HEAT PIPES

1. Introduction

Heat pipes are used to perform several important heat transfer roles in the chemical and closely related industries. Examples include heat recovery, the isothermalizingof processes, and spot cooling in the molding of plastics. Heat pipes are highly efficient, two-phase heat transfer devices with effective thermal conductivities of up to ~1000 times that of solid copper, depending on the application. A heat pipe usually begins as a tube, that is given an internal wick structure. The tube is evacuated and backfilled with a small amount of working fluid and then sealed. A heat pipe is similar to a thermosyphon. It differs from a thermosyphon by virtue of its ability to transport heat against gravity by an evaporation–condensation cycle with the help of porous capillaries that form the wick. The wick provides the capillary driving force to return the condensate to the evaporator. The quality and type of wick usually determines the performance of the heat pipe, for this is the heart of the device. Different types of wicks are used, depending on the application for which the heat pipe is being employed. As a result, the heat pipe can produce nearly isothermal conditions making an almost ideal heat transfer element. In another form, the heat pipe can provide positive, rapid, and precise control of temperature under conditions that vary with respect to time.

The heat pipe is self-contained, has no mechanical moving parts, and requires, in its basic form, no external power other than the heat that flows through it. The heat pipe, which has been called a thermal superconductor, was described initially in 1944 (1) but commercial use did not follow. The same basic structure was again applied in 1963 in conjunction with the U.S. space nuclear power program (2).

2. Principles of Operation

The heat pipe achieves its high performance through the process of two-phase heat transfer and consists of three sections: evaporator, condenser, and adiabatic region. The evaporator section is mounted to the heat-generating components or submerged in a hot fluid, while the condenser is thermally coupled to a heat sink, radiator, or cold fluid. The adiabatic section allows heat to be transferred from the evaporator to the condenser with very small heat losses and temperature drops. Figure 1 presents comparison of the operation principles of basic heat pipe and a thermosyphon.

Inside the container of heat pipe there is a liquid under its own pressure, which enters the pores of the capillary material, wetting all internal surfaces. Applying heat at any point along the surface of the heat pipe causes the working fluid to evaporate or change phase from liquid to vapor. The vapor travels through the center of the pipe to the other end—the condenser end—where a heat sink or other means remove the heat. The release of heat causes the vapor to condense back to liquid for the wick to absorb. The liquid working fluid in

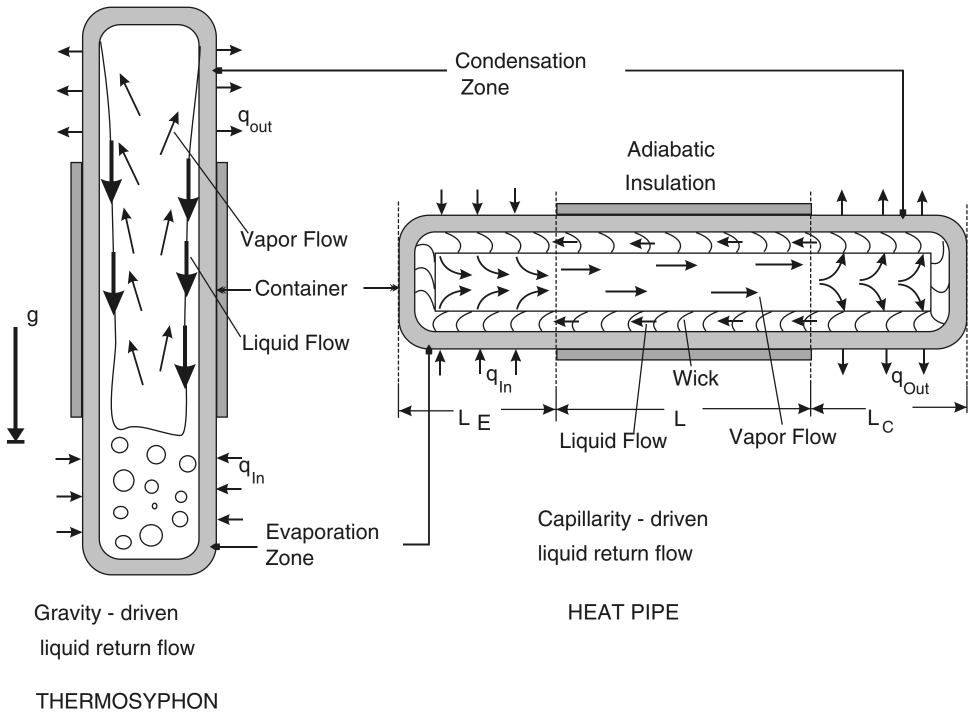

Fig. 1. Comparison of operation principles of heat pipe and thermosyphon.

the heat pipes is carried in the wick by capillary action back to the evaporator zone while in thermosyphons this liquid return is driving by gravity only.

The liquid is a substantial vapor pressure, generally >2.7 kPa (20 mm Hg), at the minimum desired operating temperature. The highest possible latent heat of vaporization is desirable to achieve maximum heat transfer and temperature uniformity with minimum vapor mass flow rate.

The unique aspect of the heat pipe lies in the means of returning the condensed working fluid from the condenser section to the evaporator. Condensate return is accomplished by means of a specially designed wick, which enhances the power handling capability as well as enables fluid return in horizontal and "against gravity" (evaporator above the condenser) orientations, with performance depending on the type of wick structure used. The surface tension of the liquid is the active force that produces wick pumping, which is a familiar process in lamp wicks and sponges. Using proper design, a substantial liquid mass flow rate can be sustained against the pressure head of the counterflowing vapor or even against a slight gravitational head. The performance of the wick is set by its pore radius and permeability. The pore radius determines the pumping pressure the wick can develop, while permeability determines the frictional losses of the fluid as it flows through the wick. In those applications where the heat source is below the heat sink, the condensate returns by gravity, ie, heat pipe without a wick represents a conventional thermosyphon (see also EVAPORATION).

The heat pipe consists, then, of the following components: A closed, evacuated vessel (evacuation is required to establish a contaminant-free system and to prevent air or other gases from interfering with the desired vapor flow), a wick structure of appropriate design, and a working fluid at the desired operating temperature. Heat pipes may also include gas reservoirs (variable conductance/diode heat pipes) and liquid or gas traps (diodes).

In order for a heat pipe to operate, the maximum capillary pumping head, $(\Delta P_c)_{\max}$, must be able to overcome the total pressure drop in the heat pipe, which consists of the pressure drop required to move the vapor from the evaporator to the condenser, ΔP_v, the potential head due to difference in elevation between the evaporator and the condenser, ΔP_g, and the pressure drop required to return the liquid from the condenser to the evaporator, ΔP_l. The basic condition for proper operation of heat pipe can thus be expressed in the form:

$$(\Delta \mathrm{P}_c)_{\max} \geq \Delta P_v + \Delta P_g + \Delta P_l$$

Under this condition, there is liquid flow toward the evaporator, and heat can be transferred. If this condition is not met, the wick will dry out in the evaporator region and the heat pipe will cease to operate. The pressure difference in the vapor is a direct function of the mass flow rate and an inverse function of the cross-sectional area of the vapor space. The mass flow rate is related directly to the transferred power and inversely to the latent heat of vaporization. The gravitational head can be either positive or negative, depending on whether it aids or opposes the desired flow in the wick.

3. Design Features and Operational Limits

Heat pipes can be designed to operate over a very broad range of temperatures from cryogenic (less than -243°C) applications utilizing titanium alloy/nitrogen heat pipes, to high temperature applications ($>2000^\circ$C) using tungsten/silver heat pipes. There are many factors to consider when designing a heat pipe: compatibility of materials, operating temperature range, power limitations, thermal resistances, and operating orientation (3–6).

Heat pipes can operate in the fixed conductance, variable conductance, or diode mode. The fixed conductance heat pipe can transfer heat in either direction and operates over broad temperature ranges, but has no inherent temperature control capability. Constant conduction heat pipes allow isothermalization of shelves, radiators and structures; spread heat from high heat dissipating components; and conduct heat away from heat generating devices.

The heat pipe has properties of interest to equipment designers. One is the tendency to assume a nearly isothermal condition while transporting useful quantities of thermal power. A typical heat pipe may require as little as one thousandth the temperature differential needed by a copper rod to transfer a given amount of power between two points. For example, when a heat pipe and a copper rod of the same diameter and length are heated to the same input temperature ($\sim 750^\circ$C) and allowed to dissipate the power in the air by radiation and natural convection, the temperature differential along the rod is 27°C and the power flow is 75 W. The heat pipe temperature differential was $<1^\circ$C; the power was 300 W. That is, the ratio of effective thermal conductance is $\sim$1200:1.

A second property, closely related to the first, is the ability of the heat pipe to effect heat-flux transformation. As long as the total heat flow is in equilibrium, the fluid streams connecting the evaporating and condensing regions essentially are unaffected by the local power densities in these two regions. Thus the heat pipe can accommodate a high evaporative power density coupled with a low condensing power density, or vice versa. It is common in heat transfer applications for the intrinsic power densities of heat sources and heat sinks to be unequal. This condition may force undesired performance compromises on the equipment or process in question. The heat pipe can be used to accomplish the desired matching of power densities by simply adjusting the heat input and output areas in accordance with the requirements. Heat flux transformation ratios exceeding 12:1 have been demonstrated in both directions, ie, concentration and dispersion of power density. It is not uncommon in chemical applications for flame heat sources to be employed to establish desired reaction temperatures and rates. The natural power density from the flame can be appreciably greater than that desired locally within the reaction vessel. A heat pipe can collect the power at high density from the flame and distribute it at low density over large areas within the vessel.

The third characteristic of interest grows directly from the first, ie, the high thermal conductance of the heat pipe can make possible the physical separation of the heat source and the heat consumer (heat sink). Heat pipes >100 m in length have been constructed and shown to behave predictably (7). Separation of source and sink is especially important in those applications in which chemical incompatibilities exist. For example, it may be necessary to inject heat into a reaction vessel. The lowest cost source of heat may be combustion of hydrocarbon fuels. However, contact with an open flame or with the combustion products might jeopardize the desired reaction process. In such a case it might be feasible to carry heat from the flame through the wall of the reaction vessel by use of a heat pipe.

The fourth characteristic, temperature flattening, makes use of all three of the preceding properties. The evaporation region of a heat pipe can be regarded as consisting of many subelements, each receiving heat and an influx of liquid working fluid and each evaporating this fluid at a rate proportional to its power input. Within the limitations discussed in the following sections, each incremental unit of evaporation area operates independently of the others, except that all are fed to a common vapor stream at a nearly common temperature and pressure. The temperature of the elements is, therefore, nearly uniform. It can be seen that the power input to a given incremental area can differ widely from that received by other such areas. Under other circumstances, a nonuniform power profile would produce a nonuniform temperature profile. In the case of the heat pipe, however, uniformity of temperature is preserved; only the local evaporation rate changes. In this fashion, the heat pipe can flatten the very nonuniform power input profile from a flame, delivering heat to the sink with the same degree of uniformity as if the heat source were uniform. Another example is the use of a heat pipe to cool simultaneously, and to nearly the same temperature, a number of electronic components operating at different power levels.

The most important heat pipe design consideration is the amount of power the heat pipe is capable of transferring. Heat pipes can be designed to carry from few watts up to several kilowatts, depending on the application. If driven beyond its capacity, however, the effective thermal conductivity of the heat pipe will be significantly reduced. Therefore, it is important to ensure that the heat pipe is designed for safely transport of the required heat load.

The wick has a finite pumping capacity for returning the condensed working fluid from condenser to evaporator against a frictional or gravitational head. The total thermal power transfer capability of the heat pipe is the product of the latent heat of vaporization and maximum mass flow rate of the fluid that can be sustained by the wick. Operation at greater power results in evaporation rates exceeding the rate of liquid return. The resulting dryness can lead to an uncontrolled rise in temperature in the uncooled section of the evaporator, and ultimate failure. The effect of gravity is similar. If the desired operation requires that the liquid flow be upward against gravity or another accelerating force, operation is affected adversely to the degree that it is a function of the lift height, liquid density, and the mass flow rate.

In many applications, especially in the chemical and semiconductor fields, the closest possible approach to isothermal operation may be desired. Under these conditions, the effects of vapor velocity must be considered if the velocity of the vapor exceeds about Mach 0.2, when a noticeable temperature differential shows itself in the heat pipe. If near isothermal operation is desired, designers restrict the vapor velocity to lower levels.

An absolute upper limit on operating temperature exists for any given fluid and vessel combination. This limit is determined by the creep or rupture strength of the vessel, ie, the ability of the vessel to contain the increasing vapor pressure of the working fluid.

The maximum heat transport capability of the heat pipe is governed by several limiting factors, which must be addressed when designing a heat pipe. There are five primary limitations of heat transport inside heat pipe: viscous, sonic, flooding, capillary, and boiling limits. These heat transport limits are a function of the heat pipe operating temperature. The envelope of these limits is shown generically in Figure 2. Curve A represents limits associated with vapor

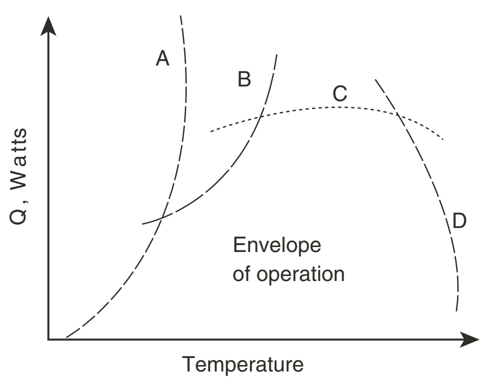

Fig. 2. The axial heat flow, Q, versus operating temperature showing the envelope of heat pipe operating limits: curve A represents limits associated with vapor flow, curve B represents the entrainment limit, curve C describes a wicking limit and curve D is the boiling limit.

flow, ie, either insufficient working fluid vapor pressure is available to transport vapor along the length of the heat pipe (viscous limit) or the vapor flow has reached the sonic velocity (sonic limit). Curve B represents the entrainment limit that occurs when friction with the outgoing vapor prevents the returning liquid from reaching the evaporator. This is sometimes referred to as a flooding limit. Curve C describes a wicking limit and occurs when the capillary pressure developed in the wick can no longer support the total pressure drop in the fluid flow path (includes liquid, vapor, and gravitational effects). Curve D is the boiling limit which occurs when vapor is generated within the capillary structure in an uncontrolled manner, much the same as film boiling.

4. Suitable Working Fluids and Selection of Materials

The first consideration in the identification of a suitable working fluid is the operating vapor temperature range. Within the approximate temperature band, several possible working fluids may exist, and a variety of characteristics must be examined in order to determine the most acceptable of these fluids for the application considered. The prime requirements are compatibility with wick and wall materials, good thermal stability, wettability of wick and wall materials, vapor pressure not too high or low over the operating temperature range, high latent heat, high thermal conductivity, low liquid and vapor viscosities, high surface tension, acceptable freezing point.

In heat pipe design, a high value of surface tension is desirable in order to enable the heat pipe to operate against gravity and to generate a high capillary driving force. In addition to high surface tension, it is necessary for the working fluid to wet the wick and the container material, ie, the contact angle should be zero or very small. The fluid vapor pressure, a contributor to the vapor density, is one of the fastest changing functions of temperature. The vapor pressure over the operating temperature range must be sufficiently large to avoid high vapor velocities, which tend to set up large temperature gradients and thus cause flow instabilities.

A high latent heat of vaporization is desirable in order to transfer large amounts of heat with minimum fluid flow, and hence to maintain low pressure drops within the heat pipe. The thermal conductivity of the working fluid should preferably be high in order to minimize the radial temperature gradient and to reduce the possibility of nucleate boiling at the wick or wall surface. The resistance to fluid flow could be minimized by choosing fluids with low values of vapor and liquid viscosities. The melting point of the fluid is not only important in determining the minimum operating temperature, but also determination of the start-up and storage characteristics. If solidification of the fluid is expected, care must be taken to avoid stresses, caused by density changes, which may distort the vessel or wick. The relationship of the liquid density to the surface tension is used to determine the lifting height of the fluid in a given wick structure and the extent to which operation can be expected in opposition to an accelerative force such as gravity.

Special consideration must be given to the processing of heat pipes to be used at temperatures <250 K. As the temperature drops, the vapor pressure of the fluid falls off. This allows any noncondensable gas created by contamination to expand, thus blocking portions of the heat pipe from active use.

The operating lifetime of a given heat pipe is usually determined by corrosion mechanisms. The repetitive distillation or refluxing of the working fluid can cause rapid mass transport of dissolved material unless careful attention is paid to compatibility. The result can be solution of the wick or vessel in the condenser region and clogging of the wick in the evaporator. Steps must also be taken to ensure the purity of the fluid charge. Small quantities of impurities can accelerate the corrosive action in some systems. There are standard cleaning and filling methods for a variety of working fluid/wall material combinations (3). A number of pairs of materials have long (thousands of hours) undegraded life, when properly processed (Table 1).

Table 1. **Pairs of Materials Having Long Operating Life**[a]

Fluid	Wick-vessel material	Temperature range, K
liquid nitrogen	aluminum stainless steel	60–100
ammonia	aluminum stainless steel carbon steel nickel	200–330
acetone	aluminum stainless steel cooper brass	305–405
methanol	copper nickel stainless steel	230–400
water	copper nickel	280–500
rubidium	stainless steel molybdenum niobium	600–1100
potassium	stainless steel nickel molybdenum niobium	800–1200
sodium	stainless steel inconel molybdenum tungsten niobium hastelloy X	900–1500
lithium	molybdenum tungsten niobium tungsten-rhenium tantalum	1300–1900
silver	tungsten tantalum tungsten-rhenium	1700–2200

[a]Ref. 3–6.

The wick structure is the pumping system that moves the condensate from the condenser region to the evaporator region. The selection of a suitable wick for a given application involves consideration of its form factor or geometry. The basic material generally is chosen on the basis of the wetting angle and compatibility considerations. The wick and vessel materials are generally the same to minimize electrochemical effects. The factors that must be considered in wick design are often conflicting so that each specific heat pipe requires a separate study to determine the optimum structure. Compromises are made between the small capillary pore size desired for maximum pumping pressure and the large pore size required for minimum viscous drag, especially for very long heat pipes or for those that must pump against gravity.

Thickness of the wick is its important feature, which must be optimized. The heat transport capability of the heat pipe is raised by increasing the wick thickness. The cross-sectional area of the wick is determined by the required liquid flow rate and the specific properties of capillary pressure and viscous drag. The mass flow rate is equal to the desired heat-transfer rate divided by the latent heat of vaporization of the fluid. Thus the transfer of 2260 W requires a liquid (H_2O) flow of 1 cm^3/s at 100°C. Because of the porous character, wicks are relatively poor thermal conductors. Radial heat flow through the wick is often the dominant source of temperature loss in a heat pipe; therefore, the wick thickness tends to be constrained and rarely exceeds 3 mm. The overall thermal resistance at the evaporator also depends on the conductivity of the working fluid in the wick.

Several wick structures are in common use. First is a fine-pore [0.14–0.25 mm (100–60 mesh) wire spacing] woven screen that is rolled into an annular structure consisting of one or more wraps inserted into the heat pipe bore. The mesh wick is a satisfactory compromise, in many cases, between cost and performance. Where high heat transfer in a given diameter is of paramount importance, a fine-pore screen is placed over longitudinal slots in the vessel wall. Such a composite structure provides low viscous drag for liquid flow in the channels and a small pore size in the screen for maximum pumping pressure.

Where complex geometries are desired, the wick can be formed by powder metallurgy techniques, ie, a dry powder is sintered in place, often around a central mandrel, which is then removed. Such wicks can be made with extremely small pore sizes, providing good pumping pressures, but tend to have high viscous drag properties. The drag may be offset by longitudinal liquid passages formed in the metal powder. Since the size of the particles used in forming the sintered structure can be varied, a tailored high performance wick can be made using this process. Sintered-powder metal-wick heat pipes can be made to work in any orientation, even with the pipe vertical and the heat source at the top. This capability makes the sintered-powder metal-wick structure a very high performance system, particularly suitable for applications on such as notebook computers where the use-orientation of the heat pipes is uncertain. For heat pipes of considerable length where minimum viscous drag is required, an arterial wick geometry has been employed, ie, a tubular artery, often formed of screen, is attached to the wick that lines the inside walls of the heat pipe. The inside of the artery provides a low drag passage for liquid flow.

Fibrous materials, like ceramics, have also been used. In general, they have smaller pores. The main disadvantage of ceramic fibers is that they have little stiffness and usually require a continuous support by a metal mesh. Thus while the fiber itself may be chemically compatible with the working fluids, the supporting materials may cause problems. More recently, interest has turned to carbon fibers as a wick material. Carbon fiber filaments have many fine longitudinal grooves on their surface, can generate high capillary pressures and are chemically stable. A number of heat pipes that have been successfully constructed using carbon fiber wicks seem to show a greater heat transport capability.

The capillary capability could be improved by using an advanced wick structure—graded wick (8). While uniform wicks are easy to manufacture, they do not provide the maximum capillary capability required in many applications, especially for heat pipes that are operating against gravity and are long. Because the liquid vapor pressure differential changes continuously from the evaporator to condenser, a graded wick that corresponds to this change is able to provide the maximum capillary capability and the minimum liquid flow resistance.

The vessel in which a heat pipe is enclosed must be impermeable to assure against loss of the working fluid or leakage into the heat pipe of air combustion gases or other undesired materials from the external environment. In the quiescent, cold state, the heat pipe is evacuated except for the working fluid and is generally under an external atmospheric pressure. As operation is initiated, the vapor pressure of the working fluid rises and offsets the external pressure. Frequently, the heat pipe operates at a vapor pressure exceeding the external pressure. Under these conditions, a heat pipe may be designed to conform with established pressure vessel codes, considering both rupture and creep strengths.

The vessel, as well as the wick, must be compatible with the working fluid. Where possible, the wick and vessel are made of the same material to avoid the formation of galvanic corrosion cells in which the working fluid can serve as the electrolyte. In addition to its role within the heat pipe, the vessel also serves as the interface with the heat source and the heat sink.

5. Variable-Conductance Heat Pipes

Variable conductance heat pipes (VCHP) are applied in thermal control to keep the temperature of a heat source as constant as possible for varying thermal loading conditions, ie, the heat throughput and the temperature of the heat sink. Several methods to achieve VCHP behavior are described and discussed in the literature (9–11), eg,

- Liquid flow control by interrupting or impeding the return of the condensate in the wick. For dissipative heat sources this means just providing "on–off" control, ie, thermal switching.
- Vapor flow control by interrupting or throttling the vapor flow between the heat pipe evaporator and condenser, which gives rise to the pressure

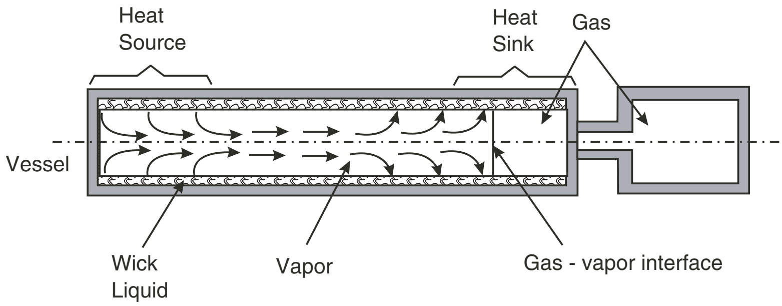

Fig. 3. Schematic diagram of a gas-controlled heat pipe.

difference, hence the temperature difference, between these regions. The latter means a variable conductance.

- Condenser flooding by noncondensable gas, the so-called gas-loaded VCHP.
- Condenser flooding, being analogous to the gas-loaded concept, but using excess liquid (instead noncondensable gas) to vary the active condenser area.

The gas-controlled heat pipe operates so that its access to the heat sink varies in proportion to changes in power input, while preserving its operating temperature at a very nearly constant value. Changes of power input by a factor exceeding 30:1 have been recorded with a change in temperature of $<1^\circ$C. This extremely precise temperature regulation is accomplished through simple principles and without resort to external sensing and control mechanisms. The operation is as follows: the heat pipe vessel is extended to include a volume of inert gas at a predetermined pressure (Fig. 3). The effect upon the heat pipe of this gas pressure is similar to the effect on the boiling point of water of the ambient air pressure, ie, the operating temperature is established as the point on the fluid vapor pressure–temperature curve where the vapor pressure equals the gas pressure. During heat pipe operation, the kinetic energy of the highly directional vapor flow sweeps the gas to the condenser of the heat pipe. The gas and vapor remain highly segregated as long as the mean free path of a vapor molecule in the gas is short, corresponding to a pressure of ca $\geq$20 kPa ($\geq$0.2 atm). Under these conditions, the gas–vapor interface is extremely sharp and heat pipe action ceases beyond this point. The location of the interface is indicated by an abrupt drop in temperature.

As the heat input to such a gas-controlled, constant-temperature heat pipe is increased, the operating temperature tends to remain constant because the location of the interface moves so as to expose to the vapor an increased access area to the heat sink. The degree of temperature control is determined by the ratio of the total gas volume to the displaced gas volume. This volume need not be large to effect precise temperature control because the temperature is a very slow function of the fluid's vapor pressure. A device of this type provides similar regulation under conditions where the heat sink properties vary with time. It also starts quickly and smoothly from a cold, frozen condition under which a conventional heat pipe might stall. The control point of a gas-controlled heat pipe can be varied with the pressure of the gas. Devices of this type have been used for measuring vapor pressures, regulating the temperature of semiconductors (qv), and establishing thermal control of orbiting spacecrafts.

6. Pulsating Heat Pipes

Meandering tube Pulsating Heat Pipes (PHP) consist of a metallic tube of capillary dimensions wound in a serpentine manner (Fig. 4). This tube may be either be open loop (tube ends not connected to each other) orclosed loop (tube ends connected to each other in an endless loop). PHP is first evacuated and then filled partially with a working fluid, which distributes itself naturally in the form of liquid−vapor plugs and slugs inside the capillary tube. One end of this bundle of tubes receives heat transferring it to the other end by a pulsating action of the liquid−vapor system. An optional adiabatic zone may exist between evaporator and condenser sections.

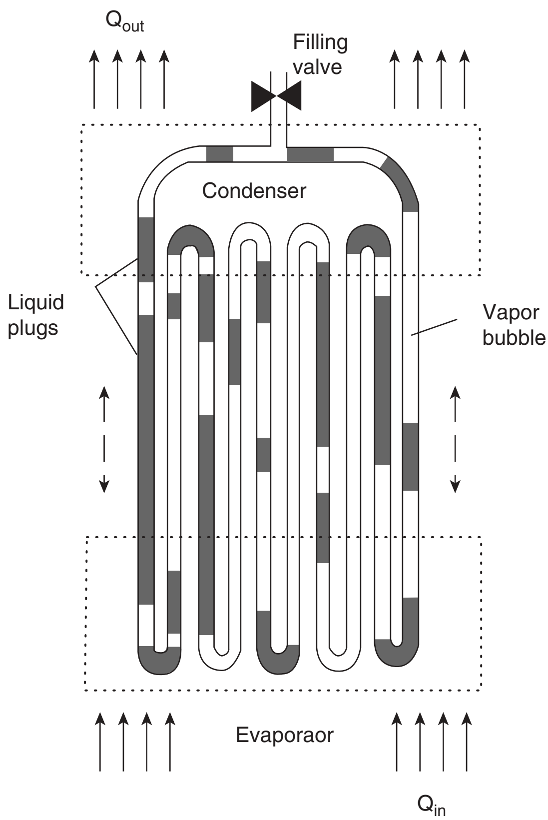

Fig. 4. Schematic of a pulsating heat pipe.

Among basic features of PHP are

1. Absence of wick structure.
2. Self-exited thermally driven oscillations (without external mechanical power source).
3. Surface tension predominates; although gravity may affect the performance.
4. Latent as well as sensible heat transport possible by the self oscillating working fluid.

A PHP is essentially a nonequilibrium heat transfer device. The performance success of PHP primarily depends on the continuous maintenance or sustenance of these nonequilibrium conditions within the system. The liquid and vapor slug transport is because of the pressure pulsations caused in the system. Since these pressure pulsations are fully thermally driven, because of the inherent construction of the device, there is no external mechanical power source required for the fluid transport.

The complexity of thermofluidic transport phenomena in the PHPs is so overwhelming that a comprehensive theory and reliable data or tools for the design of PHPs are still a subject of further research (12–14).

7. Loop Heat Pipes and Capillary Pumped Loops

Loop heat pipes (LHPs) and capillary pumped loops (CPLs) are two-phase heat transfer devices that utilize the evaporation and condensation of a working fluid to transfer heat, and the capillary forces developed in fine porous wicks to circulate the fluid. The LHPs and CPLs consist of sealed tubes connecting the evaporator, the heat source, with a condenser, and the heat sink. The working fluid circulates due to the capillary pressure gradient developed in the wick. Typical loop designs also incorporate a reservoir (hydroaccumulator) for liquid management purposes during start-up and normal operating conditions. The reservoir temperature can either be unregulated, for fixed conductance applications, or thermostatically regulated for variable conductance applications. Unregulated reservoir designs are sized to hard fill after start-up thus allowing the condenser to be fully open during normal operation. In this case, the source temperature is also unregulated and the operating temperature will vary as a function of heat load and heat sink temperature conditions. Regulated reservoir designs are thermostatically controlled and are sized to provide sufficient liquid displacement to operate the condenser from fully open to fully closed under all operating conditions. In this case the source temperature can be regulated, within the accuracy of the thermostat, independently of heat loads, heat sink conditions or operating temperature. The primary difference between the CPL and LHP is the location of the reservoir. The CPL reservoir (Fig. 5) is located remotely from the evaporator and is cold biased using either the sink or the subcooled liquid returned from the condenser. The LHP reservoir (Fig. 5), on the other hand, is thermally and hydraulically coupled to the evaporator with a secondary wick. This difference in the reservoir location is responsible for the

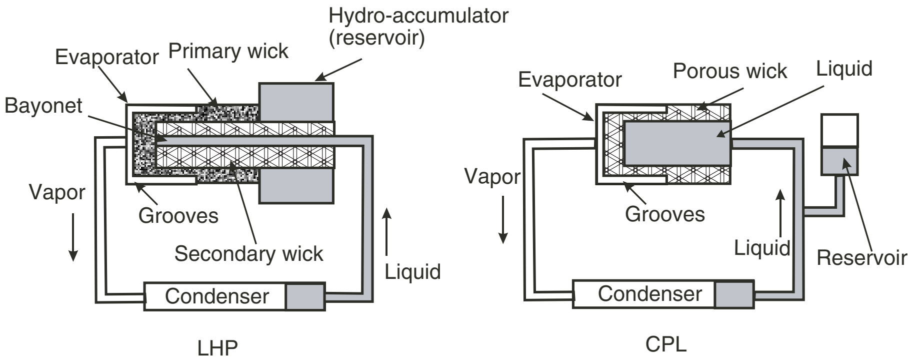

Fig. 5. Loop heat pipe and capillary pumped loop.

primary difference in the behavior of the two systems (15). The LHP was first developed in the former Soviet Union in the early 1980s (16), about the same time that the CPL was developed in the United States (17,18).

The LHP is known for its high pumping capability and robust operation because it uses fine-pored metal wicks and the integral evaporator/hydroaccumulator design. The primary wick in the evaporator is made with fine pores that serve to develop a capillary pressure to circulate fluid around the loop. The secondary wick in the hydroaccumulator is made with larger pores that manage fluid entrance and exit. The two-phase hydroaccumulator stores excess liquid and controls the operating temperature of the loop. As heat is applied to the evaporator, liquid is vaporized and the menisci formed at the liquid/vapor interface in the evaporator wick develop capillary forces to draw the vapor through the vapor line to the condenser. Vapor condenses in the condenser and the capillary forces continue to push liquid back to the evaporator. The waste heat from the heat source provides the driving force for the circulation of the working fluid. As a result, no external pumping power is required.

The secondary wick provides a liquid link between the hydroaccumulator and the evaporator so that the evaporator will always be replenished with liquid. There are two major advantages of such a design. First, the loop can be started by directly applying power to the evaporator without the need of preconditioning. Second, the evaporator is tolerant of vapor bubbles in its liquid core. Because the primary wick is made of metal powder with a high thermal conductivity, liquid evaporation usually takes place inside the evaporator core and vapor bubbles are present there in most operations. To prevent vapor bubbles from accumulating inside the evaporator core, the secondary wick design incorporates vapor arteries that allow vapor bubbles to vent to the hydro-accumulator. Regardless whether or not vapor bubbles are present, the evaporator core can be considered as an extension of the hydroaccumulator, and both have the same absolute pressure during steady operation.

8. Applications in the Chemical Industry

With its superior characteristics, heat pipe technology is playing a more and more important role in the waste heat recovery, energy-saving and environmental protection units and in industrial process equipment. The primary application of heat pipes in the chemical industry is for combustion air preheat on various types of process furnaces that simultaneously increases furnace efficiency and throughput and conserves fuel. Advantages include modular design, isothermal tube temperature eliminating cold corner corrosion, high thermal effectiveness, high reliability and options for removable tubes, alternative materials and arrangements, and replacement or add-on sections for increased performance (see FURNACES, FUEL-FIRED). Separate type heat pipe technology has made heat exchange possible at long distance where mixing is not allowed and where multiple heat sources (or heat sinks) are used.

The dual-wall heat exchange characteristics of the heat pipe are an important guarantee for the safe, reliable and long-term operation. With traditional one-wall heat-exchange apparatus, the equipment should be stopped for repair even when only one heat exchange element is damaged. This is not the case with the heat pipe equipment. Even if there is damage to a single heat pipe in the apparatus comprising heat pipe arrays, the two different types of heat exchange fluids will not be mixed, and therefore the overall heat exchange effect will not be affected.

The principal competing technology is provided by the rotary regenerative heat exchanger. The main advantages of the heat pipe exchanger lie in its ease of cleaning and its ability to sustain a high pressure differential between the air and gas streams without leakage. When compared to rotary regenerative and tubular exchangers, heat-pipe units are generally smaller in size than tubular exchangers and somewhat larger than rotary units. Cold spots within the exchanger, and resulting corrosion, are generally less of a problem than with either alternative design.

Typically, an array of finned heat pipes is placed so that heat is transferred from a hot exhaust gas stream to an incoming cold air stream. Heat-pipe heat exchangers range in size from a few hundred watts for electronic control cabinets to several hundred thousand watts for large-scale preheating of combustion air. A typical exchanger is shown in Figure 6**a** and 6**b**. Solvent recovery is accomplished when outgoing exhaust gases from chemical processes are cooled below their dew point, forcing condensation of solvents they may contain.

The heat flux exchange and self soot-blowing characteristics of heat pipe are important technical guarantee to prevent dew-point corrosion and dust clogging in industrial equipment. It has been proved that such accidents as deterioration of equipment efficiency or even forced outage due to clogging and dew-point corrosion of large power station boilers, various industrial waste heat boilers in high dust content environment and other heat exchange equipment in dusty environment can be prevented and avoided when they are replaced with heat pipe heat exchangers.

With the development of fine chemical industry, higher requirements have been raised on the spray drying technology for powder materials, which require a hot air of 450–600°C or even higher temperature in many applications. It is quite difficult to heat the air to such a temperature range with conventional heat exchange equipment. If the flue gas of fuel is used directly, pollutants may be carried with it, rendering the product quality not up to the specification.

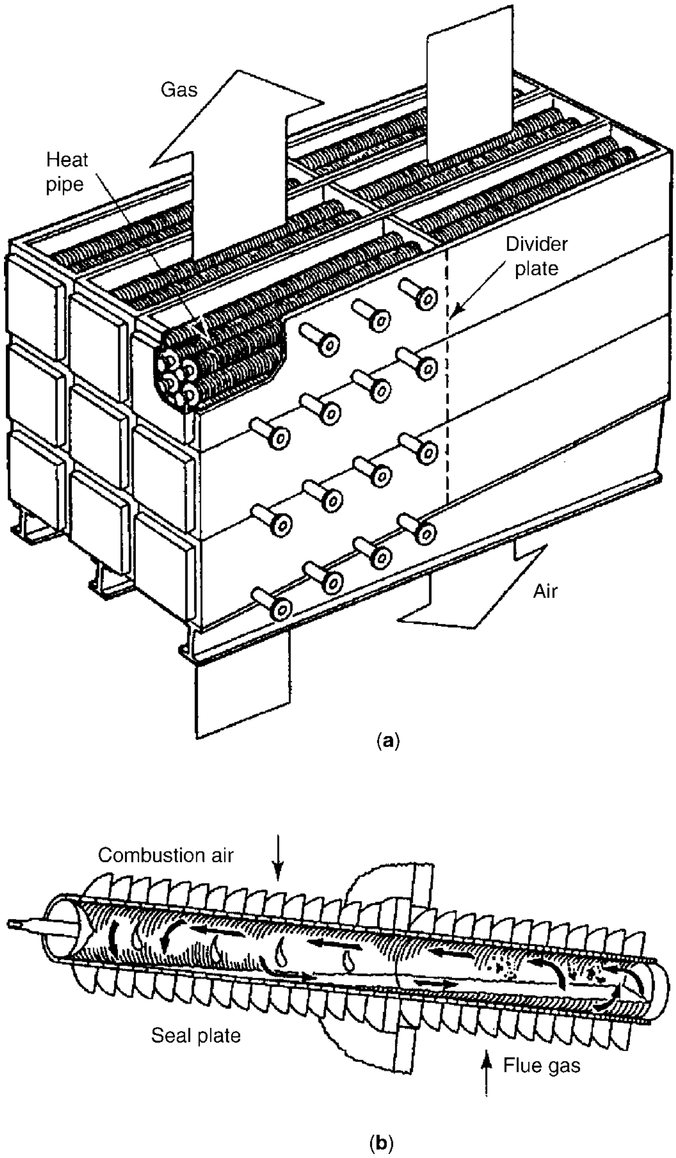

Fig. 6. (**a**) Air preheater using heat pipes; (**b**) typical heat pipe used in air preheater. (Courtesy ABB Air Preheater, Inc.)

Heat pipes are used for local temperature control in the injection molding of plastics. A heat pipe is often used to force local cooling within a mold to speed operation, control viscosity, retention of material in a difficult mold area, or to reduce thermal stresses on cooling.

High temperature heat pipes using liquid metals as working fluids are used to provide a uniform environment for a variety of chemical processes. Isothermal furnace liners, used as inserts in conventional tubular furnaces, are annular

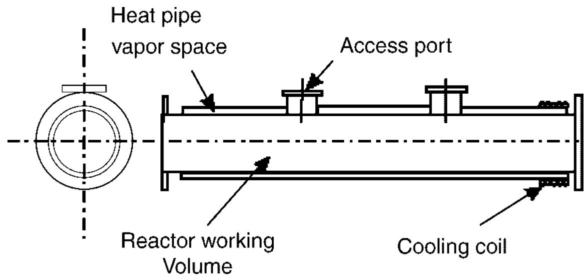

Fig. 7. Isothermal tubeflow reactor. (Courtesy Dynatherm Corp.)

heat pipes which receive their heat input along the outer diameter and provide an extremely uniform, ie, near isothermal, temperature environment to the work zone on the inside. Units of this type are used for the growth of semiconductor crystals, vapor deposition, and other processes requiring uniform temperatures. Isothermal chambers ranging up to 1.2 m in diameter and 2.4 m in height have been made, providing temperature uniformly of ±1°C or better throughout this volume at temperatures in the range of 500−1000°C. Figure 7 is a line drawing of an isothermal reactor.

The homogeneous temperature and heat shielding performance of heat pipes can solve such problems as nonhomogeneous temperature distribution in a chemical reactor and reaction deviating from optimum reaction temperature, the overheating decomposition due to uneven pipe wall temperature in petroleum crackers and heat dissipation for the nuclear reactor vessel body.

To improve the chemical reactor, key equipment in industrial processes with the heat pipe technology will not only be beneficial to energy optimization of the reactor itself. More importantly, it is good to chemical reaction to raise the output and yield, thus bringing the industrial production equipment level onto a new step.

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