Heat pipes cool gear in restricted spaces

Fluid that cycles in tubes through evaporation and condensation process reduces temperatures around even high-power electronic subassemblies

by Alan J. Streb, *Dynatherm Corp., Cockeysville, Md.*

□ Convective cooling of electronic components—even when heat sinks are used to increase the heat-radiating area—is not always enough to keep operating temperatures within limits. A simple alternative is the heat pipe, which uses fluids cycling through liquid and vapor phases to conduct heat away from temperature-sensitive components.

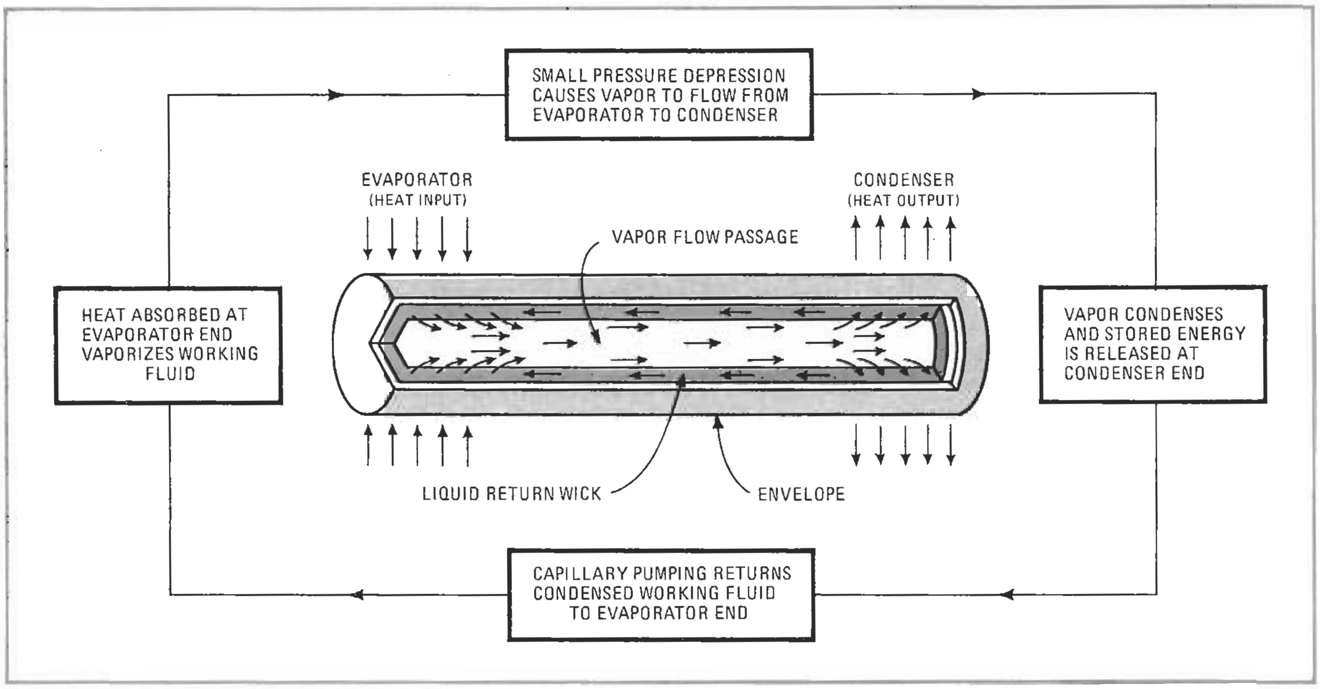
Although standardized heat-pipe cooling systems for electronic components and systems do not yet exist, heat-pipe technology has matured to the point where a wide range of practical configurations can be produced economically for many applications.

As shown in Fig. 1, a typical heat pipe consists of a sealed tube lined with a capillary pumping structure, or wick, which is saturated with a working fluid. As heat is added at one end of the tube, the working fluid is vaporized and moves down the tube until it condenses at a cooler site and reverts to the liquid state. As liquid is returned to the heat source via capillary action in the wick, heat is continuously transferred from one region to another through the nearly isothermal process of evaporation and condensation.

The efficiency of transferring heat energy is largely determined by the heat pipe's capability to conduct the vapor from the heat source to the heat sink and to return liquid from the condenser to the evaporator. Capabilities depend on fluid properties, wick configuration, and heat-pipe geometry and orientation.

Heat pipes have been successfully operated over the range from cryogenic to liquid-metal temperatures to convey heat from equipment dissipating power ranging from a few watts to thousands of watts. For any desired temperature range, a number of appropriate working fluids, containment-vessel materials, and wick designs are available. For cooling of electronic components, fluids such as water or organic fluids, contained in pipes made of such materials as aluminum, copper, or stainless steel, can dissipate as much as a kilowatt.

Water has proved to be the most desirable heat-pipe fluid for the temperature range of electronic compo-

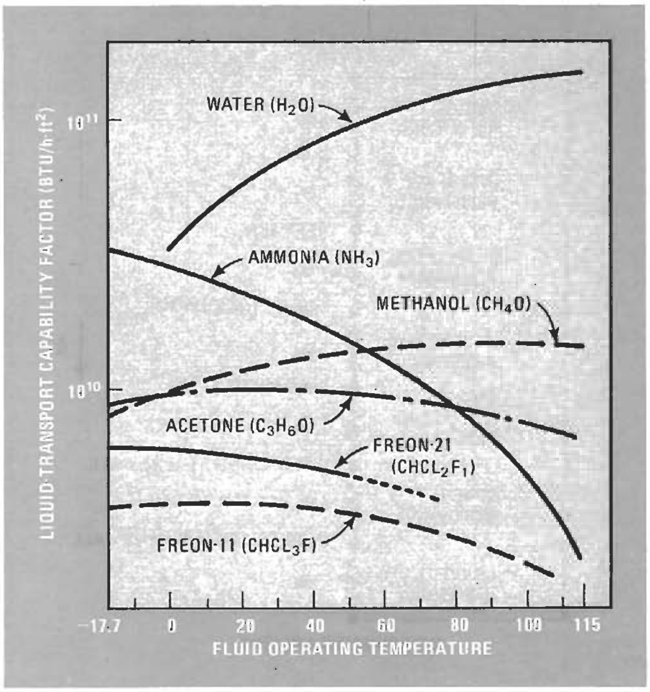


1. Heat Pipe. Using the properties of a fluid as it cycles between the liquid and vapor states, a heat pipe can cool the environment of temperature-sensitive components in enclosed spaces. Water in copper has proved the most desirable combination for electronic parts.

nents, 50°C to 200°C. Figure 2 shows the relative heat-transport capability of a number of fluids for this range. Since water is compatible with copper and copper alloys, but few other containment materials, copper is most widely used in the construction of heat pipes for cooling electronic components and packages.

The physical properties of the heat-pipe working fluid—especially heat of vaporization, surface tension, liquid density, and liquid viscosity—establish the heat-transport capability of the heat pipe. Since these properties are temperature-dependent, the performance of the heat pipe operating with a given fluid is temperature-dependent. One fluid will, therefore, function most effectively over any particular temperature range.

Although the temperature of the vapor within the heat pipe is nearly constant over the length of the device, the temperature varies at the evaporator and condenser regions, where heat is conducted through the walls and the liquid film that lines the walls. This results from the thermal resistance of the container and the working fluid. However, proper design of the containment vessel and the wick can minimize this resistance.



2. Working Fluids. Over a wide temperature range, water has a higher heat-transport capability than other fluids for heat pipes.

Designing a heat pipe

For a given heat-pipe geometry, the maximum heat-transport capability may be estimated by:

$$Q_{max} = ad^2/l$$

where Q_{max} is the maximum heat-pipe heat-transport capability in watts, d the inside diameter of the heat pipe in inches, l the heat-pipe length from midpoint of evaporator to midpoint of condenser in inches, and a is a constant.

The value of the constant is determined by the geometry of the heat-pipe wick, working fluid, and orientation. Values of this constant for a typical copper-water heat pipe configuration are presented in Fig. 3.

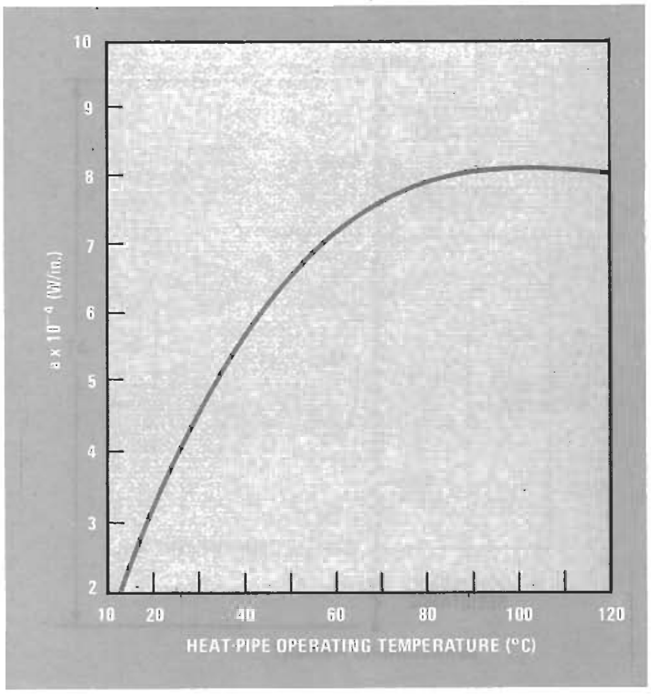
The maximum temperature gradient across a heat pipe can be estimated for a given heat pipe geometry from:

$$\Delta T = (Q/b)(1/A_{evap} + 1/A_{cond})$$

where ΔT is the over-all temperature drop in degrees fahrenheit, Q the heat transport in watts, A_{evap} the total area of the evaporator in square inches, A_{cond} the total area of the condenser in square inches, and b is a constant.

The constant in this equation has a value determined by the heat pipe's configuration. For a typical copper-water heat pipe,

$$b = 3 \ W/in.^2 {}^\circ F$$



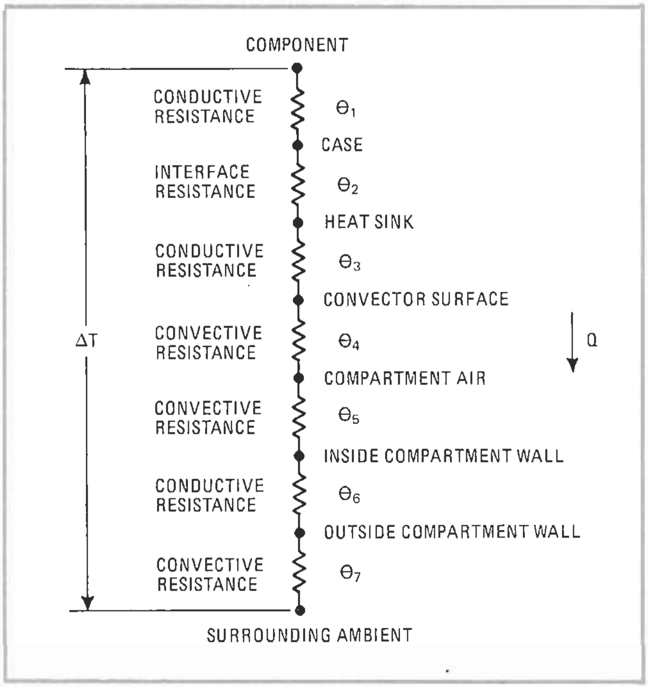
3. Heat transport. For a copper heat pipe using water as the working fluid, the heat-transport constant varies with temperature.

A first-cut selection of the size of heat pipe required for a particular application can be determined from these equations. But to optimize the heat pipe, the designer must also consider such other factors as the relative position of the evaporator and condenser, both with respect to each other and to the horizontal plane.

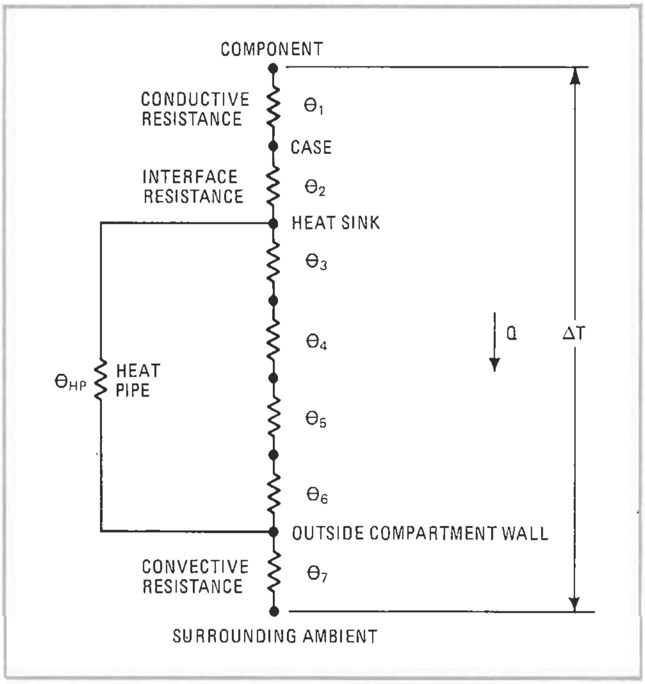
The pressure developed by capillary pumping within the heat pipe must balance the losses in viscous pressure within the system, as well as differences in elevation pressure that may be caused by locating the heat source above the heat sink. Because the capillary-wick structure is only capable of a limited rise in liquid-pumping pressure, adverse orientation of the heat pipe can degrade its performance.

Calculating heat flow

Lowering the condenser end will degrade the steady-state heat-transporting capability of the heat pipe, and that capability will go to zero if the condenser end is lower than the evaporator by an amount in excess of a



4. Analogy. Thermal resistances met by heat as it flows from a component to its surroundings are analogous to electrical resistances.



5. Short-circuit. A heat pipe can act as a thermal short-circuit to help heat flow to the surrounding ambient.

dimension called the static-wicking height. The static-wicking height, which is a function of the working fluid, the temperature, and the capillary size, ranges from eight to 16 inches for a typical water-filled heat pipe.

In an electronic system, heat flows from a source through a series of thermal resistances to the surroundings. The rate of heat flow depends on the total effective thermal resistance of the path and the total temperature difference between the source and the surroundings. This is similar, of course, to an electrical circuit, since voltage difference is analogous to temperature difference, current to heat flow, and electrical resistance to thermal resistance.

In Fig. 4, the "circuit" for heat flow from a heat-producing component, through thermal resistances, to the surrounding ambient is shown. Heat (Q) is driven through thermal resistances (Θ) by a temperature difference (ΔT) so that

$$Q = \Delta T/\Sigma\Theta$$

The series-thermal-resistance path shown in Fig. 4 is idealized. In most practical situations, parallel paths are also present, but these resistances may be combined to an equivalent thermal resistance through an analog of Kirchoff's Law. The major contributors to the total effective thermal resistance in a system like that of Fig. 4 are usually those resistances external to the component itself, i.e., Θ_2 through Θ_7; therefore, techniques to improve heat transfer are often sought in these areas.

Because of its inherently low thermal resistance and the relative insensitivity of resistance to length, a heat pipe is an efficient conductor of heat. All of the resistances Θ_3 through Θ_6 can be bypassed by interposing a heat-pipe shunt between the component case and the compartment wall, as shown in Fig. 5.

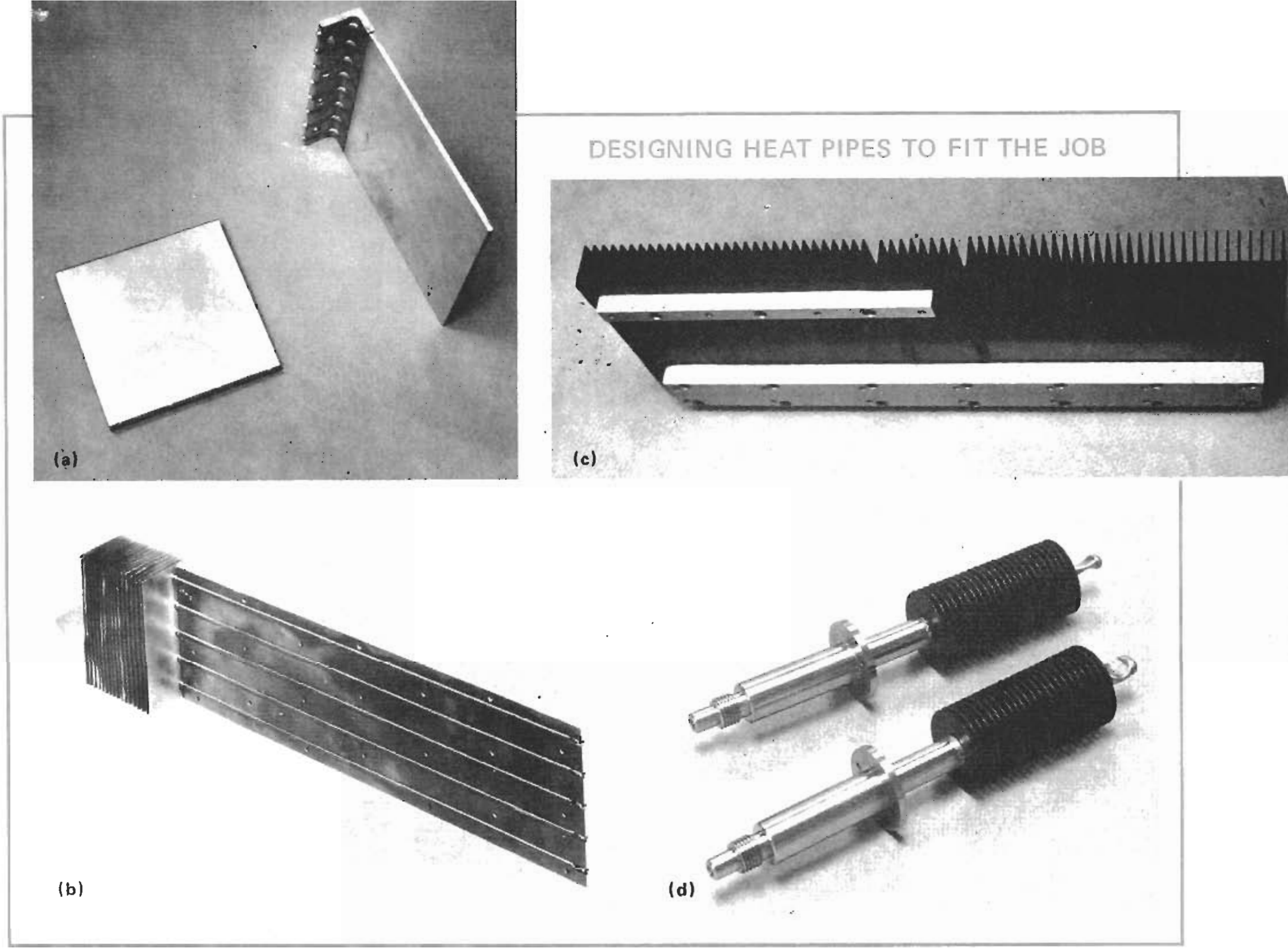
If all the convective resistances (Θ_4, Θ_5, and Θ_7) are approximately equal, all the conductive resistances (Θ_1, Θ_3, and Θ_6) are approximately equal, and all of these thermal resistances are much larger that the thermal resistance of the heat pipe, Θ_{HP}, the total thermal resistance of the circuit with the heat pipe is approximately one third of the total circuit resistance without the heat pipe. The heat pipe acts as a thermal short-circuit.

Beating the heat

Heat pipes can substantially reduce the thermal resistance between the heat source and the heat sink in a wide variety of applications. They are especially valuable in cooling systems that have confined spaces, as well as in enclosed products. In one computer system, conduction had to be used to remove heat generated by large numbers of densely mounted components on a printed-circuit board. The glass-epoxy board itself did not have sufficient thermal conductivity, even when augmented with heavy layers of copper.

To solve the problem, a flat-plate heat-pipe panel (Fig. 6a) was designed to serve as a structure/thermal base for two board assemblies—one on each side. Heat absorbed by the panel surface from the card-mounted components is transferred to the two edges of the heat-pipe panel, where the panel interfaces with its mounting rails. The heat absorbed at the rails is conducted through the enclosure and dissipated to an external air or liquid cooling system. The effective over-all thermal conductivity of the panel is eight times that of copper.

Another difficulty arose when a high-density solid-state microwave amplifier for military applications had to be cooled by natural convection only, yet the circuitry had to be enclosed and sealed within an existing package designed for outdoor use. The ambient temperature extremes were therefore substantial, and the internal and external heat sinks were limited.



6. Configuring coolers. A flat-pole heat pipe (a) conducts heat away from printed-circuit boards in a computer system. Five heat pipes were brazed onto an aluminum baseplate to cool a microwave amplifier in an enclosed assembly (b). The entire rear wall of the enclosure in a sealed numerical-control system forms a heat pipe (c) to distribute the heat, and fins on the outer surface dissipate it. A heat pipe serves both as drive shaft and heat sink with integral fins for heat dissipation in a motor for a servo-control drive in an airborne system (d).

A heat pipe with integral fins (Fig. 6b) was devised to cool the amplifier assembly. The heat sink consists of an aluminum baseplate to which five heat pipes are brazed at equal intervals. Heat is transported by the heat pipes to copper fin plates outside of the sealed enclosure. Between a component mounted at any location along the 23-inch-long mounting plane and the ambient air near the fins, the thermal resistance totals 0.66°C/w. The unit is designed for a nominal heat throughput of 85 w.

Cooling a sealed enclosure

At another installation, a numerical-control system for a machine tool required a sealed enclosure to prevent contamination from dirt and oil vapor. As a result, heat removal became a problem. The conventional solutions were found to be either thermally inadequate or too complex and costly.

A large heat-pipe assembly was developed to serve as the entire rear wall of the enclosure (Fig. 6c). The outward-facing surface of the heat sink includes sufficient finned surface to dissipate the entire thermal load by natural convection. A single flat-cross-section heat pipe applied across the interior surface of the heat sink distributes the heat uniformly over the large panel area.

Heat-generation is predominantly associated with a power supply that is conductively coupled directly to the interior of the heat-sink panel. Over-all effective resistance of the heat sink from the subsystem mounting pad to the environment is 0.25°C/w. The unit is rated for a maximum heat input of 150 w.

To achieve the required performance in a compact drive motor for a servo control in an airborne system, efficient removal of a substantial heat load generated in the rotating armature was necessary. Circulation of a fluid through the armature would have necessitated the use of rotating seals and added undesirable volume and weight to the assembly.

A heat pipe was designed to serve both as a drive shaft and heat sink (Fig. 6d). The end external to the motor frame contains integral fins for heat dissipation. The armature winding is pressed onto the heat-pipe shaft. Heat generated within the armature winding is conducted through the armature to the evaporator end.

Heat is transported isothermally down the length of the shaft and delivered to the finned convector by the heat-pipe operating cycle. The heat is dissipated from the fins by convection and radiation. A thermal resistance of less than 5°C/w is achieved between the armature shaft interface and cooling air. The assembly is designed for a nominal rating of 15 w. □