Experimental Investigation on Multi-Turn Oscillating Heat Pipes

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Abstract: ***Thermal management is the challenge of the day in electronic product development. Presently, the chip heat flux level ranges between 40 to 120 W/cm^2. It is expected to increase to 200 W/cm^2 in the next few decades. Several cooling methods are employed to cool the electronic devices. Heat Pipe is being explored for electronic cooling devices with promising results. Even though the conventional heat pipes are excellent heat transfer devices their application is mainly confined to transferring small amount of heat over relatively short distances. Oscillating Heat Pipes (OHP'S) has proved to transport heat for longer distances, helping in placing the condenser away from compact cabinets. OHP'S is simple in structure with a small diameter pipe filled with certain working fluid in it and extended from the heat source to sink. OHP'S uses the technique of transporting the working fluid by means of differential pressure across liquid slugs and vapor plugs from evaporator to condenser and back. The fluid from the evaporator is pushed towards the condenser in the form of discrete liquid slugs and vapor bubbles. The vapor gets partially condensed at the condenser and looses the heat and returns to evaporator to complete the cycle. The heat transfer in a OHP'S is due to the sensible heat and latent heat combination. In the present work experimental studies are carried out on a five-turn OHP. Copper is used as a material in the evaporator and condenser sections. Glass tube is used as a material in the adiabatic section. Copper and glass tubes are connected with the help of silicon rubber tubes. Acetone, Methanol & Ethanol are used as the working fluids and their suitability in the operation of OHP'S is tested. At first stage of the present work experiments are conducted for different heat input and fill ratio. The effect of working fluids on the performance of OHP'S is studied by comparing parameters like thermal resistance and heat transfer coefficient. From the results it is found that Acetone is the most suitable working fluid among all the individual fluids used for OHP'S operation in the present work. It is also found that the heat transfer and fluid flow performance of OHP is better at a fill ratio of 80%.***

Keywords: Multi-turn oscillating heat pipes

1. Introduction

1.1 Thermal Management of Electronics

The past few decades have seen an escalation of power densities in electronic devices and in particular microprocessor chips. Together with the continuing trend of reduction in device dimensions, this has led to dramatic increase in the thermal issues within electronic circuits. Thermal management is therefore becoming increasingly more critical and fundamental to ensure that electronic devices operate within their specifications. In order to satisfy the junction temperature requirements in terms of performance and reliability, improvements in cooling technology is required. The task of maintaining acceptable junction temperature by dissipating the heat from the integrated circuit chips is a significant challenge to the thermal engineers.

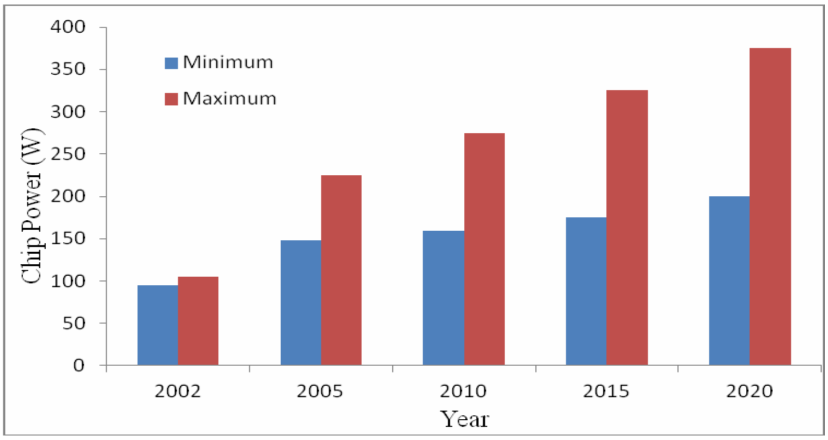

Figure 1.1 High Performance Chip Power Trends [1]

The electronics cooling is viewed in three levels, which are non-separable [1]. First, maintenance of chip temperature at a relatively low level, despite of high local heat density. Second, this heat flux must be handled at system or module level. Finally, the thermal management of the computer machine room, office space, or telecommunication enclosure. The thermal design of the system is influenced by the key drivers like chip size, power dissipation, junction temperature and ambient air temperature.

Semiconductor industries are taking great amount of effort over the years to reduce the size of the devices. With the increase in power dissipation and reduction in the size, the growth in power density is expected to increase further over the next decade as shown in Figure 1.1 and Figure 1.2

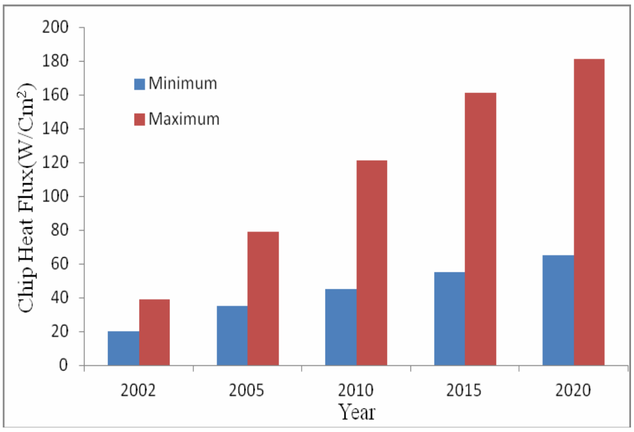

Figure 1.2 High Performance Chip Heat Flux Trends

The increasing power density indicates the thermal management solutions play an important role in determining the future semiconductor device technology.

Classification of Cooling Methods

In general, cooling methods in electronics [2] are classified into two types:

1) Active Cooling
2) Passive Cooling

Active Cooling

Mechanically assisted cooling sub systems are termed as active cooling systems. Active cooling has advantages of high cooling capacity. They provide such an efficient cooling that the systems can be cooled to even below the ambient temperatures. Air/liquid jet impingement, forced liquid convection, spray cooling, thermoelectric cooling and refrigeration cooling are few active cooling techniques.

Passive Cooling

The cooling systems which are not assisted by mechanical equipment are the passive cooling systems. The conventional passive cooling techniques include heat spreaders and heat sinks to the electronic packages. Recent technology development shows the use of thermal energy storage with phase change materials and integration of the heat pipes to the electronic packages. These are used to achieve high cooling capacity and are ideal for electronic cabinet cooling.

Different Cooling Methods

The different cooling methods [1] are:

1) Air cooling
2) Liquid cooling
3) Refrigeration cooling
4) Thermoelectric cooling
5) Heat pipes

Air Cooling

Air cooling is the simplest method of electronic cooling most widely used in thermal control for variety of electronic systems. The advantages of air cooling are its ready availability and ease of application. The air cooling can be done in two ways; one is by natural convection and other by forced convection. It is common knowledge that air rises as it is heated due to its resulting decrease in density (convection). The air flow resulting from this convection process is referred to as laminar flow. This process provides a natural means of removing heat generated by electronic components. Advantages of applying natural air cooling include low to no maintenance requirements, no resulting wear and tear, and no noise emission during application. The most prevalent disadvantage of using natural air cooling is that it results in very low levels of cooling. Air blowers/fans are used in forced air cooling in order to increase the air velocity. This increased velocity aims to produce turbulent air flow rather than a laminar flow, effectively increasing heat dissipation to the surrounding atmosphere. The advantage of using forced air is that it has a far better cooling effect than natural air cooling. Disadvantages include the high amount of noise produced during application as well as resulting wear and tear.

Liquid Cooling

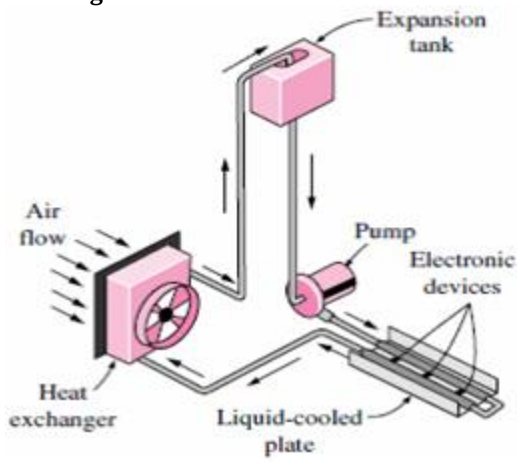

Figure 1.3 Schematic of an Indirect Liquid Cooling System

Liquid cooling is more effective than air cooling for high power electronic applications as the heat transfer coefficients are higher. However, there are some inherent problems such as leakage, corrosion, extra weight and condensation in liquid cooling making its scope limited for fewer applications.

The liquid cooling may be of two types. One, the cooling systems where the fluid is in direct contact with the electronic devices and two, where the fluid is not in contact with the electronics directly(Figure 1). Some of the examples of liquid cooling are (1) Single-phase liquid impingement jet cooling, (2) Pool boiling or two phase liquid spray cooling, (3) Indirect liquid cooling using heat exchangers. The heat transfer from the components to the fluid may be by natural convection or forced convection or pool boiling depending on the temperature levels involved in the system and fluid properties.

Refrigeration Cooling

Refrigeration cooling technique is one of the most promising cooling techniques to keep the junction temperature below the maximum operating temperature and handle high heat dissipation applications (Figure 2). The advantages of the refrigeration cooling technique are

1) To maintain a low junction temperature and at the same time dissipate high heat fluxes
2) To increase the device speed due to a lower operating temperature and
3) To increase the device reliability and life cycle time

because of a lower and constant operating temperature.

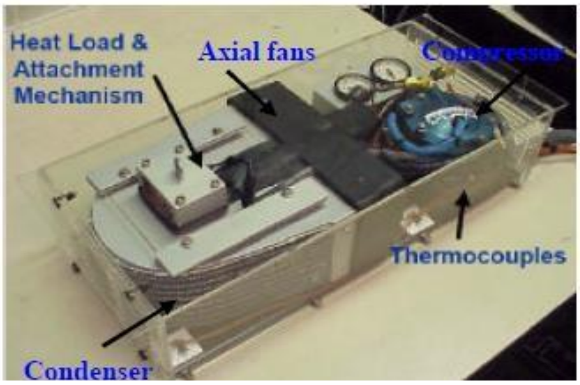

Figure 1.4 Small-Scale Refrigeration Cooling System

Disadvantages of the refrigeration cooling technique are
1) Increased complexity and cost
2) Need for additional space to fit the components of the refrigeration system and
3) Decrease of the system reliability as a result of an additional moving component, i.e., the compressor.

Thermo Electric Cooling

The Peltier Effect is one of the three thermoelectric effects. The other two are known as See beck Effect and Thomson Effect. Whereas the last two effects act on a single conductor, the Peltier Effect is a typical junction phenomenon Thermoelectric cooling uses the Peltier effect to create a heat flux between the junctions of two different types of materials. A Peltier cooler, heater or thermoelectric heat pump transfers heat from one side of the device to the other side due to the temperature gradient with the aid of electrical energy (Figure 1.5). Such a device is also known as a Peltier device, Peltier diode, cooling diode, Peltier heat pump, solid state refrigerator or thermoelectric cooler.

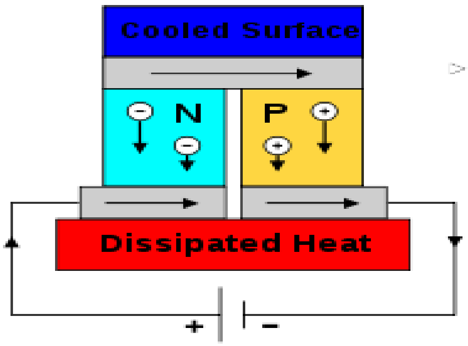

Figure 1.5 Thermoelectric Phenomenon's for Cooling of Electronic Equipment

Heat Pipes

A heat pipe is a passive two phase heat transfer device capable of transferring large quantities of heat with a minimum temperature drop (Figure 1.6) Heat pipes, due to their unique physical features, operational characteristics and applications, deserve a special mention in the field of electronics thermal management.

Figure 1.6 Heat Pipe Assembly Used in Mother Board

In the above section different cooling methods employed in the cooling of electronic components are discussed in detail. Among all the cooling methods heat pipes are found to be more suitable. Hence the present work is directed towards developing of a suitable OHP for the electronic cooling application.

Hence in the next section heat pipes are explained in detail rather than any other cooling method

1.2 Conventional Heat pipe

1.2.1Construction and Working

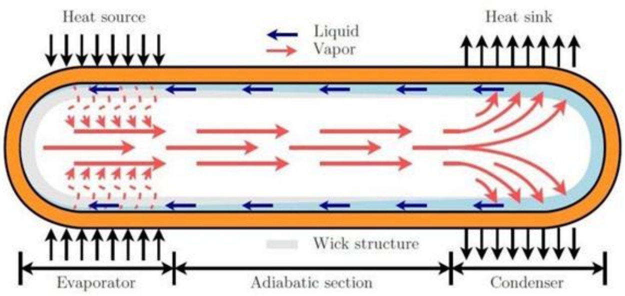

Figure 1.7 Schematic Diagram of Conventional Heat Pipe

The construction and working of conventional heat pipe [3] is as described. The components of a conventional heat pipe are a sealed container, a wick structure and a small quantity of working fluid which is in equilibrium with its own vapor (Figure 1.7). It encompasses three essential parts: an evaporator, an adiabatic transport section and a condenser. A heat flux entering the evaporator, for instance from a hot component, vaporizes any available coolant liquid, thereby absorbing large quantities of heat. The vapor, indicated by the red arrows, travels through the adiabatic transport section to the condenser, propelled by the difference in pressure. In the condenser the vapor condenses as the temperature is lower, releasing its latent heat. This heat can be extracted from the heat pipe by a heat sink. To complete the cycle, the condensed liquid must be pumped back to the evaporator, as indicated by the blue arrows. The fluid return is facilitated by a capillary or wick structure, indicated in gray. The wick structure, saturated with the liquid phase of the working fluid, is able to transport the fluid, due to the capillary pressure caused by the difference in curvature of the liquid menisci. This process will continue as long as there is sufficient pressure to drive the condensate back to the evaporator.

The vapor pressure changes along the heat pipe are due to friction, inertia, evaporation and condensation effects while the liquid pressure changes mainly as a result of friction. The liquid- vapor interface is flat near the condenser end cap corresponding to a zero local pressure gradient at very low vapor flow rates. When body forces are present such as gravitational force, the liquid pressure drop is greater, indicating that the capillary pressure must be higher in order to return the liquid to the evaporator for a given heat load. At moderate vapor flow rates, dynamic effect causes the vapor pressure drop and recovery along the condenser section

1.2.2. Limitations of Conventional Heat Pipes

Conventional Heat pipes are excellent heat transfer devices but their application is mainly confined to transferring small amount of heat over relatively short distances when the evaporator and condenser are at same horizontal level. This limitation on the part of the conventional heat pipes is mainly due to the major pressure losses associated with the liquid flow through the porous structure. Also, there will be viscous interaction between the vapor and liquid phases, called entrainment losses. For the applications involving transfer of large amount of heat over long distances, the thermal performance of the heat pipes is badly affected by increase in these losses. For the same reason conventional heat pipes are very sensitive to the change in orientation in gravitational field. In the top heat mode positions(evaporator at the top, condenser down), the pressure losses due to the mass forces in gravity field adds to the total pressure losses and further affect the efficiency of the heat transfer process.

As a result of these limitations, different solutions involving structural modifications to the conventional heat pipe have been proposed. Some of these modified versions of heat pipe incorporated arterial tube with relatively low hydraulic resistance for the return of the liquid to the heat supply zone while others provided spatial separation of the vapor and liquid phases of a working fluid at the transportation section.

Though these heat pipes are able to increase heat transport length and transfer significant amount of heat they are very sensitive to orientation in the gravity field. The advantages provided by the spatial separation of the transportation line and usage of non-capillary artery tube are combined together in loop heat pipes (loop schemes) popularly known as Oscillating Heat Pipes (OHPs). As a result, this loop scheme makes it possible to develop heat pipes with higher heat transfer characteristics while maintaining normal operation at any orientation in the gravity field.

1.3 Oscillating Heat Pipes (OHP)

Oscillating Heat Pipes (OHPs), a concept proposed by Akachi [1990] [4] seems to meet all the present day cooling requirements. OHPs are highly attractive heat transfer elements, which due to their simple design, cost effectiveness and excellent thermal performance may find wide applications. These heat pipes are able to overcome some limitations of conventional heat pipes. (e.g., the capillary and entrainment limits). Although grouped as a subclass of the overall family of heat pipes, the complexity of thermo-hydraulic coupling is distinctly unique. OHPs are essentially non equilibrium heat transfer devices.

Construction and Working Principle of OHP

Oscillating, or oscillating heat pipes comprise a tube of capillary diameter, evacuated and partially filled with the working fluid. Oscillating heat pipe configurations are shown schematically in Figure

1) Typically, a Oscillating heat pipe comprises a serpentine channel of capillary dimension, which has been evacuated, and partially filled with the working fluid. Surface tension effects result in the formation of slugs of liquid interspersed with bubbles of vapor

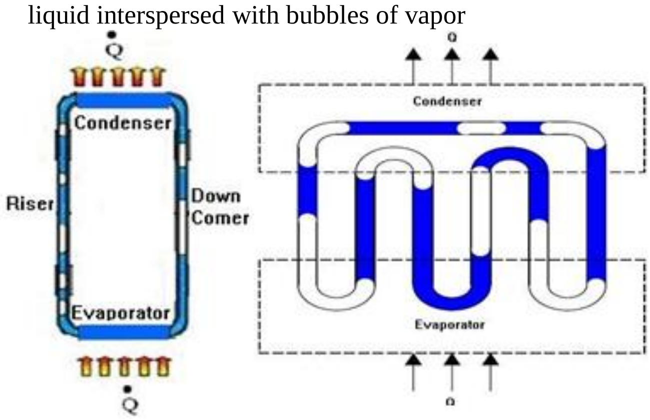

Figure 1.8 Schematics of a Single Loop and Multiple Loops Oscillating Heat Pipe

OHP is a device consisting of a tube of small diameter. The device may be of single loop or with multiple loops (Figure 1.8)

A multiple loop OHP consists of a small diameter tube that crosses a condenser and evaporator region multiple times. The tube is filled with a working fluid such that only the fluid and its vapor phase exist. The tube"s inner diameter must also be small enough for the capillary forces of the fluid to create vapor bubbles (plugs) and liquid slugs. Thus the vapor plugs completely block the flow of the liquid. This keeps the plugs and slugs in a linear arrangement within the tube as seen in Figure 6. Heat transfer in an OHP is associated with liquid and vapor motions induced by the pressure difference. Evaporation at a higher temperature in the evaporator produces a higher vapor pressure. The same is the case for the condenser where condensation and reduced temperature at the condenser cause a decrease in pressure. The increased pressure in the evaporator and decreased pressure within the condenser causes a pressure imbalance. Due to the random arrangement of liquid slugs and vapor plugs within an OHP, this pressure imbalance forces the hot vapor and liquid from the evaporator to the condenser. Subsequently, the cool vapor and liquid flows from the condenser to the evaporator, resulting in an oscillating motion. The oscillating motion consists of small rapid movement within portions of the tube and in some cases bulk motion through the entire OHP.

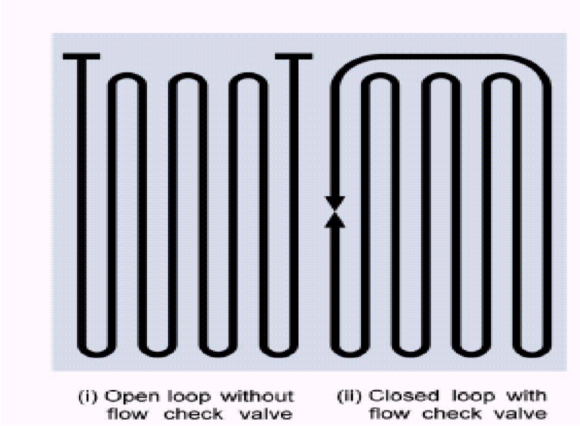

Figure 1.9: Open Loop and Closed Loop Arrangement of OHP

There are two general types of OHP named as open and close loop OHP (Figure 1.9). The closed loop OHP is a continuous tube in which the fluid passes through the evaporator and condenser multiple times continuously. The open loop OHP is similar except that the two ends of the tube are sealed. Generally, close loop OHPs perform better than open loop.

Most of the OHPs are made of copper, aluminum and/or glass. Copper and aluminum with their high thermal conductivity are better suited for OHP. Glass has been used in several experiments for flow visualization.

The parameters affecting the performance of closed loop OHP have been summarized by Groll and co-workers as [5]

- Working fluid
- Internal tube diameter
- Total tube length
- Length of condenser, evaporator and adiabatic sections
- Number of turns or loops
- Orientation.

Applications of OHP

Some of the typical applications of OHP [6] are:

- Laptop Computers
- High-performance processors (CPU, GPU)
- Aerospace; space craft temperature equalization, component cooling
- Low maintenance/high reliability applications
- Noise-sensitive environments where heat can be dissipated to a larger remote heat sink

1.4 Summary

In this chapter, the importance of cooling, in modern electronic devices are discussed. Different cooling methods are discussed in detail. The importance of heat pipes in cooling of electronic components is established. The working principle of conventional heat pipe is explained along with its limitations. Then the working and applications of Oscillating heat pipes are explained in detail. In the next chapter, literature survey related to OHP is presented.

2. Literature Survey

In this section, literature available on the thermal management of electronics and different cooling methods are reviewed. The effect of various working fluids on the performance of the OHP reported in the literature is presented. Also the effect of mixture of various working fluids on the performance of OHP reported in the literature is discussed. The effect of heat input on the performance of OHP available in the literature is reviewed. The study on effect of various fluids on the performance of OHP helps us to optimize the best working fluid.

Literature Review

Thermal Management of Electronics

Shanmuga Sundaram Anandan et al [1] [2008] reviewed all the available cooling techniques and they concluded that, the research needs are to be focused to investigate advanced cooling technology that uses high performance heat pipe, thermo electric coolers, low acoustical novel micro fans for air cooling, and phase change material based cooling to satisfy the thermal technology needs. They also mentioned that challenges of cooling electronic equipment's may be expected to continue through the remaining of this decade.

Saket Karajgikar [2] [2010] has discussed about the miniaturization of the electronic devices and the effect of temperature on the performance of the electronic components and concluded that, almost 55% of all the electronics fail due to improper thermal management. Thus, thermal management plays a key role in current as well as in the development of new technology. For all electronic devices, reliability and performance can be improved by decreasing its operating temperature.

Development and Basic Principles of Oscillating Heat Pipes

Although the fundamental aspect of a `Oscillating Heat Pipe' is contained in the patent by *Smyrnov* and *Savchenkov* [1975], the exploitation of the concept from engineering point of view was done by *Hisateru Akachi* [4]. Thus, the first examples of the family of modern OHPs appeared in 1990 [Akachi, 1990] as shown in Figure 2.1. In this patent, 24 different preferred embodiments of what is referred to as Loop TypeHeat Pipewere described. All the proposed structures were characterized by the presence of at least one non-return flow check valve integrated in the tubes for imposing a preferred flow direction. The typical tube inner diameters employed were 2.5 mm or more, always ensuring that the inner diameter is below a maximum permissible value.

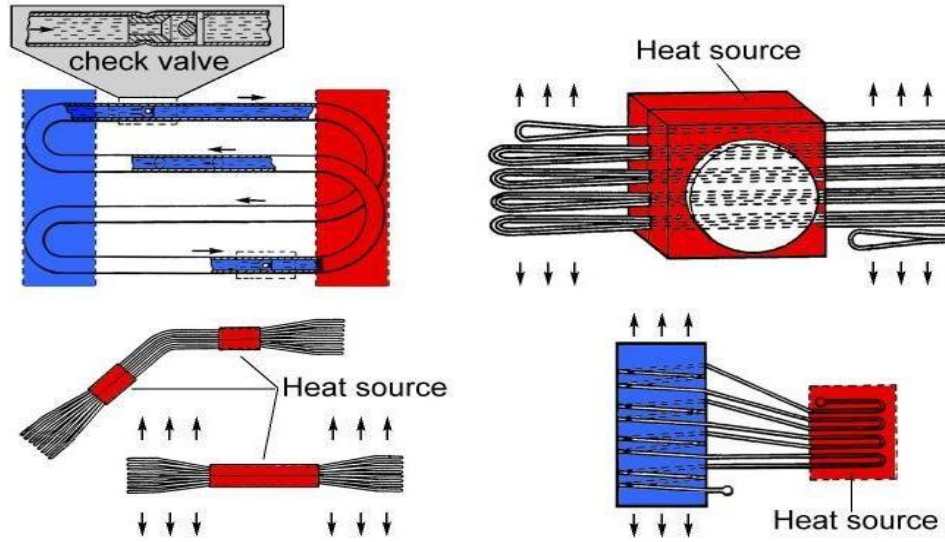

Figure 2.1 Loop Type Heat Pipe and its Different Design Variations [Akachi, 1990]

Long-term reliability issues of the flow check valves and their inability to deliver the desired results, if further miniaturization of the pipe cross section is done, lead to the development of loop type heat pipes without check valves [Akachi, 1993, 1996]. These structures, as shown in Figure 2.2, represent the true Oscillating Heat Pipes. Open loop and closed loop structures, having internal tube diameters of the order of 1.0 mm, were proposed. Structures were fabricated with metallic tubes (ID 0.7 mm, OD 1.0 mm) and filled with R-142b. Experimental results for a power range of 5 to 90 W in top and bottom heating mode obtained an average thermal resistance from 0.64 to 1.16 K/W.

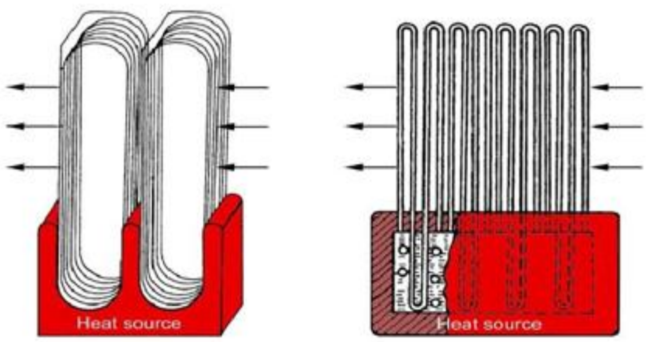

Figure 2.2 Oscillating Heat Pipe as Described by Akachi [1993-1996]

Maezawa et al [7] [1995] studied an open loop OHP consisting of 20 turns of copper tube (ID 1.0 mm) of total length 24 meters. R-142b was used as the working fluid. Heat was supplied with flat electrical heaters sandwiched around the evaporator section and a water jacket was used in the condenser section.

Fill ratio and inclination were varied and the typical results with the set-up are shown in Figure 2.3 Temperature fluctuations at the adiabatic wall section were also recorded.

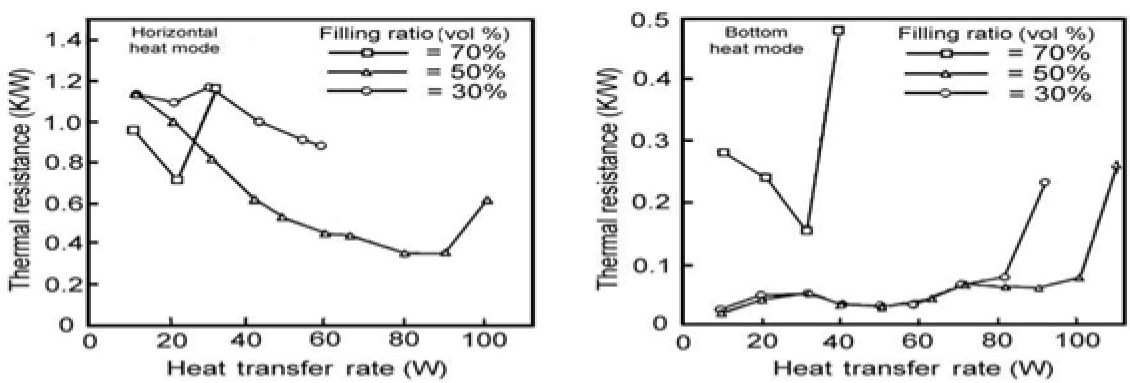

Figure 2.3 Experimental Setup and Typical Results of Maezawa et al[1995]

Important Factors Affecting the Performance of OHP

Manfred groll et al [8] [2003] in their work attempted to define the device (OHP), in terms of controllable thermo – mechanical boundary conditions. Such an exercise deemed necessary to benchmark the operational performance limits and to help in system analysis. Here, they have concluded that, the important parameters affecting the performance of Oscillating heat pipes are, diameter of the heat pipe, fill ratio, working fluid, & heat input. They also concluded that, there are at least three thermo-mechanical boundary conditions i.e. internal tube diameter, input heat flux and fill ratio, which are to be satisfied for the structure to behave as a true OHP.

Nagvase S.Y.et al [9] [2013] have reviewed and they have concluded that, the performance of OHP depends on many parameters namely

1) Design/Geometric Parameters: Diameter and material of tube, Orientation of OHP, Number of turns.
2) Operating Parameters: Fill ratio, Heat flux/Temperature, Dry out condition, Properties of working fluid.

Effect of Various Parameters on the Performance of OHP

Sameer Khandekar et al [10] [2003] conducted experiments on a OHP made of copper capillary tube of 2mm inner diameter. Three different working fluids viz. water, ethanol and R-123 were employed. The OHP was tested in vertical (bottom heat mode) and horizontal orientation. Here authors have concluded that, for a given heat input requirement, an operationally better performing and self- sustained thermally driven Oscillating action of the device was only observed in the filling ratio range 25–65% depending on the working fluid. Above this range the overall degree of freedom and the pumping action of bubbles was insufficient for rendering good performance. Below a certain range of filling ratio, partial dry out of the evaporator was detected.

Zhang *et al* [11] [2004] carried out an experimental study on OHP with FC – 72, ethanol and water as working fluids. The experimental set up consists of copper capillary tubes of inner diameter 1.18 mm and the number of turns was 3. The authors observed that the amplitude of thermal oscillations reported was small for FC – 72 compared to water and Ethanol due to its lower surface tension. The oscillation movement in the channels was found to be faster in case of FC – 72 compared to the other two fluids. This faster movement of FC – 72 in the channels was attributed to its lower latent heat value. They also showed that there is a minimum heat input that initiates OHP working in the looped mode and such a minimum heat input is a strong function of the working fluid. They suggested water as the better working fluid beyond the minimum heat input. They also showed that FC – 72 is more suitable for low heat flux situations.

Honghai Yang et al [12][2008] made an experimental study on two flat plates closed loop Oscillating heat pipes in a thermal spreader configuration, made of aluminum with overall size 180× 120 × 3 mm^3; one structure having 40 parallel square channels with cross-section 2 × 2 mm^2, while the second with 66 parallel square channels with cross-section 1 × 1 mm^2 was used. The working fluid employed was Ethanol. From this work they have concluded that, the cross-sectional shape of the device is an important parameter which affects not only the flow pattern transitions due to the effect of sharp angled corners, if present, it also has a bearing on the acceptable diameter of a OHP. The fill ratio is a critical parameter, which needs to be optimized to achieve maximum thermal performance and/or minimum thermal resistance for a given operating condition.

Meena *et al* [13] [2009] studied the effect of working fluid on the performance of a closed loop OHP with check valves. Their experimental setup was made of copper tubes with 1.77 mm inner diameter and with 10 turns. They maintained equal lengths of 5 cm, 10 cm and 15 cm in evaporator, condenser and adiabatic sections in the setup. A fill ratio of 50% was used and they used R123, Ethanol and Water as working fluids. They showed that the critical heat flux decreases with increase in the evaporator length. They also observed that the working fluid with lower latent heat of vaporization (R – 123) exhibits a higher critical heat flux.

*Dadong Wang*et al [14] [2010] carried out an experimental research on Oscillating heat pipes using different mixtures of working fluids. In this paper, experimental researches on a vertical looped Oscillating heat pipe (OHP) was done at 60% fill ratio and power inputs (Q) of 20 W, 40 W, 60 W, 80 W and 100 W. The OHP is made of copper tubes with internal diameters 2mm and wall thickness 1mm. Experimental investigations in this work indicated working fluid is an important factor for the performance of OHPs. Methanol, ethanol, acetone; water and different binary mixtures are selected as working fluids. The evaporation section temperature (Te) and the condensation section temperature (Tc) are recorded to find the characteristics of the thermal resistance (R). According to the experimental results, the thermal resistance decreases with the increase of the heating power at the same fill ratio. The thermal resistance decreases more slowly and the differences of the thermal resistances are smaller with every working fluid for the power inputs larger than 60 W. For the pure working fluids OHP, the sequence of the thermal resistances is acetone, methanol, ethanol, and water from small to large. From 20 W to 100 W, Te and Tc of methanol and ethanol are close and have the same trend. For the methanol/water OHP, the thermal resistance of methanol/water is lower than that of methanol and water. The evaporation section temperature of methanol/water is lower than that of methanol and water.

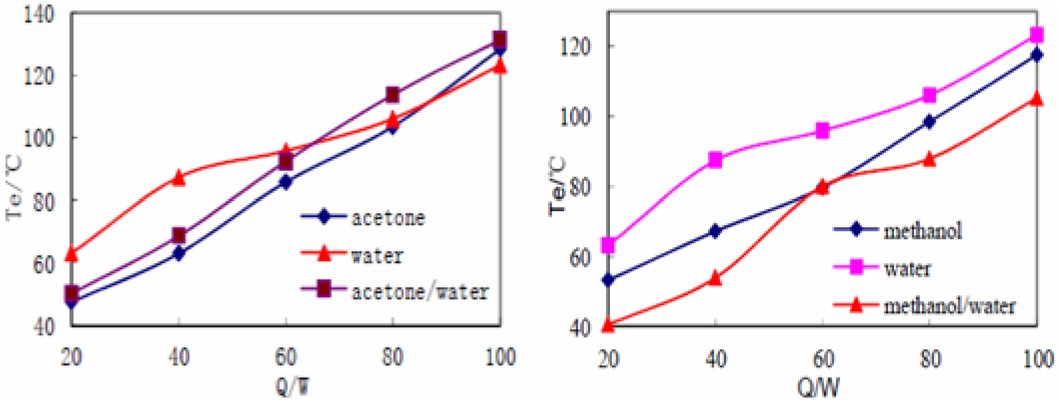

Figure 2.4 Thermal Resistance of Acetone/Water & Methanol/Water OHP at Different Power Inputs by Dadong Wang [2010]

For the acetone/water OHP, the thermal resistance of acetone/water is between that of acetone and water. The evaporation section temperature of acetone/water and that of acetone have the same trend and the condensation section temperature of acetone/water is close to that of acetone from 20 W to 100 W. For the ethanol/acetone OHP, the thermal resistance of is higher than that of ethanol and acetone. Methanol/water OHP has better heat transfer performance than pure working fluids OHP, acetone/water OHP and acetone/water OHP.

Mauro Mameli [15][2011] *et al*, in their experiment made an attempt to understand the flow patterns at various heat inputs. In this work, they have used ethanol as working fluid and the filling ratio 65%. In this work they have proposed a method to find the local heat transfer co efficient. In this work they have concluded that, when the number of turns is small a critical heat flux between 5.2 and 6.5 W/cm^2 is needed to ignite a stable fluid motion and reach an acceptable pseudo steady state. When a stable steady state is reached, a net circulation, together with an oscillation component, is always recognizable at each heat input level. *Khedkar et al* [16] [2012] in their work highlighted the thermo hydrodynamic characteristics of OHP. In this work they have concluded that for a OHP to work effectively three parameters are very important, they are internal tube diameter, the heat flux applied and the amount of working fluid in the system. They have also presented that, for a working fluid to give good results it should have the following characteristics namely, compatibility with the heat pipe material, thermal stability, wettability, reasonable vapor pressure, thermal conductivity.

Rahul S. Borkar et al [17] [2012]in their work mentioned that, selection of working fluids depends on the desired performance from the device and the performance of device depends on the thermo physical properties of working fluids i.e. saturation temperature, viscosity, surface tension, sensible heat, latent heat etc. Working fluids having lower saturation temperature, lower latent heat, high specific heat and low dynamic viscosity give better thermal performance. Different input parameters are internal tube diameter, input heat flux, fill ratio, number of turns, device orientation, size and capacity of condenser and evaporator also important parameters for thermal performance of OHP. They have concluded that saturation temperature of working fluids effect the temperature difference between evaporator and condenser section and therefore lower saturation temperature working fluids gives better performance. Low latent heat and high specific heat working fluids are more efficient because of fast evaporation. Low dynamic viscosity reduces shear stresses along the wall and consequently reduces the pressure drop that reduces required input heat flux for pulsation. *Pramod R. Pachghare et al* [18] [2012] in their experimental investigation used copper capillary tube having internal and external diameter 2.0 mm and 3.6 mm respectively.

For all experimentation, fill ratio was 50 %, number of turns was 10 and different heat inputs of 10 to 100W were supplied to OHP. For all OHPs, Vertical bottom “heat mode” position is maintained. The equal lengths of evaporator, adiabatic and condenser sections were 50 mm each. Working fluids are selected as methanol, ethanol, acetone, water and different binary mixtures. The graphs were plotted, in order to study, characteristics of the thermal resistance and average evaporator temperatures at different heat input for various working fluids. From this work they have concluded that for pure and binary working fluids of OHP, thermal resistance is decreases with the increasing heat input (Figure 2.5).

The dry-out for the water methanol, water-acetone and water-ethanol is at 85W, 80W and 90W heat input respectively, which is approximately the algebraic mean value of the boiling point of binary mixture. In all working fluids, pure water is having more thermal resistance. Whereas pure acetone is having lesser thermal resistance. So in this set-up, pure acetone gives best thermal performance in comparisons with the other pure and binary mixtures. No measurable difference has been recorded between the OHP running with pure and binary mixture working fluids, in terms of overall thermal resistance. Working fluid Behavior is strongly dependent on the thermo-physical properties, but latent heat of Vaporization is the main property that strongly affects the thermal performance.

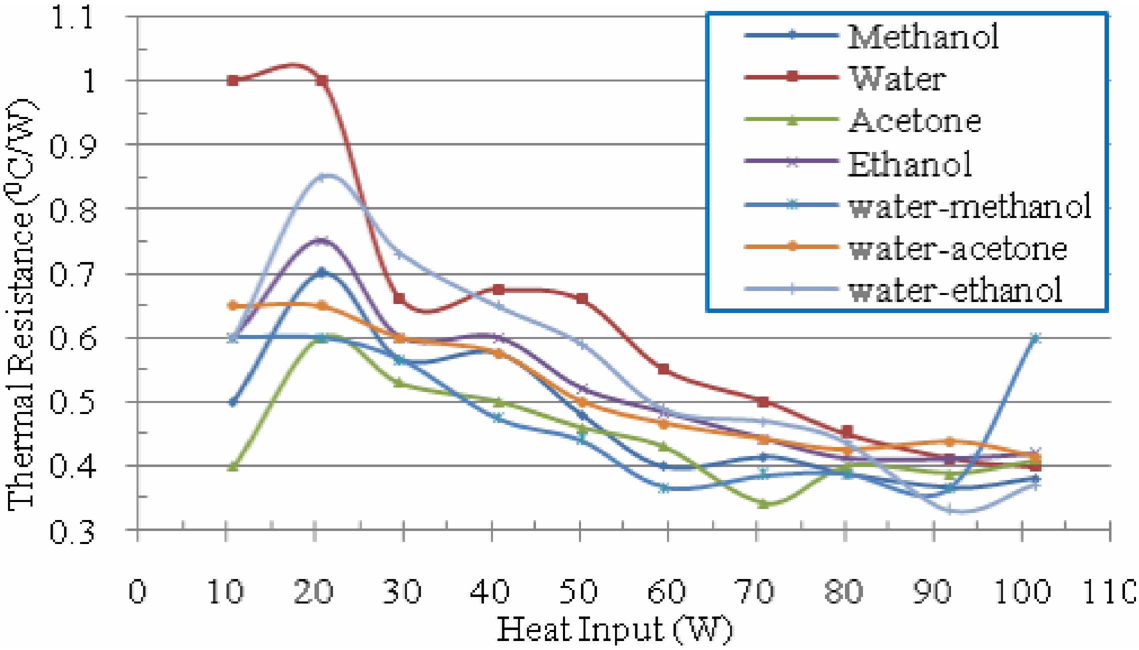

Figure 2.5 Thermal Resistance vs. Heat Input Plot by Pramod R. Pachghare [2012]

Bhawna Vermaet [2013]*et al* studied the performance of the OHP using methanol & distilled water as working fluids. From their experimental work ,they have concluded that, minimum start-up power for water as working fluid in OHP are at 50% and 60% filling ratio while for methanol as working fluid, they are at 30% and 40% filling ratio. The optimum filling ratio for a minimum thermal resistance was found to be 50% for water and 40% for methanol. In vertical orientation of OHP, the resistances observed are 0.492 and 0.51°C/W for water and methanol respectively. Hence the optimum fill ratio was taken as 50% for water and 40% for methanol. The heat transfer coefficient on evaporator side, for both the liquids, was almost similar, while there was an appreciable difference in heat transfer coefficients on condenser side. The start-up temperature and startup time at all orientations can be considerably reduced by using methanol as working fluid in OHP. At optimum fill ratio, the minimum thermal resistance of water charged OHP at 45°inclination and horizontal orientation was found to be 0.55°C/W and 0.81°C/W respectively while that of methanol charged OHP, is 0.52°C/W and 0.63°C/W at 45°inclination and horizontal orientation respectively. Hence it may be concluded that the OHP charged with methanol can be considered as orientation free.

Summary of the Literature Survey

The literature review on the thermal management of electronics shows that, temperature build up is one of the major causes of failure in electronic components and it also highlights the role of heat pipes in thermal management of electronics.

1) The exclusive literature reviewed shows that the experimental studies of OHP are mainly focused on the measurement of evaporator temperature, condenser temperature, adiabatic temperature and temperature difference between evaporator and condenser which has led to the determination of
2) thermal resistance and heat transfer coefficient.
3) The experimental studies also highlight the influence of various parameters on the performance of OHP, such as the effect of heat load, fill ratio, diameter of tubes, length of evaporator and condenser sections, orientation and working fluid on the heat transfer characteristics of OHP.
4) The working fluid with lower latent heat value is considered in the literature as the more suitable working fluid for OHP operation
5) The experimental studies also highlight that when the mixture of two fluids is used as working fluid, the results obtained were different from the individual fluids used to form the mixture.

Problem Formulation

From the literature survey it is concluded that Acetone, Ethanol & Distilled water are the most widely studied working fluids. The other parameters which influence the design of an OHP are:-

1) Diameter
2) Fill ratio
3) Heat load
4) Number of turns

In the present work, a 5 turn OHP is fabricated & tested for its heat transfer and fluid flow performance. The effect of the above mentioned parameters is studied by experimentation. Acetone, Methanol & Ethanol are used as the working fluids and their suitability in the operation of OHP is tested.

Objectives of the Project work

- To carry out detailed experimental studies on a five-loop OHP to study the heat transfer and fluid flow characteristics with different working fluids.
- In the present work, experiments are carried out with acetone, Methanol & Ethanol as working fluids at different fill ratios & heat load.
- The effect of working fluids, fill ratio and heat load on the performance of OHP is studied by comparing the parameters like thermal resistance and heat transfer coefficient.

Summary

In this section, the literature available on the thermal management of electronics, different parameters affecting the performance of OHP are discussed. Problem formulation is arrived at based on the literature review. Objectives of the present work are designed. In the next chapter, fabrication of OHP and experimentation are explained in detail.

3. Fabrication and Experimentation

Introduction

Working fluid is the one of the important factors affecting the performance of OHP. The aim of this project is to test the effect of different working fluids for the performance. Therefore the experiment was envisaged to understand the operational phenomena under the influence of various working fluids. The following section briefly describes the devices used in the present experimental setup. Thereafter, a brief description and procedure of the experimental setup follows.

Experimental Setup

The basic components used in the presently developed OHP are

- Copper tubes
- Glass tubes
- Silicon rubber tubes
- Heater
- T- type thermocouple
- Data logger
- Needle valve
- Cooling arrangements
- Glass wool

Copper Tubes

In the present work, copper is used as the tube material which is an excellent conductor of heat. It has a thermal conductivity of 386W/mk. Copper tubing (Figure 3.1) is highly exploited for its thermal conducting efficiency. In the present study, copper tubing is employed at the evaporator and condenser sections to ensure a rapid heat transfer in OHP. The inner diameters of the copper tubes are 2mm and having a thickness of 0.5mm.The physical properties of copper is tabulated in the Table 3.1.

Figure 3.1 Copper Tubes

Table 3.1 Physical Properties of Copper

Physical Properties of Copper	
Phase	Solid
Density	8.94 $g \cdot cm^{-3}$
Liquid density at melting point	8.02 $g \cdot cm^{-3}$
Melting point	1357.77 K
Boiling point	2835 K
Heat of fusion	13.26 $kJ.mol^{-1}$
Heat of vaporization	300.4 $kJ.mol^{-1}$
Specific heat capacity	(25 C) 24.440 $J \cdot mol^{-1} \cdot K^{-1}$

Glass Tube

In order to study the fluid flow in the OHP, a glass tube is connected to the copper tubes for a length of 65mm. The glass tube (Figure 3.2) also acts as the adiabatic section as it is an insulator; it helps in the flow visualization. In the present study, Boro-Silicate glass of inner diameter 2 mm and outer diameter 3mm is employed.

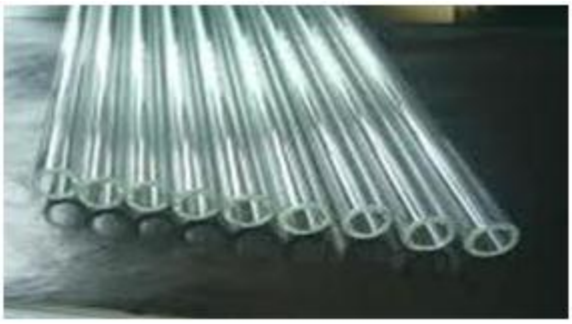

Figure 3.2: Glass Tube

Silicon Rubber Tubes

Silicon tubes (Figure 3.3) are used as connectors between glass and copper tubes. They have high flexibility, elasticity, longer life and are resistant to chemical reactions. Also, their physical properties are not easily altered. In the present study, silicon rubber tubes are employed because they are thermal insulators and can withstand high temperatures up to 400^{0}C. They are leak proof but they tend to expand at higher temperatures. In the present study, the silicon rubber tubes of 2mm inner diameter and 4mm outer diameter are used.

Figure 3.3: Silicon Rubber Tube

Heater

A heater is an object that emits heat or causes another body to achieve higher temperature. An electric heater is an electrical Appliance that converts electrical energy into heat. The heating element inside every electric heater is simply an electrical resistor, and works on the principle of Joule heating. In the present study a Mica Strip Heater

(Figure 3.4) of heating capacity 0-250 W is used to heat the working fluid.

Figure 3.4: Mica Strip Heater

All electrical resistance elements create heat, but some systems are better at transferring this energy. The adhesive surrounds the resistance wire and transfers the thermal energy directly to the surface of the load. The outer aluminum sheath spreads heat evenly over the entire surface of the tape and also reflects heat back onto the load. The end result is a highly efficient heating source with maximum heat being transferred to the desired material.

T-type Thermocouple

Figure 3.5 T – Type Thermocouple

Thermocouples are used to measure the temperatures. In the present work T-type thermocouples (Figure 3.5) are used. Type T thermocouples have a positive copper wire and a negative Constantan wire. They are commonly used for moist or sub-zero temperature monitoring applications because of superior corrosion resistance and greater homogeneity of the component wires that reduce errors due to temperature gradients. The operating temperature range of T type thermocouples used in the present work is -50 to 400 °C with a maximum error of ±0.1°C. In the present experimental setup totally six thermocouples are used, four in the evaporator section and two in the condenser section.

Temperature Data Logger

A temperature data logger, also called temperature monitor, is a portable measurement instrument that is capable of autonomously recording temperature over a defined period of time. The digital data can be retrieved, viewed and evaluated after it has been recorded. This includes many data acquisition devices such as plug-in boards or serial communication systems which use a computer as a real time data recording system. In the present experiments, a temperature data logger from a company „Measurement Computing" is used for the recording temperature values. The temperature values are recorded with a frequency of 1 Hz.

Cooling Arrangements

A water cooling arrangement is provided in the condenser to cool the working fluid of the OHP. The cold water enters the condenser from a constant head water container and the rise in the temperature of the cooling water is maintained around 1^0C to 2^0C by controlling the water flow rate.

Glass wool

Glass wool (Figure 3.6) is a form of fiberglass where very thin strands of glass are arranged into a spongy texture similar to steel wool. It is uniformly smeared throughout the set-up so as to ensure that the experimental setup is well insulated.

Figure 3.6: Glass Wool

Description of Experimental Set-Up

Experiments will be conducted on a five turn closed loop Oscillating Heat Pipe. Various performance parameters such as temperature difference, thermal resistance and heat transfer coefficient will be evaluated and analyzed for different working fluids with varying heat loads at different fill charge ratios. Fig. 3.7 shows the schematic diagram of the proposed experimental setup. In this setup, copper will be used as the capillary tube material in the evaporator and condenser sections with inner diameter of 2 mm and outer diameter of 3 mm.

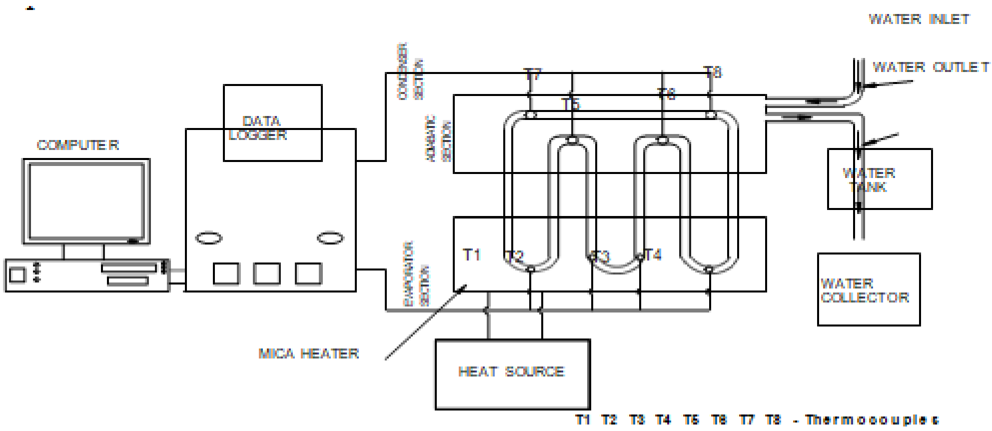

Figure 3.7: Schematic of the Experimental Setup of a three turn closed loop PHP

In the present proposal, copper is considered as the case material for the OHP. Fluids like Acetone, Methanol, Ethanol are used as the working fluids. The fluid selection is made based on their properties like latent heat, specific heat and surface tension as these properties ensure the quick movement, proper capillary pressure and heat transfer.

The total length of the proposed OHP will be 1860 mm. The evaporator and condenser lengths will be 480 mm. In order to visualize the flow in the OHP, a borosilicate glass tube of 2 mm inner diameter and 4 mm outer diameter will be connected to the copper tube for a length of 190 mm. Silicon rubber tubes will be used as connector between glass and copper tubes. A heater of 0-250W capacity will be employed during the experiment for heating the working fluid. Six T type thermocouples, four in the evaporator and two in the condenser section will be fixed on the surface of the tube for temperature measurement.

The fill ratio used in an OHP has a significant effect on the performance of OHP. It is reported in the literature that an OHP works as a good heat transport device when the fill ratio is between 50% to 80%. Hence, the fill ratio was maintained between 50% to 90%.

Transient and Steady state Experiments were conducted at different heat loads, fill ratio and for different working fluids. Each experiment was continued till the steady state is reached. The temperatures will be recorded with a frequency of 1 Hz using a temperature data logger. The experimental setup was well insulated with glass wool to avoid heat loss to the surroundings.

Figure 3.8 shows the actual experimental setup used for experimentation.

Figure 3.8: Experimental Set-Up

Working Fluids

The first consideration is the identification of a suitable working fluid and the operating temperature range. Within the approximate temperature band, several possible working fluids may exist. A variety of characteristics must be examined in order to determine the most acceptable of these fluids for the application considered. In the present work based on the available literature, Acetone, Ethanol and Methanol are used as the working fluids. So here suitability of these three fluids in the working of OHP is explored. The properties of these working fluids are listed in the table 3.2.

Table 3.2 Important Physical Properties of Individual Working Fluids

Fluids	Boiling Point (^{0}C)	Specific Heat C_P (J/kg K)
Acetone	57	2031
Methanol	64.7	2533
Ethanol	78	2470

Experimental Procedure

1) Before filling the working fluid, it is ensured that there is no other fluid exists inside the tubes of OHP.
2) The required amount of working fluid is then filled by opening the valve.
3) The cooling water is allowed to the condenser section of OHP from the constant water bath.
4) The required wattage is set using the power supply unit. In the present work, the experiments were conducted by varying the heat inputs from 50W to 120W respectively.
5) The temperature data logger is then switched on to record the temperature readings and the frequency of data logging is adjusted to 1 Hz so that one temperature value recorded in one second.
6) Transient experiments are conducted with different working fluids viz. Acetone, Ethanol, Methanol
7) The various temperatures are recorded with the help of data logger.

Summary

In this chapter the details of the experimental set up is discussed. Materials selected in the experimental setup and experimental procedure is discussed. Different working fluids used and their important physical properties are mentioned. In the next chapter, results and discussions of this experimental study are presented.

4. Results and Discussion

Transient and steady state experiments are conducted with different working fluids namely Acetone, Ethanol and Methanol. Temperature readings are recorded by using data logger until the steady state is reached. Using these values different parameters namely heat transfer coefficient and thermal resistance are evaluated. These values are compared and discussed to draw the conclusions.

Individual Fluids

Effect of heat input on evaporator temperature for ethanol

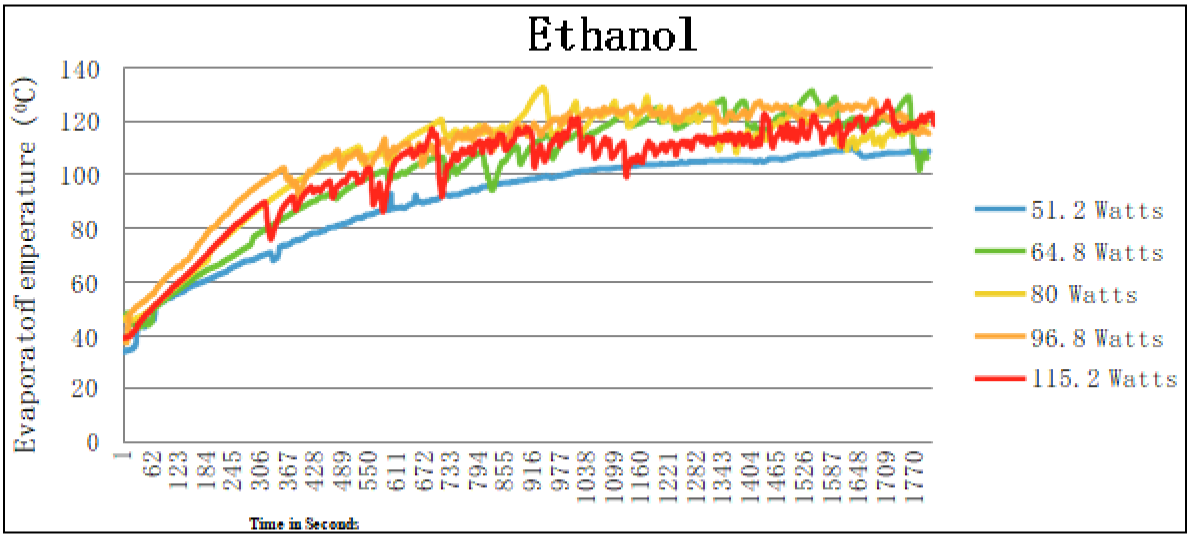

Figure 4.1 Variation of Evaporator Temperature with Time for Different Heat Inputs for Ethanol

Figure 4.1 shows the variation of evaporation temperature with time for different heat inputs when Ethanol is used as the working fluid. The movement of fluid will be smooth only if there is enough heat flux to change the phase of the fluid. It can be seen from the graph that as the time increases, the evaporator temperature also increases also, as the heat input increases, the temperature of the evaporator also increases.

Effect of heat input on condenser temperature for ethanol

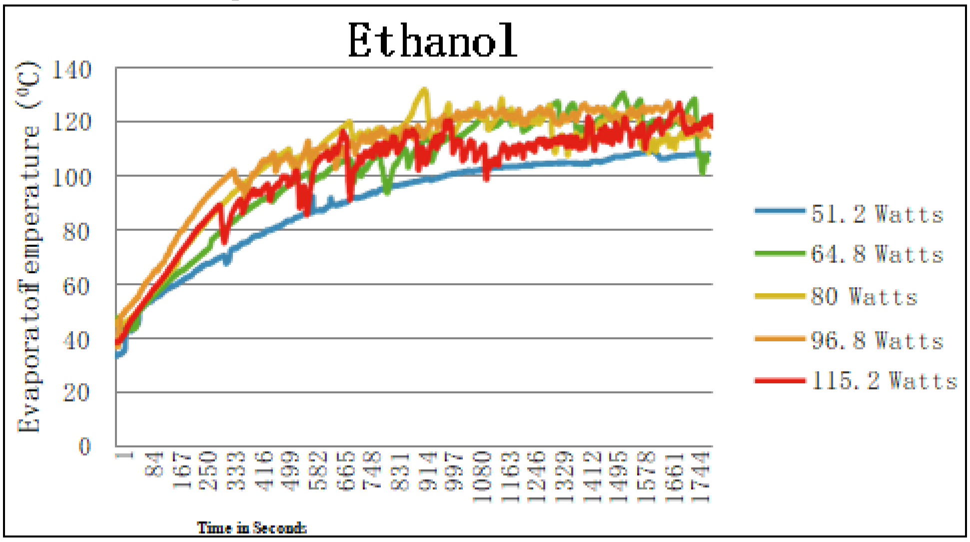

Figure 4.2 Variation of Condenser Temperature with Time for Different Heat Inputs for Ethanol

Figure 4.2 shows the variation of Condenser temperature with time for different heat inputs when Ethanol is used as the working fluid. Also from the above plot it is clear that as the heat input is increased, the condenser section temperature decreases. This happens because as the heat input is increased the movement of the fluid becomes smoother and continuous resulting in the increased heat transfer rate.

Effect of Heat Input on Temperature Difference between Evaporator and Condenser for Acetone.

Figure 4.3 shows the variation of temperature difference between evaporator and condenser for different heat inputs when Acetone is used as the working fluid. It is clear from the graph that as the heat input is increased the temperature difference decreases. As the movement of the fluid is not continuous and slow at lower heat inputs it is associated with lot of perturbation and hence temperature difference is higher for lower heat inputs. As the heat input is increased, the movement of the fluid becomes smooth, continuous and fast reducing the temperature difference due to increased heat transfer rate.

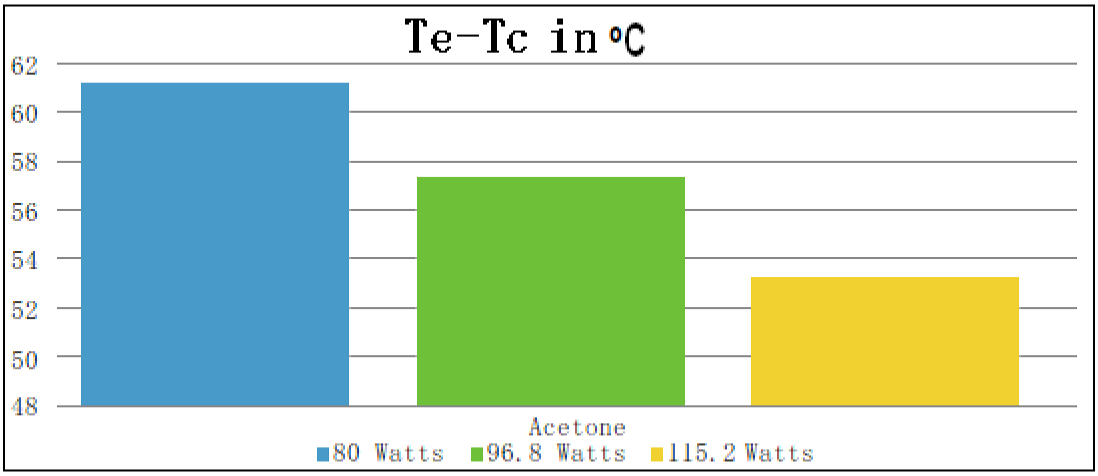

Figure 4.3 Variation of Temperature Difference with Time for Different Heat Inputs for Acetone

Effect of Working Fluid on Temperature Difference at 80 W

Figure 4.4 shows the variation of temperature difference between the evaporator and condenser with time for different working fluids at a heat input of 80W.

It is observed that the temperature difference between the evaporator and the condenser is less for Acetone and more for other fluids. This shows that Acetone can transfer heat with less temperature difference compared to other fluids.

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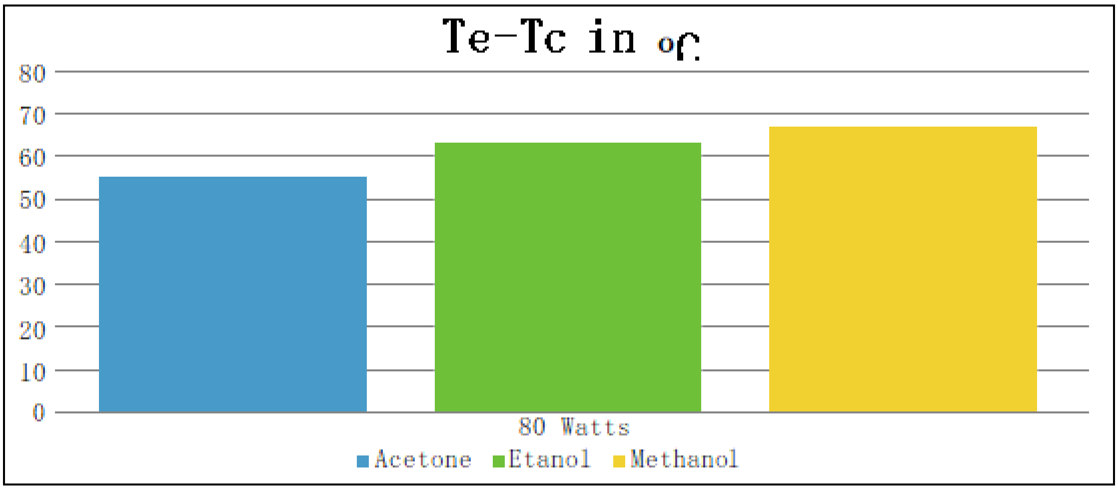

Figure 4.4 Effect of Working Fluid on the Temperature Difference between Evaporator and Condenser

Thermal Resistance

Thermal resistance is analogous to electrical resistance. Electrical resistance is computed as the difference in voltage between two points divided by the electrical current flowing between them. This analogy is based on the fundamental similarity between voltage and temperature, current conduction and heat conduction: Electrical conduction occurs in response to a voltage difference; heat conduction occurs in response to a temperature difference.

Thermal Resistance is defined as the difference in temperature between two closed isothermal surfaces divided by the total heat flow between them. It further requires that all of the heat which flows through one surface also flows through the other and that no net thermal energy accumulation occurs in the volume between the surfaces.

So, Thermal resistance of the heat pipe is given by,

$$R = [(Te - Tc) / Q]^0 \text{C/W} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.1$$

Where, Q = Heat input (W)

T_e = Average evaporator temperature (^{0}C)

T_c = Average condenser temperature (^{0}C)

Effect of Fill Ratio on Thermal Resistance (R)

Figure 4.5 show the variation of thermal resistance with heat input for Acetone. The figure shows that the thermal resistance decreases with increase in heat input in case of all fill ratios considered. It also shows that the thermal resistance of OHP is less at a fill ratio of 80%. This is due to the fact that there is sufficient fluid inventory at higher fill ratio which enables efficient heat transfer.

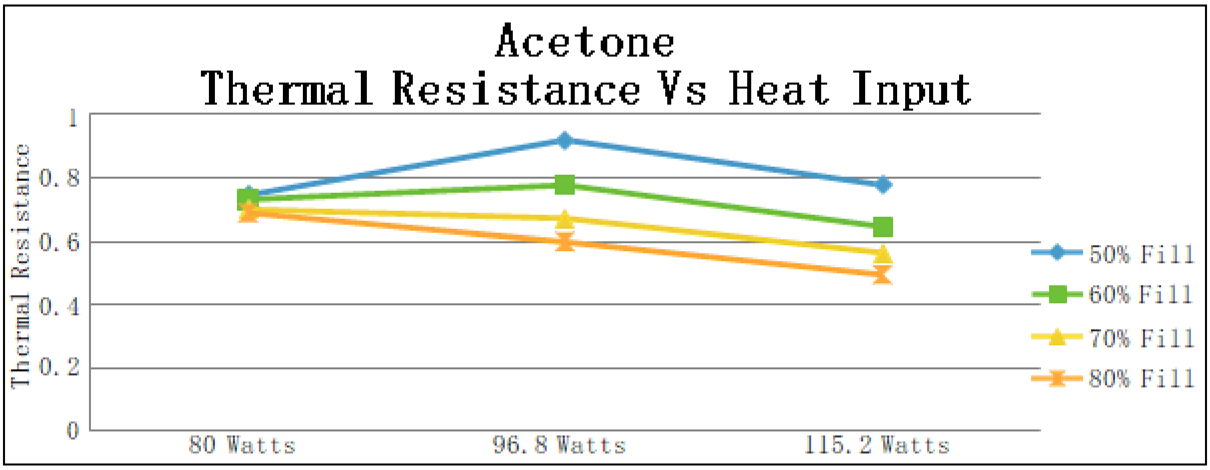

Figure 4.5 Effect of Fill Ratio on Thermal Resistance of Acetone

Effect of Heat input on Thermal Resistance R_{th}

The table 4.1 shows the values of thermal resistance at different heat inputs for various fluids. Figure 4.6 shows the thermal resistance for different fluids considered in the study at steady state. From the figure, it is clear that the thermal resistance of Acetone is less compared to other fluids considered due its lower value of latent heat and temperature difference between evaporator and condenser. Hence, Acetone can be considered as the suitable working fluid for OHP operation.

Table 4.1 Effect of Heat Input on the Thermal Resistance for Various Fluids for a Fill Ratio of 80%

Heat Input (W)	Thermal Resistance (^{o}C/W)		
	Acetone	Ethanol	Methanol
51.2	0.884	1.246	1.176
64.8	0.515	0.875	0.828
80	0.689	0.877	0.748
115.2	0.495	0.568	0.565

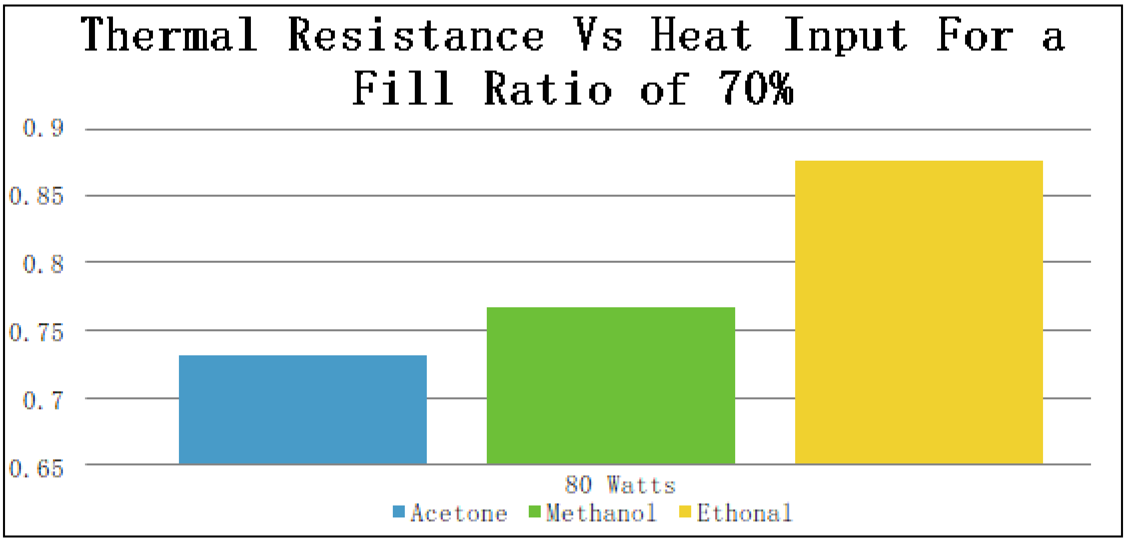

Figure 4.6 Effect of Heat input on Thermal Resistance

Heat Transfer Coefficient (h)

Heat transfer coefficient is a quantitative characteristic of convective heat transfer between a fluid medium (a fluid) and the surface (wall) flowed over by the fluid.

The convective heat transfer co-efficient of OHP is given by

$$h = [Q / (As\ (Te - Tc))]\text{W/ m}^2\text{K} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.2$$

Where,

A_s-surface area of condenser section (m^2)

A_s -π.d.L

d- Inner diameter of the OHP

L- Total length of the condenser section

Effect of Fill Ratio on Heat Transfer Coefficient (h)

Figure 4.7 shows the variation of Heat Transfer Coefficient with heat input for Acetone. The figure shows that the heat transfer coefficient increases with increase in heat input. The figure shows that the Heat transfer co-efficient increases with increase in heat input in case of all fill ratios considered. It also shows that the heat transfer coefficient of OHP is more at a fill ratio of 80%. This is due to the fact that there is sufficient fluid inventory at higher fill ratio which enables efficient heat transfer.

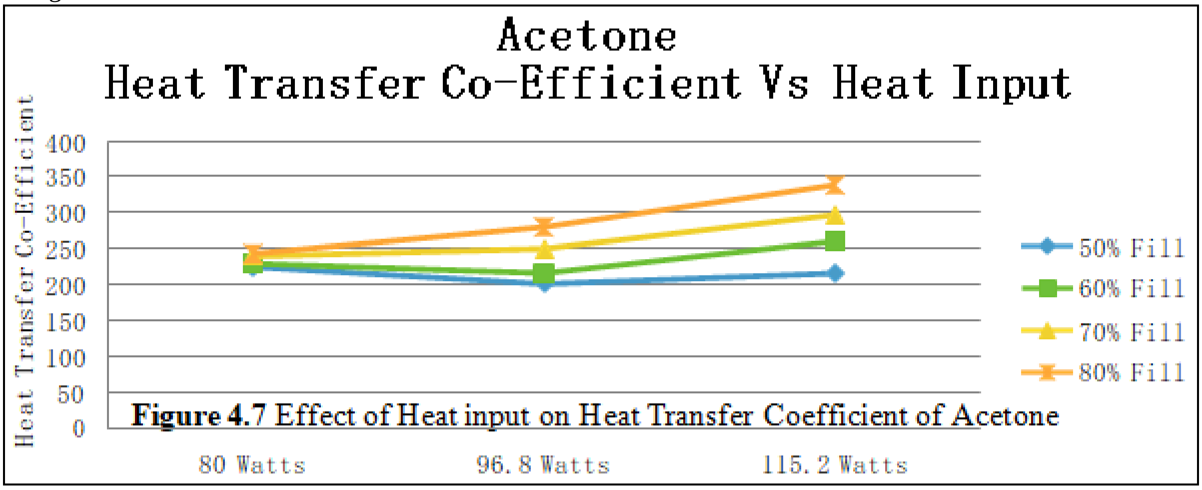

Figure 4.7: Effect of Heat input on Heat Transfer Coefficient of Acetone

Effect of Heat input on Heat Transfer Coefficient (h)

The table 4.2 shows the values of thermal resistance at different heat inputs for various fluids. Figure 4.8 shows the heat transfer coefficient for different fluids considered in the study at steady state. From the figure, it is clear that the heat transfer coefficient of Acetone is more compared to other fluids considered due its lower value of latent heat and temperature difference between evaporator and condenser. Hence, Acetone can be considered as the suitable working fluid for OHP operation.

Table 4.2 Effect of Heat Input on the Heat Transfer Coefficient for Various Fluids for a Fill Ratio Of 80%

Heat Input (W)	Heat Transfer Coefficient(W/m^2k)		
	Acetone	Methanol	Ethanol
51.2	189.413	142.4115	134.368
64.8	324.952	202.333	191.448
80	243.025	223.909	191.024
96.8	279.604	298.421	266.413
115.2	337.935	296.454	294.804

Figure 4.8 Shows the Effect of heat input on heat transfer Coefficient for Different fluids at a fill ratio of 70%

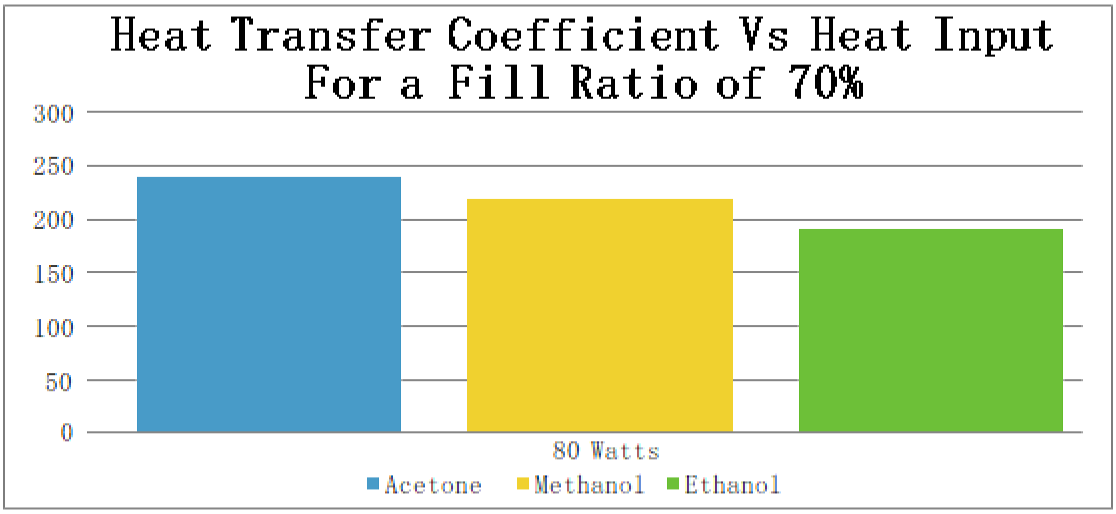

Figure 4.8: Effect of Heat input on Heat Transfer Coefficient for different fluids

4.4 Summary

In this section the experimental results are presented and discussed in detail. In the beginning results obtained by using only individual fluids are presented along with different fill ratios.

5. Conclusions

This work presents the experimental investigations on a multi loop OHP. The effect of heat input, thermal resistance and heat transfer co-efficient on the performance of OHP are studied through experimentation. The following are the conclusions drawn from the experiments conducted on OHP using different working fluids.

1) Acetone, Methanol & Ethanol are individually are tested for its suitability in OHP.
2) More random and intermittent motion of the working fluid with higher perturbations are observed at lower heat input of 51.2 W compared to higher heat input of 96.8 W and 115.2 W.
3) It is evident from the accomplished work that OHP has lower temperature difference between the evaporator and condenser, when Acetone is used as working fluid as compared to Methanol & Ethanol
4) The results indicate that Acetone can transfer more heat with less temperature difference and less thermal resistance. Thus Acetone can be considered as the more suitable working fluid for OHP operation.
5) The experiments conducted indicate that Methanol can also be used as efficient working fluid and exhibits lower thermal resistance values compared to Ethanol.

6. Scope for Future Work

Even though the literature available on the OHP is vast, the literature available on the modeling of the OHP is less. The present study can be further extended with the following suggestions kept in mind.

- Experiments can be conducted for different OHP diameters.
- More number of U-turns can be considered in the construction of OHP.
- Filling ratio of the working fluid can be varied.
- A suitable numerical modeling can be initiated on OHP.
- The similar experiment can be carried out under different vacuum conditions.
- More Number of fluids can be tested.

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