A Critical Review - Optimization of Heat Pipe

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***Abstract*— The heat pipe is an extremely effective device, and is capable of transferring large quantities of heat through relatively small cross-sectional areas and with very small temperature differences between the evaporator and condenser side without any power input. The heat pipe is a chamber of different cross-section whose inner surfaces are lined up with a porous capillary wick. Heat pipes can enhance the heat transfer capabilities without needing a significant temperature gradient between heat sources and heat sinks. The effectiveness of heat pipes is due to the latent heat of phase change of the working fluid within(i) condensation and (ii) evaporation stages. The latent heat of phase change greatly exceeds the sensible heat capacity. Heat pipes may rely on gravity, wicks, centrifugal force or in some cases even a magnetic field to help return condensate flow from the condenser to the evaporator. Wicks in heat pipes are classified into three groups: sintered, groove and mesh types. The wick structure ensures that the liquid phase of working fluid returns to the evaporator by capillary force. This paper includes the study of wick structure and to find the optimized wick structure. The heat transfer limitations determine the maximum heat transfer rate for a particular heat pipe under some normal working conditions.**

Keywords: Wick structure, capillary limit and boiling limits.

I. INTRODUCTION

There have been many applications of heat pipes in various industries such as chemical and petrochemical, power generation, HVAC (heating, ventilation and air conditioning) systems, metallurgical, ceramics and cement, electronic, mechanical, and aeronautical [1]. The heat pipe has three different cross-sections whose inner surfaces are lined with a porous capillary wick. The wick structure is the section which ensures that the liquid phase of working fluid returns to the evaporator by capillary force. Hence, its study is of importance. Though Heat pipe without wick which can also be termed as thermosyphon can work efficiently, but at the horizontal heat mode, it cannot work because working fluid inside heat pipe cannot return to the evaporator section to absorb heat. Therefore, wick was made inside heat pipe structure possible to absorb working fluid by capillary pressure, and then it can work in any orientation.

Vapor chamber includes a container, a wick structure, and a vacuum space. The wick structure consists of metal mesh, sintered copper powder, grooves etc on the container. The working fluid is made to pass into the container and provides heat transfer by phase change. The liquid phase of working fluid is vaporized to vapor phase by absorbing heat on the evaporator, and the vapor subsequently moves to the condenser through the vapor core. Then, vapor phase of working fluid is condensed to liquid phase by releasing heat on the condenser section, and the liquid subsequently returns to the evaporator through the wick.

II. HEAT PIPE

A heat pipe is a two phase device which allows heat to be transported over a certain length with very little temperature difference, at great speed, and is often referred to as superconductor. The idea of the heat pipe was first suggested by Gaugler in 1942 [2]. It’s independent invention by Grover in the early 1960s that the remarkable properties of the heat pipe became appreciated and serious development work took place [2].

It consists of three main sections, the evaporator section, the adiabatic section and the condenser section; the functional principles are the evaporation of the working fluid in the evaporator, the transport of the working fluid as vapor along the adiabatic section with little temperature loss and the condensation of the working fluid at the condenser section. A typical heat pipe as shown in Fig 1 has one evaporator section that takes heat from a source. The heat absorbed in the evaporator causes change of phase of the working fluid and liquid changes to vapor. The increased vapor pressure in the evaporator causes the vapor to exit from the evaporator section and it travels through the adiabatic section. By travelling the adiabatic section, vapor reaches the condenser region where condensation rejects the latent heat of the fluid to the sink. The condensed liquid is pumped back to the evaporator by a combination of the capillary pumping action and/or bulk forces. This fluid cycle is repeated during the normal operation of the heat pipe and can continue as long as there is sufficient vapor pressure and capillary pressure to support this operation at the evaporator end the liquid recedes into the wick pores so the menisci in the pores at the vapor interface are highly curved. On the other hand, the liquid menisci at vapor interface in the condenser end are almost flat. This difference in the interface curvature of the menisci at the vapor interface coupled with the surface tension of the working fluid causes a capillary pressure gradient at the liquid-vapor interface .This capillary pressure gradient pumps the working fluid against various pressure losses such as friction, inertia and against body forces [3]. This is illustrated in Fig 1.

Heat pipes are effective because the latent heat of phase change of the working fluid greatly exceeds its sensible heat capacity.

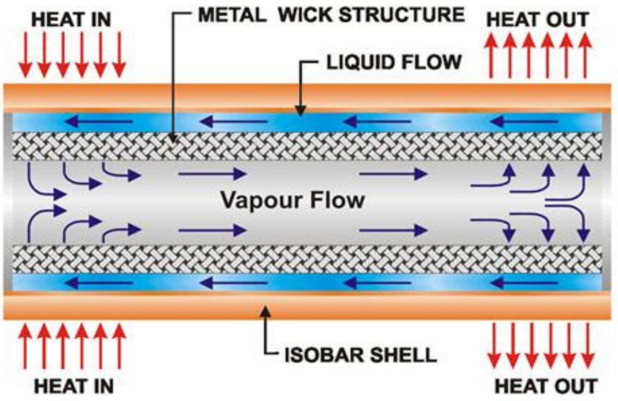

Fig 1.Schematic of operation of Heat pipe [4].

The vapour moves rapidly from the evaporator to the condenser because the vapour pressure of the working fluid at the evaporator is higher than the vapour pressure at the condenser. Liquid movement is in the opposite direction to vapour movement, where the movement of the liquid from the condenser to the evaporator is facilitated either by capillary force using wick [3] or gravity induced/type effect. At the heat source, heat is extracted due to latent heat of evaporation where the working liquid phase-changes to vapour at the evaporator, while heat is released at the heat sink where the vapour phase-changes back to liquid (releasing latent heat of condensation) at the condenser.

The charge ratio of a heat pipe is a parameter that defines the volume of liquid in the heat pipe to the total overall volume of the heat pipe. Heat pipes are usually denoted by two types of critical heat fluxes, i.e. nucleate boiling (see Fig. 2) and dry-out [4].

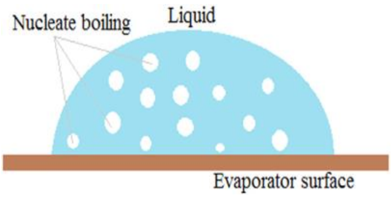

Fig. 2 Nucleate boiling [5]

Nucleate boiling occurs when surface temperature of the heat pipe wall is a few degrees centigrade above saturated fluid temperature. When dry-out starts to occur, the droplets are continually torn from and re-join the thin liquid film around the channel wall due to rapid convection. At the location of the dry-out, the liquid film gradually disappears, causing the heat transfer coefficient to drop off drastically.

A heat pipe is created by removing air from the empty heat pipe and then filling it with a fraction of a working fluid which matches the desired operating temperature of the heat pipe. Alternatively, the pipe is heated until the working fluid boils and then sealed while it is hot. For selection of the working fluid, surface tension is an important property. Higher surface tension will increase the capillary effect and it must be chemically stable in the presence of wicks. Depending on the type of heat pipes used (which will be described in the next section), wicks can be optional. 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. The wick structure is typically metal powder or a series of grooves parallel to the pipe axis. The heat pipe may not need a wick structure if gravity or other sources can overcome surface tension, therefore causing the condensed liquid to flow back from the condenser to the evaporate or. Heat pipes that use gravity for assistance are called thermal diodes or thermosyphons.

Alternative techniques apart from gravity and capillary actions include centripetal forces and osmosis. Sharp angled corners are sometimes used to provide capillary pressure too.

The heat pipe can be a highly effective tool for thermally managing and controlling chemical processes that are exothermic or endothermic as they provide: (i) separation of heat source and heat sink, (ii) keeping temperature uniform and constant, and (iii) temperature control, i.e. fast response time [6].

Heat pipes can be used in various temperature ranges. Yang et al. [2] grouped the heat pipes into four categories:

1. >700K: Working fluids are typically liquid metal;
2. 550–700K: Long carbon chain organic fluids such as naphthalene and biphenyl;
3. 200–550 K: Water, ammonia and short carbon chain organic fluid such as methanol, ethanol and acetone;
4. 1–200K: Noble gasses, oxygen and nitrogen.

These working fluids have very low values of the latent heat of vaporization and low surface tensions; hence have lower heat fluxes than the first three categories.

Heat pipes are typically made using copper due to their inherent high thermal conductivity. To manufacture lighter heat pipes without compromising thermal conductivity, alloys of aluminium, titanium and magnesium have been used but are susceptible to corrosion [7]. These alloys must be corrosion protected; otherwise non-condensable gas generated as a result of the corrosion will jeopardize the performance of the heat pipes. Using lighter wick materials could also be an option, but most progress has been made by improving the mass transfer performance of the wick rather than making it lighter. Alternatively, miniature is a ti on of the heat pipe can also be an option.

III. WICK STRUCTURE

The wick is made of different materials and has been one of the most investigated aspects of heat pipes due to its capillary action. It is usually made of a porous material. A grooved structure can also be used. It works in the same way as the cotton strip inside the lamp works i.e. the cotton has an internal pore which helps the oil to flow in upwards direction or anti-gravity direction. The wick structure too, has the same working principle. The performance of a heat pipe under specific orientations is 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.

A. Need of Wick Structure

The wick provides a means for the flow of liquid from the condenser to the evaporator section of the heat pipe. It also provides pores that are required at the liquid–vapor interface for development of the required capillary pressure. An effective wick requires large internal pores in a direction normal conductive heat flow path for minimization of the radial surface to liquid–vapor surface temperature drop. To satisfy these requirements, following types of wick structure have been developed to the heat flow path. This will minimize liquid flow resistance. In addition, small pores are required for the development of high capillary pressure and a highly conductive heat flow path for minimization of the radial surface to liquid–vapor surface temperature drop. Its performance is a function of its thickness, pore size and porosity. The thicker the wick is, the higher the through put of the condensate liquid return flow. Also, a thicker wick reduces return flow pressure drop. Wick thickness also creates extra thermal resistance between inner heat pipe and its outer environment. Finer pores will increase capillary action while higher porosity increases liquid permeability which will offset increased hydraulic resistance of finer pores. Due to the complex relationships between heat transfer and the geometric structure of the heat pipe Zhang et al. [8] have applied Pareto genetic algorithm to multi-objectively optimize heat pipe design. The additional benefit of wicks with higher porosity is reducing heat leakage from the condenser into the evaporator [9]. Porous wicks can be either of two types, dispersed and non-dispersed, as shown in Fig. 3. At high heat fluxes, a mono-porous wick is in tolerant of nucleate boiling as a vapour blanket thermal insulator can form at the evaporate or wall and thus result in poor heat pipe performance [10]. In more complex capillary structures (i.e. sintered and mesh), the exact location of both the liquid and the vapour can be difficult to predict theoretically (using Darcy’s law) or experimentally. To visualize the fluid motion and structure, transparent heat pipes are required [11]. Experimentally, temperature measurements are used to estimate the maximum power and the overall thermal resistance.

B. Types of Wick Structure

Two main types of wicks: homogeneous and composite.

Homogeneous-These type of structures are made from one type of material or machining technique. These types of wicks are constructed from a single material that has a uniform cross section. They tend to have either high capillary pressure and low permeability or the other way around. They are simple to design, manufacture, and install (Faghiri,1995). The common materials used include metal screens, sintered metal felts, sintered metal powders and axially grooved wicks (Fig 3). Each type of wick made from these materials has its own advantages and limitations, and a detailed discussion on this topic is beyond the scope of this paper.

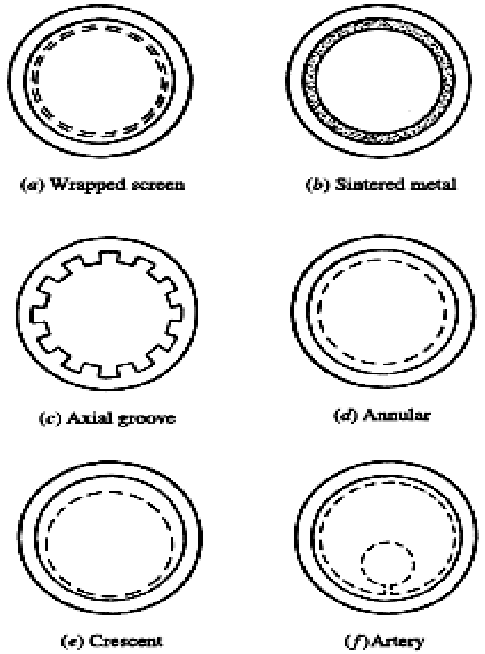
(*a*) Wrapped screen
(*b*) Sintered metal
(*c*) Axial groove
(*d*) Annular
(*e*) Crescent
(*f*) Artery

Fig. 3 Cross sections of homogenous wick structures [12]

Composite-These types of materials are made of a combination of several types or porosities of materials and/or configurations. They tend to have a higher capillary limit than homogeneous wicks but cost more (Faghiri,1995).A composite wick structure is built using two or more materials taking advantage of their respective strengths.

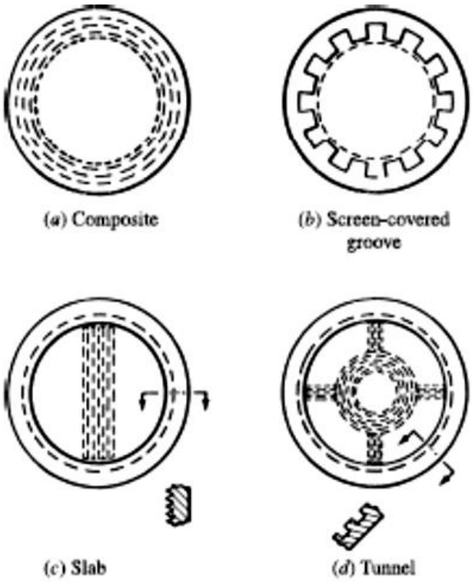
(*a*) Composite
(*b*) Screen-covered groove
(*c*) Slab
(*d*) Tunnel

Fig. 4 Cross sections of composite wick structures [12]

A composite wick typically handles two main functions i.e capillary pumping and liquid transport in different sections of the wick. A typical example is a screen wick covering the axially grooved wick structure as shown in Fig 3.

These are the homogeneous wicks made of a single material, examples of which are shown in Fig. 2, and the composite wicks containing two or more materials, with some other examples

All the composite wicks shown in Fig. 4 have a separate structure for development of the capillary pressure and liquid flow.

Typically, the porous wick structure can consist of the following types: sintered, groove, and mesh [9].

i). Sintered type

Mishra et al. [13] Fabricated wicks with high porosity using carbonyl nickel powder. Optimisation was achieved using a cylindrical wick (length to diameter ratio of 10) with porosity value of 64%, average pore size of 5 μm and a permeability of $1*10^{-13}$ m^2

Xin et al. [14] fabricated wicks by sintering powder containing nickel to copper ratio of 9:1, at a temperature of 650 1C for 30 min. Achieved porosity of upto 70%, permeability of 10^{-13} m^2 and mean pore radius of 0.54 μm

Li et al. [15] experimentally verified that the capillary pumping performance can be described with an exponentially increasing equation, where the capillary pumping rate increases with the increasing porosities.

Santos et al. [16] fabricated ceramic porous wick with porosity of 50%, pore radius distribution 1–3 μm and a permeability value of around $3.5*10^{-14}$ m^2. At an operational temperature of 100 ^{0}C, upto 25W and 15W of heat can be transfer reducing acetone and water at steady state conditions.

Eduardo et al. [17] fabricated wicks sintering powder containing (i) carbonyl nickel powder, (ii) atomized nickel powder, and (iii) mixture atomized and carbonyl nickel powder. The best pore size is achieved via mixture, in the range of 2–24 μm in pore size and porosity of approximately 50%.

Vasiliev [18] titanium sintered powder was used in loop heat pipe and sorption heat pipe evaporators with ammonia as a working fluid. Heat transfer intensified upto 4500 W/m^2/K in the former, while the latter achieved three times the heat transfer capability of the former Bi-porous wick.

Semenic and Catton [19] tested the performance of both mono-porous wicks and bi-porous wicks and found that the best bi-porous wick has critical heat flux at 990W/ cm^2.

Cao et al. [20] fabricated bi-porous wicks with copper powder, where large/small pore-diameter ratios are 200/80, 400/80 and 800/80 μm. Their bi-porous wicks have a much higher heat transfer coefficient and critical heat flux compared to mono-porous wicks. For a given fine pore diameter, there is an optimal large pore diameter

Yeh et al. [10] for optimal performance, particle sizes of pore former should be between 20–32 μm with a content of 25%. The maximum heat transfer capability is 570W for a bi-porous wick and 350W for the mono-porous wick. The evaporative heat transfer coefficient of the bi-porous wick is approximately six times higher than the mono-porous wick.

Li et al. [8] fabricated bi-porous nickel wicks using cold pressing sintering and loose powder sintering techniques. The former provided the optimal wick performance 700 1C. The pore former content is 30% by volume with porosity of 77.40%, permeability of $3.15*10^{-13}$ m^2. During sintering for wick production, a piece of graphite sheet was placed in the furnace for uniform heating of the wick, to avoid thermal stress deformation.

During sintering for wick construction, the powder should be sintered at temperatures between that of half its melting point and close to melting. Higher sintering temperature will result in better mechanical strength. Different materials require different sintering atmospheres, for example nickel powder should be sintered at a reducing atmosphere to restore the surface of the particles [9]. At high heat flux conditions, the flow rates of both fluid phases (liquid and vapour) are equally large in the evaporator. As such, mono-porous wicks will produce high hydraulic resistance, causing the evaporator to dry-out. The best mono-porous wicks have critical heat flux at 300W/cm^2 [19]. A bi-porous wick (as shown in Fig. 5) can overcome problems associated with high heat flux conditions.

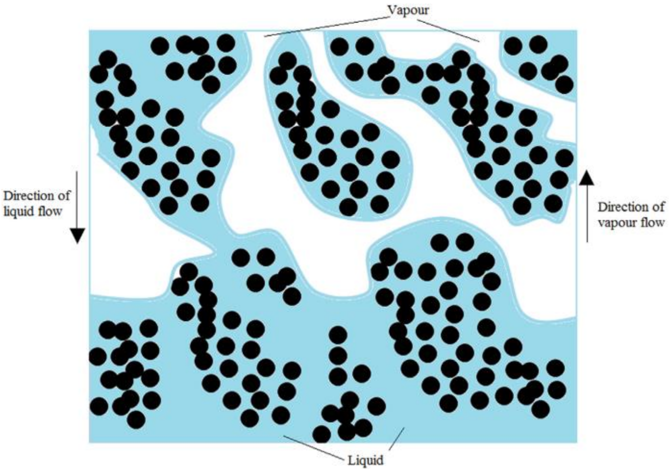

Fig. 5. Bi-porous wick

This allows the wick to achieve better performance where by the bigger pores can reduce liquid hydraulic resistance, whilst the finer pores can provide sufficient capillary force. A non- dispersed bi-porous wick can provide higher porosity than a dispersed bi-porous wick as the former not only decreases the effect of heat leakage (into evaporator) through the wick, but also provides larger surface area for liquid film evaporation. In addition, large pores generated by dissolving the pore formers in the non-dispersed form are easier to control than those of dispersed form [20]. The history of bi-porous wicks can be traced back to Vityaz et al. [22] who produced it by dispersion. They utilized the surface oxidation on a sintered copper wick structure to generate the pores which have bimodal pore size distribution, with increased heat transfer capability. Konev et al. [23] proved that this type of wick enhances the heat transfer more than a mono-porous wick, because the former provides extra heat surface area [24]. This also prevents a vapour blanket from forming within the wick [25]. Semenic and Catton [19] noted that capillary pressure in abi-porous wick is only significantly a function of the finer pores.

ii) Groove type

Zhang et al. [8] mathematically studied and optimised Ω-shaped micro grooves (Fig. 6) via Pareto genetic algorithm. A smaller wicks lot width and larger wick diameter will enhance the heat transfer capability between condenser and evaporator, but will also increase the total radial thermal resistance (between inner heat pipe and its outer environment). A larger number of grooves and a larger vapour core diameter will also enhance the heat transfer.

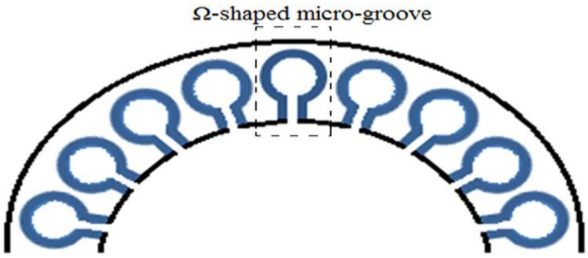

Fig.6. Cross-sectional area of Ω groove type heat pipe [8].

Ma and Peterson [26] experimentally measured heat transfer of triangular grooves with an apex angle of 60^0 and showed that heat transfer performance is a function of optimum groove configuration

Stroes and Catton [27] Compared tilted triangular and sinusoidal grooves, with ethanol as the heat transfer fluid. Sharper apex of the former induces better capillary action than the latter. The latter has larger surface area for surface evaporation therefore supports higher heat fluxes instead

Anand et al. [28] studied the onset and propagation of the dry-out point in tilted V-shaped microgrooves, with pentane as working fluid. When heat pipe is inclined, the position of the dry-out point is closer to the condenser end. The radius of meniscus curvature is a function of the capacity to replenish the evaporator. The value of the curvature should be monotonically decreased from the condenser to the evaporator to maintain sufficient replenishment

Jiao et al. [29] mathematically modeled the effect of contact angle on the meniscus radius, thin film profile and heat flux distribution in micro-trapezoidal grooves. Showed that the capillary pressure govern the maximum heat transfer capability while the thin film evaporation determines the effective thermal conductivity. The ratio of the heat transfer through the thin film region to the total heat transfer through the wall of the vapour phase decreases when the contact angle increases

Lips et al. [30,31] Observed that nucleate boiling at the evaporator of flat plate heat pipes at _3 W/cm2 and that bubbles did not inhibit mass transfer between two ends of the heat pipe, contrary to literature. Heat flux for evaporator dry-out is much higher than the heat flux at the onset of nucleate boiling. Capillary limit instead of boiling, which causes the dry-out.

Several theoretical, experimental and optimization approaches on improving heat and mass transfer performance have been investigated. The types of grooves that have been studied vary from triangular, rectangular, trapezoidal and “Ω” shaped grooves [8]. Several researchers [32–34] have discovered groove alignment is important to achieve higher dry-out fluxes. The horizontal and vertical orientations of grooves can achieve superior critical heat fluxes relative to isotropic permeability heat pipes [35, 36]. The creation of the miniature axial groove show ever increases the cost.

iii) Mesh type

Brautsch and Kew [37] Studied stainless steel mesh with water as working fluid. As heat flux is increased, small bubbles form on pipe wall surface and then in the mesh wick. With further increase in heat flux, vapour blanket was formed, leading to intermittent local dry-out, hence reducing thermal performance. Maximum heat flux increases with wick thickness but also increases thermal resistance

Kempers et al. [38] studied copper–water heat pipes with screen mesh wicks. Effective thermal resistance decreases with an increase in heat flux while constant at higher heat fluxes. Non-linearity is more pronounced with fewer mesh layers. Small increase in thermal resistance with thicker wick, Maximum heat transfer increases with more meshes. With working fluid below the amount needed to fully saturate the wick lowers effective thermal resistances, but greatly reduces the maximum heat transfer rate

Wong et al. [39] Studied transparent circular heat pipes of length 150 mm and inner diameter 5 mm, with two layers of screen mesh. Two different meshes were tested (with diameters of 114 mm and 55 mm respectively). Observed nucleate boiling for heat fluxes higher than $15 W/cm^2$ Sintered mesh

Wong et al. [40]; Liou et al. [41] Studied transparent flat plate heat pipes made of sintered screen meshes but they did not visually observe nucleate boiling even for high heat fluxes ($60 W/cm^2$)

Li etal. [42, 43] Studied sintered screen meshes (wire diameters of 56 μm, 114 μm and 191 μm). Evaporator heat transfer coefficient is independent of wick thickness, but critical heat flux increases proportionally to this thickness. The evaporator heat transfer coefficient decreases with the wire diameter, but is not strongly dependent on the porosity. The critical heat flux increases with both the wire diameter and the porosity

Mesh types can be divided into sintered and non-sintered types as summarized. Types of heat pipes the conventional heat pipe has been illustrated in Fig.1, and will not be further described in this section since the basic principles of operation have already been described in the introduction.

C. Properties Affecting Wick Design

1. High pumping pressure- A small capillary pore radius i.e channels through which the liquid travels in the wick, affect greatly in a manner that results in a large capillary pressure
2. Permeability- large pore radius results in low liquid pressure drops and low flow resistance.

Design choice should be made that balances large capillary pressure with low liquid pressure drop. Composite wicks tend to find a compromise between the two.

3. Thermal conductivity - A large value will result in a small temperature difference for high heat fluxes [3].

IV. OPERATING LIMITS

The performance and operation of a heat pipe is limited by certain parameters. A phenomenon which limits heat transport in heat pipes includes capillary forces, choked flow, interfacial shear, etc. The heat transfer limitations depend on dimensions of the pipe, working fluid, wick parameters, and operating temperature [1]. Chaudhry et al. [44] has succinctly summarized the distinctive features, limitations, applications and operating temperatures of heat pipe type, also shows the similarities and differences that these various types share between themselves. Fig. 7 shows the various types of limits of operation in heat pipe.

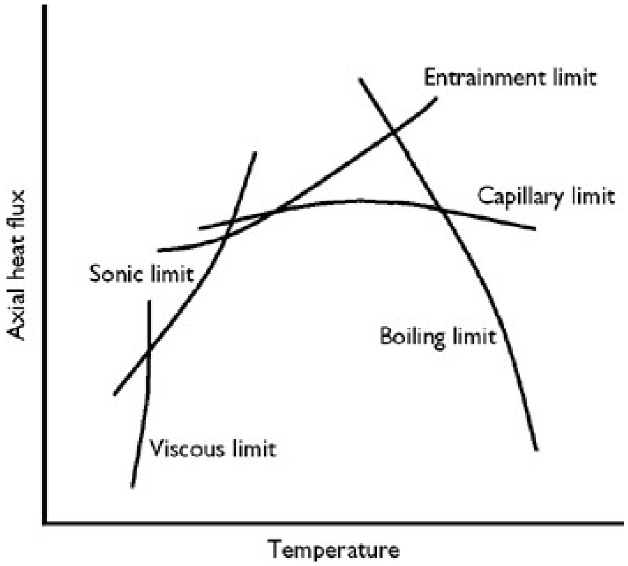

Fig.7. Limitations of heat pipes

A. Capillary Limit

The difference in the capillary pressure between liquid and vapor interfaces governs the operation of the heat pipes. The capillary limit is encountered when the capillary pressure is not enough to pump the liquid back to evaporator causing the dry out of the wick of the evaporator end. The physical structure of the wick is one of the most important reasons for this limit and the type of working fluid also affects it [12].

The flow in heat pipe is possible because of the vapor pressure gradient and the liquid pressure gradient along the length is necessary for the flow of liquid back to the evaporator. In addition, there are pressure gradients due to phase change taking place at the evaporator of the heat pipe (Fig 2). For the heat pipe to work as it usually does, the capillary pressure should be greater than all the pressure gradients across the liquid-vapor path.

B. Sonic Limit

The evaporator and condenser sections of the heat pipe act like a nozzle where vapor flows from the adiabatic section into or out of the end sections. The converging-diverging nozzle like nature of the vapor flow path inside the Heat pipe imposes a choking flow condition on the vapor velocity.We know that the velocity at a choke point cannot be greater than the local speed of sound. This is called the sonic limit and the heat transfer can now only increase if the operating temperature of the heat pipe is increased.[12,45].

C. Boiling Limit

A typical cylindrical heat pipe receives heat at the evaporator end where it is transferred to the working fluid radially. When the input flux is sufficient, nucleation sites are formed inside the wick where bubbles are trapped in the wick, blocking liquid return that results in evaporator dry out [45]. As compared to the other heat pipe limits, boiling limit is a radial flux constraint and not an axial flux constraint [12,46].

D. Entrainment Limit

As liquid and vapor move in opposite directions in heat pipe, the vapor exerts a shearing force on the liquid at the liquid-vapor interface. If this shear force exceeds the surface tension of the liquid, liquid droplets are entrained into the vapor flow while going towards condenser section. [45,47].

E. Viscous Limit

At low temperatures or low vapor densities, the viscosity of the vapor flow may be dominant as the flow progresses from evaporator to the condenser end. If the vapor pressure in the condenser is very low then the heat transfer under such a condition is limited. This usually occurs during the startup condition of a heat pipe [12]

F. Condenser Limit

If non-condensable gases are accumulated at the condenser end, they reduce the working length of the condenser end, limiting the heat removing capacity of the condenser. This limit increases the possibility of capillary limit [12,46].

V.CONCLUSIONS

The following conclusions can be extracted

1) Diverse types of heat pipes have been reviewed in this paper, as well as the types of wicks that can be found in current research to improve the performance of the heat pipe.
2) An examination was also carried out on some promising hybrid technologies such as heat storage for change phase materials, thermosyphon.
3) The heat transfer coefficient is found to be maximum in the circular shape geometry, and increases with the heat input increase.
4) The variation of friction coefficients of all grooved pipe is independent of Reynolds Number but it was found that the friction in the circular groove shape is the lowest Compared to the other shapes.
5) Heat source orientation and gravity have less effect on sintered powder metal heat pipes due to the fact that the sintered powder metal wick has the strongest capillary action.
6) It is not desirable to use groove or mesh heat pipes when the orientation of the evaporator (heat source) is on top of the condenser (heat sink).
7) Combination of circular wick with sintered powder can suit the application. Also, there will be two advantageous effect whereby reducing the limitations.

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