated boiling* depending on the bulk liquid temperature. Boiling is said to be *subcooled* (or *local*) when the temperature of the main body of the liquid is below the saturation temperature T_{sat} and *saturated* (or *bulk*) when the temperature of the liquid is equal to T_{sat} . Boiling exhibits different regimes depending on the value of the excess temperature ΔT_{excess} . Four different boiling regimes are observed: natural convection boiling, nucleate boiling, transition boiling, and film boiling. These regimes are illustrated on the *boiling curve*.

The rate of evaporation and the rate of heat transfer in nucleate boiling increase with increasing ΔT_{excess} and reach a maximum at some point. The heat flux at this point is called the *critical* (or *maximum*) *heat flux*, $\dot{q}_{\text{max}}$. The rate of heat transfer in nucleate pool boiling is determined from

$$\dot{q}_{\text{nucleate}} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left[\frac{C_{pl}(T_s - T_{\text{sat}})}{C_{sf} h_{fg} \text{Pr}_l^n} \right]^3$$

The *maximum* (or *critical*) *heat flux* in nucleate pool boiling is determined from

$$\dot{q}_{\text{max}} = C_{\text{cr}} h_{fg} [\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4}$$

where the value of the constant C_{cr} is about 0.15. The minimum heat flux is given by