A review on the heat transfer fluids for pulsating heat pipes

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ABSTRACT
Advancements in the field of electronics due to miniaturization and compaction have not only improved the performance of the electronic devices but have resulted in increased heat evolution from the devices. This heat evolution if not properly managed can lead to failure of the devices due to overheating. Hence, thermal management plays a key role in deciding the performance of such devices and is also a challenge for engineers and scientists. A gradual evolution in the field of thermal management has led to the development of highly efficient heat transfer devices. Pulsating heat pipes is one such promising device that can be used for better thermal management of the modern day electronic devices. The important task of heat transfer in a pulsating heat pipe is due to the working fluid present inside the heat pipe. Different types of working fluids have been used for testing the thermal performance of pulsating heat pipes. Nano fluids which are the recent additions in the family of working fluids are gaining importance due to their increased heat transfer abilities. This paper considers the review of the working fluids under various aspects.

Keywords- Pulsating heat pipes, working fluids, nano fluids, Condenser, Devices.

1. INTRODUCTION

Advancements in the field of electronics have led to an improvement in the performance of the modern day electronic devices due to miniaturization and compaction. This has resulted in an increase in heat flux at the chip level and thereby increasing the junction temperatures. Engineers and scientists faced a real challenge to look for alternative means to reduce the heat evolution without compromising on the performance of the devices Ananda.S etal [3].

To meet this requirement, an efficient heat transfer device is needed. Conventional cooling using air or water, jet impingement, spray cooling were some of the earlier methods used for cooling electronic devices G.Karimi etal [10]. The cooling devices are required to be used in conditions of low gravity and limited spacing and can be easily manufactured Zhang.X etal [47].

Consequently, heat pipes were introduced in 1960's.Heat pipes are two phase heat transfer devices having a sealed metallic tube with a wick structure inside it Faghri [47]. Although, heat pipes found to be initially successful, had several limitations. Low heat transfer efficiency in vertical mode of operation, burning of the wick structure due to overheating and low heat transfer efficiency when transporting heat for long distances were some of the major limitations [20].

To overcome the limitations of the heat pipe, a new type of heat pipe called the pulsating heat pipe (PHP) or Oscillating heat pipe (OHP) was first introduced in the 90's by Akachi [1]. Due to high heat transfer efficiency, easy and low cost fabrication and micro gravity operation has attracted the attention of many researchers Niloofar Mohammadi etal [27].

A PHP has a set of meandering tubes bent into a number of turns. PHP has three sections: evaporator section, adiabatic section and condenser sections (fig.1). The evaporator section receives heat from the source. The adiabatic section helps in transporting the heat to the condenser end. The condenser section is a cooler section where the PHP dissipates the heat. A number of design variations (Fig.2) of PHP are available such as the Open loop PHP (OLPHP), closed loop PHP (CLPHP), closed loop PHP and with check valves (CLPHP/CV) and PHP with open ends. Among all the designs, the most popular and most efficient is the CLPHP. Hence, this review considers the analysis of CLPHPs. A working fluid is filled partially into the CLPHP and it naturally distributes into liquid slugs and vapor plugs. The working fluid absorbs the heat in the evaporator and gets converted into vapor bubbles. The formation of vapor bubbles increases the pressure in the evaporator section. This rise in pressure pushes the liquid slugs and vapor bubbles towards the condenser. In the condenser, the vapor bubbles collapse and the pressure reduces. This difference in pressure between the evaporator and condenser is the driving force for the pulsating movement of the working fluid inside the PHP.Since a working fluid forms a medium of heat transfer for the PHP, its study is important. Fluids such as acetone, methanol, ethanol, water, heptane and others have been used as working fluids in the pulsating heat pipes. Recently, nano fluids which is a mixture of nano particles and a base fluid have been used as working fluids in PHPs. The nano fluids have been found to provide promising results in terms of better thermal performance and are 'gaining importance.

Few reviews on the working fluids of pulsating heat pipes are available. Wei Yu and Huaqing Xie[32] reviewed the preparation, stability mechanisms and applications of nano fluids. In their review, the latest preparation methods, stability mechanisms, methods to evaluate stability and ways to enhance the stability of nanofluids have been considered. The current and future applications of nanofluids in different fields like energy, bio-medical and mechanical have been discussed. Faghri [47] reported a detailed review on the heat pipes. In the review, types of heat pipes, performance parameters, constructional features and their limitations have been thoroughly discussed. Zhang and Faghri [47] reviewed the advances and unsolved issues of PHPs.Nagvase and Pachghare [29] have reviewed on parameters affecting the functioning of pulsating heat pipes.Xin Tang et.al.[46]have reported the recent experimental and numerical investigation on PHP. From the above mentioned literature review it can be noted that, reviews on pulsating heat pipes focusing on working fluids of PHPs are few in number. Hence, this paper focusses on the working fluids of PHPs.

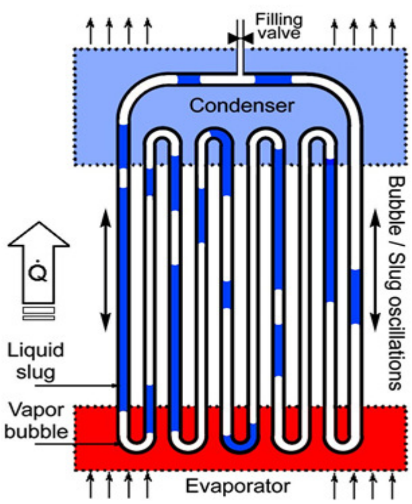

Fig.1 Schematic sketch of Pulsating heat Pipe

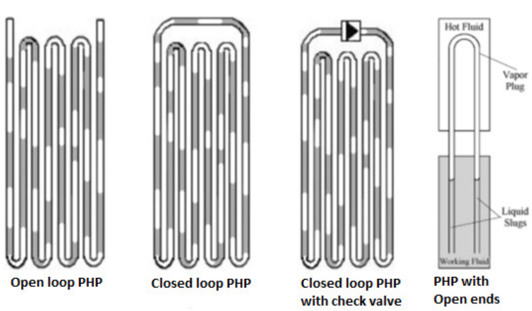

Fig.2 Design Variations of PHP

2. PRINCIPLES OF OPERATION OF PHP

2.1 *Thermodynamic principle*

The PHP is considered as a non-equilibrium heat transfer device as there is a continuous imbalance created in both the pressure and temperature at the evaporator and condenser ends. Although not conclusive (Khandekar et.al[23] attempted to explain the operation of PHP through basic thermodynamic principles. The principle explained considers numerous assumptions.

2.2 *Heat transfer principle*

The majority of the heat transfer inside a PHP is said to take place through sensible heat (Shafii et al. 2002). The heat transfer through latent heat is insignificant. This is also confirmed by Khandekar et al.[23] Although latent heat is considered insignificant, the phase conversion from liquid to vapor and vapor to liquid takes place through latent heat in the evaporator and condenser respectively. The formation of vapor bubbles in the evaporator and its collapse in the condenser creates the pressure imbalance and hence provides the necessary driving force for the working fluid movement. The fluid temperature increases in the evaporator and it decreases in the condenser due to heat dissipation. Thereby, the heat is transported from evaporator to condenser. Heat transfer from the tube wall to the liquid takes place through a thin liquid film and this requires complex analysis Zhang and Faghri [47].

2.3 *Fluid flow principle*

As soon as the working fluid is introduced into the PHP tubes, it distributes itself naturally into liquid slugs and vapor bubbles Khandekar et. al [23], [24]. This tendency for slug and bubble formation arises due to the capillary effect of the PHP tubes. The surface tension of the working fluid results in the menisci being formed at the ends. Normally the vapor bubbles are surrounded by thin liquid film through which the heat transfer takes place Khandekar et.al [24], Zhang and Faghri [47].Due to the heat addition and heat removal in the evaporator and condenser, a pulsating movement is observed. There can be different forces acting on the fluid coupled with heat and mass transfer taking place and are as shown in fig.3. The viscous forces generate shear stresses (τ) at the wall and may cause viscous dissipation. The magnitude of the shear stress developed depends upon the type of flow whether laminar or turbulent Zhang and Faghri [47]. Gravity force (g) acts along the fluid flow or against it depending upon the orientation of the PHP. The pressure forces (F_1 and F_2) act oppositely on a liquid slug and vapor plug.

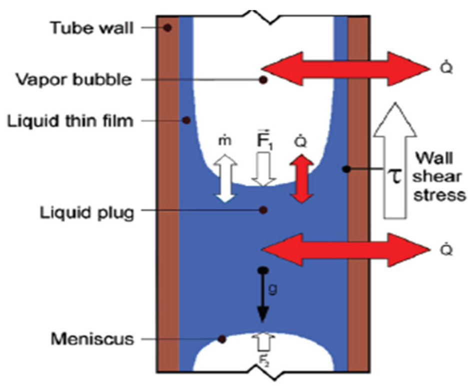

Fig. 3 Fluid flow inside a PHP

3. EFFECIENCY PARAMETERS OF PHP

The efficiency or heat transfer capability of a PHP is obtained by considering the following parameters. The parameters are: Thermal resistance (Rth) (eqn.1) and heat transfer co-efficient (h) (eqn.2). The relations for which are as given below.

$$R_{th} = \frac{T_e - T_c}{Q}, °C/W \quad (1)$$

$$h = \frac{Q}{(T_e - T_c)A_s}, \frac{W}{m^2 °C}$$
(2)

Lesser value of Rth and higher values of h suggest the increased heat transfer efficiency of a PHP.

4. FACTORS AFFECTING THE PHP PERFORMANCE

State of the art on PHPs reveal that there are few important parameters affecting the thermal performance of a PHP and they are as follows.

1) Inner Diameter of the PHP tubes
2) Filling ratio
3) Heat input
4) Orientation of PHP
5) Number of turns
6) Working fluid

4.1 *Inner diameter of the PHP tubes*

The inner diameter is a parameter which affects the very definition of pulsating heat pipes Karimi and Culham [10] For the successful pulsating action of the working fluid inside the PHP, the inner diameter of the PHP tubes should be less than the critical or maximum diameter, D_{crit}. The critical diameter can be obtained from eqn.3.If the inner diameter D< $D_{critical}$, surface tension forces dominate and stable liquid slugs are formed. But, if D >$D_{critical}$ then all the working fluid stratifies due to gravity and the PHP will then function as an interconnected array of two-phase thermosyphons Karimi and Culham [10];Piyanun Charoensawan et al[31].

$$D_{crit} = \sqrt{\frac{B_o \sigma}{g(\rho_l - \rho_v)}} \quad (3)$$

B_o denotes the Bond number which is a dimensionless number and is a ratio of gravitational force to surface tension force. The theoretical maximum inner diameter occurs when the square of Bond number is equal to 4.

4.2 *Fill ratio*

The fill ratio also called as charge ratio and is the volume of the working fluid in reference to the total volume of the PHP (eqn.4). It is denoted by the symbol ϕ.

$$\Phi = \frac{Volume of liquid}{Total volume of PHP} \quad (4)$$

Fill ratio can significantly affect the performance of a PHP. For a given PHP, there exists two operating extremities of Fill ratio: 0% and 100% Khandekar and Groll [23]. 0% Fill ratio refers to a completely dry PHP without any liquid. The heat transfer only takes place by conduction with high thermal resistance. On the other hand, for 100% fill ratio, the PHP acts as a single-phase thermosyphon. In this mode of operation, there are no bubbles in the tube, hence no pulsating effect (Khandekar and Groll [23]; Nagvase et al.[29]. In between these two extremities lies a range (20% to 80%) where a true pulsating action of the PHP can be observed (Khandekar and Groll [23]. Fig.4 shows the effect of fill ratio on various fill ratios (Khandekar and Groll [23]. It can be observed that, the optimum fill ratio (providing maximum heat transfer) lies between 30 and 40%. Thereafter, the heat transfer reduces. At higher fill ratios of 80% and above, the PHP functions as a single phase thermosyphon.

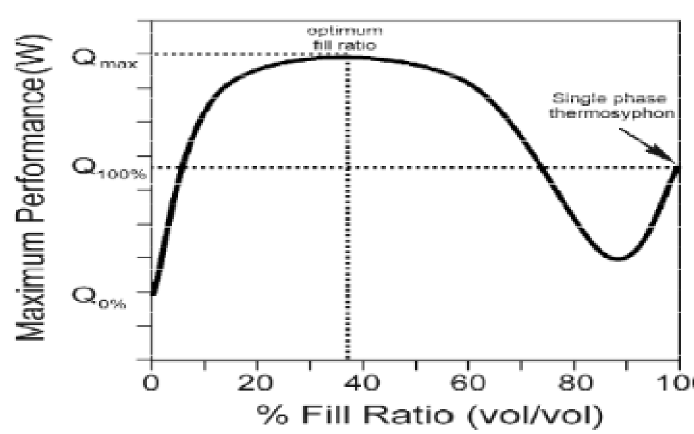

Fig.4 Effect of Fill ratio on thermal performance of PHP

4.3 Heat Input

The only source of energy input for a PHP is the heat input. The heat input is utilized for the circulation of the working fluid inside the PHP. It can also change the functioning of PHP. The marked changes in the behavior of PHP are noticed as: changes in flow patterns, changes in fluid velocity and amplitude, flow instabilities due to changes in bubble sizes Zhang and Faghri [47].

It is observed that, at very low heat inputs, the working fluid did not circulate and hence startup was delayed. At higher heat inputs, pulsating flow with changes in direction was observed. This flow was a combination of slug and bubble flow. The majority of the heat transfer took place through sensible heat. With further heat input, the flow stabilized and was unidirectional. The flow changed from semi-annular to annular from the normal slug flow regime. In the annular flow regime, latent heat was mostly utilized for heat transfer. Annular flow diminished with further increase in heat input and led to dry out. During the dry out condition, the heat flux at the evaporator increases rapidly. The dry out conditions are driven by thermodynamic considerations which require further investigations.

A. 4.4 ORIENTATION of PHP

Although PHPs are considered to operate in any orientation, it has been observed that the orientation affects the performance and is not an independent factor. Orientation has to be combined with the number of turns of PHP to assess the performance (Zhang and Faghri [47]. It has been found that, a PHP having fewer turns can be operated in the vertical position (+90°). But a PHP with fewer turns cannot be operated in the horizontal mode of operation (0°). A successful operation of PHP in the horizontal mode requires a minimum number of turns below which the PHP shows bad performance. (Hudakron et al.[44]; Charoensawan et al.[31].However, in many cases, vertical orientation with bottom heating has provided better results than operating the PHP in horizontal mode.

B. 4.5 Number of turns

The number of turns may affect the thermal performance of a PHP. The number of turns can also overcome the effects of gravity. For example, with more number of turns, a PHP can function in the horizontal mode of operation or in the top heat mode (evaporator on top and condenser at the bottom). In case the number of turns are less than a critical value, a PHP may not be able to function in the above mentioned modes. In some cases the working fluid does not circulate and leads to dry out .With the increase in the number of turns, the heating area increases and the pressure difference created in each turn will add to the total driving force. The number of turns for each PHP configuration is however different and requires further investigation

C. 4.6 Working fluid

As compared to the heat transfer in a bare metal tube PHP, the heat transfer in a fluid filled PHP is better. The bare metal PHP has the limitation of transporting heat only by conduction. While in a working fluid filled PHP the heat transport is through the sensible and latent heat portions of the working fluid which is in addition to the PHP metal tube conduction.

Although a number of working fluids are available, it is required that, they should operate well in the required temperature range. Since PHPs are used in different applications apart from electronics cooling, the right choice of working fluid has to be made. A number of characteristics have to be considered, the thermo-physical properties of the working fluid are very important in this aspect (Nagvase and Pachghare [29]; Niloofar Mohammadi et al.[27]; Zhang and Faghri[47]; Karimi and Culham [10]. The other factors being wettability, material compatibility for the tube material, thermal conductivity and moderate vapor pressure.

4.6.1 Important thermo-physical properties of working fluids

Surface tension

The surface tension is a property which affects the capillary action in a PHP (Hosoda et.al 1999). The surface tension causes the working fluid to distribute itself naturally into liquid slugs and vapor bubbles inside the PHP Khandekar and Groll [23](Tong et al.2001). From eqn.1 we observe that increase in surface tension increases the critical inner diameter and also increases the pressure drop Zhang and Faghri [47]. Hence, more heat is required to vaporize the increased volume of fluid and also to maintain a constant pulsating action. Working fluids with low surface tension is preferred. Surface combined with contact angle hysteresis generates additional pressure drop. (Nagvase and Pachghare [29], Khandekar [23].

Specific heat

It is a property which shows the amount of heat being transported through sensible heat. As the majority of the heat in a PHP is transferred through sensible heat, increase in specific heat of the working fluid improves heat transfer. Working fluid with high specific heat has the capacity to carry more heat from the evaporator to release it in the condenser. This will improve the thermal performance. Hence, working fluid with high specific heat is preferred. In some cases, the nature of flow was affected, where slug flow changed to annular flow Khandekar et al[23]. However, the exact effect of specific heat is still not understood and requires further investigations.

Viscosity

Viscosity is a property affecting the flow of working fluid in a PHP. As the viscosity increases, the friction between tube wall surfaces and the fluid increases and results in a pressure drop. High viscosity also retards the faster movement of liquid inside the PHP and generates high shear stresses (Verma et al.2013). Hence, a working fluid with low viscosity is preferred.

(dP/dT) $_{sat}$

It denotes the change in pressure with change in temperature at saturated conditions. With a high (dP/dT) sat value, the sensitivity for pulsations increases, a small change in evaporator temperature can cause large changes in pressure. Since pulsations increases, efficient movement of working fluid by effective bubble pumping action inside the PHP is ensured. (Khandekar et al.2003). Similarly, instantaneous collapse of vapor bubbles is possible inside the condenser. Working fluid with a high value of (dP/dT) sat is hence desirable.

Latent heat

Among all properties of the working fluid, the latent heat of vaporization is one which strongly affects the bubble formation and liquid slug movement inside a PHP (Borkar et al.2013). The movement of the working fluid through phase change from evaporator to condenser is by means of latent heat of evaporation. This property also helps in identifying suitable working fluids Charoensawan et al [31]. A low latent heat of evaporation promotes faster bubble formation and its collapse at a given temperature and pressure Hoshoda et al[12]. Due to this, a quicker startup is possible and the movement of the liquid inside the PHP is faster and results in better heat transfer performance. A lower value of latent heat can be responsible for maximum heat transport inside a PHP. Charoensawan et al.[31] in their experiments on a 10 turn PHP used three working fluids such as ethanol, R123 and water. They demonstrated that by changing the working fluids from R123 to ethanol and to water the critical heat flux increased. The increase in critical heat flux was due to high latent heat of the working fluid which delayed the bubble formation. Qingping Wu et al. [32] suggested that a link between heat absorbed and latent heat of the working fluid exists. In their experimental investigations on methanol, they investigated properties such as latent heat, surface tension and viscosity. A correlation was developed to analyze the sensitivity of each property. It was concluded that among all the properties the influence of latent heat was maximum.

Apart from the above mentioned thermo-physical properties the compatibility with the PHP tube material and generation of non-condensable gases have considerable effect on the PHP thermal performance. With the non-compatibility of a working fluid with the PHP tube material may lead to low thermal performance and corrosion. A galvanic cell may also result inside the PHP thus reducing the thermal performance.The table 1(Bhagat and Watt 2015),Nagvase et al[29] shows the compatibility of different working fluids with different PHP materials.

Table 1: Working fluids compatibility

Working Fluid	Material			
	Copper	Aluminum	Stainless Steel	Brass
Acetone	Yes	Yes	Yes	Yes
Water	Yes	No	Yes	Yes
Ammonia	Yes	Yes	Yes	NA
Ethanol	Yes	Yes	NA	Yes
Methanol	Yes	Yes	Yes	Yes
Propanol	Yes	Yes	NA	Yes
Heptane	Yes	Yes	NA	Yes

Legend: Yes- Compatible; No- Not compatible; NA- data not available.

Although the reasons for the formation of Non-condensable gases inside a PHP may be many but the most important cause is the working fluid (Brent S Taft[6].Non-compatibility of working fluid with the PHP tubes may initiate chemical reactions leading to the formation of non-condensable gases.

For many applications, water may be considered as a suitable working fluid due to its high latent heat, high (dP/dT) $_{sat}$ value, high specific heat and high thermal conductivity. But due to its high surface tension it causes problems in flow by generating additional friction and hence can limit the oscillatory movement. Methanol on the other hand has a low surface tension by which it may be used in low temperature applications. Table 2 provides information about the important properties of commonly used working fluids.

Table 2: Properties of working fluids at 80°C

Working Fluid	Latent heat (kJ/kg)	Surface tension N/m $\times 10^{-3}$	Dynamic Viscosity (N-s/m^2) $\times 10^{-3}$	Specific heat (C_{pl}) (kJ/kg-K)
Acetone	495	16.2	0.192	2.39
Ethanol	960	17.3	0.432	3.03

Methanol	1084	17.5	0.271	2.52
Heptane	330	14.35	0.239	2.47
Water	2309	62.69	0.463	4.197

4.6.2 Effect of working fluid on thermal performance of PHP

Working fluids like water and R-11 were used for the first time in the PHP developed by Akachi H [1]. It was claimed that the working fluids which were found not suitable for conventional heat pipes could be used for PHPs. The thermal resistance values reported was ranged from 0.082 to 0.233 K/W for water and 0.077 to 0.189 K/W for R – 11 in the heat load range of 92 to 310 W. In their study, R- 11 was found to be the most suitable fluid for PHP.

Charoensawan et al [31] conducted experimental investigations on a range of PHPs with Water, ethanol and R – 123 as the working fluids. The CLPHPs had an inner diameter of 2mm and 1mm.The authors showed that the relative share of latent heat and sensible heat was mainly influenced the working fluid properties. They also found that the bubble nucleation, collapse, shapes and bubble pumping action were influenced by the working fluid. They found that, for 1mm diameter PHP, R-123 and ethanol provided good results. On the other hand, water showed better performance in case of 2mm diameter PHP.

An experimental study on PHP was carried out by Zhang et al[48] with FC – 72, ethanol and water as working fluids. They 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 PHP 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.

Riehl 2004 conducted experimental investigations on an open loop PHP (OLPHP). Five working fluids: isopropyl alcohol, ethanol, methanol, acetone and water were used. The OLPHP was operated both in the vertical and horizontal orientations. The inner diameter of the tubes were 3mm. The experiments showed better performance in horizontal orientation for all working fluids. However, acetone was the best working fluid for vertical orientation and methanol for horizontal orientation.

Borgmeyer and Ma [7] carried out experimental investigations on flat plate PHP. The PHP had rectangular channels milled on a flat plate. Three working fluids were used: HPLC water, ethanol, fluetc PP2 and flourinert. The PHP charged with water for 50% fill ratio did not function in the horizontal mode. But when charged with ethanol and fluetec PP2 showed appreciable movements. Both the velocity and displacement for ethanol were the highest for ethanol as compared to fluetec for different heat inputs. At 100W, the maximum displacement recorded for fluetec PP2 and ethanol was 0.07mm and 0.59mm respectively. The velocity was 11mm/s and 1.4mm/s for ethanol and flutec PP2 respectively. This large difference was due to the high density and high viscosity of fluetc PP2 as compared to ethanol which results in impeded motions. However, flourinert showed increase in displacement and velocity with small increase in inclination angle from 0° to 5°.

Dadong Wang and Xiaoyu Cui[8] investigated the effect of pure and mixture of working fluids on the thermal performance of a PHP. They used acetone, methanol, ethanol and water as pure working fluids and the mixtures of working fluids like acetone/water, ethanol/water and ethanol/acetone. The fill ratio used was 60% and with heat inputs of 20W, 40W, 60W, 80W and 100W. It was found that, the thermal resistance for pure fluids increased in the order acetone, methanol, ethanol and water. For the mixture of fluids, the thermal resistance of methanol/water was lower than methanol and water. The acetone/water PHP provided the thermal in between that of acetone and water. However methanol/water PHP showed better performance as compared to methanol and water individually as shown in fig.5.

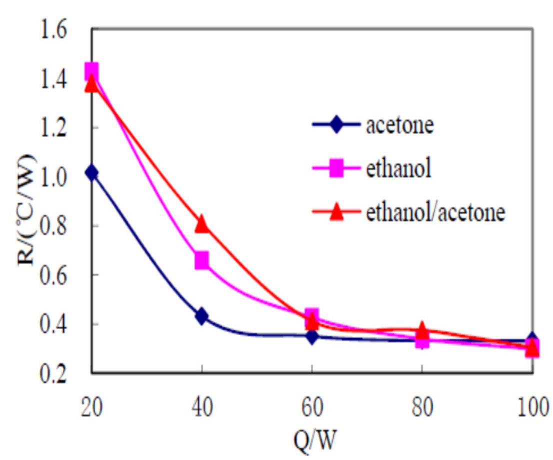

Fig.5 variation of Thermal resistance with heat load for ethanol/acetone mixture

Ramanarasimha et.al [20] conducted an experimentally study on a single loop PHP with four working fluids: acetone, ethanol, methanol and water. Both the heat input and internal pressure of the PHP were varied. Internal pressure was varied by using a vacuum pump. The results of the study showed that at low heat inputs the working fluid motion was not continuous. The atmospheric conditions was found to be more suitable for better heat transfer than evacuated conditions as indicated by the low temperature difference between evaporator and condenser. Acetone showed overall better performance in terms of low thermal resistance (Fig.6) as compared to water, ethanol and methanol.

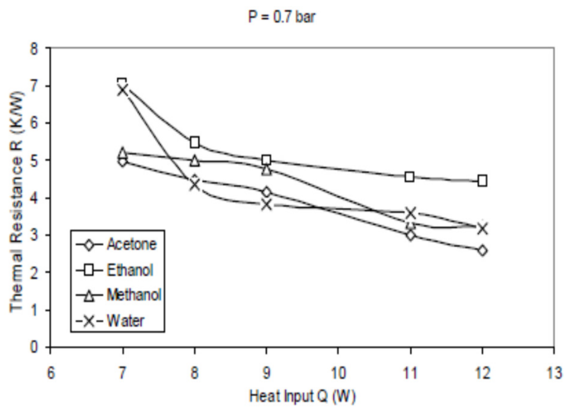

Fig.6 variation of Thermal resistance with heat input for different working fluids at 0.7bar pressure

R.Naik et al. [9] experimentally investigated the thermal performance of a single loop PHP using acetone, ethanol and methanol as the working fluids. The inner diameter of the PHP tubes was 1.95mm and the outer diameter was 3mm. The PHP was tested both in the horizontal and vertical orientations. 60%, 70% and 80% were the fill ratios and heat input was varied between 8W and 16W in steps of 1W. From fig.6 it may observed that acetone showed better performance (low thermal resistance) both in the vertical and horizontal mode of operations. Acetone also provided a better heat transfer coefficient as compared to other working fluids. It was concluded that for a 60% fill ratio for all heat loads in the horizontal orientation a single loop PHP was capable of providing better results.

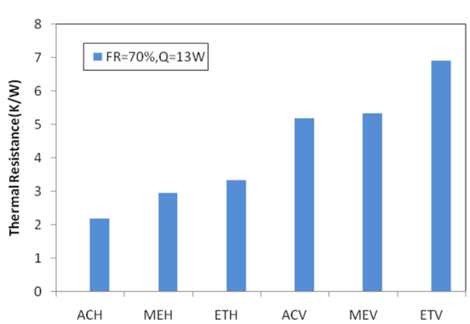

Fig.7 Variation of Thermal resistance for different working fluids.

A flow visualization study of a PHP was conducted by Koji Fumoto et al. [21]. The internal diameter of the PHP tubes was 2 mm. The PHP tube channels were made of Teflon and the number of channels were 12.The working fluids used were water, ethanol and self-rewetting fluids. The self-rewetting fluids used were alcohols such as pure and aqueous pentanol. The surface tension of water, ethanol and pure pentanol decreases linearly with increase in temperature whereas the variation is abrupt in case of aqueous pentanol as shown in fig.7. This results in changes in flow boiling behavior and also initiates surface tension driven convection .Flow visualization of the working fluids revealed that liquid slug displacement increased with self-rewetting fluid (aq.pentanol) as compared to normal fluids .It was also observed that the temperature difference between evaporator and condenser was lesser in a self-rewetting fluid in comparison with the normal fluids thereby suggesting better heat transport.

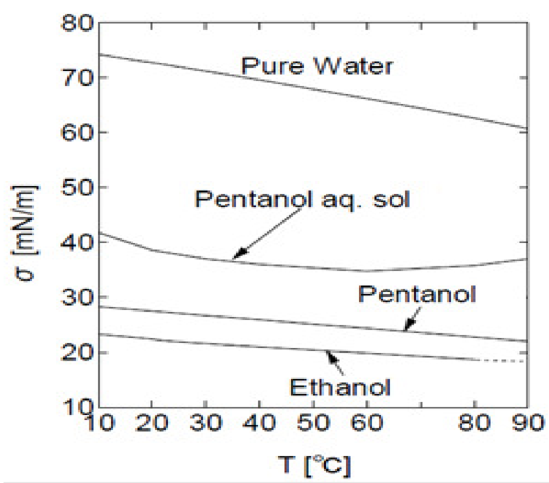

Fig.8 Variation of surface tension with temperature for different working fluids.

4.7 Nano Fluids as working fluids for PHP

Although the concept of suspending solids for enhancing thermal conductivity of fluids was conceived a century ago, it was unpopular due to shortcomings such as: Rapid particle settling in the fluid, erosion of heat transfer device pipelines, clogging of flow channels and increased pressure drop of the fluid. By the advancement of technology, nano-meter sized particles have been developed. These particles have different mechanical, thermal, physical and optical properties compared to their parent materials. Nano fluids are the suspensions of nano particles in base fluids. Nano particles are of three major types: Ceramic particles (CuO, Al_2O_3, SiO_2, TiO_2 and SiC) Metallic particles (Cu, Fe, Au and Ag) and Carbon nano-tubes (CNT's).The base fluids used are water, ethylene glycol, transformer oil and toluene (Das et al.2006).

Nano fluids when used as working fluids in a PHP, improves the thermal performance (Goshayeshi et al 2015) due to: (i)Increase in thermal conductivity of the working fluid by the presence of nano particles (ii)The Brownian motion of nano particles is enhanced with increase in temperature and thereby improves convective heat transfer. The thermal conductivity of a nano fluid is better than conventional working fluids Das et al[9]. By the virtue of pulsating movement of the nano fluid inside a PHP, the nano particles are well dispersed and hence do not settle down. The size of nano particles used are normally less than 100nm which does not choke the tube passage through which they are flowing Mohammadi et.al [26].The surface heat transfer area of the evaporator is increased due to the nucleation sites created by the nano particles present in the nano fluid Karthikeyan et al [19].

4.7.1 Thermal conductivity of nano fluids

In any heat transfer application the thermal conductivity of the medium transporting the heat plays a major role. For example the thermal conductivity of the refrigerant is important in transporting heat from the evaporator to the condenser. Similarly, in case of a PHP, working fluid with better thermal conductivity is preferred. In 1995, Argonne laboratory of USA found that by dispersing nano particles in a fluid improved its thermal conductivity Kumaresan and Venkatachalapathy [11] ,Choi and Eastman [15]

In 1877, Maxwell suggested a relation to find the effective thermal conductivity of a two phase (solid-liquid mixture) at low concentrations (eqn.4)

$$k_{eff} = \frac{k_p + 2k_b + 2(k_p - k_b)\phi}{k_p + 2k_b - (k_p - k_b)\phi} k_b \qquad (5)$$

Batchelor and O'Brien in 1977, developed a model (eqn.4) (Choi and Eastman 1995) to find the effective thermal conductivity of a two phase system containing metal powders with diameters in the range of micrometers.

$$k_{eff} = k_o\left(4\ln(k_m/k_o) - 11\right) \qquad (6)$$

Where k_m is the thermal conductivity of the metal particles and k_o is the thermal conductivity of the base fluid.

Different methods are employed for measuring nano fluid thermal conductivity. Transient hot wire method, parallel plate method and temperature oscillation method are those commonly used Mohammadi et al[26].Choi and Eastman [15] proved for the first time that the thermal conductivity of a base fluid improves by adding small quantities of nano sized particles. This was proved by adding small concentrations of copper nano particles or copper nano tubes into liquids such as ethylene glycol and oil. The thermal conductivity of the resulting solutions increased by 40% and 150% respectively.Das et al [9] has reported that, thermal conductivity of nanofluids is dependent on operating temperature. In addition to this, Patel et al. [30] also showed that increase in thermal conductivity can also result from continuous movement of nanoparticles. While, Qu et al. [33] have shown that increase in thermal conductivity is due to the nano particle concentration.

Murshed et al.[43] investigated the thermal conductivity enhancement of a TiO_2-water based nano fluid. The thermal conductivity was measured using the hot wire method. The results of the investigation indicated that the thermal conductivity of the nano fluid increased by nearly 33% over that of the base fluid (water). Eastman et al.[15] found that the thermal conductivity of ethylene-glycol-Copper nano fluid increases more than that of the pure ethylene glycol or ethylene glycol containing the same volume fraction of the copper oxide nano particles. The thermal conductivity was found to increase by 40%. Measuring the thermal conductivity of fluids containing oxide nano particles, (Lee at al 1999) found that the thermal conductivity of oxide based nano fluids is better than fluids without nano particles. The experimental results agreed well with the results of the Hamilton-Crosser model which could also predict the thermal conductivity of nano fluids containing Al_2O_3 particles. However, the model was inadequate in providing correct results for CuO based nano fluids.

4.7.2 Preparation of Nano fluids

The preparation of nano fluids plays a key role in the heat transfer enhancement of nano fluids. The nano fluids should be stable suspensions with very little or no agglomeration of nano particles in the base fluid Das et al[9]. Nano fluids can be prepared by two methods: (i) One step method (ii) Two step method.

Physical vapor deposition method, chemical reduction method and liquid chemical method are the common procedures adapted in a one-step method Kumaresan & Venkatachalapathy [11]. The one-step method is less time consuming and chances of agglomeration of nano particles in the base fluid is very less Das et al.[9]. One step method is suited only for low vapor pressure fluids. By using the physical method, Eastman et al [15] was able to successfully synthesize Copper-ethylene glycol based nano fluid. Copper-water nano fluid mixture was synthesized by Liu et al.[22]through chemical reduction method.

In the two step method, the nano sized particles such as metal powders, metal oxide, fiber particles and carbon nano tubes are prepared first. Various techniques used: inert gas condensation, direct gas condensation, chemical vapor condensation. The most recently used is LASER vapor deposition. The particles are then dispersed in a base fluid such as water, ethylene glycol, toluene and kerosene. The chances of agglomeration of the particles in the base fluid is high as the time required involved in the preparation is quite high Das et al [9]. Ji et al[17] prepared a nano fluid consisting of alumina nano particles and 50/50 by volume of ethylene glycol and deionized water in a two-step process. The mixture was stirred continuously using a mechanical stirrer for three days to eliminate the possibility of agglomeration of the particles in the liquid.Ma et al. [25] fabricated diamond particles of size 5-50nm by 20 kW rf plasma of frequency 14Hz. The diamond particles were mixed with HPLC water to obtain the nano fluid. The method employed was a two-step process. Although the two step method of preparing the nano fluid is commonly used, the disadvantage is that, the time required for preparation is more and chances of agglomeration of the particles is also high.

4.7.3 Effect of nano fluid on the thermal performance of pulsating heat pipe

Ma et al. [25] conducted an experimental study on a nano fluid PHP to investigate the nano fluid effect on the heat transport capability of a PHP. In their studies they used HPLC grade water and 1 vol. % diamond nano particles of 5 – 50 nm. The results of the investigation indicate that the heat transport capability of a nano fluid based PHP is enhanced as compared to water based PHP (Fig.7). Similar results were obtained by (Karthikeyan et al.[19]who conducted experimental investigations on the effect of nano fluid on thermal performance of PHP. In their study they used copper and silver colloidal nano fluids. The thermal performance was compared with normal working fluid such as DI water. The results of their study indicate that, the heat transfer capacity improved by 33% by the use of nano fluids as compared to DI water PHP. In their studies on Silver-water based PHP,Weixiu Shi et al.[45] showed that the heat transfer limit of a PHP can be significantly enhanced using a nano fluid. In addition to this, it was demonstrated that the use of silver-water PHP provided operational stability and reduced startup power.Hamed Jamshidi et.al[14] have detected the effect of concentration on heat transfer performance of a PHP. They have reported that, the heat transfer performance of a PHP decreases with decrease in nano particle concentration. The effects of magnetic field on the thermal performance of PHPs have been explored by few researchers. Maziar Mohammadi et al. [26] studied the effect of magnetic field on the water-based ferrofluid (Nano fluid) on the thermal performance of PHP. The volumetric concentrations used for Nanofluid were 2.5% and 7%. It was found that in the presence of a magnetic field, the best thermal performance was achieved for higher concentrations (7%).Whereas, in the absence of the magnetic field, lower concentration (2.5%) provided good results. This was attributed to the lower viscosity of the fluid at lower concentrations (Fig.9).Nannan Zhao et al.[28] conducted similar experiments consisting of distilled water and dysprosium (III) oxide nano particles. The average size was 98nm and mass ratios of 0.1%, 0.05% and 0.01%.From the study it was evident that, nano particles with mass ratio less than 0.1% can only improve heat transfer in the presence of the magnetic field. In addition to this they showed that the startup power required reduces due to the presence of magnetic field.

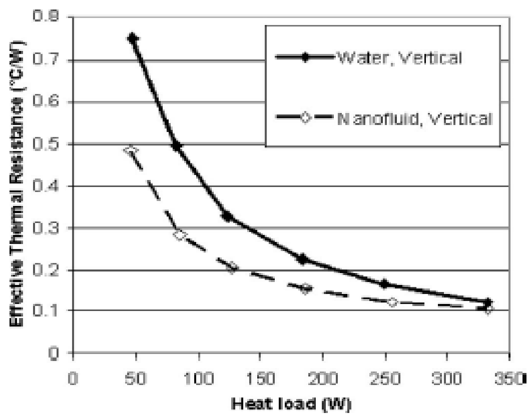

Fig.8 Thermal resistance comparison for water and nanofluid

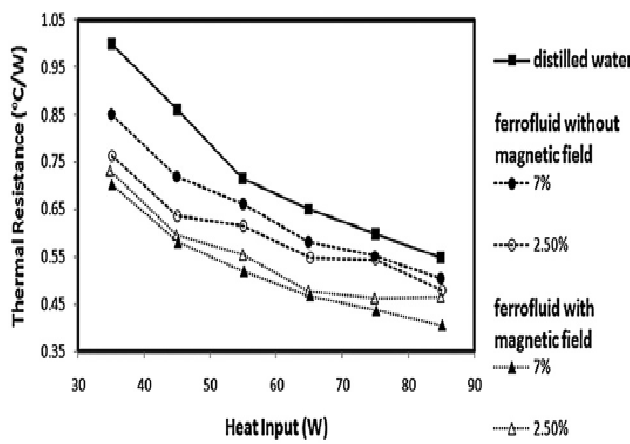

Fig 9. Variation of thermal resistance for different concentrations

For a nanofluid to exhibit improved heat transfer performances, the size and shape of the nano particles becomes important. Ji et al[17]studied the effect of shape of the nano particles on the thermal performance of PHP. In their study four sizes of the Al_2O_3 nano particles were used: 50 nm, 80 nm, 2.2

µm and 20 µm. the study revealed that by charging the php with fluids containing smaller size nano particles (80nm), the heat transfer capability could be improved. in addition to this, the shape effect on heat transfer performance of php was also studied by Ji et al.[17] in their study they used alumina nano particles of four different shapes i.e., platelet, blade, cylinder, and brick. From the results of the study it was concluded that, the cylindrical shaped nano particles gave the best performance. The brick shaped particles provided the lowest heat transfer performance.

Although a number of studies based on use of nano fluids in PHP's are reported and portray several advantages, quite a number of issues still need to be addressed and are as follows. Extensive parametric studies based on thermal conductivity, particle size, and volumetric concentration ratio of nano fluids needs to be undertaken for different combinations of nano particles and base fluids. Studies on various nano particles like Ni, Zn, Zr, ZnO, CeO_2, etc. and various base fluids like alcohols, refrigerants, oils are to be explored and their suitability as working fluids for PHPs has to be established. Studies related to particle settling, particle agglomeration, surface erosion and phase change of nano fluids are still not available.

5. CONCLUSION

A review on the working fluids (conventional and nano fluids) have been presented. Various technical aspects such as thermodynamic principles, heat transfer principles and factors affecting the PHP performance have been discussed. It was pointed out that there is a critical diameter which has significant effect on the pulsating action of the PHP. An optimum fill ratio also exist which gives the best performance for the PHP.

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