TO ANALYZE THE STUDY OF HEAT PIPE OPPORTUNITIES AND CHALLENGES

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DECLARATION

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CERTIFICATION

This is to certify that this thesis entitle “To Analyze The Study of Heat Pipe Opportunities And Challenges” is done by the following students under my direct supervision. This thesis has been carried out by them in the laboratories of The Department of Mechanical Engineering under the faculty of Engineering, Sonargaon University (SU) in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering.

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ABSTRACT

A detailed overview of heat pipes is presented in this paper, including a historical perspective, principles of operations, types of heat pipes, heat pipe performance characteristics, heat pipe limitations, heat pipe frozen startup and shutdown, heat pipe analysis and simulations, and various applications of heat pipes. Over the last several decades, several factors have contributed to a major transformation in heat pipe science and technology . The first major contribution was the development and advances of new heat pipes, such as loop heat pipes, micro and miniature heat pipes, and pulsating heat pipes. In addition, there are now many new commercial applications that have helped contribute to the recent interest in heat pipes, especially related to the fields of electronic cooling and energy. For example, several million heat pipes are now manufactured each month since all modern laptops use heat pipes for CPU cooling. Numerical modeling, analysis, and experimental simulation of heat pipes have also significantly progressed due to a much greater understanding of various physical phenomena in heat pipes , as well as advances in computational and experimental methodologies.

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CHAPTER 1
INTRODUCTION

1.1 Introduction

The heat pipe Faghri, A., 1995, **[1]** is a highly effective passive device for transmitting heat at high rates over considerable distances with extremely small temperature drops, exceptional flexibility, simple construction, and easy control with no external pumping power. Engineers, scientists and graduate students interested in heat pipe science often times struggle and spend considerable time poring through archival publications or the contents of heat pipe books in order to understand and predict a heat pipe system. The heat pipes are the one of the most efficient methods in both passive and active thermal management technologies.They are commonly used in many robotic applications functioning to keep the temperature of the robot's components in a specific operating temperature. The heat pipe is a structure, which has the high thermal conductivity that makes the transportation of heat by its heated and cooled sections. In general, heat pipes are passive thermal transfer structures, which can transport large amounts of heat over long distances. Heat pipes have three main features: (1) no moving parts; (2) using phase change processes and (3) vapor diffusion. The main structure of heat pipes consists of a tube that involves a working fluid inside in both fluid and vapor phases.Heat pipes working principle consists of three main steps, which are evaporator, adiabatic section, and condenser.First, the working fluid evaporates by the heat that from the electronic devices. Second, the vapor reaches to the condensation section as a reason of density difference between working fluid and vapor. Then, ambient temperature enables to condense vapor. Finally, the working fluid returns to the evaporation section by an influence of gravity or the wick structure of the heat pipe.Heat pipes operate in various temperature ranges depending on the working fluid and structure features, which is between −268 °C and 3229.9 °C. This feature of heat pipe makes it able to be used for many different operation and conditions, such as solar applications, nuclear applications, ceramic industry, geothermal applications, hydride storage and some applications within the automotive industry.The heat pipes are considered suitable for thermal management devices that can be widely used for different application types in various environment conditions. Because this wide range of application types and easy usage of heat pipes, they are considered as one of the best thermal management options in both passive and active thermal management systems.

Working fluid is probably the most important factor which affecting thermal performance of PHPs. During recent years, many scientists have focused on working fluids and their properties on the thermal performance of PHPs. Some correlations are proposed for PHPs heat transfer based on thermophysical properties of working fluids al studied some PHPs with different inner diameters which were filled with water and ethanol as working fluids and proposed correlation to predict their heat transfer characteristics. Their results indicated that the best working fluids may differ for different tube diameters since thermophysical properties of working fluids affects the critical diameter and thermal performance of PHP. Using nano-fluid is a method to improve heat transfer which is applied in pulsating heat pipes.Flow regime in PHPs is another parameter which affecting the thermal behavior of PHPs. Some models are proposed to predict flow regimes in PHPs. Flow patterns can be influenced by some elements such as working fluids and heat inputs generally, higher heat inputs lead to higher fraction of vapor. Hence, introducing an appropriate working fluid for a PHP depends on some factors such as tube inner diameter, heat input, inclination angle and working temperature.Studies show that even though the thermal performance of heat pipe have been a source of interest for many researchers, papers on the effects of thermophysical properties of working fluid has been more regarded. Various factors to improve thermophysical properties of working fluid in PHPs have been investigated experimentally and theoretically. In this study, influences of several thermophyscial properties of working fluid which affect heat transfer performance of PHPs are represented in order to provide adequate information for selection of working fluid based on application of PHP and working condition. In addition, valuable researches on the improvement of working fluids used in PHPs are reviewed to obtain a better insight in readers for selecting the most appropriate working fluid from the point of view of the tension, thermal conductivity and dynamic viscosity. Moreover, it is tried to collect various studies have focused on application of nano-fluid in PHPs due to their potential for improvement of thermal performance.A comprehensive literature review is conducted on the applied nano-fluids in PHPs. Results of applied nano-fluids are summarized in a Table 1 which it can provide for researchers an appropriate reference for selecting the best type and concentration of nano-fluid based on required application. In addition to thermophysical properties of working fluid, flow regime inside PHPs, which plays an important role in thermal performance of PHPs, under various working condition are reviewed in this paper.

1.2 Objective

1. To understand the working principle of heat pipe.
2 To identify applications of heat pipe in different industries.
3 To examine the opportunities in energy saving ,challenges and limitations of heat pipe.

CHAPTER 2
LITERATURE REVIEW

2 . 1 LITERATURE REVIEW

The historical development of heat pipes is closely tied to the evolution of heat transfer science and the growing need for efficient thermal management systems.Although the fundamental principles behind heat pipes namely evaporation, condensation, and capillary action were understood earlier through studies in thermodynamics, the actual device emerged much later.

The first significant step came in when Richard S. Gaugler, an engineer working for General Motors, filed a patent describing a sealed tube containing a working fluid and a wick structure. His invention outlined the essential features of a modern heat pipe, where heat applied at one end would cause the liquid to evaporate, travel as vapor, condense at the cooler end, and return via capillary action. Despite its ingenuity, this invention did not receive much attention at the time, largely because there were few technological applications that required such a device.

The concept was rediscovered and significantly advanced by George M. Grover at Los Alamos National Laboratory. Grover not only refined the design but also demonstrated the remarkable efficiency of heat pipes, showing that they could transfer heat with very small temperature differences. He was also the one who coined the term “heat pipe.” His work sparked widespread interest, especially as it coincided with the technological demands of the space age.Heat pipes became highly important in space applications, particularly through the efforts of NASA. In spacecraft and satellites, where conventional cooling methods are ineffective due to the absence of gravity, heat pipes provided a reliable and passive means of temperature control. Their ability to operate without moving parts made them especially suitable for long- duration missions in harsh environments.As technology progressed into the 1980s and 1990s, heat pipes began to find applications beyond the aerospace industry. They were increasingly used in electronics cooling, energy systems, and industrial processes. Engineers developed variations such as loop heat pipes and thermosyphons to meet different operational requirements, improving flexibility and performance.

In recent decades, the rapid advancement of electronic devices and the demand for compact, high-performance systems have driven further innovation in heat pipe technology. Modern heat pipes are now widely used in laptops, smartphones, and data centers, where efficient heat dissipation is critical. Additionally, research into micro-scale heat pipes and advanced working fluids has expanded their capabilities even further.

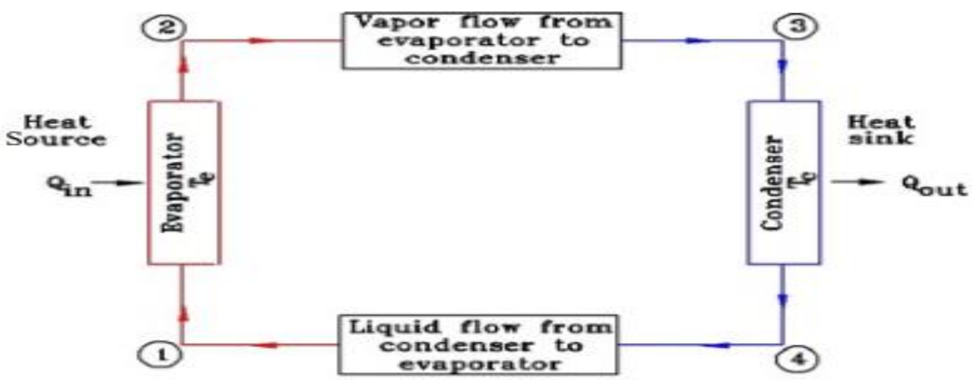
Overall, the development of heat pipes illustrates how a relatively simple physical principle evolved into a vital technology, playing a key role in fields ranging from space exploration to everyday consumer electronics.

CHAPTER 3
THEORETICAL MODEL

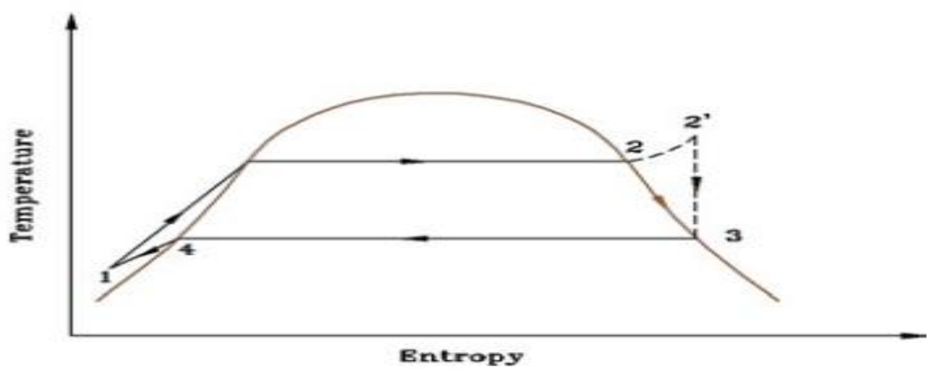
3.1 Principles of Operations

The principle of operation of a heat pipe is based on the efficient transfer of heat through a continuous cycle of evaporation, vapor flow, condensation, and liquid return inside a sealed system. It uses the natural properties of a working fluid along with capillary action to move heat with very high efficiency.

A heat pipe typically consists of a sealed tube, a working fluid (such as water, ammonia, or alcohol), and a wick structure lining the inner surface. When heat is applied to one end of the pipe called the evaporator section the working fluid absorbs this heat and begins to evaporate. As the liquid turns into vapor, it carries a large amount of latent heat energy.



a)Various components



b)Temperature-Entropy diagram

Fig 3.1 Thermodynamic cycle of a typical heat pipe

This vapor then travels through the hollow core of the pipe toward the cooler end, known as the condenser section. Because of the temperature difference between the two ends, the vapor naturally flows to the cooler region without the need for any external force or mechanical pump.At the condenser section, the vapor releases its latent heat to the surroundings and condenses back into liquid form. This released heat is what effectively removes thermal energy from the source. The condensed liquid must then return to the evaporator section to repeat the cycle.The return of the liquid is achieved through capillary action in the wick structure. The wick, which may be made of porous material, grooves, or mesh, generates a capillary force that draws the liquid back to the hot end, even against gravity. This makes heat pipes highly effective in various orientations, including zero-gravity environments such as space. The entire process is continuous and self-sustaining as long as there is a temperature difference between the two ends. Because the heat transfer relies on phase change rather than simple conduction, heat pipes can transfer large amounts of heat with very small temperature differences, making them far more efficient than solid conductors like cooper. In summary, a heat pipe operates through a closed-loop cycle where heat causes liquid to evaporate, the vapor transports energy to a cooler region, it condenses and releases heat, and the liquid returns via capillary action to repeat the process. This simple yet powerful mechanism allows heat pipes to achieve extremely high thermal conductivity without any moving parts.

3.2 Types of heat pipes

Heat pipes have been designed and built with various cross - sectional areas as small as 30 μ m width × 80 μm depth and 19.75 mm in length (micro heat pipes), and heat pipes as large as 100 m in length. All heat pipes have an evaporator and condenser section where the working fluid evaporates and condenses, respectively. Many heat pipes also have a transport or adiabatic section which separates the evaporator and condenser sections by an appropriate distance , intended to satisfy the heat pipe limitations and/or the design constraints of the application. A given heat pipe may have multiple evaporators, condensers and adiabatic sections.The working fluid is usually circulated by capillary forces in a wick. However, gravitational, centrifugal, electrostatic, and osmotic forces can also be used to return the liquid from the condenser to the evaporator. For simplicity of design and manufacturing, heat pipe containers are generally circular cylinders. Other shapes, however, such as rectangular (flat heat pipes), conical (rotating heat pipes), corrugated flexible heat pipes,and nosecap (leading edge heat pipes) geometries have been studies.

3.2.1 Capillary -Driven Heat Pipe

The capillary-driven heat pipe (conventional heat pipes) consist s of a sealed container, in which a wick is placed on the inner radius of the pipe wall (Fig. 3.2) The purpose of the wick is to provide a capillary-driven pump for returning the condensate to the evaporator section. Enough working fluid is placed inside the sealed pipe to saturate the wick with liquid. The operation driven heat pipe is as follows. Heat input to the evaporator section evaporates the liquid in the wick. The vapor then enters the vapor space and travels to the condenser section due to the higher vapor pressure in the evaporator.

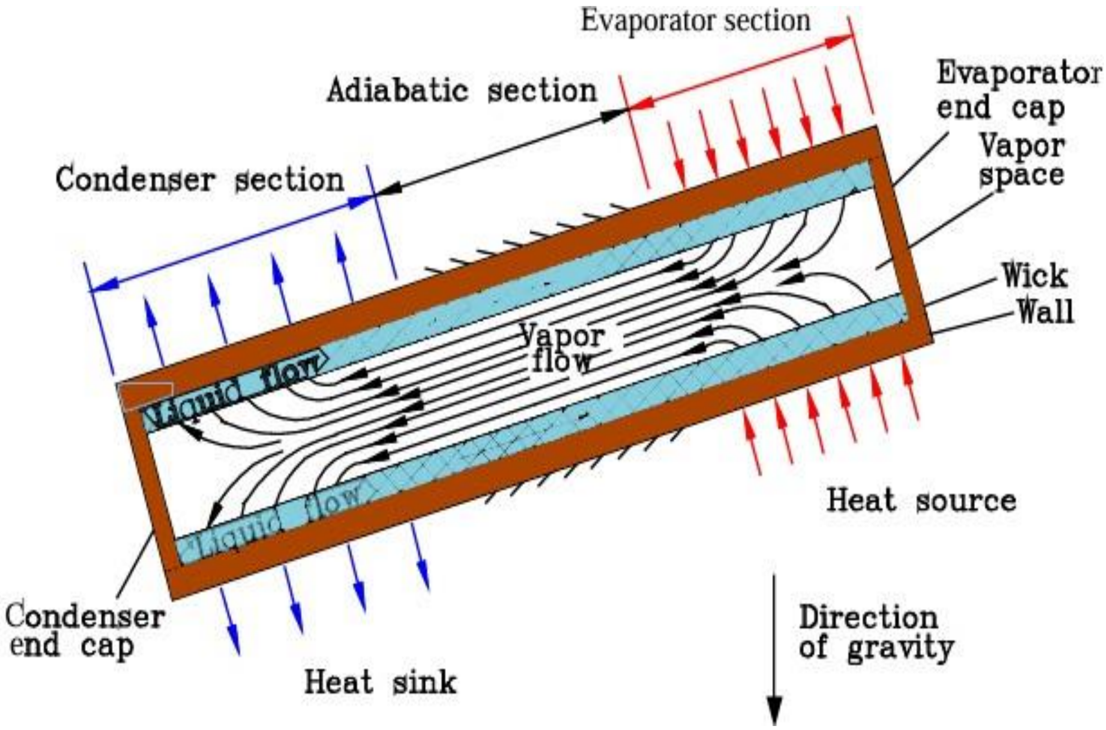


Fig 3.2 Conventional capillary-driven heat pipe

Heat removal from the condenser causes the vapor 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 -vapor 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. 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. Conventional capillary heat pipes are used in almost all laptop/notebook computers nowadays to channel heat away from the processors. The capillary heat pipe has also been widely applied to various commercial and aerospace applications.

3.2.2 Annular Heat Pipe

The annular heat pipe is similar to the conventional capillary -driven heat pipe in many ways. The main difference between the two is that the cross -section of the vapor space in an annular heat pipe is annular instead of circular (Fig. 3.3) Faghri, A., 1989, **[02]** Cao, Y., and Faghri, A., 1993a, **[03]** . This enables the designer to place wick material both on the inside of the outer pipe and on the outside of the inner pipe.

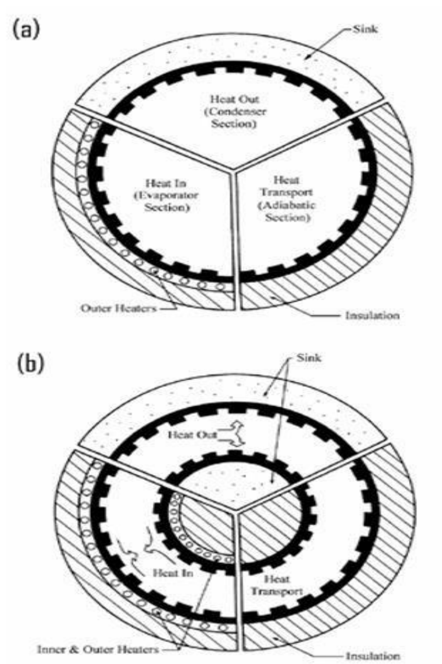


Fig 3.3 Conventional and concentric annual heat pipe design:(a)conventional: (b) concentric annual

In this manner, the surface area for heat input and output can be significantly increased without increasing the outer diameter of the pipe.Therefore, the capillary limit of the annular heat pipe is greater than that of a conventional heat pipe having the same outer dimensions. The annular heat pipe has been used as an isothermal furnace , with excellent results due to its temperature flattening capabilities and fast response time to a cold charge. This type of heat pipe can also be used to connect two circular cross - section heat pipes end-to-end by inserting the circular heat pipe into the inner pipe.

3.2.3 Rotating Heat Pipe

Rotating heat pipes can be designed in two configurations Cao, Y., and Faghri, A., 1994a, Cao, Y., 1997 **[04;06].** First, the heat pipe can be in the shape of a circular cylinder with or without an axial taper, which rotates either about its own axis of symmetry or revolves off- axis. Secondly, the heat pipe can be manufactured in the shape of a disk, where two parallel disks are joined together at the outer and inner radii to form the vapor space (Fig 3.4). Cylindrical rotating heat pipes operate in the same manner as conventional cylindrical heat pipes except that internal tapers are commonly used to aid in returning the condensate to the evaporator by centrifugal force.

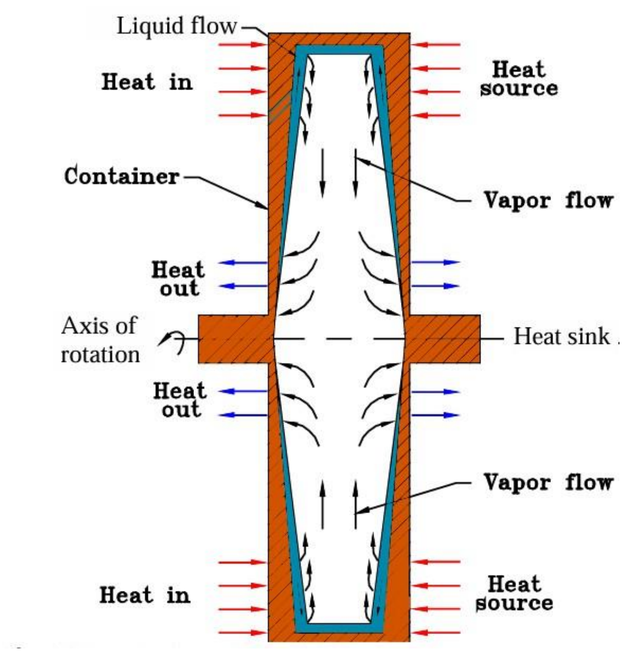
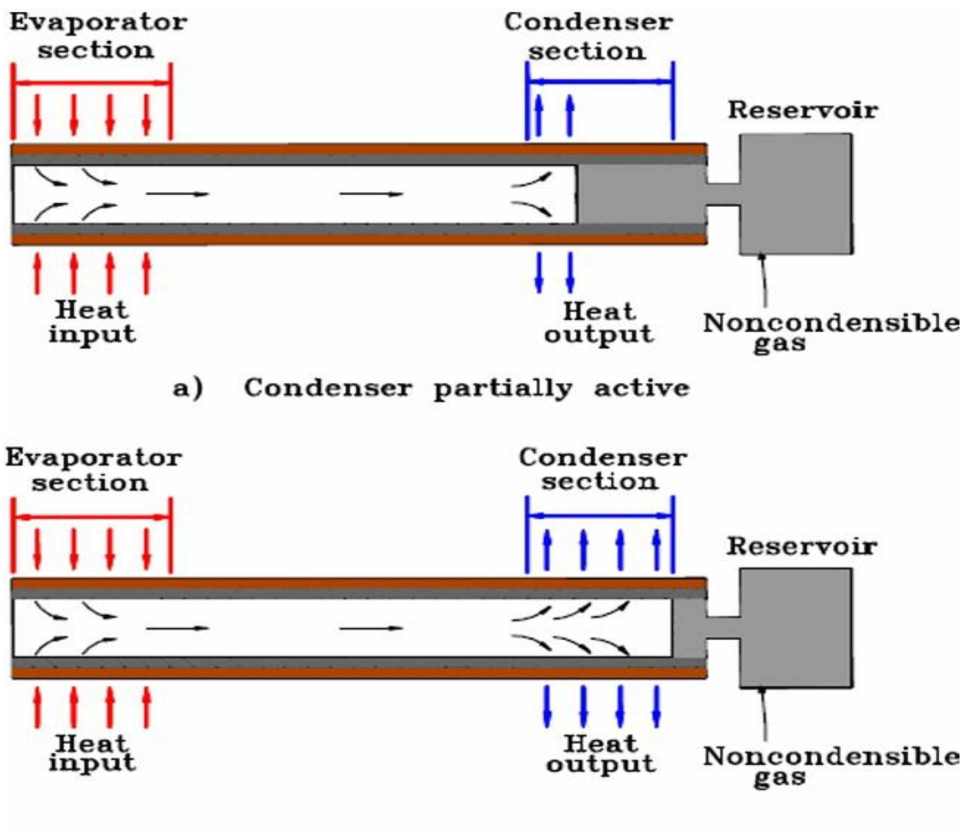


Fig 3.4 Rotating heat pipe (Radial flow)

With disk-shaped heat pipes, heat is input at the outer radii and extracted at the inner radii, which allows the condensate to be driven back to the evaporator by centrifugal force with the aid of an internal taper. Therefore, capillary wicks are not used in rotating heat pipes. Cylindrical rotating heat pipes have been used to cool the rotating parts of electric motors and metal - cutting tools such as drill bits and end mills. Disk-shaped heat pipes have been proposed to effectively turbine components and automobile brakes.

3.2.4 Gas -Loaded Heat Pipe

Gas -loaded heat pipes are one type of variable conductance heat pipes. The gas -loaded heat pipe, shown in (Fig 3.5) is the same as the capillary - driven heat pipe or the two - phase thermosyphon except that a noncondensing gas is introduced into the vapor space. During operation, this gas is swept down the length of the heat pipe by the working fluid vapor to the condenser section.



b) Condenser fully active

Fig 3.5 Operation of a gas-loaded variable conductance heat pipe

Since condensation of the working fluid does not take place where the noncondensing gas is present, a portion of the condenser is blocked from transferring heat to the heat sink (Fig. 3.5(a)). If the heat input to the evaporator section is increased, the vapor and gas temperatures both increase, which leads to the compression of the inert gas. Increases the amount of condenser surface area available to transfer heat (Fig. 3.5(b)).

This phenomenon results in the gas -loaded heat pipe being able to maintain a nearly constant evaporator temperature regardless of the heat input.

3.2.5 Capillary Pumped Loop Heat Pipe

Spacecraft and electronic systems require heat rejection systems which can remove quantities of heat on the order of 10 to 100 times that which present single -phase systems can reject. Another special type of heat pipe has been proposed and extensively tested for this purpose, the capillary pumped loop (CPL) (R[) Faghri, A., 1995 **[01].** The CPL was first proposed by Stenger (1966) at the NASA Lewis Research Center.

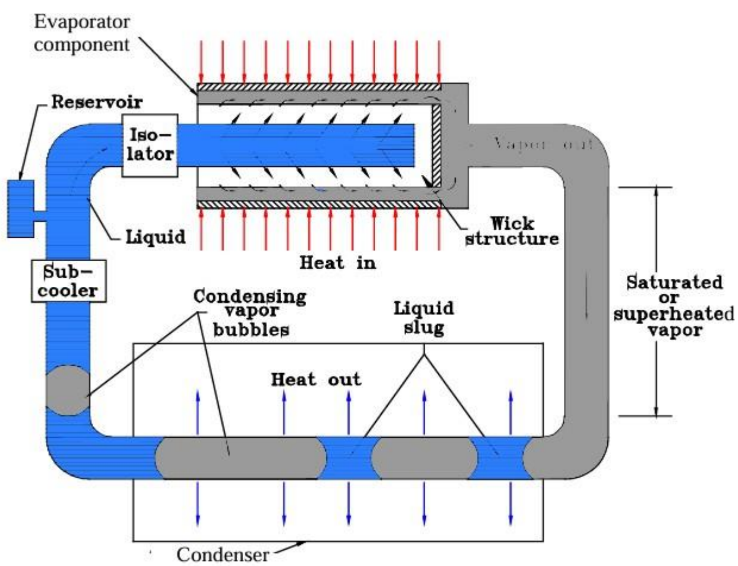


Fig 3.6 Capillary pumped looped heat pipe(CPL)

A basic schematic of the CPL is given in (Fig. 3.6) Heat is applied to the evaporator component, which consists of a hollow rod of wick material capped at one end and force fitted into an internally axially-grooved pipe. The heat applied to the outer surface of the evaporator vaporizes the liquid working fluid, which then travels down the length of the axially- grooved vapor channels and into the vapor header.The vapor travels to the condenser , where it is condensed first as a film on the inner wall of the pipe, and then as a liquid slug flow. Before reaching the evaporator, the liquid passes through a sub-cooler to collapse any remaining vapor bubbles as well as to provide additional subcooling if necessary. The capillary pressure generated in the wick structure continuously pumps the working fluid through the cycle. A two -phase reservoir is provided to control both the working fluid through the cycle and the working temperature of the system, which is similar in function to the variable conductance heat pipe. For multiple evaporator systems, isolators are provided to prevent the dep-riming of one evaporator from dep-riming the other evaporators. Despite the wide use of the CPL and LHP in space technology, fundamental confusion still exists regarding their similarities and distinctions in operation, as well as the limitations of these two devices.

3.3 working fluids and temperature ranges

Each heat pipe application has a particular temperature range in which the heat pipe needs to operate. Therefore, the design of the heat pipe must account for the intended temperature range by specifying the proper working fluid. Table 1 Faghri, A., 1995 **[01]** lists some of the commonly used and proposed working fluids, their melting and boiling points at atmospheric pressure, and their useful ranges. As a rule of thumb, the useful range extends from the point where the saturation pressure is greater than 0.1 atm and less than 20 atm. Below 0.1 atm, the vapor pressure limit may be approached. Above 20 atm, the Frontiers in Heat Pipes (FHP), 5, 1 (2014) Longevity of a heat pipe can be assured by selecting a container, a wick and welding materials that are compatible with one another and with the working fluid of interest. Performance can be degraded and failures can occur in the container wall if any of the parts (including the working fluid) are not compatible. For instance, the parts can react chemically or set up a galvanic cell within the heat pipe. Additionally, the container material may be soluble in the working fluid or may catalyze the decomposition of the working fluid at the expected operating temperature. A compilation of the most up -to -date information concerning the compatibility of metals with working fluids for heat pipes is given in Table 1 Faghri, A., 1995 **[01].** presents various working fluid boiling points and classifies them into four categories: cryogenic, low, intermediate and high temperature ranges. The working -fluid inventory of a heat pipe is the sum of the masses of the vapor and liquid phases, assuming the wick is full of liquid. This criterion is slightly over the optimum requirement because the meniscus recedes into the evaporator wick during normal operation. However, this situation is more advantageous than underfilling the heat pipe, which may significantly reduce the maximum heat transfer. With extreme overfill, however, any excess fluid might collect as liquid in the condenser section and increase the thermal resistance, thereby decreasing the heat transport capability of the heat pipe. Heat pipe fabrication, processing, and testing involve several detailed procedures which are recommended to be strictly followed in order to achieve the highest quality possible. Faghri, A., 1995 **[01]** provided a detailed procedure for the fabrication, processing, and testing of low, moderate, and high temperature.

Table-1 Generalized results of experiment compatibility tests

Working Fluid	Compatible Material	Incompatible Material
Water	Stainless Steel[a], Copper, Silica, Nickel, Titanium	Aluminum, Inconel
Ammonia	Aluminum, Stainless Steel, Cold Rolled Steel, Iron, Nickel	
Methanol	Stainless Steel, Iron, Copper, Brass, Silica, Nickel	Aluminum
Acetone	Aluminum, Stainless Steel, Copper, Brass, Silica	
Freon-11	Aluminum	
Freon-21	Aluminum, Iron	
Freon-113	Aluminum	
Heptane	Aluminum	
Dowtherm	Stainless Steel, Copper, Silica	
Lithium	Tungsten, Tantalum, Molybdenum, Niobium	Stainless Steel, Nickel, Inconel, Titanium
Sodium	Stainless Steel, Nickel, Inconel, Niobium	Titanium
Cesium	Titanium, Niobium, Stainless Steel, Nickel-based superalloys	
Mercury	Stainless Steel[b]	Molybdenum, Nickel, Tantalum, Inconel, Titanium, Niobium
Lead	Tungsten, Tantalum	Stainless Steel, Nickel, Inconel, Titanium, Niobium
Silver	Tungsten, Tantalum	Rhenium

CHAPTER 4
CAPILLARY WICK DESIGN AND STRUCTURES

4.1 Capillary wick design and structures

The wick structure within the heat pipe is present to return condensate to the evaporator section. While small pores are needed at the liquid vapor interface to develop high capillary pressures, large pores are preferred within the wick so that the movement of the liquid is not restricted too greatly. For this reason, many different types of wick structures have been developed in order to optimize the performance of the capillary heat pipe. The types of wick structures can be divided into two categories: homogeneous and composite wicks. Homogeneous wicks Faghri, A., 1995 **[01]** have the benefit of being relatively simple to design, manufacture and install. Composite wicks Faghri, A., 1995 **[01]** however, can significantly increase the capillary limit of the heat pipe, but have the drawback of high manufacturing costs. When selecting a wick structure for a particular 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:

4.1.1 Permeability:

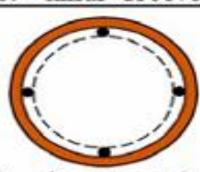
Permeability is a measure of the wick resistance to axial liquid flow. This parameter should be large in order to have a small liquid pressure drop, and therefore, higher heat transport capability

4.1.2 Effective thermal conductivity:

A large value for this parameter gives a small temperature drop across the wick, which is a favorable 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.

4.1.3 Homogeneous Wicks

Table-2 Typical homogeneous wick designs

Wick type	Capillary pumping	Thermal conductivity	Permeability	Comments
 A. Wrapped Screen	High	High	Low–average	Single or multiple wraps of wire screen mesh
 B. Sintered Metal	High	Average	Low–average	Packed spherical particles, felt metal fibers or powder
 C. Axial Grooves	Low	High	Average–high	Rectangular, circular, triangular, or trapezoidal grooves
 D. Open Annulus	Low	Low	High	Wire screen mesh spaced from wall
 E. Open Artery	Low	High	High	Wire screen mesh formed into artery and wall lining
 F. Integral Artery	High	High	Average–high	Homogeneous material with built–in arteries

Homogeneous wicks (Table 2) Faghri, A., 1995 **[01]** are constructed with one type of material or machining technique. The screen wick is seemingly the simplest and most common type of wick structure. It consists of a metal or cloth fabric which is wrapped around a mandrel and inserted into the heat pipe. After placement, the mandrel is removed, leaving the wick held by the tension of the wrapped screen, in the case of a metal fabric. For a cloth fabric, a spring may be inserted into the heat pipe to hold the wick against the inside of the pipe wall. The capillary pressure generated by a screen wick is determined by the size of the rectangular pores between the individual threads. The permeability is determinedby the number of wraps and the looseness of the wraps, which create annular gaps through which the condensate can flow. Sintered metal wicks are manufactured by packing tiny metal particles between the inner heat pipe wall and a mandrel in powder form. This assembly is then heated until the metal spheres are sintered to each other and to the inner wall of the heat pipe. Special materials are used for the mandrel so that it can be removed, leaving an open vapor space. This type of wick is obviously more difficult to manufacture compared to the simple screen wick. However, the capillary pressure developed by the sintered metal wick (and therefore capillary limit) is more easily predicted, as the annular gaps present in a screen wick present uncertainties in the permeability. Also, since a metal powder is sintered, the effective thermal conductivity is much higher than a comparable screen wick due to the poor thermal contact between the screen wraps. Axial groove wicks are formed by the extrusion or broaching of grooves into the inner radius of the pipe. Several different types of grooves have been used and proposed, which have rectangular, triangular, trapezoidal, or nearly circular cross-sections. Trapezoidal grooves are currently the most common type. The performance of axial groove wicks is excellent, provided that the application does not call for a significant adverse elevation against gravity. Since the size of the grooves are large compared to those of a screen or sintered metal wick, the capillary pumping pressure is quite small. However, the permeability and the effective thermal conductivity are very high. Drawbacks to this type of wick are the difficulty in machining the grooves for long heat pipes, which might prove to be excessively expensive, and the liquid- vapor interaction at the opening the high vapor velocities Other attractive features of axial groove wicks include the field-tested performance, reliability, and simplicity of design. The open annulus wick is simply a single-wrap screen wick, held away from the inner pipe wall by stand-offs. This provides an unimpeded return flow path between the screen and the pipe, which greatly increases the permeability over the simple screen wick, while maintaining the high capillary pressure.However,the effective thermal conductivity of this wick is very low for most working fluids due to the low liquid thermal conductivity. Difficulties in priming during startup,and depriming during near-dryout operation are common in this type of wick. The idea of an open condensate return path is also present in the artery wick, but the problem of a low effective thermal conductivity, as is present in the open annulus wick, is significantly reduced. The artery wick combines the two necessities of having a small pore radius for capillary pressure generation and having a large pore radius for high permeability. In the artery wick structure, the interior of the heat pipe is either covered by a screen wick or a sintered metal powder in the usual manner, but a hollow passage(s) running the length of the pipe is fashioned and is in communication with the rest of the wick structure. Condensate is collected within this passage(s) or artery and is pumped back to the evaporator section by the capillary forces generated at the liquid-vapor interface. Since the inner diameter of the artery is much larger than the effective pore radius of the wick, the liquid is able to easily traverse the length of the heat pipe with a minimum pressure drop. As with any design, there are difficulties associated with the artery wick. First, problems associated with the manufacturing of arteries must be addressed. The startup of artery wick heat pipes is also critical due to the inevitable presence of vapor bubbles within the artery, which effectively block liquid return. Methods of collapsing these bubbles are complicated and not always effective.

4.2 Heat transfer limitations

There are various parameters that put limitations and constraints on the steady and transient operations of heat pipes Faghri, A., 1995 **[01]** .In other words, the rate of heat transport through a heat pipe is subject to a number of operating limits. Physical phenomena that might limit heat transport in heat pipes are due to capillary, sonic, entrainment, boiling, frozen startup, continuum vapor, vapor pressure and condenser effects. The heat transfer limitation can be any of the above limitations depending on the size and shape of the pipe, working fluid, wick structure, and operating temperature. The lowest limit among the eight constraint defines the maximum heat transport limitation of a heat pipe at a given temperature. The physical phenomena for each limitation are briefly presented below. A detailed presentation of the criteria for the heat transfer limitations for heat pipes are provided in Faghri, A., 1995 **[01].**

4.2.1 Capillary Limit

The ability of a particular capillary structure to provide the circulation for a given working fluid is limited Cao, Y., 1996 **[05].** 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. This is due to the fact that the sum of the liquid and vapor pressure drops exceed the maximum capillary pressure that the wick can sustain. The maximum capillary pressure for a given wick structure depends on the physical properties of the wick and working fluid. Any attempt to increase the heat transfer above the capillary limit will cause dryout in the evaporator section, where a sudden increase in wall temperature along the evaporator section takes place.

4.2.2 Sonic Limit

The evaporator and condenser sections of a heat pipe represent a vapor flow channel with mass addition and extraction due to the evaporation and condensation, respectively. The vapor velocity increases along the evaporator and reaches a maximum at the end of the evaporator section. The limitation of such a flow system is similar to that of a converging - diverging nozzle with a constant mass low rate, where the evaporator exit corresponds to the throat of the nozzle. Therefore, one expects that the vapor velocity at that point cannot exceed the local speed of sound. This choked flow condition is called the sonic limitation. The sonic limit usually occurs either during heat pipe startup 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 vapor velocities and low densities. Unlike the capillary limit, when the sonic limit is exceeded, it does not represent a serious failure. The sonic limitation corresponds to a given evaporator end cap temperature. Increasing the evaporator end cap temperature will increase this limit to a new higher sonic limit. The rate of heat transfer will not increase by decreasing the condenser temperature under the choked condition. Therefore, when the sonic limit is reached, further increases in the heat transfer rate can be realized only when the evaporator temperature increases. 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.

4.2.3 Boiling Limit

If the radial heat flux in the evaporator section becomes too high, the liquid in the evaporator wick boils and the wall temperature becomes excessively high. The vapor bubbles that form in the wick prevent the liquid from wetting the pipe wall, which causes hot spots. If this boiling is severe, it dries out the wick in the evaporator, which is defined as the boiling limit. However, under a low or moderate radial heat flux, low intensity stable boiling is possible without causing dryout. It should be noted that the boiling limitation is a radial heat flux limitation as compared to an axial heat flux limitation for the other heat pipe limits. However, since they are related through the evaporator surface area, the maximum radial heat flux limitation also specifies the maximum axial heat transport. The boiling limit is often associated with heat pipes of non -metallic working fluids. For liquid - metal heat pipes.

4.2.4 Vapor Pressure Limit

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

4.2.5 Frozen Startup Limit

During the startup process from the frozen state, the active length of the heat pipe is less than the total length, and the distance the liquid has to travel in the wick is less than that required for steady state operations. Therefore, the capillary limit will usually not occur during the startup 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 startup limit may occur due to the freezing out of vapor from the evaporation zone to the adiabatic or condensation zone.

4.2.6 Condenser Heat Transfer Limit

In general, heat pipe condensers and the method of cooling the condenser should be designed such that the maximum heat rate capable of being transported by the heat pipe can be removed. However, in exceptional cases with high temperature heat pipes, appropriate condensers cannot be developed to remove the maximum heat capability of the heat pipe. Due to the presence of noncondensible gases, the effective length of the heat pipe is reduced during continuous operation. Therefore, the condenser is not used to its full capacity. In both cases, the heat transfer limitation can be due to the condenser limit.

4.3 Heat Pipe Start Up

The procedures typically used in designing heat pipes are based on the fact that the heat pipe is in its normal operating state, i.e., nominal temperature at the steady state. However, the heat pipe must be started from the ambient temperature, which is either lower or higher than the operating temperature . If the startup is too fast, the possibility of overheating the evaporator section can result in damage to the heat pipe. Ideally, the heat pipe should first be started by increasing (or decreasing) the temperature of the entire pipe to its operating temperature. The heat input to the pipe is then slowly increased from zero to the operating input, maintaining a uniform temperature across the length of the pipe. This procedure is not usually feasible in practice. Normally, the heat input increases suddenly from zero to the operating input, without the benefit of increasing the temperature of the entire pipe. This may result in problems occurring in the startup period, which will be discussed here for three different common situations.

4.3.1 Uniform Startup

Figure 8.1(a) shows the startup of a heat pipe in which the axial temperature is nearly uniform throughout the startup period. This type of startup profile is normally seen in heat pipes in which the working fluid in the wick is in the liquid state, and the vapor is in the continuum state. An example is a copper -water heat pipe starting from ambient temperature to some higher operating temperature. As can be seen, no problems are encountered during the uniform startup.

4.3.2 Frozen Startup

Figure 4.1(b) presents the case of a heat pipe in which the working fluid within the wick structure is initially frozen, and the vapor space is essentially evacuated. This type of frontal startup is usually found in liquid -metal heat pipes, since liquid metals are in the solid state at room temperature. Frozen startup proceeds as follow s: Heat is first conducted through the pipe wall and into the wick structure, increasing the temperature in the evaporator section only. After the working fluid in the evaporator wick is liquefied, evaporation begins to fill the vapor space with vapor. The vapor travels to the adiabatic section and condenses, releasing its latent heat and increasing the adiabatic section temperature. This front continues down the length of the pipe until it reaches the condenser end cap. At that time, the axial temperature distribution starts to become uniform, and the startup process is completed. The presence of large axial temperature gradients indicates that the sonic limit is occurring during frozen startup. In actuality, this is not a limit per se, since the heat pipe will not be damaged during this process. Another more important limit is the frozen startup limit, as previously discussed. The frozen startup limit occurs when more working fluid is evaporated than can be resupplied by the wick structure, due to the fact that the working fluid in the adiabatic and condenser sections is completely frozen. When this occurs, the evaporator section is depleted of liquid and overheats due to dryout.

4.3.3 Gas-Loaded Heat Pipe Startup

Gas-loaded heat pipes gives the startup a frontal character. Figure 4.1(c) shows the case in which the working fluid in the wick is initially liquid in a gas -loaded heat pipe. Before the heat input is applied in the evaporator, the noncondensible gas is evenly distributed throughout the vapor space. When evaporation occurs, the working fluid vapor drives the gas to the condenser end of the heat pipe. Since the gas and the vapor are essentially separated, the effect of the gas is to block the condenser section from transferring heat to the heat sink. The presence of the gas can be seen in the axial temperature profile, which has an abrupt drop at the vapor -gas interface. More heat is then fed into the pipe, increasing the wall and vapor temperatures within the evaporator and adiabatic sections. This increases the vapor pressure, which compresses the gas in the condenser section. The vapor -gas front moves downstream into the condenser section, eventually unblocking part of the condenser, so that normal operation can take place.

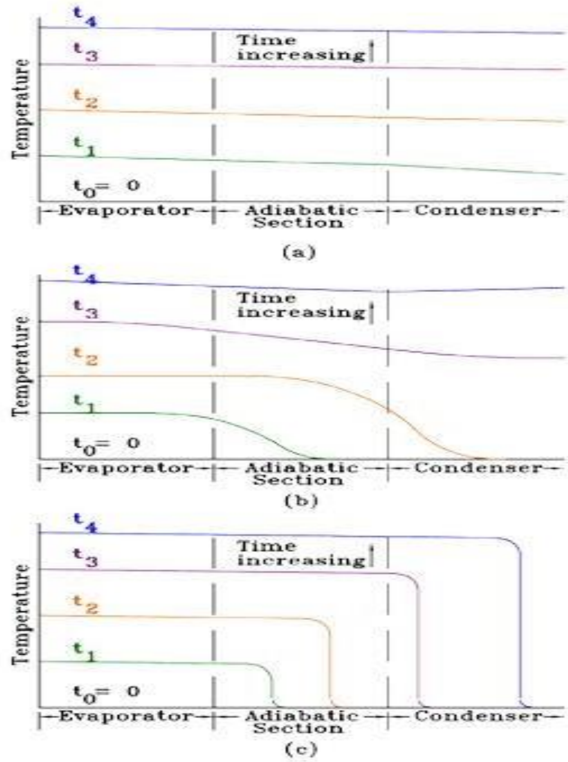


Fig 4.1 Transient axial temperature profiles during heat pipe startup: (a) Uniform startup;(b) Frozen startup;(c) Gas-loaded heat pipe.

4.3.4 Heat pipe characteristics

High Effective Thermal Conductivity The heat pipe is a device of very high thermal conductance Faghri, A., 1995 **[01]** For example, a temperature difference of 900°C is needed to transfer 1 KW heat across a 30 -mm -diameter 1 - m -long copper rod. A heat pipe of the same size can transfer the same amount of heat with a temperature difference of less than 10°C. This indicates that the heat pipe can have a thermal conductivity 90 times higher than that of a copper bar of the same size. Numerous heat pipe designs have been developed for various applications with varied heat transport capabilities. The Heat transfer characteristics of a heat pipe can be measured using a conventional configuration as shown in Fig. 4.2(a). Figure 4.2(b) shows the heat transfer rate versus the mean temperature difference between the evaporator and condenser sections of commercially available copper -water heat pipes with a screen mesh wick and different diameters. Most of the tests were made in a vertical position (gravity - assisted wicked heat pipe), where the driving force is due to both capillary pumping and gravity. A typical test for horizontal operation, as well as a comparison with a copper rod of 24.5 mm OD, are also shown in Fig. 4.2(b). The thermal response of a conventional commercial screen mesh copper -water heat pipe with 6.35 mm OD and an inner diameter of 5.85 mm in comparison with a copper pipe of the same dimension is shown in Fig. 4.2. There are commercial companies all over the world (with more concentration in the Far East) who manufacture heat pipes of different shapes and sizes for various operating temperature range.

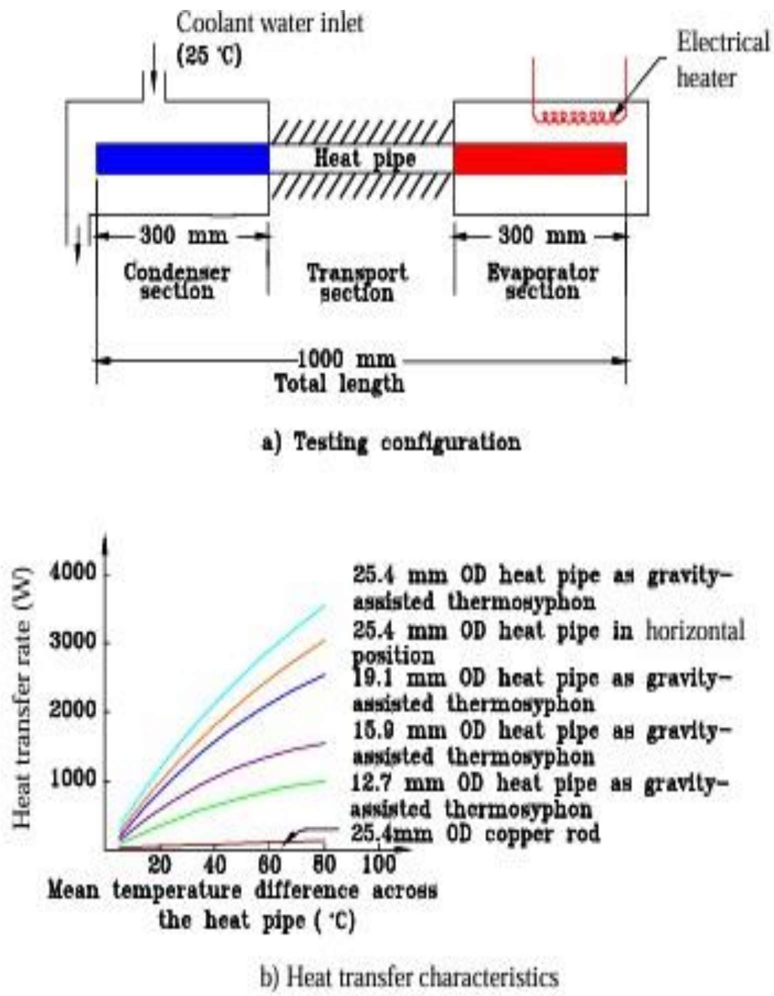


Fig 4.2 Heat transfer characteristics of some typical commercial copper-water screen mesh heat pipes.

4.4 Heat pipe analysis and simulation

Background Numerical and analytical simulation of heat pipes has progressed significantly in the last several decades. The state of the art has been advanced in steady state, continuum transient, and frozen start up simulation for high , intermediate, and low temperature heat pipes of conventional and nonconventional geometries. In determining the heat capacity transmitted through a heat pipe or heat pipe performance characteristics, it is necessary to know the liquid and vapor pressure losses in the separate segments. The thermal fluid phenomena occurring within a heat pipe can be divided into four basic categories: (1) vapor flow in the core region, (2) liquid flow in the wick, (3) interaction between the liquid and vapor flows, and (4) heat conduction in the wall.Most of the details analytical and numerical research onheat pipes has been done on the vapor core region and wall heat conduction, since the liquid flow is difficult to describe with an exact theoretical model. Because of the presence of the wick structure, the analysis of categories (2) and (3) requires some empirical information that must be obtained from experimentation. Furthermore, the analyses of categories (2) and (3) are basically similar for heat pipes of various shapes. In contrast, the dynamics of vapor flow are related to the geometry and boundary specifications for nonconventional heat pipes

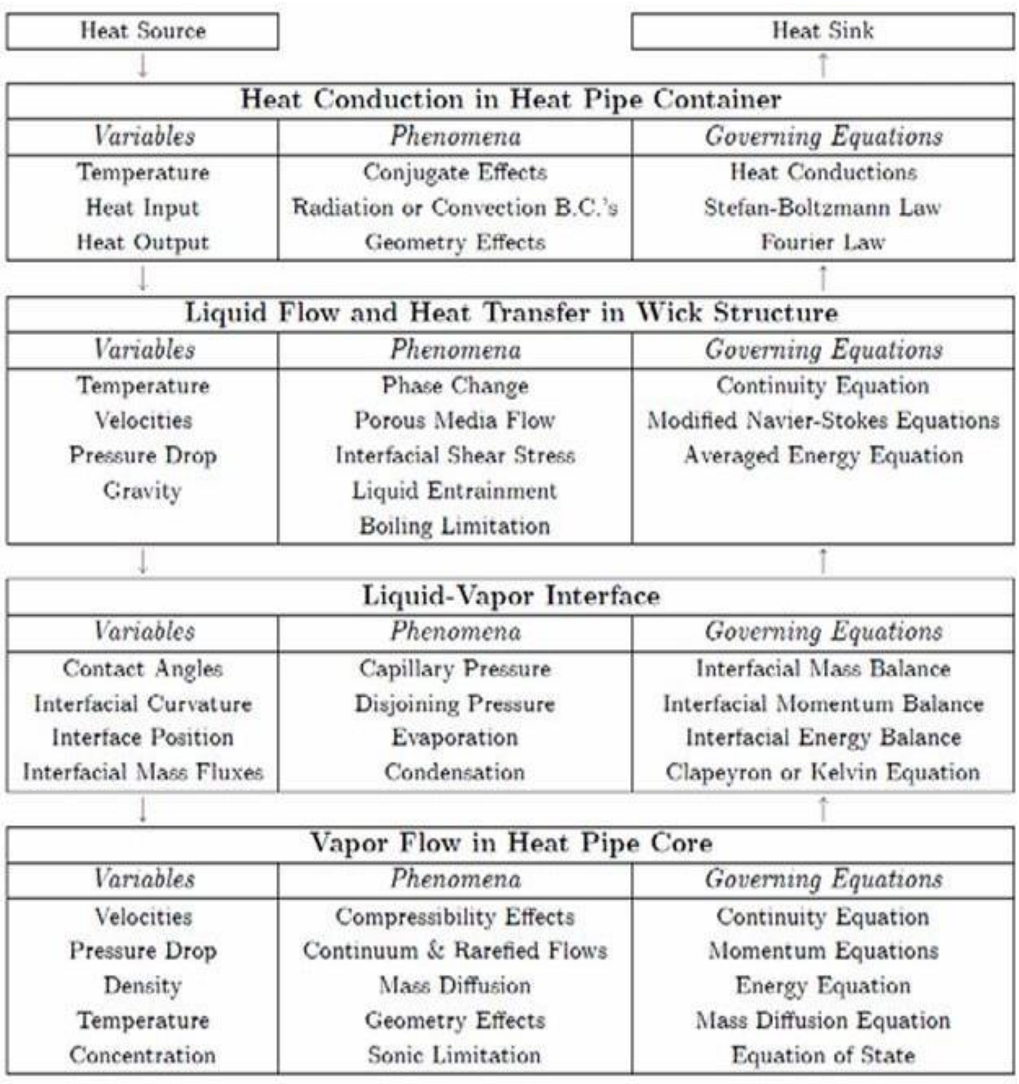


Fig 4.3 Flow chart for heat pipe operation and interaction between different regions.

The interaction between different regions can be best illustrated by following the real. Heat pipe operating condition, as shown by the flow chart in (Fig 4.3)Consider a heat pipe with a n initial operating condition. If the heat load from the heat source to the heat pipe evaporator surface is increased at t ≥ 0 to a higher level, the temperature of the container wall is increased accordingly, and more heat is transferred from the container to the heat pipe wick structure. In this case , the heat pipe container wais interacting with the heat pipe wick structure. Meanwhile, the state of the liquid -vapor interface may change due to the change in liquid pressure and temperature. The interface evaporation mass flux is also increased because more heat is transferred from the wick structure to the interface. A higher mass flux at the interface will increase the vapor velocity, and result in a change in the vapor working condition. In the above process, the liquid flow in the wick structure is interacting with vapor flow via the liquid -vapor interface. At the same time, more liquid mass may condense onto the liquid -vapor interface in the condenser section due to the higher mass flow rate from the evaporator section. This will subsequently change the interface state. The interaction between the vapor flow and the liqui d -vapor interface in this case can be called feedback. These feedback interactions will also occur between the liquid -vapor interface and wick structure, and between the wick structure and the container. In (Fig 4.3)regionscan interact only with regions dir over or below. The container region, for example, cannot interact with the vapor region directly. It can only interact with the vapor region via the wick structure region and the liquid -vapor interface. This is due to the physical locations of the different regions, which prescribe the relation between different regions. In general, all of the regions in the flow chart should be solved as a conjugate problem. However, in the real application, approximations are often introduced due to the complex nature of the problem. Some regions in the flow chart may be neglected or combined with other regions. Regions can also be decoupled from other regions. For instance, if we neglect the liquid flow in the wick structure, and solve the region as a heat conduction problem, the region associated with the wick structure may be combined with the region associated with the heat conduction in the container. If we are only interested in the vapor flow in the heat pipe, we can neglect the three preceding regions, and directly go to the fourth region associated with vapor flow. In some applications, the liquid flow in the wick structure is of interest. Therefore, the wick region can be decoupled from other regions, and solved as a one region problem with appropriate assumptions. For the convenience of analysis, the frozen start up process of a high -temperature heat pipe or frozen low -temperate heat pipe can be divided into several periods based on experimental evidence.The working fluid in the wick is frozen at the ambient temperature. For a heat pipe without any noncondensible gas present in the vapor space, the vapor core is completely evacuated before start up. Heat input is started in the evaporator section. Heat is conducted through the pipe wall and wick structure, and melting of the working fluid begins at the wall - wick interface. Because the liquid -solid interface has not reached the wick -vapor boundary, no evaporation takes place and the vapor space is still evacuated.The working fluid is completely melted in the evaporator section only, and liquid is evaporated at the liquid -vapor interface. The vapor flow in the rarefied or free molecular condition due to the low vapor pressure. Some of the working fluid in the wick is still frozen in the adiabatic and condenser sections.Continuum vapor flow is established in the evaporator section as the vapor pressure increases due to evaporation. In the remainder of the heat pipe, however, the vapor is still in the rarefied condition . The working fluid is completely melted and continuum flow is established over the entire heat pipe length. The heat pipe temperature increases steadily until the steady state is reached. 6. The heat pipe is operating under steady state operation.

4.5 Heat Pipe Applications

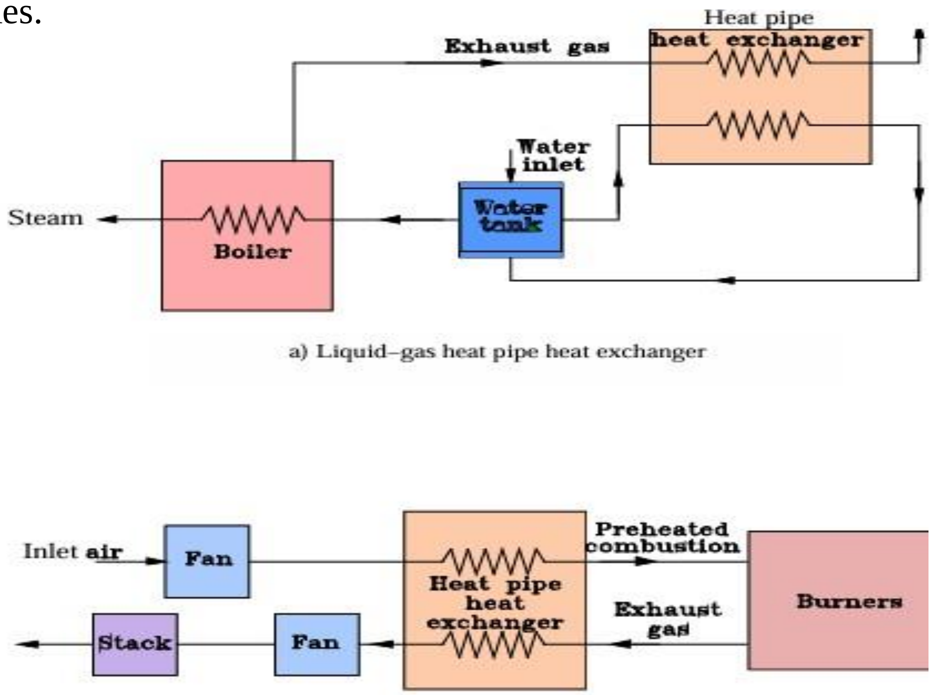
Heat pipes have been applied in many ways since their introduction in 1964 .Depending on their intended use, heat pipes can operate over a temperature range from 4.0 to 3000 K. In all cases, their applications can be divided into three main categories: separation of heat source and sink, temperature equalization, and temperature control. Due to their extremely high thermal conductivity, heat pipes can efficiently transport heat from a concentrated source to a remotely mounted sink. This property can enable dense packing of electronics, for example, without undue regard for heat sink space requirements. Another benefit of the high thermal conductivity is the ability to provide an accurate method of temperature equalization. For example, a heat pipe mounted between two opposing faces of an orbiting platform will enable both faces to maintain constant with equal temperatures, thus minimizing thermal stresses. The temperature control is a result of the capability of heat pipes to transport large quantities of heat very rapidly. This feature enables a source of varying flux to be kept at a constant temperature as long as the heat flux extremes are within the operating range of the heat pipe.

4.5.1 Electronic and Electrical Equipment Cooling

Miniaturization of electronic components is accompanied by increased demands on heat dissipation systems due to the increased density of the components. For example, the digital computer has evolved from a massive system that filled an entire room to a unit which can be stored in a small briefcase. However, the overheating problems associated with the dense packing of heat -generating integrated circuit chips used in the computer (CPU and GPU Cooling) have escalated dramatically. Since the reliability of these and other types of electronic components is sensitive to their operating temperature, steps have been taken to improve heat dissipation by using heat pipes. Other applications to electronic cooling have included rectifiers, thyristors, transistors, traveling wave collectors, audio and RF amplifiers and high density semiconductor packages After the introduction of the Pentium processor in 1993, the processor performance and power consumption trend has significantly increased annually. In the year 2000, the heat flux was approximately 10 -15 W/cm 2, eventually reaching 120 -150 W/cm² in 2010. The average power consumption for laptop/notebook computers is currently between 25 -50 W, while desktops and servers consume between 80 and 150 W. Regardless of components, power level, or type of computer/processor, as electronics are packed into smaller volume.

4.5.2 Heat Exchangers and Heat Pumps

Increases in the cost of energy have promoted the use of heat pipe technology in industrial applications. Due to their high heat transfer capabilities with no external power requirements, heat pipes are being used in heat exchangers for various applications. In the power industry, heat pipe heat exchangers are used as primary air heaters on new and retrofit boilers. The major advantages of heat pipe heat exchangers compared to conventional heat exchangers are that they are nearly isothermal and can be built with better seals to reduce leakage. Heat pipe air heaters should also be cheaper the an conventional tubular heat exchangers, as they are smaller and can be shipped in a small number of modules.



a) Liquid–gas heat pipe heat exchanger

b) Gas–gas heat pipe heat exchanger

Fig 4.4 Waste heat recovery using heat pipe heat exchangers.

Heat pipe heat exchangers can serve as compact waste heat recovery systems which require no power, a low pressure drop and are easy to install on existing lines. Heat pipe heat exchangers can be categorized into gas -gas, gas -liquid, and liquid -liquid type heat units. Among these three, gas -gas heat pipe heat exchangers have the widest application in industry. A gas -gas heat pipe exchanger consists of a group of externally finned heat pipes which reclaim waste heat).

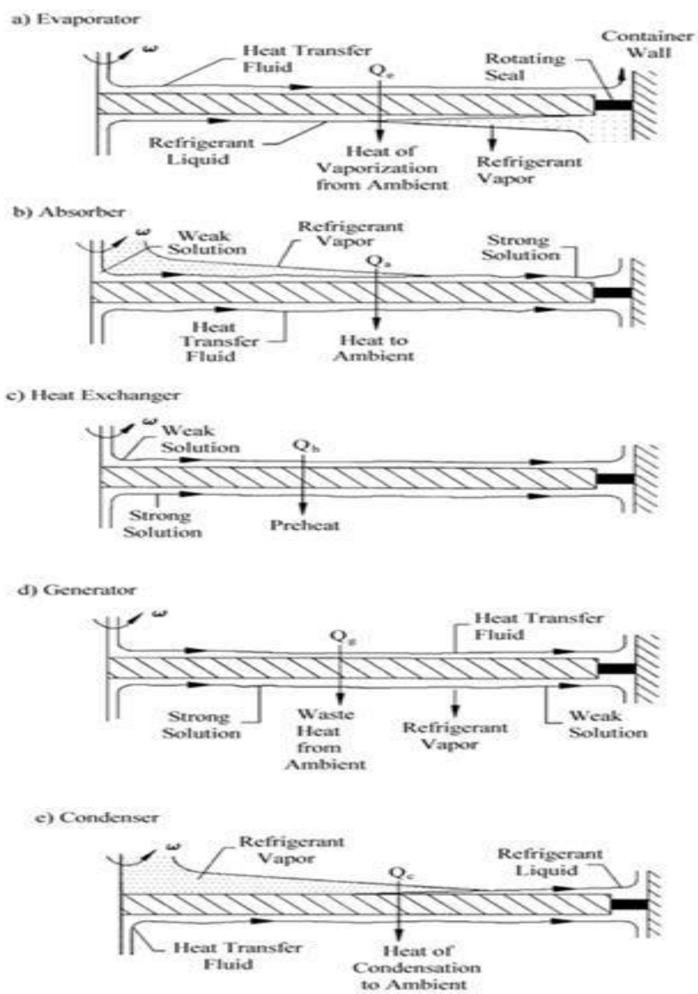


Fig 4.5 Schematic of centrifugal heat pipe heat pump vapor-absorption cycle.

These units eliminate cross -contamination due to the solid wall between the hot and cold gas streams. Also, the heat pipe design is totally reversible (heat can be transferred in either direction). Gas -gas energy recovery units typically fall into three categories: heat recovery in air – conditioning systems (low temperatures),recovery of excess process heat for space heating (moderate temperature), and recovery of waste heat from high temperature exhaust streams for reuse in the process (preheating of combustion air, for example). The units for these applications vary in size and construction depending on the specific application, but many commercial models are now available that implement this heat pipe design. Gas -liquid heat pipe exchangers are less commonly available than gas - gas models due to the fact that the present design of waste heat boilers is very efficient. In the past, exhaust heat from boilers was simply dispe rsed to the atmosphere. (Figure 4.5)shows schematics for waste heat recovery with liquid -gas and gas -gas heat exchangers. invented an innovative design for a centrifugal heat pipe vapor absorption heat pump (Fig.4.5). The heat pipes in this heat pump system are disk -shaped, with one face partially or completely being the evaporator and the opposite face partially or completely being the condenser. The wick is designed such that the centrifugal force aids in the delivery of the condensate to the evaporator. This design will significantly improve the heat and mass transfer characteristics of the rotating components of the vapor-absorption heat pump by increasing the heat pumping capacity that can be packaged in a given value. This results in a more efficient and compact vapor - absorption heat pump system.

4.5.3 Gas Turbine Engines and the Automotive Industry

The temperature limitation is one of the most crucial limiting factors related to the efficiency of a gas turbine aircraft engine or power gas turbine. An increased turbine inlet temperature decreases both the specific fuel and air consumption ,while increasing efficiency. This desire for a high turbine inlet temperature, however, is often in conflict with materials available to withstand the high temperature. As a result, innovative cooling systems for hot -gas -path components are required.Among the hot -gas -path components, the first -stage rotor blade and nozzle guide vane require the most challenging cooling consideration. In addition to improving energy utilization efficiency, effective,cooling could also drastically improve the reliability of high -speed rotating components. It has been observed that the creep life of turbine blades is reduced by half with every 10 to 15°C rise in metal temperature. Therefore, the temperature of the turbine blade must be kept within certain tolerable limits. The primary cooling technology in use today for turbine blades and nozzle guide vanes (NGVs) is the film cooling technology.Since 1995, a number of efforts have been initiated to utilize the concepts of miniature, radially rotating, high -temperature heat pipes, for gas turbine bladesand disk cooling. This also includes a series of experimental and numerical studies Cao, Y., 2010 **[07].** High temperature heat pipe cooling is a promising cooling technology for gas turbine hot components, such as first stage rotor blades, nozzle guide vanes, and rotor disks.This has the potential to significantly reduce the temperature of these hot components, allowing for a much higher gas turbine inlet temperature, while also reducing the consumption of high - pressure compressor air Alleau, T., Bricard, A., Chabanne ; Alleau, T., Bricard, A., and Thouvenin, A., 1987, " **[08 , 09]**A Stirling engine heated by sodium heat pipes has been constructed and tested Meijer, R., and Khalili, K., 1990, Khalkhali, H., Faghri, A., and Zuo, Z. J., 1999, **[10; 11]** . This engine operates at highest efficiency when the thermal energy is supplied to it at a very constant temperature and high heat fluxes. Helium is heated to increase its pressure, which is used to drive pistons.

4.5.4 Medicine and Human Body Temperature Control

Another application is of heat pipes is related to human physiology. A surgical probe incorporating a cryogenic heat pipe is being used to destroy tumors in the human body Basiulis, A., 1976 **[12].** This type of surgery, where the tissue is frozen instead rather than irradiated, is beneficial because the surrounding tissue sustains practically no damage. Also, the surgery results in very little bleeding or pain. The cryoprobe is a hand -held device with a reservoir of liquidnitrogen and a 12 -inch heat pipe extension, which is maintained at approximately 77 K for about one -half hour. Fletcher and Peterson (1997) invented a catheter using micro heat pipes that provide precis temperature control for treating diseased tissue.Another application related to human physiology concerns the control of body temperature Faghri, A., Reynolds, D., and Faghri, P., 1989b, Faghri, A., 1993b **[13; 14]** .In regions or occupations where humans are exposed to extreme temperatures, such as workers in polar regions or foundry workers, adverse health effects fromthese environments are evident. Frostbite on theextremities in cold regions and heat exhaustion in warm climates are very serious problems which must be handled with extreme care. These problems can be avoided with the use of gloves socks,and suits in which heat pipes are placed order to transfer heat either to or fromparts of the body (Fig 4.6).

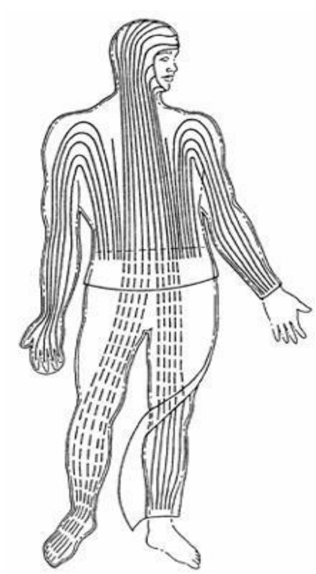


Fig 4.6 Temperature regulation system for the human body using heat pipes.

In cold climates, heat pipes could bring heat from the torso to the extremities such as the fingers, toes, and ears to prevent frostbite.(Figure 4.7)shows a conceptual design for cold weather handwear with heat pipes, where body heat is transferred from the forearm to the fingers. In very hot environments, such as those experienced by fire fighters, a cold suit employing heat pipes could be developed which would be lighter and less bulky than the suits presently worn. This type of suit would also be beneficial in the respect that the wearer would be kept cooler, resulting in more time available for extracting people from a burning building, for instance.

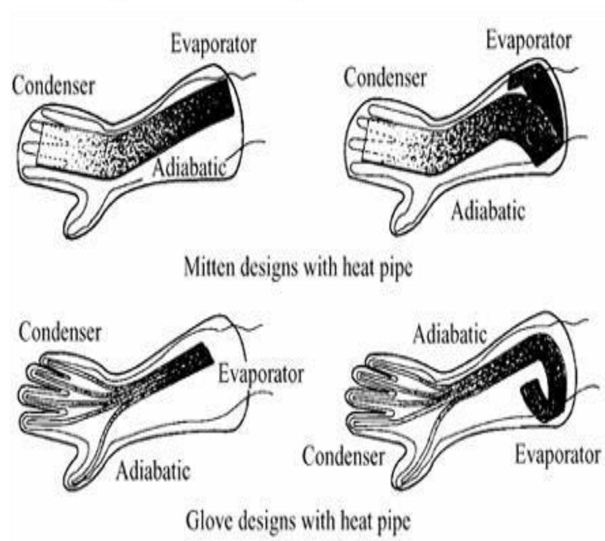


Fig 4.7 Models of cold weather handware with heat pipes.

4.5.5 Ovens and Furnaces

One of the first applications of heat pipes (actually, two -phase closed thermosyphons) was in baking ovens Anonymous, 1867, **[15]** Normal flame -heated baking ovens warmed the firebrick in the firebox, which then conducted the heat to the baking chamber so that the baked food was not contaminated by the combustion products. With the advent of the heat pipe, heat was transferred to the baking chamber by the evaporation and condensation of the working fluid within the array of tubes. This arrangement was not only more efficient, saving up to 25 percent of the fuel normally needed, but also resulted in a more uniform oven temperature. A similar concept is the gas -fired restaurant griddle, which is a flat plate heat pipe separating the gas fire from the cooking surface (Basiulis, 1976). This provides a surface with an extremely uniform temperature, even with heavy food loading. It also has the benefit of a fast warm -up time from a cold start, and the efficiency is comparable to the above -mentioned baking oven. Other food processing equipment has been designed using heat pipe technology such as braisers, kettles, saucepans, and deep fat fryers Lamp, T., 1978 **[16]** . High temperature furnaces have been developed for heat -treating, sintering, and other applications Finlay, I., Cree, D., and Blundell, D., 1976 , Brost, O., Groll, M., and Mack, H., 1990 **[17;18]** . These furnaces are actually annular heat pipes with liquid -metal working fluids. The isothermal behavior of the interior of the annular heat pipe makes it ideal for use as a furnace. The temperature gradient across the length is very small, which is always a significant problem with conventional furnaces. Due to the operation of the heat pipe, only a small portion of the outer surface of the annular heat pipe needs to be heated. Upon insertion of a cold charge, the area in contact with the cold charge becomes the condenser. Annular heat pipe furnaces are also being used in the calibration of temperature measurement devices Chengsheng, H., Tinghan, L., Yaopu, W., and Zengqi, H., 1984 , Bassani, C., Lighthart, J., Sciamanna, G., Marcarino, P., and Fernicola, V., 1990 **[19; 20]** .Thermocouples, RTD's and thermistors have been calibrated using avariable conductance heat pipe furnace; the temperature of which was measured with a traceable platinum RTD. Optical pyrometers, which measure surface temperature from the emitted radiation, have also been calibrated with heat pipe blackbody sources.

4.5.6 Transportation Systems and Deicing

Several innovations using heat pipe technology have been proposed which could improve the safety and reliability of transportation systems. Heat pipes have been used to melt the ice and snow on roadways, bridges, and aircraft runways by transporting geothermal heat stored in the ground to the pavement Suelau, H., Kroliczek, E., and Brinkman, C., 1976 , Suelau, H., Kroliczek, E., and Brinkman, C., 1976 **[21; 22]** . Shiraishi, M., Mochizuki, M., Mashiko, K., Ito, M., Sughiharu, S., Yamagishi, Y., and Watanabe, F., 1992, **[23]** presented several newly developed snow removal and deicing methods using heat pipes such as prevention of snow damage to support wires for telephone poles, a snow melting system for pavement, and a large scale snow melting system for roads in Japan. Corrugated , long heat pipes are utilized for these applications. People working on ships at sea during the winter months are plagued by the problems associated with icing. Anything exposed to the elements, such as the decks and handrails, are constantly icing over during the winter. The usual method of removing the ice is to use an axe or hatchet, which is extremely dangerous when the seas are rough. The potential for severe cuts or falling overboard is always present. To solve this problem, heat pipes have been incorporated into the decks and handrails to transport waste heat from the engine Matsuda, S., Miskolczy, G., Okihara, M., Okihara, T., Kanamori, M., and Hamada, N., 1981 **[24]** . This heat constantly melts the ice before large deposits are formed. Another similar deicing problem addressed by the use of heat pipes concerns navigation buoys Larkin, B., and Dubuc, S., 1976 **[25].** Off the east coast of Canada, navigation buoys are frequently subjected to ocean spray and freezing temperatures, which results in the buoys capsizing due to the weight of the ice. Researchers have constructed a prototype buoy which was , in essence , a large ammonia thermosyphon heated from the sea. It was experimentally determined that the superstructure of the thermosyphon was kept free from ice, but that the auxiliary float seriously iced.

CHAPTER 5
CONCLUSIONS

5.1 Conclusions

An overview of various types of heat pipes is presented in this review. This includes heat pipe fundamentals, operations, heat transport limitations, and full simulation. This review provides a self contained document to design and simulate various types of heat pipes under different operating conditions. Numerical and analytical analyses of heat pipes have progressed significantly over the last several decades. State-of-the-art modeling is capable of predicting thermal performance under various operating conditions for conventional heat pipes. In particular, advances related to the full simulation of heat pipes under steady state, continuum transient and frozen startup operation for conventional heat pipes have been very successful, despite complex multiphase and multidomain transport phenomena in heat pipes. In general, it has been shown that heat pipe simulations must include conjugate heat transfer with the wall, wick and vapor, since these affect both the transient and steady state operating conditions. More fundamental works are needed to better understand the physical phenomena of pulsating heat pipes and loop heat pipes. An accurate simulation of liquid/vapor interface, including multiphase phenomena in various wicks, is important to accurately predict the heat transport limitation of heat pipes.

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