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Heat Pipe for Aerospace Applications—An Overview

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Abstract

The paper presents an overview of heat pipes, especially those used in different space missions. Historical perspectives, principles of operations, types of heat pipes are discussed. Several factors have contributed to the science and technology of the present state-of-Art heat pipe leading to the development of loop heat pipes, micro and miniature heat pipes and micro loop heat pipes. The paper highlights the advancement of heat pipe for hypersonic cruise vehicles, loop heat pipes with higher conductance in 10 K range, heat pipe switches for temperature control of the spacecraft electronics.

Keywords

Variable Conductance Heat Pipe, Rotating Heat Pipe, Loop Heat Pipe, Micro Heat Pipe, Nanofluids

1. Introduction

A typical heat pipe consists of a sealed pipe or tube made of a material that is compatible with the working fluid such as Copper for water heat pipes, or Aluminium for ammonia heat pipes. It is a simple construction that makes a heat pipe to allow high heat transfer rates over considerable distances, with minimum temperature drops, exceptional flexibility, see **Figure 1**. Typically, a Vaccum pump is used to remove air from the heat pipe and then the heat pipe is partially filled with a working fluid and then sealed. The working fluid mass is chosen so that the heat pipe contains both vapor and liquid over the desired Operating temperature range.

In 1963, Los Alamos physicist George Grover successfully demonstrated a capillary-based heat transfer device, which he patented in the same year and coined it by the name-heat pipe. He is often referred to as the inventor of a heat pipe. Grover's inspiration for the heat pipe came from rudimentary heat-conducting pipes used by British bakers more than 175 years ago. The development of such pipes began in 1839, when American inventor Jacob Perkins patented the hermetic tube boiler. Angier March Perkins (Jacob's son) modified the tube boiler, and in 1936 he patented what he called the Perkins Tube, which saw widespread use in locomotive

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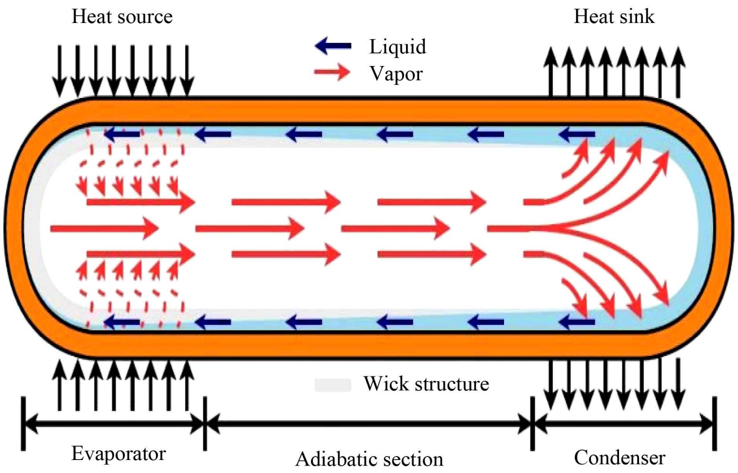

Figure 1. Schematic of a heat pipe.

boilers—and working ovens (including a mobile oven for the British Army). The Perkins Tube served as a "jumping off point" for Grover's development of modern heat pipes [1]. Although the capillary-based heat pipes were first suggested by R. S. Gaugler of General Motors in 1942 and patented the idea [2], which was not developed further. Since its beginning in early 1960s, the heat pipe technology has evolved into many different shapes and forms and has been used in numerous applications from computer cooling to spacecraft thermal control. Heat pipes have been designed and built with cross sectional areas as small as 30 µm width × 80 µm depth and 19.75 mm in length (micro heat pipe) and as large as of about 20.1 m in length used in 1300 km trans-Alaska pipe line system. Grover's suggestion was taken up by NASA, which played a large role in heat pipe development in the 1960s, particularly regarding applications and reliability in space flight. This was understandable given the low weight, high heat flux, and zero power draw of heat pipes, and that they would not be adversely affected by operating in a zero gravity environment.

The first application of heat pipes in the space program was the thermal equilibration of satellite transponders. As satellites orbit, one side is exposed to the direct radiation of the sun while the opposite side is completely dark and exposed to the deep cold of outer space. This causes severe temperature gradients affecting thus the reliability and accuracy of the transponders. The heat pipe cooling system designed for the purpose managed the high heat fluxes and demonstrated flawless operation with or without the gravitational influence. The cooling system developed was the first use of variable conductance heat pipes (VCHP) to actively regulate heat flow or evaporator temperature.

Heat pipes are very attractive components in the area of spacecraft cooling and temperature stabilization due to their low weight penalty, zero maintenance, and reliability. Maintaining isothermal structures is an important task with respect to orbiting astronomy experiments under the adverse solar heating. During orbit, an observatory is fixed on a single point such as a star. Therefore, one side of the spacecraft will be subjected to intense solar radiation, while the other is exposed to deep space. Heat pipes have been used to transport the heat from the side irradiated by the sun to the cold side in order to equalize the temperature of the structure. Heat pipes are also being used to dissipate heat generated by electronic components in satellites [3]. Early experiments of heat pipes for aerospace applications were conducted in sounding rockets which provided six to eight minutes of zero-g conditions. In 1974, ten separate heat pipe experiments were flown in the International Heat Pipe Experiment [4]. Also heat pipe experiments were conducted aboard the Applications Technology Satellite-6, in which an ammonia heat pipe with a spiral artery wick was used as a thermal diode [5]. With the use of the space shuttle, flight testing of prototype heat pipe designs continued at a much larger scale. A 6-ft. mono groove heat pipe radiator with Freon 21 as the working fluid was flight tested on the eighth space shuttle flight [6]. The Space Station Heat Pipe Advanced Radiator Element consisting of a 50-ft. long high capacity mono groove heat pipe encased in a radiator panel, was flown on the space shuttle during 1989 and also, two heat pipe radiator panels were separately flight tested in a shuttle flight of 1991 [7] [8]. Heat pipe thermal buses were proposed to facilitate a connection between heat-generating components and external radiator [9]-[11]. The components may be designed with a clamping device which can be directly attached to the heat pipe thermal bus at various points in the spacecraft. In 1992, two different axially grooved oxygen heat pipes were tested in a Hitchhiker Canister experiment that was flown aboard the Shuttle Discovery (STS-53) by NASA and the Air Force to determine startup behavior and transport capabilities in micro gravity [12].

An advanced capillary structure which combined re-entrant and a large number of micro grooves for the heat pipe evaporator was investigated in microgravity conditions during the 2005 FOTON-M2 mission of the European space agency [13]. Swanson presented the NASA thermal technical challenges and opportunities for the new age of space exploration with emphasis on heat pipes and two phase thermal loops [14].

Presently, un-cooled mirrors are limited to only a few seconds of use prior to distortion from thermal overheating. Water-cooled mirrors have longer service times, but are subjected to high internal pressures causing distortion, which must be removed by polishing it under pressure. A heat pipe laser mirror was designed and fabricated in order to test the feasibility of this technology compared to water-cool or un-cooled mirrors for high power lasers [15]. A copper-water heat pipe mirror was constructed, which was not affected by the problems associated with conventional mirrors due to the heat pipe action. The conducted experiments used a 10 kW carbon dioxide laser, and it was found that heat pipes can be successfully used if the heat pipe is sufficiently preheated. Thermal diodes were proposed for use of cooling low-temperature sensors, such as an infrared detector in low sub-solar earth orbits [16]. This type of heat pipe was intended mainly due to its characteristics of being able to cool the instrument during normal operation, but effectively insulating it when exposed to an external heat flux. One type of thermal diode uses a liquid reservoir at the evaporator end of the heat pipe, which does not communicate with the wick structure. During normal operation, the reservoir is empty. If the condenser is subjected to an external heat flux, however, the working fluid condenses in the reservoir, causing the wick to dry out. This results in the heat pipe becoming an insulator, because heat can only be conducted axially through the thin pipe wall. Heat pipes have also been qualified and/or used for thermal control applications in avionic systems including aircrafts with more electric architectures. There was a proposal to replace the radioisotope thermoelectric generating systems by the radioisotope Stirling systems as a long-lasting electricity generation solution in space missions due to their higher efficiency [17]. In the current radioisotope Sterling systems if the Stirling engine stops, the heat removal from the system would be ceased and the insulation will be spoiled to prevent damage to the lad fuel, and the mission will be ended. The alkali-metal variable conductance heat pipes were proposed and tested to allow multiple stops and restarts of the Stirling engine [18]. In the proposed design, the evaporator of the heat pipe is connected to the heat generation module. During the normal operation, the heat is transferred from the heat generation unit to the heater head of the Stirling engine by evaporation and condensation of the sodium working fluid. When the Stirling engine stops, the temperature and pressure of the heat pipe working fluid increases. The higher pressure inside the heat pipe compresses the non-condensable gas and opens up a radiator through which the heat is dissipated and the system temperature stabilizes. Once the Stirling engine restarts, the temperature and pressure drop and the radiator is covered.

The fabrication and testing of leading edge shaped heat pipe were presented [19]. Reference [20] provided a feasibility study of metallic structural heat pipes as sharp leading edges for hypersonic vehicles and it was observed that the niobium alloy Ch-752 with lithium as the working fluid is an appropriate combination at Mach 6 - 8 flight with a 3 mm leading edge radius. Advanced thermal solutions provider Thermacore has announced that its heat pipe assembly has successfully completed testing at the NASA Ames Arc Jet Complex operating at very high heat flux conditions (q_{rad}) in a hypersonic leading edge simulation, making the first rigid embedded heat pipe module to operate successfully at those conditions [21]. The embedded heat pipe design as shown in **Figure 2** is a reusable alternative to traditional consumable ablative heat shield employed on hypersonic leading edge applications. This may help reducing the weight penalty of the thermal protection system for the launch vehicle.

The Constrained Vapor Bubble experiment [22] represents State-of-the-Art heat pipe research undertaken by NASA to cool International Space Station (ISS). It is the prototype for a wickless heat pipe and is the first full-scale fluids experiment as sketched in **Figure 3**, flown on the US module of the ISS. It uses a cuvette pipe, which is a rectangular-shaped glass tube made of quartz, filled with a fluid called pentane. This design allows for temperature measurements along the Constrained Vapor Bubble with great accuracy. The transparency also enables observation of the fluid flow to allow scientists to measure the size and shape of the menisci the shape of the fluid as it climbs the interior walls of the cuvette pipe. Constrained Vapor Bubble heat pipes were first tested on the ground condition and then launched into space and operated in the microgravity environment of the

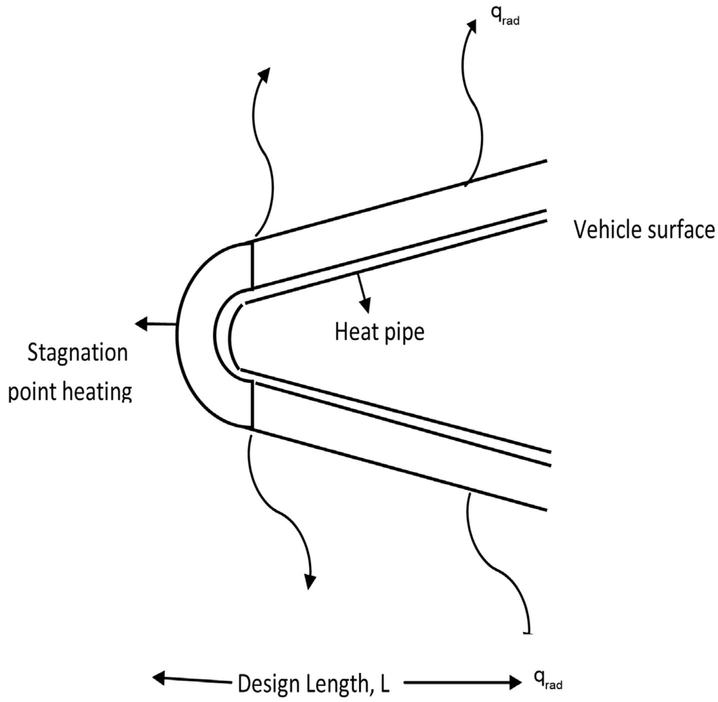

Figure 2. The local geometry and flow conditions near the leading edge.

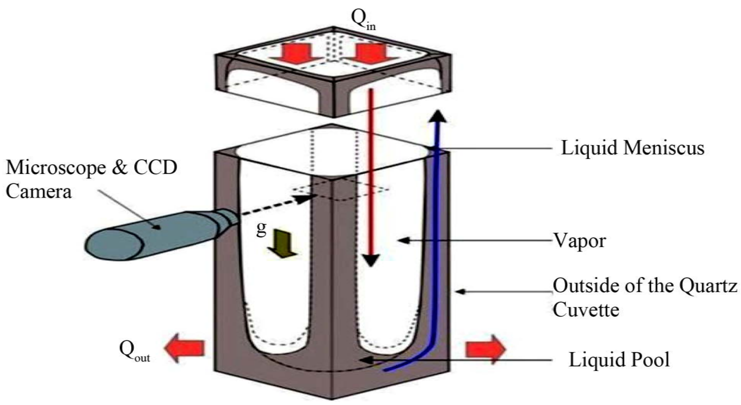

Figure 3. Constrained vapor bubble experiment for international space station.

space station. Heat pipes operate at a considerably higher temperature and pressure in microgravity than they do on Earth. The reason for this behavior is that there is no gravity-driven natural convection in microgravity, to help cool the heat pipe surface. The only way heat pipes can lose heat in space is to radiate that heat directly to the environment. It was found that the heat transfer coefficient in microgravity was higher comparable to the ground conditions.

The subject of heat pipe has attracted enormous interest among researchers and practitioners. New designs are invented for the cooling of space electronics and computers. Several millions of heat pipes of various configurations are being manufactured every month for cooling of laptop computers.

2. Heat Pipe Operation

When a heat pipe comes in contact with an external heat source at its evaporator, the heat is conducted into the liquid of the wicks in the evaporator. The liquid boils to vapor and moves to condenser via adiabatic region. The vapor condenses at the condenser and the condensate moves to the evaporator through the wicks under capillary pressure. The process is described thermodynamically by the **Figure 4** as below:

- Evaporator to adiabatic region 1 - 2: Heat applied to evaporator through external sources vaporizes working fluid to a saturated (2)or super heated (2) vapor-isothermal expansion,
- Adiabatic to condenser region 2 - 3: Vapor pressure drives vapor through adiabatic section to condenser-adiabatic expansion,
- Condenser to sink 3 - 4: Vapor condenses releasing heat to a heat sink-isothermal compression,
- Condesnser wick to evaporator wick 4 - 1: Capillary pressure created by minisci in the wick pumps condensed fluid into evaporator section-adiabatic compression,

The process repeats.

3. Types of Heat Pipes

The heat pipe must possess vapor liquid equilibrium with the saturated liquid and its vapor (gas phase). The saturated liquid vaporizes and travels to the condenser, where it is cooled and turned back to a saturated liquid. In a standard heat pipe, the condensed is returned to the evaporator using a wick structure exerting a Capillary action on the liquid phase of the working fluid. **Figure 5** presents various types of wick structures used in a heat

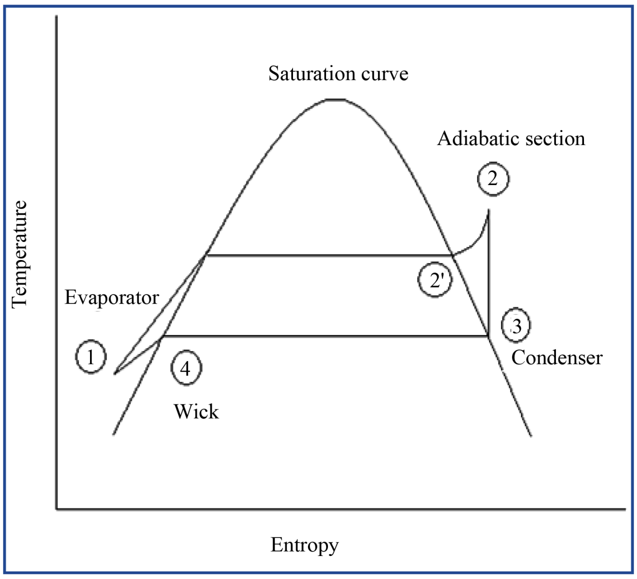

Figure 4. Thermodynamic operation of heat pipe.

Figure 5. Various wicks structures (clockwise-axial grooves, mesh screen, sintered metal powders, sintered metal powder grooves (fine grooves), sintered slabs, sintered metal powder grooves).

pipe that includes Sintered metal powder, screen, and grooved wicks, which have a series of grooves parallel to the pipe axis. The performance of the heat pipes also depends upon selecting a container, a wick, and welding materials 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 these constituents are not compatible. For example, the constituents 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 on reaching a particular temperature limit of the working fluid. The reference [23] provides the most up-to-date information presented in **Table 1** concerning the compatibility of metals with the working fluids. High quality arterial grooved heat pipes are preferred for the thermal stabilization of the satellites. There are various configurations of heat pipe available in the market for variety of applications [24] Most of the heat pipes are generally circular cylinders. Other shapes, such as rectangular (vapor chamber), conical (rotating heat pipes), triangular (micro heat pipes) and nose cap geometries (leading edge cooling) are also studied.

3.1. Variable Conductance Heat Pipe

Variable conductance heat pipe (VCHP) is a capillary driven heat pipe in which, a non-condensable gas (NCG) is added to the heat pipe, in addition to the working fluid When the VCHP is operating, the NCG is swept toward the condenser end of the heat pipe by the flow of the working fluid vapor condensing at the condenser. The NCG then blocks the working fluid from reaching a portion of the condenser. The VCHP works by varying the amount of condenser available to the working fluid. As the evaporator temperature increases, the vapor temperature (and pressure) rises, the NCG compresses, see the lower portion of **Figure 6** and condenser is more exposed to the working fluid. This increases the conductivity of the heat pipe and drives the temperature of the evaporator down. Conversely, if the evaporator cools, the vapor pressure drops and the NCG expand as seen in the upper portion of the **Figure 6** where condenser is partially active. This reduces the portion of the condenser available for condensation and thus decreases the heat pipe conductivity, and helps maintain the evaporator temperature. The first application of the VCHP to communication technology satellite was reported elsewhere [25].

Table 1. Materials compatibility relative to working fluid.

Working Fluid	Compatible Material	Incompatible Material
Water	Stainless Steel[a], Copper, Silica, Nickel, Titanium	Aluminum, Inconel
Ammonia	Aluminum, Stainless Steel, Iron, Nickel, Cold Rolled Steel	
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	
Mercury	Stainless Steel[b]	Molybdenum, Inconel, Nickel, Tantalum, Titanium, Niobium
Lead	Tungsten, Tantalum	Stainless Steel, Nickel, Inconel, Titanium, Niobium
Silver	Tungsten, Tantalum	Rhenium

[a]Sensitive to cleaning, [b]with Austenitic SS.

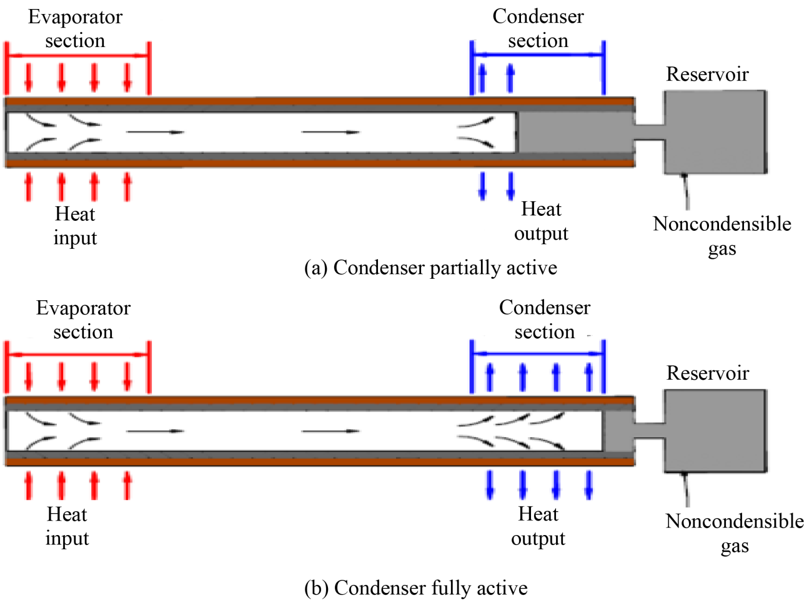

Figure 6. Variable conductance heat pipe.

There have been assumptions of flat front model [26], steady diffusive interface models [27]-[29]; and transient diffusive interface model [30] of the interface between vapor and the NCG. The diffusive interface model assumed transient one-dimensional mass diffusion across the vapor gas interface with constant properties. The temperature histories from the experimental result presented in **Figure 7** indicated the influence of the diffusion at the interface and the axial conduction in the pipe wall. Although the model was simplified by ignoring the compressibility in the vapor flow; it can well predict the transient operation of the VCHP. This was followed by a CFD model of the unsteady two-dimensional heat and mass transfer in the vapor gas region of a gas-loaded heat pipe to predict the behavior of the startup transient in the vapor gas region [31] [32]. The two-dimensional transient operation of VCHP was studied elsewhere [33]. The method was used to simulate the high temperature heat pipe with and without NCG.

3.2. Rotating Heat Pipe

A two phase heat transfer device designed to cool machinery by removing heat through a rotating shaft was reported [34], which was termed as a rotating heat pipe (RHP). As shown in **Figure 8** heat input to the evaporator vaporizes the working fluid. As in a normal heat pipe, the vapor travels down the heat pipe to the condenser, where heat is removed as the vapor condenses. While a normal heat pipe uses a wick to return the condensate, a rotating heat pipe uses centrifugal forces. A copper-water rotating heat pipe was tested with copper screen mesh wick at various heat loads [35]. An experimental test rig with a water-cooled condenser section was fabricated to study the heat transfer in the RHP for various heat loads and various rotational speeds ranging from 1000 rpm to 2000 rpm. The RHP may also act as a heat diode when it is shaped so that the liquid travels only by centrifugal forces from the nominal evaporator to nominal condenser. There is no availability of liquid when the condenser is heated.

3.3. Cryogenic Heat Pipe

The continuing growth of space-based Communications and sensors, along with the evolution of Aerospace and Avionics is driving demands for thermal control and heat removal in low temperature environments. The application of the cryogenic heat pipes in spacecrafts was reviewed elsewhere [36]. A Copper heat pipe with Acetone as a working fluid was tested on the Space Shuttle Discovery (STS-60) for the Stirling Orbital Refrigerator/Freezer Experimentation. The heat pipe was proved capable of removing up to 10 W of power between a temperature range of 213 K - 243 K. Reference [37] developed a mathematical model to predict the performance of cryogenic heat pipe under transverse vibration. The supercritical startup behavior of the cryogenic heat pipe was

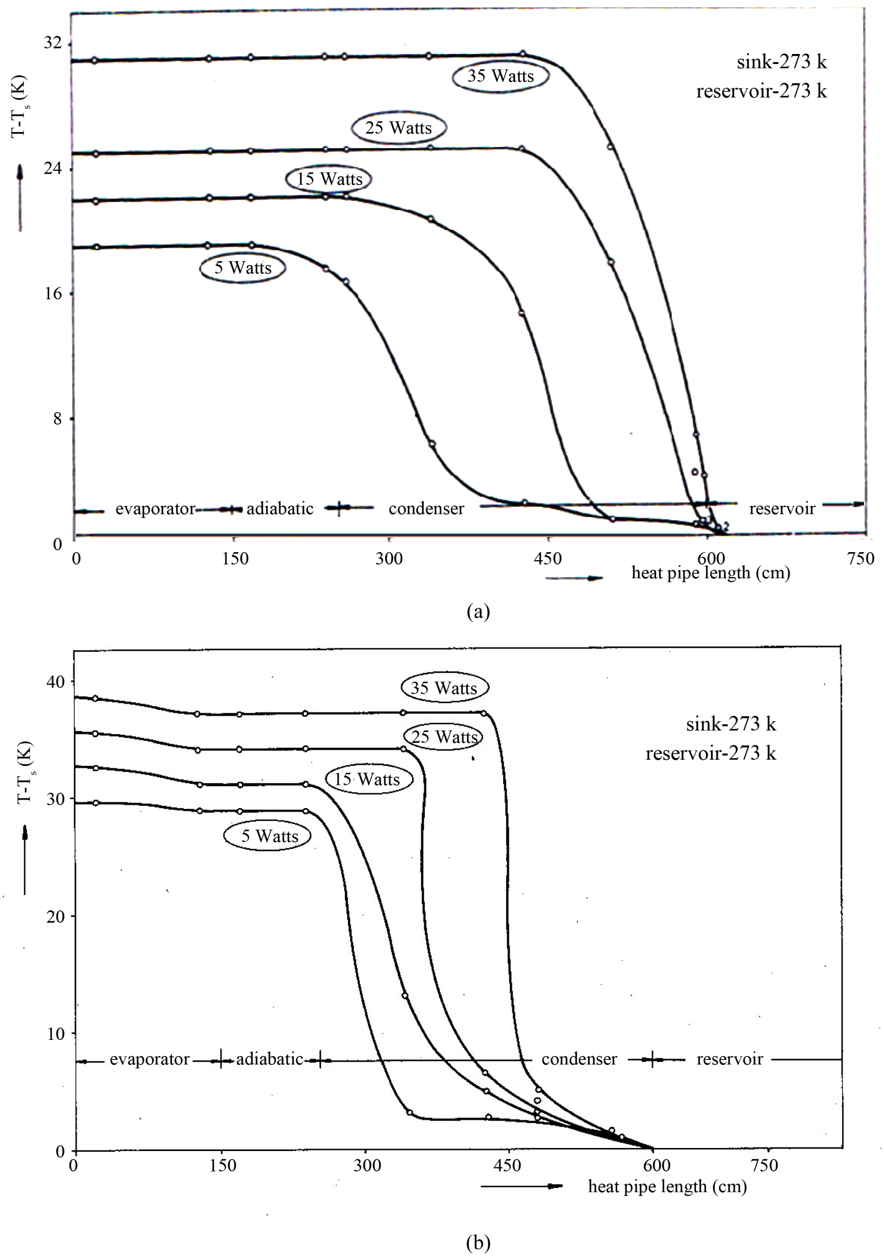

Figure 7. Wall Temperature along methanol VCHP with Control gas (a) NH3, (b) N2, [30].

studied elsewhere [38]. Reference [39] discussed thermal switching cryogenic heat pipe for thermal management of CCD cameras used for the NASA-space interferometry mission.

3.4. Vapor Chamber

The vapor chamber is a capillary driven planar (flat-plate heat pipe) design with a small aspect ratio. It is made by stamping cold forging or machining processes so that its shape is fixed. The main advantage of the vapor chamber is that it can be placed beneath the heat generating avionics components directly without adding additional thermal resistances. There are two main applications for vapor chambers [40]-[42]. First, they are used when high powers and heat fluxes are applied to a relatively small evaporator. Heat input to the evaporator vaporizes liquid, which flows in two dimensions to the condenser surfaces. After the vapor condenses on the condenser surfaces, capillary forces in the wick return the condensate to the evaporator. Note that most vapor chambers

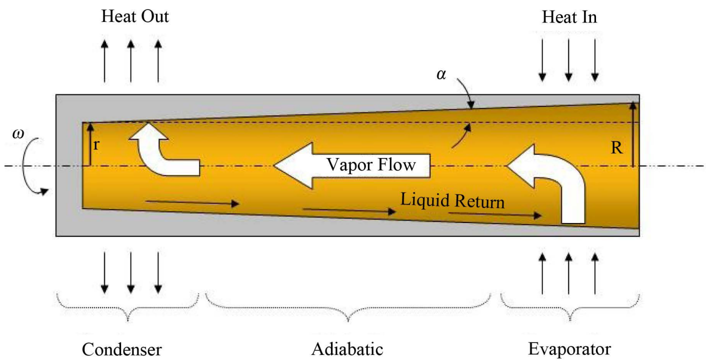

Figure 8. Flow mechanism in a rotating heat pipe.

are insensitive to gravity, and will still operate when inverted, with the evaporator above the condenser. In this application, the vapor chamber acts as a heat flux transformer, cooling a high heat flux from an electronic chip or laser diode, and transforming it to a lower heat flux that can be removed by natural or forced convection.

Second, compared to a one-dimensional tubular heat pipe, the width of a two-dimensional heat pipe allows an adequate cross section for heat flow even with a very thin device. These thin planar heat pipes are finding their way into flight sensitive applications, such as avionics packages, computers and surface mount circuit board cores. These vapor chambers are typically fabricated from aluminum extrusions, and use acetone as the working fluid. Its performance can be improved by adding more grooves for the flow of the liquid.

3.5. Loop Heat Pipe

A loop heat pipe (LHP) is a two-phase heat transfer device that uses capillary action to remove heat from a source and passively move it to a condenser or radiator [43]. LHPs are similar to heat pipes but have the advantage of being able to provide reliable operation over long distance and the ability to operate against gravity. They can transport a large heat load over a long distance with a small temperature difference. The main components of LHP are an evaporator, a condenser, a vapor line, a liquid line and a hydro-accumulator. The wick is required only in the evaporator and hydro-accumulator. The rest of the loop is made of smooth walled tubing. The hydro-accumulator is usually called as a compensation chamber. The principle of LHP is that liquid in the evaporator evaporates due to applied heat load and a meniscus is formed in the liquid-vapor interface in the wick. A pressure gradient is developed by the surface tension force that moves the vapor towards the condenser where it condenses. The liquid is pushed back to the evaporator by the same surface tension force. The compensation chamber is an integral part of the evaporator and is connected to the evaporator by a secondary wick. With a slight variation in the placing of the compensation chamber wherein it is located remotely from the evaporator, a different version of the LHP is coined as capillary pumped loop (CPL). In CPL, the compensation chamber is known as reservoir and is outside the path of the fluid circulation. Reference [44] presented the operating characteristic of the loop heat pipe. The heat transfer mechanism was investigated in the evaporator of the loop heat pipe [45] [46]. Reference [47] studied the thermo fluid dynamics of loop heat pipe operation. Different designs of LHPs ranging from powerful, large size LHPs to miniature LHPs (micro loop heat pipe) have been developed and successfully employed in a wide sphere of applications both ground based as well as space applications [48] [49]. LHP^s operating with ammonia as working fluid are currently the most popular thermal control device for high powered telecommunication satellites. The first space application of LHP occurred aboard a Russian spacecraft in 1989. LHPs are now commonly used in space aboard satellites including; Russian Granat, Obzor spacecraft, Boeing's (Hughes) HS 702 communication satellites, Chinese FY-1 Meteorological satellite, NASA space shuttle in 1997 with STS-83 and STS-94. Existing LHPs and CPLs have only one evaporator and one condenser/radiator. Recently LHP was tested with multiple evaporators and condensers also [50]. Hence, an important advancement would be the development and rigorous testing of LHPs with multiple evaporators and condensers, for satellite applications.

3.6. Micro Heat Pipe

The concept of micro heat pipe for cooling of electronic devices was proposed elsewhere [51]. The micro heat pipe was defined as a heat pipe in which the mean curvature of the liquid vapor interface is comparable in magnitude to the reciprocal of the hydraulic radius of the total flow channel. Typically, micro heat pipes, **Figure 9** have convex but cusped cross sections (for example, a polygon), with hydraulic diameter in range of 10 to 500 µm. Miniature heat pipe is defined as a heat pipe with a hydraulic diameter in the range of 0.5 to 5 mm. An overview was presented elsewhere for the development of the micro heat pipe [52]. The fabrication and experimental data on the performance characteristics of the flat water-copper heat pipe with external dimensions 2 × 7 × 120 mm have been reported with radial heat fluxes of 90 W/cm^2 and 150 W/cm^2 for horizontal and vertical applications, respectively [53]. Reference [54] studied the heat transfer limitation of the micro heat pipe and found that the maximum heat-transport capacity of a micro heat pipe depends upon the capillary and fluid continuum limit. It was found that the methanol is a better suited working fluid for the micro heat pipe with triangular cross section. The capillary limit calculated in [54] was almost double the value obtained elsewhere [55]. There is an enormous interest in the satellite building programs by the universities. Several micro and nano satellites are built and launched for experimental purposes. The thermal management of these satellites is looked upon the micro heat pipes or micro loop heat pipes.

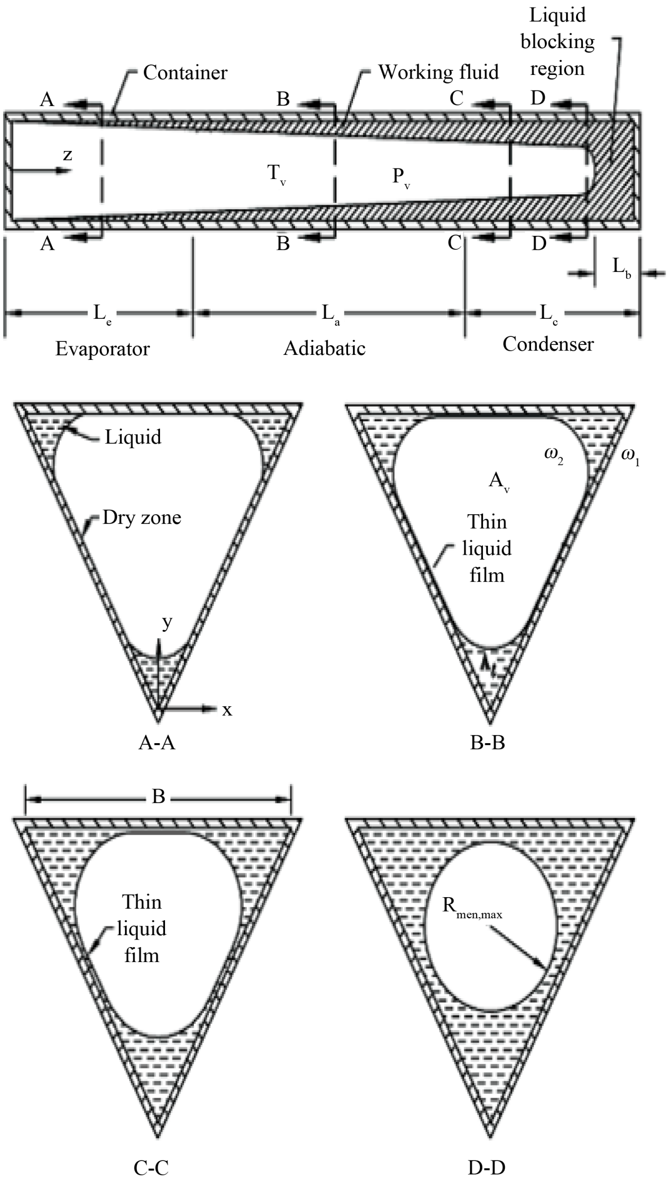

Figure 9. Schematic of Micro heat pipe.

3.7. Nano Fluids for Heat Pipe Applications

Heat pipe working fluids range from Helium and Nitrogen, for a cryogenic temperature (2 - 4 K), to liquid metals like Mercury (523 - 923 K), Sodium (873 - 1473 K) and even Indium (2000 - 3000 K) for extremely high temperatures Working fluid in a heat pipe is chosen according to the temperatures at which the heat pipe must operate, The vast majority of heat pipes for space craft and electronics cooling use Ammonia (213 - 373 K), Alcoholal (Methanol (283 - 403 K) or Ethanol (273 - 403 K)) or Water (298 - 573 K) as the working fluid. Copper/water heat pipes have a copper envelope, use water as the working fluid and typically operate in the temperature range of 293 to 423 K These working fluids have some limitations in the heat transfer rates of the heat pipe.

The recent development of nanofluids, or fluids consisting of a conventional heat transfer base with nanometer-sized oxide or metallic particles suspended within, offers the exciting possibility of increased heat transfer rates over conventional systems by more than 20%. References [56] [57] found 30% increase of the thermal conductivity by dispersing 0.1% copper particles in water. They demonstrated significant improvement of heat transfer rates by dispersing copper, alumina-and silver colloid suspensions in water. A similar enhancement of thermal conductivity was observed with copper oxide dispersed in water and ethylene glycol [58]. In addition to the heat transfer rates, the magnetic affinity of the solid particles in metallic suspensions allows for their manipulation by electromagnets, thereby eliminating the need for conventional pumps and controls and allows for enhanced heat transfer. This has created interest in the application of a novel nanofluid-based actively controlled thermal management system for small satellite applications; see [59]. The advantages of such a system include improved heat transfer performance, oil-less operation, compact size, reduced weight, and low power consumption, all of which are especially important for space, air, and even naval operations. NASA has set a road map for the development of high temperature heat pipes which will be a solution for the high heat flux encountered during ascent and reentry of the space vehicle [60]. The fluid with ultra fine suspended nano particles will be the advanced fluid for satellite applications of the heat pipe.

4. Concluding Remarks

An overview of the aerospace applications of heat pipes is presented in this article. Conventional thermal management solutions for spacecraft are being severely challenged by adverse environmental radiation. Heat pipes are well developed technology. A variety of heat pipes for cryogenic and high temperature applications have already been flown in space. Loop heat pipes and capillary pumped loops with multiple evaporators and condensers are the effective thermal management solutions for high powered communication satellites. The micro and micro loop heat pipes will play an important role in the thermal solution of small satellites. Heat pipes have emerged as an elegant and cost effective response to these challenges. The heat pipe used as a thermal protection system will be far superior to high temperature materials with the benefit of being light weight and a passive design. The wick comprises nanostructures having a differentially-spaced apart gradient along the length of the wick promotes capillary fluid flow and nanofluids as working fluids improve the heat transfer rates of the heat pipe.

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