Heat Pipes –Integrated Circuit Coolers

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Abstract: - Dissipation of heat from electronic components is a general phenomenon, and in the past several methods like the use of heat sinks, fans, coolers and convection methods have been used. The latest invention for cooling of electronic components is the heat pipes. The time of beginning of heat pipe science was near 40 years ago with first heat pipe definition and prediction of most simple cases. The interest stems in achieving extremely high heat flux near 1000W/cm^2, needed for the future generation electronic cooling application. Now at the computer age some changes of basic equations are performed, more powerful predicting methods are available with increasing awareness of complexity of heat pipes and new heat pipe generations. But even today heat pipes are not completely understood and solution strategies still contain significant simplifications depending upon its applications. Micro and miniature heat pipes have some additional complications due to its small size. A review of heat pipes is presented in this paper.

Keywords: - MHP- Micro heat pipes, mhp- miniature heat pipes, LHP- loop heat pipes, SHP- Sorption heat pipes.

Nomenclature: - A cross sectional surface area,m^2 , K permeability, Q volumetric flow rate,m^3/s, D diameter ,m, g gravity, m/s^2, hυ enthalpy of vaporization, L_{eff} effective transport zone, L length of pipe, r_c effective capillary radius, μ dynamic viscosity, ρ density, Π mathematical constant. Π=3.14, σ surface tension, θ inclination angle.

1 Introduction

In the modern world where everything seems to have been invented, challenge today lies in enhancing properties of the available materials, this can be done by increasing their efficiency. It is estimated that heat dissipated in industries is very large, which could be harmful as it exceeds the operating temperature range of several electronic chips. To cool electronic components, one can use air and liquid coolers as well as coolers constructed on the principle of the phase change heat transfer in closed space; i.e., immersion, thermosyphon, and heat pipe coolers. Each of these methods has its merits and draw-backs because, in the choice of appropriate cooling, one must take into consideration not only the thermal parameters of the cooler but also design and stability of the system, durability, technology, price, application, etc. One way to overcome the problem is the use of heat pipes.

2 Heat Pipes

The idea of heat pipes was first suggested by R.S.Gaugler in 1942 and in 1962 when G.M.Grover invented it, that its remarkable properties were appreciated & serious development began. [1]

A heat pipe is a simple device that can quickly transfer heat from one point to another, often referred to as the "superconductors" of heat as they possess an extra ordinary heat transfer capacity. Heat pipes are not in general a low cost solution to the cooling problem, but they are most effective and have great potential as power levels and volume requirements increase. There are three basic components of a heat pipe are as follows:-

2.1 The container

The function of the container is to isolate the working fluid from the outside environment. It has to therefore be leak-proof, maintain the pressure differential across its walls, and enable transfer of heat to take place from and into the working fluid. Selection of the container material depends on many factors. These are as follows:

Compatibility (both with working fluid and external environment), Strength to weight ratio, Thermal conductivity, Ease of fabrication, including welding, machine ability and ductility, Porosity, wettability.

2.2 The working fluid

A 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 or pour point. The use of working fluid is according to the application. Water is the most commonly used working fluid. Working areas of various fluids are presented in [11].

2.3 The wick or capillary structure

It is a porous structure made of materials like steel, aluminum, nickel or copper in various ranges of pore sizes. They are fabricated using metal foams, and more particularly felts, the latter being more frequently used. By varying the pressure on the felt during assembly, various pore sizes can be produced.

Fibrous materials, like ceramics, have also been used widely. They generally 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, have high capillary pressures and are chemically stable. The prime purpose of the wick is to generate capillary pressure to transport the working fluid from the condenser to the evaporator. It must also be able to distribute the liquid around the evaporator section to any area where heat is likely to be received by the heat pipe.

The most common types of wicks

(i) Sintered Powder

This process will provide high power handling, low temperature gradients and high capillary forces for anti-gravity applications. The photograph shows a complex sintered wick with several vapor channels and small arteries to increase the liquid flow rate. Very tight bends in the heat pipe can be achieved with this type of structure.

(ii)Grooved Tube

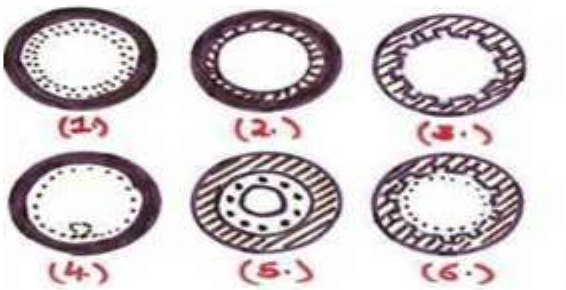
The small capillary driving force generated by the axial grooves is adequate for low power heat pipes when operated horizontally, or with gravity assistance. The tube can be readily bent. When used in conjunction with screen mesh the performance can be considerably enhanced.

(iii)Screen Mesh

This type of wick is used in the majority of the products and provides readily variable characteristics in terms of power transport and orientation sensitivity, according to the number of layers and mesh counts used.

Sintered powder metal wicks offer several advantages over other wick structures. One advantage of a heat pipe with a sintered powder wick is that it can work in any orientation, including against gravity (i.e., the heat source above the cooling source). The power transport capacity of the heat pipe will typically decrease as the angle of operation against gravity increases. Since groove and screen mesh wicks have very limited capillary force capability, they typically cannot overcome significant gravitational forces, and dry out generally occurs.

An emerging advantage of the sintered powder wick is its ability to handle high heat fluxes. Since sintered powder wicks are generally 50% porous, there is accordingly a large surface area available for evaporation. Typical sinter powder wicks handle 50 W/cm^2, and have been tested to 250 W/cm^2. In comparison, a groove wick will nominally handle 5 W/cm^2 and a screen wick will nominally handle 10 W/cm^2.



1. Net structures, 2. Sinter Structures
3. Open structures, 4,5 and 6. Combined structures

Figure.1 Different structures of the capillary layer

Additionally, since a sintered powder wick is integral with the heat pipe envelope, and the fluid charge is only enough to saturate the wick, the heat pipe can be subjected to freeze/thaw cycles with no degradation in performance. Moreover, the heat pipe including the sintered powder wick structure can be bent in different shapes. The above attributes make the sintered powder wick the optimal structure for many thermal management solutions.

3 Heat Pipe Operation

Heat pipes are sealed vacuum vessels that are partially filled with a working fluid, typically water in electronic cooling, which serves as the heat transfer medium.

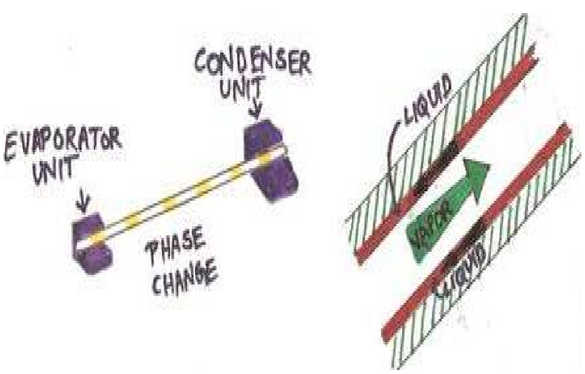


Figure.2 Concept of heat pipe

The heat pipe envelope is made of copper in a myriad of shapes including cylindrical, rectangular, or any other enclosed geometry. The wall of the envelope is lined with a wick structure, which provides surface area for the evaporation/condensation cycle and capillary capability.

Since the heat pipe is evacuated and then charged with the working fluid prior to being sealed, the internal pressure is set by the vapor pressure of the working fluid. As heat is applied to the surface of the heat pipe, the working fluid is vaporized (Figure 2). The vapor at the evaporator section is at a slightly higher temperature and pressure than other areas. This creates a pressure gradient that forces the vapor to flow to the cooler regions of the heat pipe. As the vapor condenses on the heat pipe walls, the latent heat of vaporization is transferred to the condenser. The capillary wick then transports the condensate back to the evaporator section. This closed loop process continues as long as heat is applied.

Figure 2. As heat is applied to the surface of the heat pipe, the working fluid is vaporized. For a heat pipe to function properly, the net capillary pressure difference between evaporator (heat source) and condenser (heat sink) must be greater than the sum of all pressures losses occurring throughout the liquid and vapor flow paths. This relationship, referred to as the capillary limitation, can be expressed mathematically as follows

$$\Delta P_{cmax} \geq \Delta P_l + \Delta P_v + \Delta P_g$$

ΔP_{cmax} is the maximum capillary pressure difference generated within the capillary wicking structure between the evaporator and condenser, ΔP_l and ΔP_v are the viscous pressure drops occurring in the liquid and vapor phases, respectively, and ΔP_g represents the hydrostatic pressure drop.

$\Delta P_l = \frac{Q \mu L_{eff}}{K A_l \Delta l_v}$ liquid pressure drop from the Darcy's law.

$\Delta P_v = \frac{128 \mu Q L}{\pi d^4}$ vapor pressure drop from and

ΔP_g Hagen Poiselle equation. When the maximum capillary pressure is equal to or greater than the sum of these pressure drops, the capillary structure can return an adequate amount of working fluid (priming or repriming of the heat pipe) to prevent the evaporator wicking structure from drying out. When the sum of all pressure drops exceeds the maximum capillary pumping pressure, the working fluid is not supplied rapidly enough to the evaporator to compensate for the liquid loss through vaporization, and the wicking structure becomes starved of liquid and dries out (depriming of the heat pipe). This condition, referred to as capillary limitation, varies according to the wicking structure, working fluid, evaporator heat flux, operating temperature, and body forces.

4 Micro and Miniature heat pipes

These are small scale devices that are used to cool micro electronic chips. Micro channels in these heat pipes are fluid flow channels with small hydraulic diameters. The hydraulic diameter of micro heat pipes is on the order10-500µm, and miniature heat pipes is on the order 2-4nm. Smaller channels application is desirable because of two reasons (i) higher heat transfer coefficient, and (ii) higher heat transfer surface area per unit flow volume. MHP's are promising to cool and heat some biological micro-objects. The phenomena of MHP's is often available in nature, the operation and functioning of sweat gland [2] can be taken as example. Open- type mini/micro heat pipes are suggested in [3,4] as a system of thermal control of biological objects and drying technology.

The most efficient improvement of the micro heat pipe parameters can be obtained, if the surface of the evaporation and condensation zones would be dramatically increased. Various structures of heat pipes were grooved to increase the surface of evaporation. V shaped micro heat pipes were the first one of them. However, more recent works indicate that for a typical micro heat pipe with V-shaped corners, the maximum heat transfer coefficient can not be determined by simply assuming the minimum capillary radius. Instead a true capillary limit, which considers the combined effect of the capillary pumping pressure, the liquid viscous pressure losses and the liquid-vapor interaction must be used. The later grooved structures were the triangular and the trapezoidal-grooved micro heat pipes, where the surface of evaporation and condensation were further increased for better performance of the heat pipes. The detailed theoretical and experimental analysis of the V-shaped and triangular groove structure are presented in [5] and the analysis of trapezoidal grooves is presented in [6]. Recently a review paper on MHP/mhp for the cooling of electronic devices was published in [7]. The experimental data on silicon micro heat pipe filled with methanol or water were published in [8].

4.1 Micro heat pipe with sintered powder wick inside

By applying capillary-porous coating the surface of evaporation and condensation can be increased tremendously. This is done by applying copper sintered powder. The heat transfer about 3-4 times more is achieved when compared to grooved surface heat transfer. For example, for copper sintered powder structure disposed on the surface of horizontal copper tube and propane as a working fluid the evaporative heat transfer coefficient is 8 times as high as boiling heat transfer coefficient on the same diameter smooth tube at heat flux up to $q=10^4$ W/m^2, and 6 times at $q>10^4$ W/m^2.The detailed working of Open loop and Closed loop heat pipe and comparative analysis for flattened MHP's are available in [9].

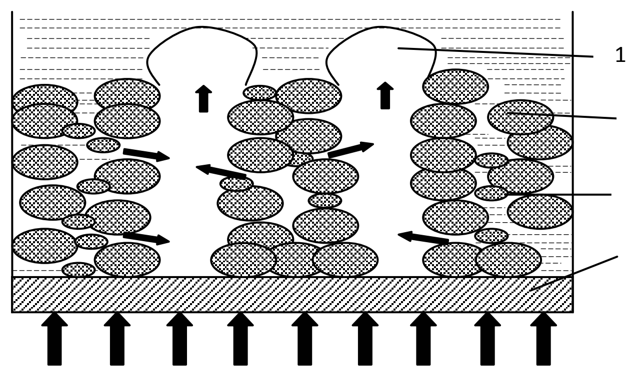


Figure 3. Micro heat pipe phenomena available in the capillary-porous structure, the element of the MHP evaporator [3-5]. 1. Vapour 2.powder rticle 3.meniscus 4.Heat exchange surface

4.2 Micro loop heat pipes

LHPs are passive, high thermal conductivity devices. This technology was invented in the former Soviet Union in the 1980s for spacecraft thermal control. Heat enters the evaporator and vaporizes the working fluid at the wick outside surface. The vapor flows down a system of grooves and headers in the evaporator and the vapor line toward the condenser, where it condenses as heat is removed by the cold plate (or radiator). The reservoir (or condensation chamber) at the end of the evaporator is designed to operate at a slightly lower temperature than the evaporator (and the condenser). The lower saturation pressure in the reservoir draws the condensate through the condenser and liquid return line. The fluid then flows into a central pipe where it feeds the wick. A secondary wick hydraulically links the reservoir and the primary wick.

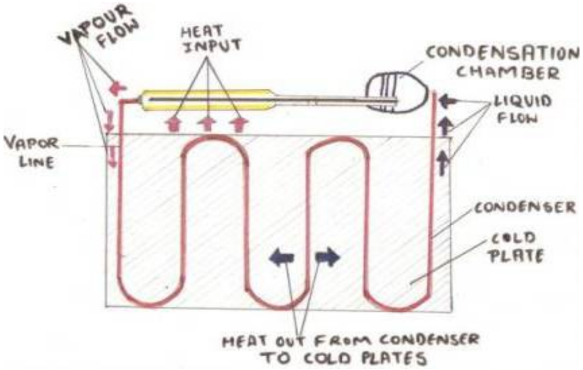


Figure.4. LHP schematic

`LHPs are made self-priming by carefully controlling the volumes of the reservoir, condenser, and vapor and liquid lines so that liquid is always available to the wick. The reservoir volume and fluid charge are set so that there is always fluid in the reservoir even if the condenser and vapor and liquid lines are completely filled. In general, small pore size and the resultant large capillary pumping capability are very desirable in a wick. Unfortunately, the capillary pumping capability of a wick is inversely proportional to its permeability (a measurement of the pressure drop during flow). The designer must balance the wick pumping capability against the wick permeability when designing a heat pipe or loop heat pipe
In a heat pipe, the wick extends along the entire length so there are long lengths (and large pressure drops) for the liquid flow in the wick. In contrast, there is only a short flow path for liquid inside a LHP wick. Consequently, LHPs can have much finer pore sizes and higher pumping capability. This allows for heat transport across long distances, against large adverse elevations or accelerations, and through flexible liquid and vapor lines. Flexible liquid and vapor lines allow the use of LHPs with deployable radiators and for vibration isolation between the evaporator and condenser.

To date Nickel, Stainless Steel, Titanium and Monel wicks with effective pore radii as small as 0.85µm and porosity as great as 75% have been manufactured.

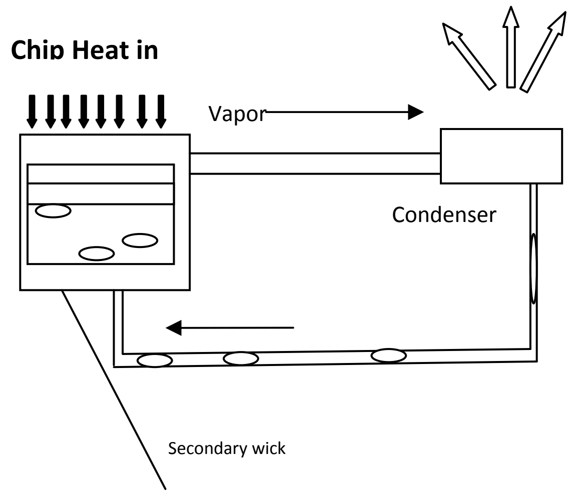


Figure 5.Micro loop heat pipe – the electronic micro chip cooler

Most current LHPs use ammonia as the working fluid and operate at temperatures between -40 and 70°C. Propylene and ethane have been used in LHPs operating at lower temperatures. A number of applications are emerging that will require operation at temperatures between 70 and 250°C. Water is a good working fluid in this temperature range. However, most current LHPs are fabricated with aluminum and stainless steel parts, neither of which is compatible with water. A recent spacecraft radiator trade study found that radiators with titanium/water heat pipes or LHPs had the highest specific power in the temperature range from 20 to 275°C. In addition, titanium LHPs would increase the specific power by roughly 1/3 when compared with titanium heat pipes. Titanium has a number of advantages over other materials are as follows:
Titanium has high strength and low density, ideal for low mass radiators. Titanium has a coefficient of thermal expansion that better matches the carbon-carbon fins than stainless steel. Titanium is compatible with a large number of fluids, including ammonia, water and the alkali metals.

5 Sorption heat pipes

SHP is beneficial for the power electronic components cooling (IGBT, Thyristors, etc.) especially for transport application, high power electronic component cooling (laser diodes) and for the space two-phase thermal control systems. SHP is a combination of a heat pipe and solid

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sorption cooler with some specific interaction between these elements [9].

This device is based on the enhanced heat and mass transfer in conventional heat pipes with sorption phenomena of sorbent bed inside it. Sorption micro heat pipes include the advantages of conventional heat pipes and sorption machines in one unit. The major advantage is its ability to ensure the convective two-phase heat transfer through capillary porous wick under the pressure drop due to sorbent action inside the heat pipe .In the sorption heat pipe the same working fluid is used as sorbate and as a heat transfer media. The sorption heat pipe includes some basic phenomena interacting with each other (1) in the sorbent bed there is a vapor flow (two phase flow) with kinetic reaction rate and pressure, vapor pressure, geometry, conductive and convective heat transport with radial heat transfer ;(2) in the condenser and evaporator there is a vapor flow, liquid flow, interface position ,radial heat transfer with kinetic reaction pressure, liquid pressure, vapor pressure, condensation and evaporation, shear stress, geometry ,adhesion pressure, convective heat transport, radial heat transfer under the influence of gravity field. Very important feature –cryogenic sorption heat pipe(hydrogen, oxygen, and nitrogen) has no needs to be protected against super pressure influence at room temperatures, because the pressure inside is regulated by the sorption structure and basically low(fig.6).

For loop heat pipe the maximum pressure rise due to surface tension effects in the wick can be evaluated by Laplace equation:

$$(p_c)_{max} = 2\sigma/r_c \qquad (1)$$

Where σ is a surface tension of the working fluid and r_c ,the effective capillary radius of the wick.

In the real LHP design capillary pressure drop depends on some LHP parameters and need to be

$$\Delta P_c \geq \Delta P_v + \Delta P_l + \Delta P_w + \Delta P_g \quad (2)$$

Where ΔP_v and ΔP_l are the pressure drop in the vapor and liquid lines; ΔP_w ,the pressure drop in the wick pores and $\Delta P_g = \rho_l \, g L_{eff} \sin\theta$,pressure drop due to gravity field action .In real devices this pressure head is less 1 b.

For sorption heat pipe the maximum pressure rise is determined by the vapor difference in the evaporator
and adsorber following Clausis – Clapeyron equation:

$$dL_n P/d(1/T) = -L/R \quad \text{or} \quad -\Delta H/R \qquad (3)$$

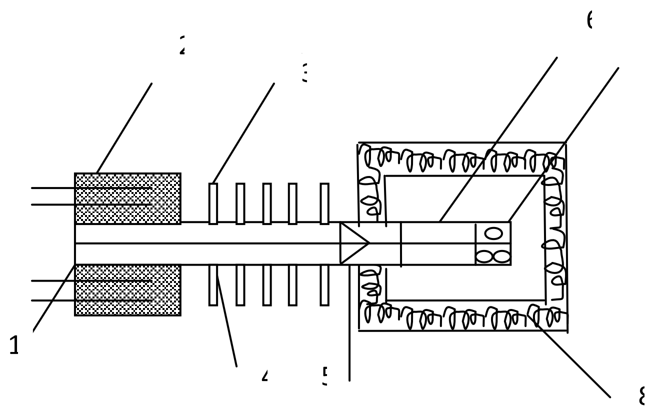

Figure 6. Micro / mini –sorption heat pipe: 1-sorption canister;2- sorbent material ;3-micro fins;4- evaporator ;5-porous valve;6- second evaporator / condenser ;7- liquid accumulator; 8- thermal insulation

For such fluids as ammonia the pressure drop in the sorption heat pipe could be near 10 b, it is 10 times more to compare with conventional heat pipe.

The investigation of the Sorption and Heat exchange-processes in a heat pump with the use of a thermosiphon is presented in [10].

6 Conclusion

All in all it is necessary to understand all the basic heat and mass transfer to understand the working principle of heat pipe. On a first look a heat pipe seems to be a very easy tool to transport energy, but if one looks closer, it is a very complex heat and mass transfer which takes place in a heat pipe.

The existing technologies of heat pipes production must be significantly improved in order to face the new challenges in electronic and fuel cells cooling. The heat transfer limit ought to be increased by optimizing the geometric and operating parameters. Unfortunately most of developed thermal modules are 1D models. In order to predict the heat transfer limit and temperature distribution of a comprehensive 3D model that includes heat transfer in liquid and vapor must be developed.

Heat pipes are now being combined with other technologies to help meet these emerging requirements. In situations where the heat to be rejected is several kilowatts, large heat pipe assemblies can be used. Ultimately, these large cooling units might be the best solutions for keeping pace with the increasing heat loads of power semiconductors. After cooling the electronics, which generate the most heat, there is always heat from other electronics in the cabinet. A sealed air-to-air heat exchanger is best for dealing with the residual heat inside the cabinet. In order to find MHP/mHP commercial application in micro electronic cooling it must compete with other cooling methods, such as forced convection, impingement and two phase direct cooling in areas such as manufacturing cost and reliability. Optimization of copper sintered powder wick in miniature copper/water heat pipes is a good challenge to improve the mHP parameters. Theoretical simulation of mHP with different wick structures (sintered powder, mesh structure, wire bundle) is an efficient tool to perform the comparisons of mHP efficiency.

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