Heat Pipes – A Review on Performance Parameters

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Abstract: Heat pipes are popular passive heat transfer devices owing to their high efficiency. Over the last several decades, several factors have contributed to a major transformation in heat pipe science and technology. In this paper, an overview of heat pipes is presented which includes principles of operations, types of heat pipes, heat pipe performance characteristics, limitations, various applications of heat pipes and gaps in the research of Thermosyphon and wicked heat pipes.

***Index Terms* - Heat Pipe, Two phase closed Thermosyphon(TPCT), Wick, Heat Pipe Limitations, Heat Pipe Performance**

I. INTRODUCTION

Heat pipe is a passive device which operates by utilizing the latent heat of an internal working fluid to transfer large amounts of heat, nearly isothermally, with a minimal driving temperature difference through a small cross-sectional area. Heat Pipe combines the principles of both Thermal Conductivity and Phase Transition to effectively transfer heat between two solid interfaces (Source and Sink).

A Heat Pipe is created by removing air from empty heat pipe and then filling it with a fraction of a working fluid that is in equilibrium with its own vapour and matches the desired operating temperature of the heat pipe. Heat Pipe is heated until the working fluid boils and then is sealed while it is hot.

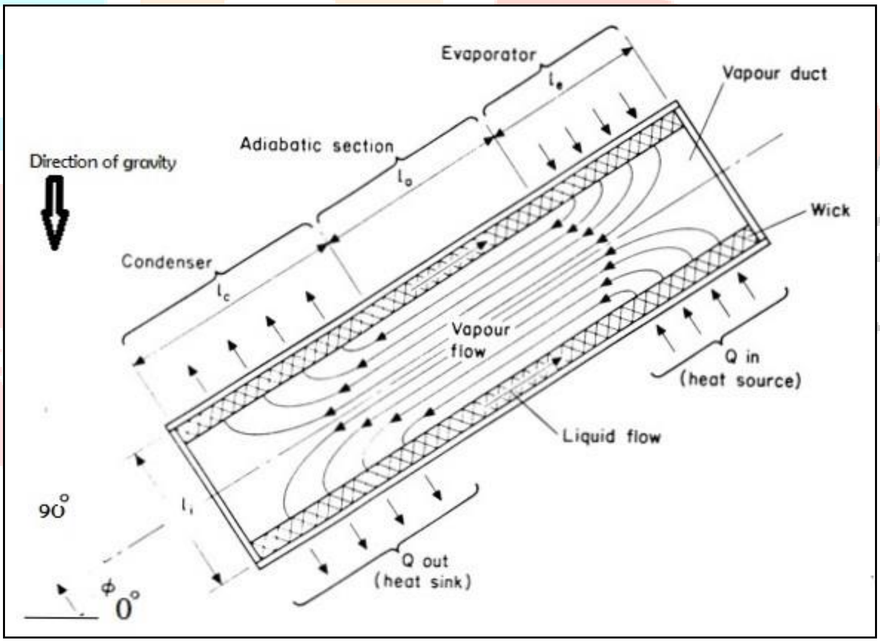

Figure 1

A Heat Pipe is divided into three segments: evaporator, adiabatic and condenser sections based on their external thermal boundary conditions as shown in Figure 1.

When heat is applied to the evaporator section, the liquid in contact with the thermally conductive solid surface turns into vapour by absorbing heat equal to latent heat from that surface. The vapour moves rapidly from evaporator to condenser through the adiabatic section when the vapour pressure of the working fluid at evaporator is greater than the vapour pressure of the working fluid at condenser. At the condenser, the vapour releases its Latent heat and turns back to liquid. This liquid travels back to the evaporator either by capillary force (using wick), centrifugal force or gravity and the cycle repeats itself. High Surface Tension increases the Capillary effect which helps the working fluid to travel back to evaporator, when a wick is used. Due to very high heat transfer coefficients for boiling and condensation, heat pipes are highly effective thermal conductors.

II. FEATURES OF HEAT PIPE

The most important heat pipe design consideration is the amount of power a heat pipe is capable of transferring. Heat pipes can transfer much higher powers for a given temperature gradient than the best metallic conductors. The maximum power that the heat pipe can carry can be set either by the heat source and heat sink conditions, or by internal heat pipe limits. Heat Pipes have high thermal conductivity, high heat flux and are passive heat transfer devices which do not require large temperature gradient between heat source and heat sink for efficient heat transfer.

A unique feature of Heat pipe is that the evaporator and condenser sections can be separated by a large distance and yet experience a minimal temperature difference. Heat Pipes are effective because the latent heat of phase change of working fluid greatly exceeds its sensible heat capacity. The lightweight construction and simplicity, as well as widely varying sizes, shapes and materials, allows heat pipe performance to be fine-tuned for a wide range of applications and temperatures.

III. TYPES OF HEAT PIPES

The way the vapour and the liquid flow to the condenser and to the evaporator respectively depends on the type of heat pipe. Heat pipes are broadly classified as:

1. Wickless Heat Pipes / Gravity assisted heat pipes
2. Wicked Heat Pipes / Capillary driven heat pipes

Wickless Heat Pipes / Gravity Assisted Heat Pipes

Heat Pipes may not need a wick if gravity or any other sources can overcome surface tension, causing condensed liquid to flow back from condenser to evaporator. Heat Pipes that use gravity are called “Thermal Diodes or Thermosyphons.” Exclusion of the wick leads to a unique feature of Thermosyphons allowing them to behave as thermal diodes, where heat can flow in an upward direction only.

A two-phase closed thermosyphon (TPCT) is a gravity assisted wickless heat pipe. For best Heat Pipe performance, the condenser section is located above the evaporator so that the condensate is returned by gravity as shown in Figure 2.

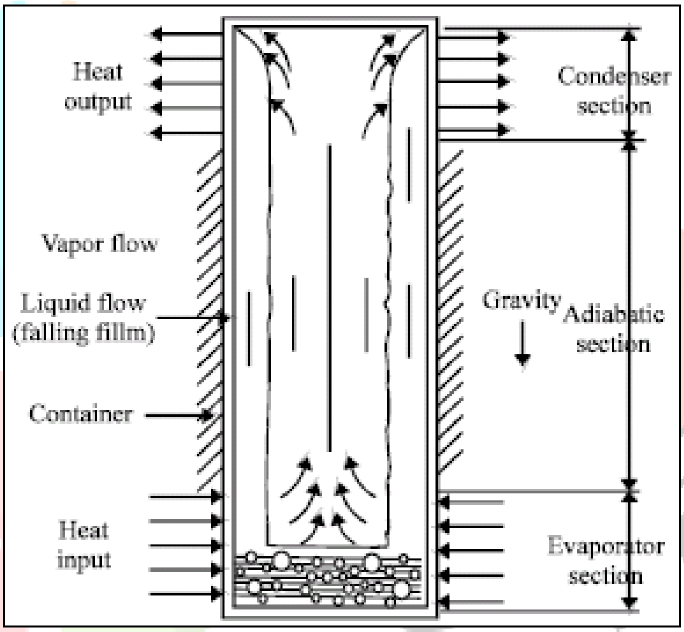

Figure 2

The operation of the thermosyphon is sensitive to the working fluid fill volume. It has been shown experimentally that the maximum rate of heat transfer increases with the amount of the working fluid up to a certain value.

Wicked Heat Pipes / Capillary Driven Heat Pipes

The capillary driven heat pipe (conventional heat pipe) consists of a sealed container, in which a wick is placed on the inner radius of the pipe wall as shown in Figure 3.

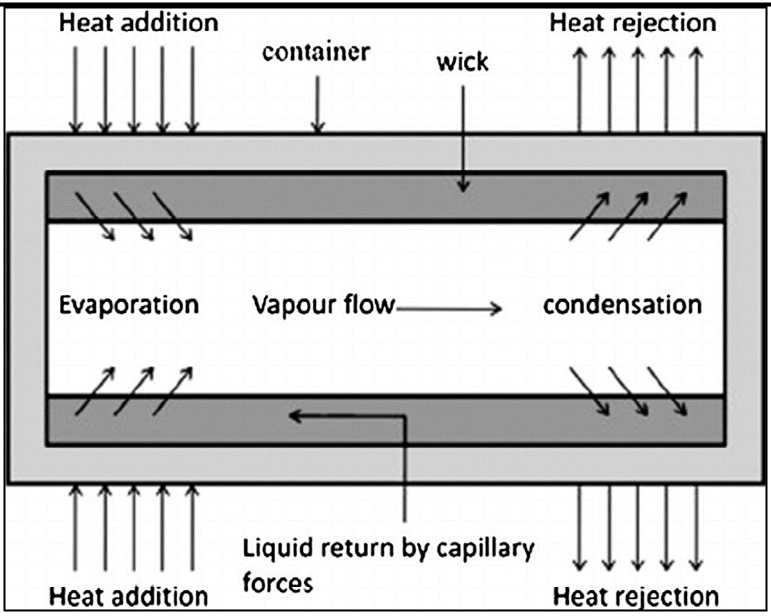

Figure 3

The purpose of the wick is to provide a capillary driven pump for returning the condensate to the evaporator section. The presence of the wick allows a Heat Pipe to operate even in zero-gravity Environments, regardless of orientation relative to the gravity vector. Enough working fluid is placed inside the sealed pipe to saturate the wick with liquid. The operation of the capillary driven heat pipe is as follows. Heat input to the evaporator section evaporates the liquid in the wick. The vapour then enters the vapour space and travels to the condenser section due to the higher vapour pressure in the evaporator. Heat removal from the condenser causes the vapour to condense, releasing its latent heat of vaporization. The condensate is then pumped back to the evaporator section by the capillary force generated at the liquid-vapour interfaces of the pores in the wick. Due to the two-phase nature of the capillary heat pipe, it is ideal for transferring heat over long distances with a very small temperature drop, and for creating a nearly isothermal surface for temperature stabilization. Alternative techniques apart from gravity and capillary actions include Centripetal forces and Osmosis.

Role of Wicks

Role of wicks in heat pipes is to direct condensed liquid from condenser to evaporator of the Heat Pipe. Wicks provide extra surface area to exert capillary pressure on the liquid phase of the working fluid to direct it back to the evaporator end.

Wick performance is a function of thickness, pore size and porosity. The thicker the wick, the higher the throughput of condensate liquid return flow. Thicker wick reduces return flow pressure drop. Wick thickness creates extra thermal resistance between inner heat pipe and its outer environment. The type, thickness, porosity and structure of the wick, and even the contact condition between the wick and the container wall, all affect the performance of the evaporator. At a low heat flux, the heat transfer across the wick is basically by conduction and convection, without boiling.

Wick Structure

While small pores are needed at the liquid vapour interface to develop high capillary pressures, large pores are preferred within the wick so that the movement of the liquid is not restricted much. For this reason, many different types of wick structures have been developed to optimize the performance of the capillary heat pipe.

The types of wick structures can be divided into two categories:

1. **Homogeneous wicks:** They have the benefit of being relatively simple to design, manufacture and install

2. **Composite wicks:** They can significantly increase the capillary limit of the heat pipe but have the drawback of high manufacturing costs.

Types of Wicks

Screen Wick: simplest and common type of wick (metal or cloth fabric)

Sintered metal wick: Tiny metal particles in powder form

Axial Grooved Wick: Formed by Extrusion or Broaching of grooves into the inner radius of the heat pipe.
Types of Grooves are Rectangular, Trapezoidal, Triangular and Circular. The most common type is Trapezoidal groove

Open Annulus Wick: Single wrap screen wick

Composite Wick: Pores of different sizes
Small/Fine Pores - have high capillary pressure

Large Pores - High porosity increases permeability of liquid return path which will offset increased hydraulic resistance of finer pores

Simplest type of Screen Wick: Two Screens with different pore sizes

Groove and Screen Wick: Axial Grooves covered with single wrap of small pore screen can solve many problems associated with homogenous axial groove wick. Since screen effectively separates the liquid and vapour flows, the entrainment of the liquid into the vapour flow by the interfacial shear is nearly eliminated.
Composite wick can be used in adverse gravity fields because the screen generates the needed capillary pressure

Slab Wick and Circumferential Grooves: Used where vapour velocities are low

Selection of a Wick

The appropriate choice of a wick configuration is application-specific, and is based on material compatibility, performance, and cost. When selecting a wick structure for an application, one must keep in mind the benefits and drawbacks of each type of wick.

There are three properties of wicks that are important in heat pipe design.

1. **Minimum capillary radius:** This parameter should be small if a large capillary pressure difference is required, such as in terrestrial operation for a long heat pipe with the evaporator above the condenser, or in cases where a high heat transport capability is needed.

2. **Permeability:** Permeability is a measure of the wick resistance to axial liquid flow. This parameter should be large to have a small liquid pressure drops, and therefore, higher heat transport capability.

3. **Effective thermal conductivity:** A large value for this parameter gives a small temperature drops across the wick, which is a favourable condition in heat pipe design. A high thermal conductivity and permeability, and a low minimum capillary radius are somewhat contradictory properties in most wick designs. For example, a homogeneous wick may have a small minimum capillary radius and a large effective thermal conductivity but have a small permeability. Therefore, the designer must always make trade-offs between these competing factors to obtain an optimal wick design.

IV. PARAMETERS THAT AFFECT THE PERFORMANCE OF HEAT PIPE

From an industrial point of view, an important outcome of heat pipe studies is the determination of the overall performance of the various heat pipes.

The performance can be typically expressed in terms of:

1. system thermal resistance and
2. system capacity to function in given operating conditions

A good heat pipe is characterized by a low thermal resistance and a high dry-out tolerance. The thermal resistance of a heat pipe usually depends on the heat transfer at the evaporator and condenser and thus on many parameters as the working fluid, the fluid fill charge, and the effective thermal conductivity of the wick (when exists), but also on other phenomena as the operating regime, or the partial or total dry-out of the evaporator. Enhancement in critical heat flux, the effective conductance of liquid and effective thermal conductivity of wick structure play the main role in the enhancement of thermal performance.

Some of the parameters that affect the performance of heat pipes are:

1. Working fluid
2. Material
3. Filling Ratio
4. Vacuum Level
5. Orientation

Working Fluid

Temperature Ranges and Types of Working Fluid

Heat Pipes can operate at any given temperature if the operating temperature is between the Triple Points and Critical Points of the working fluid used.

Cryogenic Temperature Range: 4K to 200K

Working Fluid - Noble gases like Helium, Argon and Krypton, Oxygen and, Nitrogen.

Amount of heat transferred for Cryogenic Heat pipes is low due to low heats of vaporization, high Viscosity and small Surface Tensions, low heat flux of the working fluid.

Low Temperature Range: 200K to 550K

Most Heat Pipe applications fall into this category.
Working Fluid - Water, Ammonia, Acetone, Freon compounds like Ethanol, Methanol.
Water is widely used as it has large heat of vaporization, large surface tension and is safe

Intermediate Range: 450K to 750K

Working Fluid - Mercury, Sulphur, Naphthalene, Biphenyl.

Mercury has high Thermal Conductivity but has problems with wetting the wick and wall, making it difficult to use in Capillary Heat Pipes. Toxicity of mercury is also a significant problem.

High Temperature Range: > 750K

Working Fluid - Sodium, liquid metals like Lithium, Cesium, Silver and Sodium-Potassium Compound. Very high heat transfer rates are possible as the working fluids have high Thermal Conductivity, High Latent Heat of Vaporization and High Surface Tension.

Selection of Working Fluid

Heat pipe working fluid and wick material is selected depending on the operating temperature range of the heat pipe. For a heat pipe to be operational, it must contain both liquid and vapour phases of the working fluid. In other words, it must be at saturated conditions. Therefore, fluids can only operate (theoretically) between the triple (freezing) point and the critical point, where vapour and liquid phases have the same properties. The thermal performance of a heat pipe depends on the thermo-physical properties of working fluid. Therefore, the selection of suitable working fluid becomes crucial.

Important properties considered for selection of working fluid

Surface Tension: For selection of the working fluid, surface tension is an important property. Working fluid with higher surface tension increases the Capillary effect enabling better wetting of wick and pipe wall material which helps the working fluid in travelling back to evaporator.

Latent heat: Working fluid with high latent heat of Vaporization minimizes the amount of working fluid and leads to decrease in pressure drop of heat pipe.

Vapour pressure: optimum vapour pressure desirable

Thermal conductivity: Thermal Conductivity of Heat Pipe is defined by Evaporation and Condensation properties of working fluid

Wettability of inner tube material wall and wick

Viscosity: Working fluid with lower viscosity is desirable to reduce flow resistance

Compatibility: Compatibility of the fluid with case and wick material is very important. Incompatible heat pipe material with working fluid can result in decomposing of the working fluid leading to corrosion and chemical reaction of non-condensable gases, causing failure of heat pipe.

Melting and boiling point

Thermal stability: Good

Materials of Heat Pipe

Metals

Metals are considered due to their Mechanical Strength and high Thermal Conductivity.

Copper: Used in the temperature range of 0 ^{0} C to 200 ^{0} C (Low Temperature Range). Heat Pipes are typically made of copper due to their inherent high Thermal Conductivity.

Aluminium: Low weight

Stainless Steel: Should not be used when water is the working fluid

Non-Metals

Silicon: Alternate to metals

Polymer based casings: Used because of their low cost and flexibility

Lighter Heat Pipes

To manufacture lighter heat pipes without compromising on Thermal Conductivity, alloys of Aluminium, Titanium and Magnesium have been used but are susceptible to corrosion. These alloys must be corrosion protected, without which Non-condensable gas generated because of corrosion will jeopardize the performance of heat pipes.

Using lighter wick is also an option but most progress has been made by improving the mass transfer of wick rather than making it lighter. Miniaturization of heat pipe is also an option.

Fluid-Material compatibility

One important factor is finding which fluid gets along with which wall material. There are a lot of possibilities, which have been well discovered and extensively used:

Acetone, Methanol & Water - with Copper
Freon - with high grade Steel and Aluminium
Ammonia - with Aluminium, Nickel and Steel
Potassium - with high grade Steel
Sodium - with high grade Steel, Nickel and Inconel
Lithium - with Niobium, Tantalum, Tungsten and Molybdenum
Silver - with Tantalum and Tungsten

Longevity of heat pipe can be assured by selecting the appropriate container, wick and welding material compatible with each other and the suitable working fluid.

Filling Ratio

Filling ratio is the ratio of volume of working fluid to volume of evaporator section of the heat pipe. There are two operational filled ratio limits. At 0% filled ratio, a heat pipe structure with only bare tubes and no working fluid, is pure conduction mode heat transfer device with a very high undesirable thermal resistance. A 100% fully filled heat pipe is identical in operation to a single phase thermosyphon. When the charge amount was smaller, there was more space to accommodate vapour and make the pressure inside heat pipe become relatively lower. It helped working fluids undergo vaporization and enhance its heat transfer performance.

Vacuum Levels

At sea level (atmospheric pressure) water boils at 100 ^{0} C (212 ^{0} F), but at the top of a mountain, the boiling point is less than 100^0 C (212 ^{0} F) because the pressure of air is less on the mountain. Based on this principle, the boiling temperature in Heat Pipes can be reduced by decreasing the pressure of air to less than atmospheric pressure (Vacuum pressure or Vacuum level) inside the heat pipe. If a sealed heat pipe has a high vacuum pressure, two phase heat exchange will occur easily. On the other hand, if the heat pipe has a low vacuum pressure, the non-condensable gas will block the vapour channel and result in very poor heat dissipation.

Orientation

The orientation of a heat pipe plays an important role in its performance. The performance of a heat pipe under specific orientations is directly related to its wick structure. Wick structures with low capillary limit work best under gravity-assisted conditions, wherein, the evaporator is located below the condenser. The high capillary pumping pressure achieved by using sintered powder metal wick due to its small pore size, allows a Heat Pipe to operate in any orientation. The power transport capacity of a heat pipe will typically decrease as the angle of operation against gravity increases. Other wick structures do not work as well in non-vertical orientations because they cannot lift the returning working fluid along the length of heat pipe against gravity.

V. LIMITATIONS OF HEAT PIPE

During steady state operation, the maximum heat transport capability of a heat pipe is governed by several limitations, which must be clearly known when designing a heat pipe. The heat transfer limitation can be any of the below depending on factors such as, the size and shape of the pipe, working fluid, wick structure and operating temperature.

Boiling Limit

This limitation is due to the large liquid fill ratio and high radial heat fluxes in the evaporator section. Under this limitation, at the critical heat flux, vapour bubbles coalesce near the pipe wall prohibiting the contact of working liquid to wall surface, resulting in the rapid increase in evaporator wall temperature. If this boiling is severe, it dries out the wick in the evaporator, which is defined as the boiling limit. The boiling limit is often associated with heat pipes of non-metallic working fluids. For liquid-metal heat pipes, the boiling limit is rarely seen.

Dry-out Limit

This limitation is due to the relatively small filling ratio. The condensate falls along the wall and reaches the evaporator. The condensate starts evaporating and boiling by the input power and as it comes closer and closer to the bottom, the thickness of the condensate film is thinner. It eventually dries out, so the wall temperature rises from the bottom of the evaporator at the limitation.

Capillary Limit

The ability of a capillary structure to provide the circulation for a given working fluid is limited. This limit is commonly called the capillary limitation or hydrodynamic limitation. The capillary limit is the most commonly encountered limitation in the operation of low-temperature heat pipes. It occurs when the pumping rate is not sufficient to provide enough liquid to the evaporator section. Any attempt to increase the heat transfer above the capillary limit will cause dry-out in the evaporator section, where a sudden increase in wall temperature along the evaporator section takes place.

Sonic Limit

The vapour velocity increases along the evaporator and reaches a maximum at the end of the evaporator section. The limitation of such a flow system is like that of a converging diverging nozzle with a constant mass flow rate, where the evaporator exit corresponds to the throat of the nozzle. Therefore, it is expected that the vapour velocity at that point cannot exceed the local speed of sound. This choked flow condition is called the sonic limitation. This limit usually occurs either during heat pipe start up or during steady state operation when the heat transfer coefficient at the condenser is high. The sonic limit is usually associated with liquid-metal heat pipes due to high vapour velocities and low densities. Operation of heat pipes with a heat rate close to or at the sonic limit results in a significant axial temperature drop along the heat pipe.

Entrainment Limit

A shear force exists at the liquid-vapour interface since the vapour and liquid move in opposite directions. At high relative velocities, droplets of liquid can be torn from the wick surface and entrained into the vapour flowing toward the condenser section. If the entrainment becomes too great, the evaporator will dry out. The heat transfer rate at which this occurs is called the entrainment limit. Entrainment can be detected by the sounds made by droplets striking the condenser end of the heat pipe. The entrainment limit is often associated with low or moderate temperature heat pipes with small diameters, or high temperature heat pipes when the heat input at the evaporator is high.

Vapour Pressure Limit (Viscous Limit)

At low operating temperatures, viscous forces may be dominant for the vapour flow moving down the heat pipe. For a long liquid-metal heat pipe, the vapour pressure at the condenser end may reduce to zero. The heat transport of the heat pipe may be limited under this condition. The vapour pressure limit (viscous limit) is encountered when a heat pipe operates at temperatures below its normal operating range, such as during start up from the frozen state.

Frozen Start up Limit

During the start-up process from the frozen state, the active length of the heat pipe is less than the total length, and the distance the liquid must travel in the wick is less than that required for steady state operations. Therefore, the capillary limit will usually not occur during the start-up process if the heat input is not very high and is not applied too abruptly.

However, for heat pipes with an initially frozen working fluid, if the melting temperature of the working fluid and the heat capacities of the heat pipe container and wick are high, and the latent heat of evaporation and cross-sectional area of the wick are small, a frozen start-up limit may occur due to the freezing out of vapour from the evaporation zone to the adiabatic or condensation zone.

Flooding Limit

The flooding limit is the most common concern for long thermosyphons with large liquid fill ratios, large axial heat fluxes, and small radial heat fluxes. This limit occurs due to the instability of the liquid film generated by a high value of interfacial shear, which is a result of the large vapour velocities induced by high axial heat fluxes. The vapour shear hold-up prevents the condensate from returning to the evaporator and leads to a flooding condition in the condenser section. This causes a partial dry out of the evaporator, which results in wall temperature excursions or in limiting the operation of the system.

Limitations in Thermosyphon Heat Pipes

The sonic and vapour pressure limits are constraints to the operation of the thermosyphon as with capillary driven heat pipes. The entrainment limit is more profound in the thermosyphon than in capillary-driven heat pipes due to the free liquid surface. The counterpart of the entrainment limit in thermosyphons is called flooding limit which is the most severe limitation in the operation of these systems. The boiling limit in thermosyphons is due to film boiling, rather than nucleate boiling as in capillary-driven heat pipes. For small liquid fill volumes, the dry out limit may be reached, where all the working fluid is held in the liquid film, and no liquid pool exists. In this case, any further increase in the input heat will cause a severe temperature to increase at the bottom of the evaporator section.

A wick structure is sometimes included in the design of thermosyphons to postpone flooding and improve the contact between the wall and the liquid. The capillary limit is generally of no concern in the operation of the thermosyphon since gravity is the major driving force for condensate return.

A Two phase closed Thermosyphon (TPCT) can be used in much wider thermal and temperature Ranges than a wicked HP since it does not have the large flow Resistance or low boiling limit inside the wick, as the condensate Liquid in the TPCT is returned to the heated side of the system under the effect of gravity, instead of capillary forces in wicked HPs. However, TPCTs have major limits on the maximum amount of thermal energy that can be transferred due to viscous, sonic, dry-out, flooding and entrainment limits.

Limitations in Capillary Driven Heat Pipes

Generally, the most commonly encountered limitation to the performance of a capillary-driven heat pipe is the capillary limit. This occurs when the wick cannot return enough liquid to the evaporator section to keep it saturated. At this point, the evaporator wall experiences a sudden, continuous increase in temperature.

VI. APPLICATIONS OF HEAT PIPE

Solar

Types of heat pipes that can be used - Thermosyphon, Loop, Flat Plate and Wicked heat pipe.

Hybridization of Heat Pipe Technology

Heat pipe is a highly flexible technology which can be incorporated into other types of related technologies. For Example, Heat Pipe Heat Exchanger (HPHE):

1. Gas to Gas - widest application in Industry such as Air conditioning, Space heating and Waste heat recovery
2. Gas to Liquid - less commonly used
3. Liquid to Liquid

Medicine and Human Body Temperature control

1. A surgical probe incorporating a cryogenic heat pipe is being used to destroy tumors in the human body
2. In regions or occupations where humans are exposed to extreme temperatures such as workers in polar regions or in foundry, problems like frostbite or exhaustion can be avoided with the use of gloves, socks, and suits in which heat pipes are placed to transfer heat either to or from parts of the body

Personal Computer and Laptop cooling

To remove heat away from components such as CPUs and GPUs to heat sinks where thermal energy may be dissipated into the environment.

Conventional capillary heat pipes are used in almost all laptop/notebook computers now a days to channel heat away from the processors.

Space

The capillary heat pipe has also been widely applied to various space and aerospace applications.

Electronic cooling

Used to cool transistors and high-density semi-conductors.

Production Tools

An important application of heat pipes is in the field of die casting and injection molding

Automotive Industry

Used for cooling components such as head lamps, navigation electronic devices, power drive unit, battery, and fuel etc.,

VII. GAPS IDENTIFIED IN THE RESEARCH OF TWO PHASE CLOSED THERMOSYPHON (TPCT)

1. Literature about transient behaviour of TPCT has not been investigated sufficiently.
2. More fundamental work and accurate simulations of liquid vapour interface are needed to better understand the physical phenomena of TPCT.
3. TPCTs are under investigated and analyzed especially in compact and solar applications.
4. Problems and challenges on heat and mass transfer mechanisms of TPCT.
5. More experimental and numerical studies are needed to understand optimum fill ratio for TPCT. The study of TPCT with low fill ratio is a matter of interest.
6. Experimental studies are needed to enhance the level of confidence in the prediction of the operating limit.
7. A comparison of TPCT with wicked heat pipe and other two-phase devices such as Two-phase loop Thermosyphon (TPLT) could be a matter of additional research activities.
8. Further investigations of working fluid and different system configurations need to be studied.
9. A specific field of research is in low to medium temperature for solar application (as most TPCT devices are at operating temperatures less than 100 ^{0}C for thermal control applications).

VIII. GAPS IDENTIFIED IN THE RESEARCH OF WICKED HEAT PIPES

1. Heat pipe simulations must include conjugate heat transfer with the wall, wick and vapour, since these affect both the transient and steady state operating conditions
2. An accurate simulation of liquid/vapour interface, including multiphase phenomena in various wicks, is important to accurately predict the heat transport limitation of heat pipes

IX. FUTURE SCOPE OF WORK

There is lot of scope for future work for enhancing heat transfer using heat pipes. Heat pipes can be constructed with different wick structures and various working fluids available. The importance of research on thermosyphons is critical, despite the age of the early research in this field. These systems are more and more optimized, and studies are aimed to push their operating limits, especially in terms of heat power, heat flux density and operating temperature. In addition, with advances in automation and development in material sciences, new heat pipe materials can be investigated to deal with challenging areas that have so far been out of reach for conventional solutions, particularly in dealing with high temperature and strongly contaminated flows. Using nanofluids as working fluid is another area in which a lot of research is being carried out. Optimization can be performed between various heat pipe models, shapes, working fluids, wick structures, fill ratios, tilt angles and heat inputs. Even different phase change materials can be used along with the heat sink. Three-dimensional analysis can also be performed for more accurate results by choosing appropriate turbulence models.

In parallel, the continuous progress in new materials and manufacturing processes enables the spreading of heat pipes in many other industrial applications. The addition of heat pipes in a range of temperature scales and applications are a clear indication of the potential for such a technology, but there are significant modelling issues which are hindering the performance.

X. CONCLUSIONS

This paper presents a review of heat transfer performance of heat pipes and provides an overview of heat transfer parameters responsible for the change in their thermal performance. Gaps in the research of Two phase closed Thermosyphon heat pipes and wicked heat pipes have been identified which helps the researchers to undertake research work in that area. More research work is required to identify the hidden causes/mechanisms which directly or indirectly play a role to change the thermal performance of heat pipes. The possibility of the existence of interrelations among all the mechanisms also needs further research to obtain positive results.

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