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ADVANCEMENTS IN HEAT PIPE SCIENCE AND TECHNOLOGY

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Abstract— **During the past fifty years, numerous studies had been carried out on heat pipes and the development of predictive tools for the heat pipes design remain challenging even today. This had thus made heat pipe, still the object of more than 250 scientific articles each year. Our aim is to understand the different practices and scientific approaches followed by scientists in the field of heat pipe science. Further in this paper, we had analysed how heat pipes had evolved over the years. The different types of heat pipes are analysed to identify the phenomena involved in this particular system. Advancements are categorized based on the characterization, based on the working fluid used, heat transfer in thin liquid films and system modelling. This review is aimed at high lighting the advances in heat pipe science and to draw perspectives on emerging scientific results [1].**

Keywords— **Heat pipe; Thermal physics; Heat transfer engineering; Working fluid; Fluid transfer**

I. INTRODUCTION

The heat pipe is a remarkable achievement of thermal physics and heat transfer engineering in this century because of its unique ability to transfer heat over long distances without considerable losses. It also portraits exceptional flexibility, has a simple construction and have easy control with no external pumping required [2]. It is estimated that in some cases, a heat pipe is 1000 times better than a solid copper conductor and so are they used in many industrial applications. The authors strive to understand the key features which will lead to the strategies which will help us better understand the different types of heat pipes.

Riffat and Ma (2007) proposed a review of heat pipe developments, technologies and applications between the years 2000 and 2005 and noted the different advances during this particular time frame. It was evident that new wick structures for conventional and flat heat pipes were proposed and working fluids with much more efficiency were incorporated. Moreover, a new type of loop heat pipes (LHP and CPL) were developed for mass consumption in the Industrial sector. It was also noted that, more studies were carried out on flexible heat pipes as well as micro heat pipes. Traditional topics like high temperature heat pipes and applications in space were also on the rise. Interesting studies on phase change material coupled with heat pipes for air-conditioning systems were also studied. Last but not the least, development of new models and mathematical methods for designing new heat pipes were also reported.

A decade later, the research field on heat pipes have change substantially. It appears that nowadays, more of experimental work are done compared to simulation, numerical analysis and modelling, which leaves analytical approach on the verge of extinction. More number of papers are titled on their performance like: air conditioning, solar collector, cryogenic applications, automobile, thermo- electric generators and energy storage. Another sector gaining popularity is on the importance of using working fluids and how it affects the efficiency of the pipe. Working fluids such as water, ethanol and various other mixtures are on the rise. The material of the heat pipe is one other topic that catch a lot of eye. Various papers on metal, copper, silicon, aluminium, glass, ceramic, copper oxide (CuO) were also seen. It was analysed that our progress in manufacturing sector had promoted to the development of micro heat pipes and light weighted heat pipes [3]. The least favoured topics were on effect of gravity forces, magnetic and electric field. Some studies were also carried out on the inclination angle of heat pipes. It was understood that, heat pipes were of interest to the communities of solar and renewable energy applications, industrial applications and electronic cooling applications.

The goal of this particular review is to give an overview of the various current approaches used by the research community on heat pipes and thus identify the main phenomena involved in these systems respectively. A brief history is presented and the recent advancements made in terms of working fluid, phase change material, heat transfer in thin films and heat pipe modelling are included.

II. HISTORY

The Heat pipes were first patented as a light weight heat transferring device by Gaugler (1944) [1]. Though many attempts were made to improve this technology and since back then the technology did not demand for a sophisticated two-phase passive heat transferring device, much of an attention was not paid on it. But later in 1964, when George Grove [3] and his team used this concept in their space program and its applications at the Los Alamos National Laboratory, only then did it start getting considered. He is also credited with coining the term "Heat Pipe" for this heat transmitting device and subsequently developing its many applications as we know now.

Many of its applications include enhancing the thermal performance of heat exchangers in microelectronics; energy saving in classical heating, ventilating, and air conditioning (HVAC) systems for operating rooms, surgery centers, hotels, clean rooms, etc.; temperature regulation systems for the human body; and other industrial sectors including spacecraft and various types of nuclear reactor technologies as a fully inherent cooling apparatus [6].

The research on applications of Heat pipes at Los Alamos were based on thermionic energy conversion systems in space, which were operating at an excess temperature of 1500 K. In this experiment, heat pipes were specifically used for heating thermionic emitters, for cooling thermionic collectors, and for radiation of heat to space fluids.

George Grover (1964) realized that: "The "pumping" action of surface tension forces may be sufficient to move liquids from a cold temperature zone to a high-temperature zone (with subsequent return in vapor form using as the driving force the difference in vapor pressure at the two temperatures) to be of interest in transferring heat from the hot to the cold zone. Such a closed system, requiring no external pumps, may be of particular interest in space reactors in moving heat from the reactor core to a radiating system. In the absence of gravity, the forces must only be such as to overcome the capillary and the drag of the returning vapor through its channels."

The Heat pipe made by Grover was a sodium heat pipe, 90 cm long with a 1.9 cm outer diameter (OD), operated at 1100 K with 1 kW heat input and was used in the experimentation with Water and Sodium as working fluids and the results of which were published in *The Journal of Applied Physics*.

This was the advent of a new technology that in the subsequent years gained more applications in many disciplines of science because of its unique properties and characteristics.

III. OVERVIEW OF HEAT PIPE TECHNOLOGIES

According to Ray et al. (2013), heat pipe can be considered as a system which transfers high heat flows from a heat source to a heat sink with a low thermal resistance using liquid vapour phase change [1].

A fluid at its saturated point is filled inside a cavity in the heat pipe. When the liquid comes into contact with a heat source it evaporates and condenses into the heat sink. The quality and the type of heat pipe decides the method by which vapor and the liquid flow to the condenser and evaporator.

There are many differences between conventional loop heat pipes and oscillating. The plethora of heat pipes in the family of conventional include thermo syphons, cylindrical heat pipes, flat plate heat pipes and rotating heat pipe. The liquid flows from the condenser to evaporator either due to gravity, centrifugal forces or a combination of all these forces. In LHP and CPL, the liquid and vapour flow in separate lines. CPL is different from LHP in the place of the reservoir. The oscillating heat pipes or pulsating heat pipes are built of a single meandering tube placed between heat source and heat sink, the diameter of which resembles the fluid capillary length leading to the dissipating of the fluid within the tube into the liquid plugs and vapourous plugs. The extensive vapourisation and condensation of the liquid generates self-sustained oscillations in the liquid, which leads to an efficient heat transfer from the source to the sink [14]. These systems are cost effective and can be easily manufactured but their behavior and efficiency is difficult to predict, hence, rarely used in the industry.

There are some of the common features shared by all heat systems. Liquid vapour phase change heat transfer is present in all heat pipes. The capillary force plays a big role in all the systems.

The similarity of the phenomena involved in the function of heat pipes leads to the easy understanding of one kind of heat pipe which leads to understanding of one kind of heat pipe which leads to understanding of the other kinds also.

IV. TYPES OF HEAT PIPES

The different sections of a heat pipe include evaporator and condenser and the working fluid evaporates and condenses. An adiabatic section, present in many heat pipes separates the evaporator and condenser section by a definite distance, thus satisfying the design constraints of the application. In some cases, they may even house multiple evaporators, condensers and adiabatic sections. The liquid from the condenser to the evaporator can be returned through gravitational, electrostatic and osmotic forces.

Based on the specific application of a heat pipe, different configuration of heat pipes are made. Cylindrical heat pipes are made for their simplicity of design and ease of manufacturing. Other shapes include, rectangular, conical, nose-cap and corrugated flexible heat pipes. Some of the unique designs are discussed below:

A. Capillary-Driven heat pipe

The wick of the Capillary driven heat pipe is placed on the inner radius of the pipe wall of a sealed container. The wick's purpose is to provide a capillary driven pump, so that it can return the condensate to the evaporator section. The capillary limit is the most commonly encountered limitation and is occurred when enough liquid is not returned to the evaporator section, where it is to be kept saturated [4]. A sudden and continuous increase in temperature is experienced in the evaporator wall at this point. These type of heat pipes are commonly used in laptops and various commercial and aerospace application nowadays.

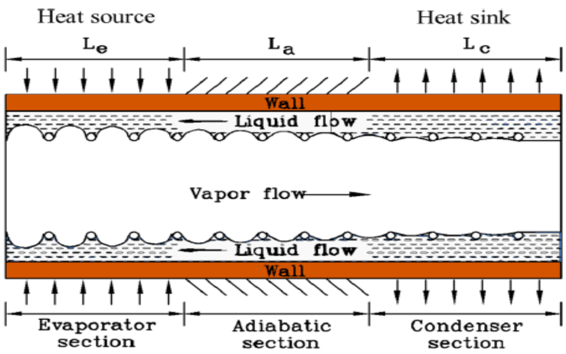


Fig. 1. Schematic representation of Capillary-Driven heat pipe

B. Annular Heat Pipe

The annular and conventional heat pipes are strikingly similar to each other. The only difference is that, the vapor space of the annular heat pipe is annular in cross-section whereas the conventional type sport a circular cross-section. Thus, the wick is placed, both on the inside outside of the outer and inner pipe respectively. Thus, the outer diameter of the pipe can be increased, without increasing the surface area for heat input and output. They are widely used in isothermal furnaces because of their temperature flattening capabilities and fast response time to cold charge.

C. Loop Heat Pipes (Capillary Pumped Loop)

They are completely passive (minimal moving parts), two-phase heat transferring devices that are flexible, routable and are bendable. They can be operated as Thermal diodes to prevent backward heat leak and can be used in cooling the dispersed control system found in modern military aircrafts.

D. Pulsating Heat Pipes (Oscillating)

Comprises of a tube of capillary diameter, which is evacuated and is partially filled with a working fluid. Primarily it consists of a serpentine channel of capillary dimensions, which is evacuated and is filled with a working fluid partially. Surface tension causes the formation of slugs of liquid interspersed with bubbles of vapor. When one end of the evacuated tube is heated, working fluid is evaporated and increase the vapor pressure, thereby causing the bubbles in the evaporator zone to grow and this pushes the liquid towards the low condenser (low temperature). When the condenser is cooled, this results in the reduction of vapor pressure and condensation of bubbles in that section of the heat pipe [5]. The oscillation motion is the end effect of the rise and collapse of bubbles in the evaporator and condenser section respectively.

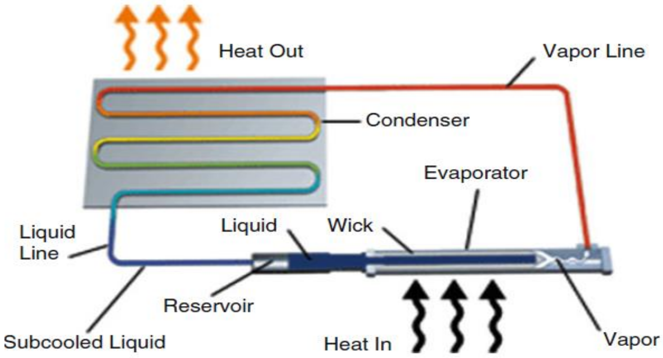


Fig. 2. Schematic of loop heat pipe

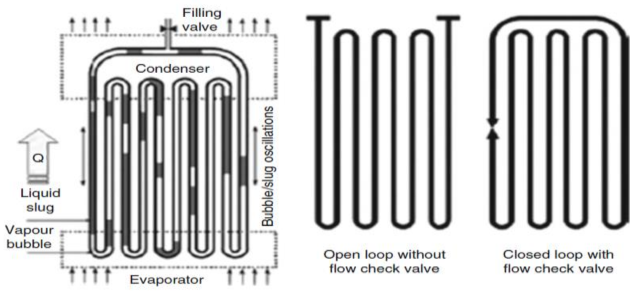


Fig. 3. Schematic representation of pulsating heat pipe

E. Micro Heat Pipes (MHPs)

The MHP is a device with a hydraulic diameter of 100 µ and a length of several centimeters. It's much smaller than a conventional heat pipe. It does not contain a wick structure to assist in the return of the condensate to the evaporator section, but uses the capillary force generated in the sharp edges of the pipe's cross section.

The conventional methods of cooling are not ideal enough to overcome the heat problems generated in a system, so a small scale and high-performance cooling device is needed [15]. At present, micro heat pipes are fabricated using micromachining technology (MEMS) and is tested to verify the operation of micro heat pipe as a thermal heat spreader.

Fig. 4. Schematic of micro-heat pipe

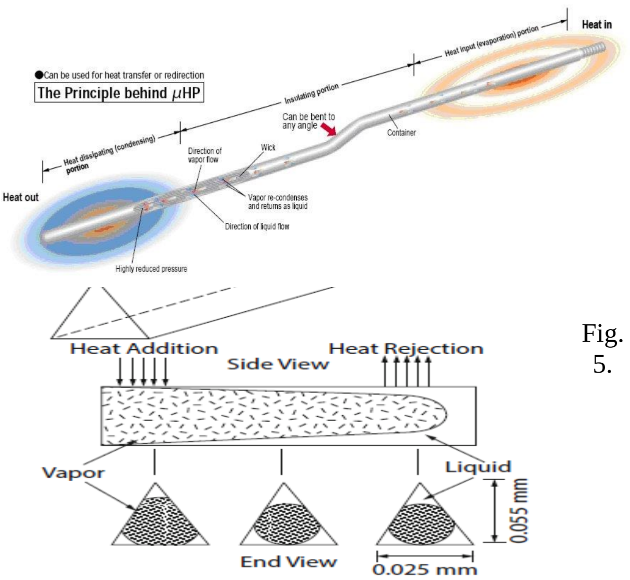


Fig. 5. Micro-heat pipe

The Micro Heat Pipe is a closed cylindrical pipe that contains a liquid. The heat gained would be carried to the other end of the pipe with cooler temperature. At this end, the liquid in steam form would be condensed and all the heat released is carried. This fluid is then taken to the hot end and whole process is repeated. This is very useful in small machineries like laptop and cameras. It's very dependable and has a very long lifetime.

F. Variable Conductance Heat Pipes (VCHP)

Variable conductance can be achieved by modulating several individual conductance's that make the overall conductance. They are grouped into the following categories:

(a) Gas-loaded Heat Pipe

A fixed amount of non-condensable gas is introduced into the heat pipe, which forms a "plug" during operation and blocks the vapor flow. During the event of a "fill-on" operation, a reservoir is added to accommodate the gas. When vapor flows from evaporator to condenser, the non-condensing gas gets swept to the accumulator in the cold end of the heat pipe. This gas then forms a barrier to the vapor flow thereby effectively "shuts off" the condenser. The conductance of the condenser depends on factors such as the system's operating temperature, heat source and sink conditions, reservoir size and temperature etc.

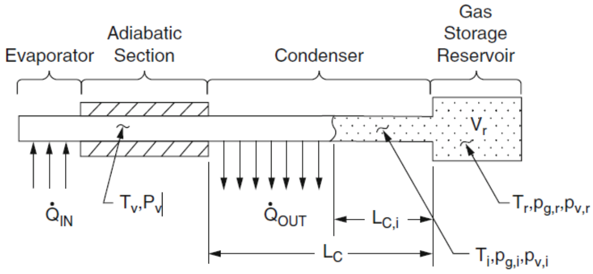
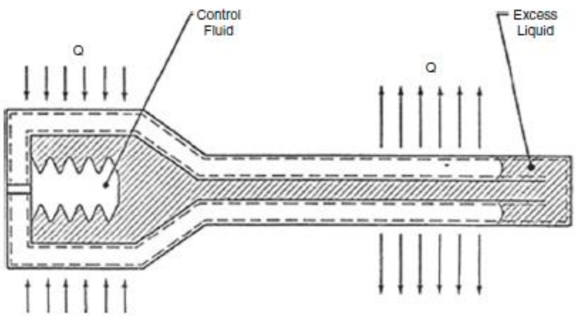


Fig. 6. Gas-loaded variable conductance heat pipe

(b) Excess-Liquid Heat Pipe

This technique uses a reservoir inside the heat pipe envelop and it's less sensitive to variations in sink conditions. The total volume of the reservoir is varied by the aid of a bellow which contains an auxiliary fluid which is in equilibrium with its vapor. This adjustment of the bellows



allows system temperature to be altered therein allowing the excess liquid to move into or out of the condenser. When the condenser temperature rises above the evaporator, the direction of vapor flow is reversed. The excess liquid from the reservoir is then drained into the normal evaporator section thereby blocking the vapor flow and the section for heat rejection. Thus, the source of heat is blocked from the hot condenser end and thus the heat piping action is only effective in forward mode.

Fig. 7. Variable conductance heat pipe

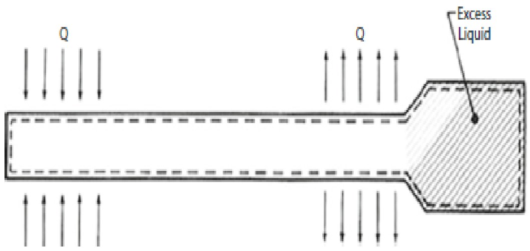


Fig. 8. Variable thermal diode heat pipe

(c) Liquid flow control

It involves either interrupting or impeding the condensate return in the wick in order to "dry out" the evaporator. It achieves control over the evaporator conductance by affecting the circulation of the working fluid and thereby creating a hydrodynamic failure in the evaporator section.

Fig. 9 is a liquid trap diode heat pipe for aerospace application. A wicked reservoir is placed at the evaporator end and it does not communicate with the primary wick, so when the temperature gradient is reversed, liquid is evaporated at the hot side of the pipe and is then condensed and trapped within the reservoir. Therefore, the wick is partially saturated and the condensate cannot to the heat input section and so the heat piping action is "shut off".

Fig. 10 is a gravity-operated diode heat pipe. Here, when the temperature gradient is reversed, it causes the liquid to collect at the bottom of the pipe and so it cannot be pumped back against the gravitational force.

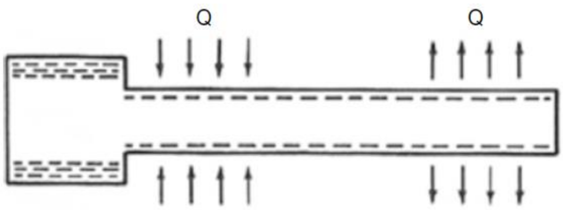


Fig. 9. Liquid trap diode heat pipe

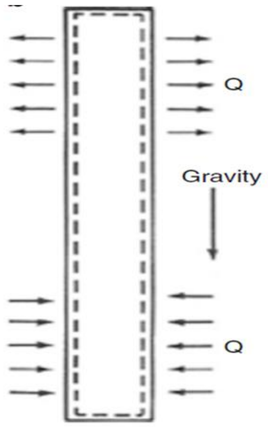


Fig. 10. Gravity operated diode heat pipe

(d) Vapor Flow Control

It involves throttling the vapor as it moves from the evaporator to the condenser. This in turn creates a pressure drop and thus the temperature drops.

Fig. 11 is a sketch of vapor-modulated variable conductance heat pipe. To affect the throttling action, bellows and auxiliary fluids are used. A rise in heat load or source temperature will lead to a rise in vapor temperature which will cause the control fluid to expand and partially close the throttling valve thereby causing a pressure difference [9]. It must be noted that, the pressure difference should not exceed the capillary pressure developed by wick.

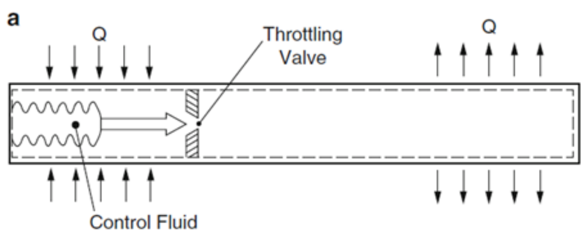


Fig. 11. Vapor modulated thermal conductance

G. Rotating and Revolving Heat Pipes

The condensate is returned to the evaporator through centrifugal force and capillary wick is also not required in rotating or revolving heat pipe. They are used to cool components of turbine and electric motors. Fig. 12 shows a rotating heat pipe as the shaft of electric motor. Fig. 13 is an illustration of revolving heat pipe that rotates around an axis located at some distance and is parallel to the center axis of the pipe and is used to equalize the temperature in a rotating print head drum. The speed of revolution is the most important parameter affecting the heat pipe transfer performance very similar to rotating heat pipes.

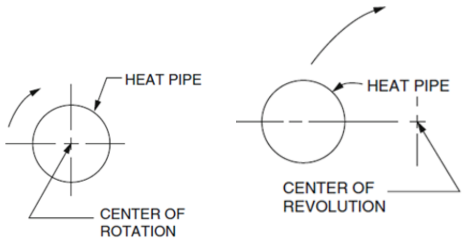


Fig. 12. Rotating and revolving heat pipes

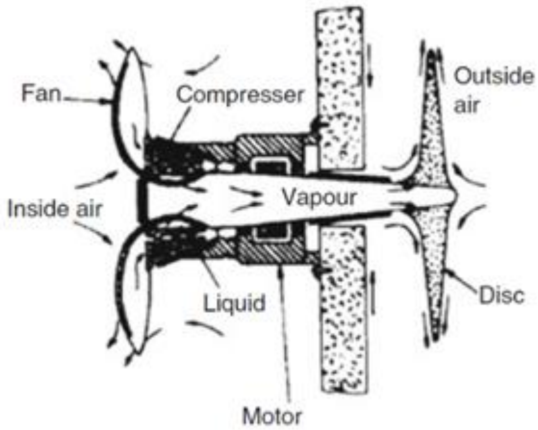


Fig. 13. A compact air-conditioning unit based on the wickless rotating heat pipe

H. High-Temperature Heat Pipes

These heat pipes are widely used in service conditions like ocean floor to geosynchronous orbit. They have improved processes like glass making, industrial applications like oil-shale extraction, and high-tech applications such as epitaxial deposition.

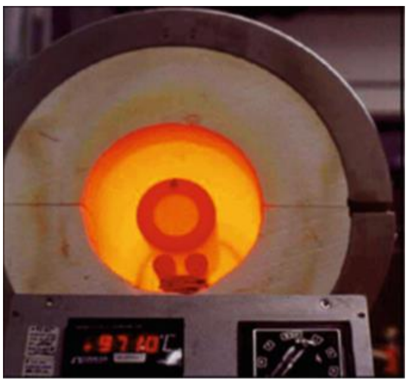


Fig. 14. High-temperature heat pipe at 971°C

I. Cryogenic Heat Pipes

These heat pipes were used for cooling detectors in satellite infrared scanning systems. The working fluid in these heat pipes was nitrogen and had a temperature range between 77 and 100 K. Liquid oxygen was also used for attaining this temperature range.

Experimental studies carried out by European Space Agency reveal comprehensive data on stainless steel heat pipes, where the working fluid were methane, ethane, nitrogen or oxygen. These heat pipes were 1 m in length and had an outer diameter of either 3.2 or 6.35 mm [11]. The heat transfer capability was up to 5 W m, and vapor temperatures 70-270 K.

These heat pipes are to be tested in vacuum chamber, which prevents convective heat exchange and a cold wall may be used to maintain the required environmental temperature. Radiation can be prevented by super insulating the heat pipe, fluid lines and the cold wall. The most preferred capillary structures for cryogenic heat pipes are copper wool, ceramics made of sintered metal particles and a spiral thread combined with a channel.

V. APPLICATIONS OF HEAT PIPE

A. Electronic Components

Cooling of electronic components like semi-conductor devices, ICPs, and transistors play a big role in the application of heat pipes in the industry. Heat pipes are widely used in electronic components as the device itself and to mount a component onto a plate where heat pipes are inserted.

B. Spacecraft

Heat pipes are used in spacecrafts at vapour temperature up to 200° C and more widely along with other areas too. There are articles sighting the use of heat pipes for space craft temperature equalization, temperature control and radiator design, component cooling and space nuclear power sources [12].

C. Energy Conservation

Due to its supremacy in heat transfer, heat pipes are important counter parts for applications involving conservation devices. Since energy conservation is the need of the hour, heat pipes have proven advantages in this technology.

D. Preservation of permafrost

McDonnell Douglas corporation placed one of the largest contracts for Alaska pipe line service company [6]. This was based on the inherent quality of heat pipes to prevent thawing of permafrost and the heat from the ground being transmitted upward to a radiator located above the ground level [13].

E. Thermometer Calibration

Heat pipe inserts are developed by IKE, Stuttgart. The heat pipes are being operated inside a conventional tubular furnace, providing isothermal conditions, which is an ultimate necessity for temperature-sensor calibration [6]. Fixed point cell heating, crystal growing and annealing are some of the temperature sensitive processes making use of isothermal working spaces produced by heat pipes.

F. Heat pipe furnace

IKE also developed a high temperature heat pipe furnace for material processing in a microgravity environment in temperature ranges of 900e1500° C. Heat pipes are being successfully used as part of a fully inherent system for heat transfer comprising of its safety factors.
Today many companies such as thermacore with their high temperature heat pipe technology are making use of it from ocean floor to lunar surfaces [8]. Wide range of high-tech electronics are also making use of this technology. In short, the technologies of heat pipes are being applied from womb to tomb.

G. Heat Exchangers

One of the most efficient ways adopted by device for heat recovery is by the method of employing a Heat exchanger made of heat pipe. Heat pipes are most commonly used than conventional methods because large quantities of heat can be transported over considerable distance through a small cross-sectional area with no additional power input to the system. Some of the other benefits of using heat pipes are: simplicity of design and manufacturing, very minimal temperature drops between the ends, extremely wide temperature application range (4-3000 K) and the unique ability to control and transport high heat rates at various temperature levels [7]. By employing heat pipe heat exchangers, we can drastically reduce our primary energy consumption, thereby help reduce the production of carbon dioxide.

Heat pipe heat exchangers were produced commercially during the mid-1970s and since then have found numerous applications in many industries. These applications can be further divided into three main categories respectively:

(a) Heat recovery in air conditioning devices.

(b) Heat recovery from the process exhaust stream to reuse in the process.

(c) Heat recovery from the process exhaust system to preheat air for space heating.

VI. CONCLUSION

There are many research studies both experimental and theoretical underway so as to make us aware of the various types of heat systems. The new systems of visualisation and instrumentation has made significant advances in the knowledge and functioning ability of different heat systems and also enable increased performance of heat pipes and boost in the technology even in the industrial scale.

Some of the proposed research works envisage new geometries and types of capillary structure which paved the way to new challenge i.e., miniaturisation of the systems, the more impressive outcome related to PHPs [10]. Reliable predictive tools to predict the chaotic behaviour of the system is another challenging task, which is expected to be fulfilled in another few years. Another challenge could probably be to couple these microscale models to the system scale models, because the physical topological and chemical properties of the materials are poorly known. Hence the heat pipe research community and material science research community have to work hand in hand in order to answer these issues. We can hope that progress in other fields can also bring new waves to the understanding of the tools in the systems. Anyway, one can conclude that the study of heat pipes will remain a challenging and exciting topic at least for the next couple of decades.

VII. AKNOWLEDGEMENT

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VIII. REFERENCE

[1] Lips, S., Sartre, V., Lefevre, F., Khandekar, S., & Bonjour, J. (2016). OVERVIEW OF HEAT PIPE STUDIES DURING THE PERIOD 2010-2015. Interfacial

Phenomena and Heat Transfer, 4(1), pp. 33–53. https://doi.org/10.1615/interfacphenomheattransfer.2016016345

[2] Mathioulakis, E., & Belessiotis, V. (2002). A new heat-pipe type solar domestic hot water system. Solar Energy, 72(1), pp. 13–20. https://doi.org/10.1016/s0038-092x(01)00088-3

[3] Arab, M., & Abbas, A. (2014). A model-based approach for analysis of working fluids in heat pipes. Applied Thermal Engineering, 73(1), pp. 751–763. https://doi.org/10.1016/j.applthermaleng.2014.08.001

[4] Vasiliev, L. L. (2005). Heat pipes in modern heat exchangers. Applied Thermal Engineering, 25(1), pp. 1–19. https://doi.org/10.1016/j.applthermaleng.2003.12.004

[5] Zhang, Y., & Faghri, A. (2008). Advances and Unsolved Issues in Pulsating Heat Pipes. Heat Transfer Engineering, 29(1), pp. 20–44. https://doi.org/10.1080/01457630701677114

[6] Zohuri, B. (2020). Functionality, Advancements and Industrial Applications of Heat Pipes (1st ed.). Academic Press, pp. 100–139.

[7] Sharma, A., Jain, S., & Kaushik, S. C. (2014). U-SHAPED HEAT PIPE HEAT EXCHANGER FOR AIR-CONDITIONING APPLICATION. Heat Pipe Science and Technology, An International Journal, 5(1–4), pp. 619–626. https://doi.org/10.1615/heatpipescietech.v5.i1-4.720

[8] Choi, J., Yuan, Y., Borca-Tasciuc, D.-A., & Kang, H. (2014). Design, construction, and performance testing of an isothermal naphthalene heat pipe furnace. Review of Scientific Instruments, 85(9), 095105. https://doi.org/10.1063/1.4894526

[9] Advanced Cooling Technologies. (2020, June 1). Variable Conductance Heat Pipes - VCHP. Www.1-Act.Com. https://www.1-act.com/products/variable-conductance-heat-pipes/

[10] Faghri, A. (2014). HEAT PIPES: REVIEW, OPPORTUNITIES AND CHALLENGES. Frontiers in Heat Pipes, 5(1), pp. 44–48. https://doi.org/10.5098/fhp.5.1

[11] Yan, Y. H., & Ochterbeck, J. M. (1999). Analysis of Supercritical Startup Behavior for Cryogenic Heat Pipes. Journal of Thermophysics and Heat Transfer, 13(1), pp. 140–145. https://doi.org/10.2514/2.6412

[12] Sherman, A., & Brennan, P. (1976). Cryogenic and Low-Temperature Heat Pipe/Cooler Studies for Spacecraft Application. Journal of Spacecraft and Rockets, 13(5), pp. 288–293. https://doi.org/10.2514/3.57090

[13] LIU, J., LIN, L., & PEI, G. (2010). Numerical Simulation of Soil Temperature Field Surrounding Underground Heat Pipe in Permafrost Region. Physical and Numerical Simulation of Geotechnical Engineering, pp. 70–76. https://doi.org/10.5503/j.pnsge.2010.01.010

[14] Senjaya, R., & Inoue, T. (2014). Oscillating heat pipe simulation considering dryout phenomena. Heat and Mass Transfer, 50(10), pp. 1429–1441. https://doi.org/10.1007/s00231-014-1354-9

[15] Shukla, K. N. (2009). Heat Transfer Limitation of a Micro Heat Pipe. Journal of Electronic Packaging, 131(2), pp. 1–3. https://doi.org/10.1115/1.3103970