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Nano fluid- An alternative fluid in Pulsating Heat Pipe/Oscillating Heat Pipe

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Abstract: *The present article reviews the various features of nano fluid as an alternative fluid in pulsating heat pipe(PHP) which has high thermal performance required in cooling technologies of electronics engineering along with the factors affecting the performance of PHP with nano fluids. The need of nano fluid in heat pipes is discussed. Effect of nanofluid on heat transport capability of PHP/OHP is covered. Reasons for improved heat transfer with nano fluids are discussed. Effects of nano fluids on various parameters like Rwall, Ri-v,Revap&Rcond, flow pattern, startup of a PHP & thermal resistance are included. Results of experiment performed to study the effect of nano fluid concentration on thermal resistance of PHP have also been discussed. It is concluded that nano fluids are potential fluids to be used as working fluid in PHP.*
Keywords: *pulsating heat pipe/oscillating heat pipe, nanofluids, working fluids, heat transfer enhancement, thermal resistance, startup of PHP.*

Abbreviations and Nomenclatures

D_{max}	maximum diameter	μ	dynamic viscosity of fluid
σ	surface tension of fluid	g	acceleration due to gravity
ρ_l	density of liquid	k	thermal conductivity
ρ_v	density of vapor	ρC_p	heat capacity
ΔP_g	pressure difference	l	length of pipe
φ	angle between heat pipe and horizontal axis	N_a	surface active nucleation site density
D_b	bubble release diameter	T_w	wall temperature
f	bubble release frequency	T_{sat}	saturation temperature
A_e	area of evaporator	θ	contact angle of bubble with wall
DI	de-ionized	R_{l-v}	resistance in two phase flow along heat pipe length
FR	filling ratio	R_{cond}	resistance of condenser
PHP	pulsating heat pipe	R_{wall}	resistance of wall
OHP	oscillating heat pipe	R_{evap}	resistance of evaporator

I. Introduction

Miniaturization is in vogue and this euphoria has especially gripped the electronics and allied industry. The insatiable urge for going nano does not come with associated inter-disciplinary technological problems. Although this increased power-decreased size scenario has been prevalent for many decades, in recent years, thermal management has become the major feasibility bottleneck for microelectronics. High heat density has complemented to the problem of high power dissipation. Although a number of cooling technologies using miniaturized devices, large devices (e.g. transportation trucks) and new energy technology (e.g. fuel cells) are under development, they all require more efficient cooling systems with greater cooling capabilities. Particularly systems using Nano fluids may show great promise because of their manifold improved physical and chemical properties. The requirement of enhanced cooling technology which is a need of the present day technology may be met by introducing new designs for cooling devices such as micro channels and miniature Cryo-devices and enhancing the heat transfer.

Two phase traditional heat pipes prove to be a bit effective for the removal of large quantities of heat, but, as the total power increases (higher than 300W/cm^2[1]), although the pressure drop occurring in wick structures or flow paths for liquid/vapor flow in a heat pipe significantly increases due to the frictional shear stresses, which directly limits the heat transfer capability in a traditional heat pipe. Compared with the traditional heat pipe, the PHP, proposed and patented by Akachi in early 1990's [2], is a new member of the wickless heat pipes. It has excellent features, such as high thermal performance, rapid response to high heat load, simple design and low cost [3]. The PHP/OHP has a number of unique features as follows:

(i) It is an ‘‘active’’ cooling device that converts heat from the heat generating area into the kinetic energy of liquid plugs and vapor bubbles to initiate and sustain the oscillating motion.
(ii) Since both phases flow in the same direction, the liquid flow does not interfere with the vapor flow.
(iii) The thermally-driven oscillating flow inside the capillary tube effectively produces some free surfaces that significantly enhance evaporating and condensing heat transfer.
(iv) The oscillating motion in the capillary tube significantly enhances the forced convection in addition to the phase-change heat transfer.
(v) As the input power increases, the heat transport capability of a PHP dramatically increases [4].

Such heat pipes have already shown high promise for terrestrial and space applications.

The working fluids used as heat transfer fluids exhibit poor thermal conductivity which limit the heat transfer properties. Due to manifold improved thermal, mechanical, electrical and optical properties of nanometer – sized particles, nano fluids may be used in PHP/OHP systems. Das et al [5] in their review article showed great promise regarding heat transfer using nano fluids in cooling technologies. Use of Nano fluids as working fluids in PHP has attracted researchers all over the world and a number of recent high quality articles have been published on such work [4,6-12]. The present article reports a brief review of the contributions made by different workers in this direction along with its future. A brief account of working principle of PHP is also presented in the beginning. It should be noted that no review article has been published on the recent contributions on the nano fluidic effects on PHP/OHP.

II. Working Principle Of Php/Ohp

The PHP is a special type of heat pipe where the driving force is the slug/plug motion of the working fluid in the tube, generated by the evaporation. PHPs consist of a meandering tube bent to form several parallel channels (fig 1) [13]. It can be configured as an open loop, closed loop and closed loop with check valves (Fig 2). In the first one, one end of the PHP is pinched-off and welded; while the other end presents a service valve for vacuum and charge (this valve can be later removed). The Closed loop PHP is an endless tube as both ends are welded together, while closed loop with check valves incorporates one or more direction control one-way check valves in the loop so that the working fluid can circulate in specified direction only. Each PHP configuration presents particular operation modes, which are mainly guided by the chaotic slug/plug motion of the working fluid.

Karimi and Culham [14] used Akachi and Pohsek s’ [2] theoretical maximum tolerable inner diameter of PHP tube as

$$D_{max} = 2\sqrt{\frac{\sigma}{(\rho_{liq} - \rho_{vap})g}} \tag{1}$$

same as used by Khandekar[15] (but based on balance of capillary and gravity forces).

The performance of a PHP depends upon many factors like the geometrical parameters of flow channel, the working fluid, the filling ratio , number of turns, PHP configuration and the inclination angle [16].Selection of a suitable working fluid for heat transfer application depends on many considerations viz. the operating temperature range, the compatibility with the materials, the thermophysical properties of the fluid like good thermal stability, high latent heat, high thermal conductivity, low liquid and vapor viscosities, high surface tension and acceptable freezing point [17].

It is obvious from a survey of thermal properties of working fluids used today as heat transfer fluids exhibit extremely poor thermal conductivity (with the exception of liquid metals, which cannot be used at most of the pertinent useful temperature ranges)[5]. For example, water is roughly three orders of magnitude poorer in heat conduction than copper—as is the case with engine coolants, lubricants, and organic coolants. It goes without saying that all of the efforts to increase heat transfer by creating turbulence, increasing area, etc., will be limited by the inherent restriction of the thermal conductivity of the fluid. Thus, it is logical that efforts should be made to increase the thermal conduction behavior of cooling fluids.

Using the suspension of solids is an option that came to mind more than a century ago. Modern materials technology provided the opportunity to produce nanometer-sized particles which are quite different from the parent material in mechanical, thermal, electrical, and optical properties. Das et.al. [5] in their review of heat transfer in nano fluids concluded great promise for use of nanofluids in cooling technologies. Thus, nanofluid technology coupled with new heat-transfer-related studies on microchannel flow [18] has provided a new option as working fluid in PHP of revisiting suspensions of nanoparticles.

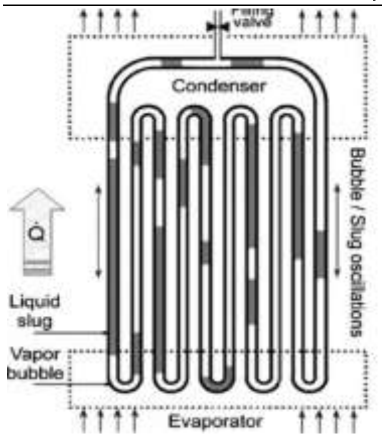

Fig 1 Schematic of a Pulsating Heat Pipe[3] .

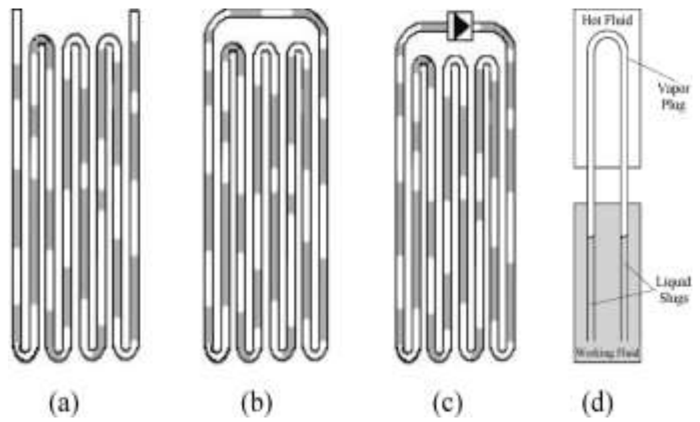

Fig 2 Different PHPs: (a) closed-end, (b) closed-loop, (c) closed-loop with check valve, and (d) PHP with open ends[16]

III. Nanofluid As The Working Fluid For Php/Ohp

TABLE 1 summarizes the work done by the various researchers using nanofluid as working fluid in PHP/OHP. The nanoparticles exhibit large surface area, less particle momentum and high mobility. The thermal conductivity of nanoparticles also significantly increases with a rise in temperature and increase in volume fractions[19,6]. Particles finer than 20 nm carry 20% of their atoms on their surface, making them instantaneously available for thermal interaction. Another advantage is the mobility of the particles, attributable to the tiny size, which may bring about micro-convection of fluid and hence increased heat transfer [7,29]. The micro-convection and increased heat transfer may also increase dispersion of heat in the fluid at a faster rate. Apart from this, the thermo-physical properties of the base fluid also gets affected by the addition of nanoparticles. It is already found that the thermal conductivity of nanofluids increases significantly with a rise in temperature [30], which may be attributed to the above reasons. The presence of nanoparticles in water increases the thermal conductivity (k) of the working fluid. The nanoparticles can absorb liquid molecules, and thus result in the formation of molecular nanolayer on the surface of nanoparticles [31,32], which has a thermal conductivity higher than that of the bulk liquid and can intensify the heat transfer in the interior of the fluid; the addition of nanoparticles to water changes the heat capacity (ρC_p) of the working fluid. For the nanofluids having a higher heat capacity than the base water, more heat will be transferred by the fluid if the flow rate remains unchanged based on the convection heat transfer theory; the dynamic viscosity (μ) of the fluid is also varied due to the addition of nanoparticles. For a nanofluid having a higher viscosity than base water, the increased viscosity means lower flow rate and thus less heat can be transferred by the fluid in the PHP. But if the concentration of the nanoparticle is less, the effect of viscosity on heat transfer can be neglected. Nanoparticles are very small, and the momentum they can impart to a solid wall is much smaller. This reduced momentum reduces the chances of erosion of components, such as heat exchangers, pipelines and pumps [17].

It is projected that the next generation of computer chips will produce localized heat flux over 10 MW/m^2, with the local power exceeding 300 W. No existing low cost cooling device can effectively manage the heat produced at this level. Combining thin film evaporation, nanofluid and oscillating motion, it can be said that PHP appears to be the most favorable option for removing heat fluxes over 10 MW/m^2 [8].

IV. Nanofluids As Working Fluid In Other Heat Pipes

Tsai et al [33] first studied the effect of nano fluids on simple heat pipe and found that the resistance of the heat pipe decreased tremendously when the base fluid was replaced by nanofluid. The circular meshed heat pipe had a length 170mm and an outer diameter of 6 mm. The heat pipe thermal resistance ranged from 0.17 to 0.215 $^0C/W$. They selected gold nano particles of different sizes. As compared to the resistance obtained with DI water, there was a reduction of 33% to 56% in the evaporator, while the reduction in case of condenser was only 7% to 20%. Tsai et al attributed low thermal resistance in heat pipe due to presence of nanoparticles to the probable reduction in bubble release diameter by way of impact of nanoparticles.

There after variety of nano particles and base fluid in heat pipe have been reported such as silver [9,34], Cu[35] and CuO[10,35,36], Al_2O_3[36,37], diamond[1,8], titanium[36,38,39], nickel oxide[40], silica[35]. A reduction in thermal resistances[34-37], reduction in liquid velocity[36](velocity is inversely proportional to density and viscosity) and reduction in startup time[10] has been observed which improved the thermal performance of the heat pipe. Other factors which improved the thermal performance were drop in temperature gradient along the heat pipe[36,37] and an enhanced overall heat transfer coefficient[10] (the metallic nanoparticle e.g. Cu will have better heat transfer enhancement than its oxide i.e. CuO, as Cu is smaller in size).

The SiO_2nanofluid deteriorates contrarily [35] the thermal performance of the heat pipe, the reason being its structure, discussed later in the paper.

V. Effect Of Nanofluid On Different Parameters Of Php/Ohp

In their model Ma et al. [1] considered the thermal energy due to temperature difference between the evaporator and condenser as the driving force for oscillatory motion. In their experimental investigation [20] temperature difference between evaporator and condenser was reported to decrease significantly from 40.9 to 24.3^{0}C when diamond nanoparticles were employed. The strong oscillatory motion made the nanoparticles to remain suspended and thus the nanofluid was a stable working fluid.

5.1 Effect of nanofluid on heat transport capability of PHP

As the heat input increases, the oscillating motion becomes stronger and stronger. The effect of operating temperature on the heat transport capability was also checked [20].The operating temperature also significantly affected the heat transport capability in the PHP and when the operating temperature was increased, the heat transport capability increased(Fig 3). However, at higher heat load and higher operating temperature no significant change was observed. The investigated PHP charged with nanofluids can reach a thermal resistance of 0.03^{0}C/W at a power input of 336 W.

Reihl in 2006 [21] studied the performance of a CuOnanofluid (5%) in water with a PHP with 6 turns. Considerable drop in temperature of the evaporator, condenser and adiabatic section was observed. In 2007 Park and Ma [22] checked the performance of the PHP using 1.0 vol % CuNi nanoparticles which were fabricated with 20 kW RF plasma with a high frequency of 13.56 MHz. The results show that the filling ratio influences the effect of the nanofluid on the heat transport capability. An optimum filling ratio was 50% was obtained. Chiang et.al. [23] used diamond nano fluid with 0.5 wt% concentration and found that optimum filling ratio depends on the structure of PHP; with 36 port PHP, the optimum filling ratio was 50% while with 26 port PHP, it was 20%.

Lin et al. [24] compared the performance of 100ppm and 450ppm silver nanofluid(size 20 nm) with the base fluid, DI water and found the optimum filling ratio as 60%. In a PHP, considerable high filling ratio hinders the pulsation of the bubble and the efficiency of heat transfer is not favourable enough. The low filled ratio gets pulsation of the bubble easily, but it is extremely easy to dry out. Hence, the optimum filling ratio comes around 50-60%, so that the effect of pulsation and bubble production gets balanced. In comparison to 450 ppm, 100ppm Ag nanofluid gave better heat transfer result. When the filled ratio was 60% and the heating power 85 W, the average temperature difference of evaporator and condenser compared with the pure water was less than 7.79^{0}C, and the thermal resistance was also less than 0.092 ^{0}C/W.

Wang et.al. [41] compared the performance of base fluid water Al_2O_3nanofluid on a PHP made of copper with a filling ratio 50%. The heat transport capability of PHP with Al_2O_3 was better than pure water above 40 W regardless of horizontal or vertical mode of operation. The optimum concentration in vertical modewas 0.5 wt% and 1% in horizontal mode. Wannapakhe et al.[25] also obtained same result for optimum concentration of Ag nano fluid 0.5%w/v. they also studied the effect of evaporator length and inclination angle on closed loop pulsating heat pipe with check valves(CLOHP/CV). The inclination angle of the CLOHP/CV has an effect on the heat transfer rate because of a pressure difference (ΔPg) brought about by the hydrostatic head of liquid being positive, negative, or zero. This depends on the fluid density, acceleration from gravity force, tube length, and inclination angle of the CLOHP/CV to the horizontal axis. The pressure difference may be determined from following Eq. [42]:

$$\Delta P_g = \rho_l g l Sin\varphi \qquad (2)$$

whereρ_l is the liquid density (kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), l is the heat pipe length (m), and φ is the angle between the heat pipe and the horizontal axis (φ is positive when the condenser is lower than the evaporator).

The heat transfer rate was maximum for an inclination angle of 90^0, which was 8.88 , 4.13 and 7.69kW/m^2 respectively for evaporator length 50mm, 100mm and 150mm, and nanoparticle concentration 0.5%w/v. The best heat flux was 13.19 kW/m^2 at an aspect ratio (Le/D) of 25, an operating temperature of 60^0 C, and a silver nanofluid concentration of 0.5 %w/v (Fig 4) [25].

Qu et.al. [11] also studied the effect of concentration of Al_2O_3 nanoparticles (56 nm) solution in water on the thermal resistance of PHP. The thermal resistance decreased from 0% to 0.9% but it increased for 1.2% concentration of nanofluid. The maximum decrease was about 0.14 ^{0}C/W (32.5%) as compared to that of water for 70% filling ratio. In the SEM studies it was shown that settlement of nanoparticles occurred both at the evaporator and the condenser, though the agglomeration was more at the evaporator. Thus, the resistance of the condenser was nearly the same for nanofluids and pure water. The change in resistance mainly occurred at the evaporator.

Studies were also conducted on similar set up to compare the performance of silica and alumina nanofluids with the base fluid water [26]. The evaporator wall temperature and the overall thermal resistance both decreased as compared to pure water but in case of silica nanoparticles, both the evaporator temperature and the total thermal resistance increased (fig 5). This effect became more prominent after the concentration of silica nanoparticle increased from 0.1% to 0.6%.

Reihl [27] conducted the studies on open loop pulsating heat pipe using Cu nano particles at a concentration of 5wt% and found a considerable improvement in the performance of the device. The mean evaporation section temperature which stabilized at 118^0C for pure water was 90^0C for nanofluid at 50W.There was also a decrease in the critical diameter of the bubbles by the use of nanofluid. For a saturation temperature of 20 ^{0}C, the critical diameter for water was 5.45x 10^{-3}m while that for water-copper nanofluid (addition of 5% by mass) wa2s 5.33 x 10^{-3}m. This directly contributed to increase the vapor bubble formation and thus the pulsations were more intense. It was also observed that the temperature differences between the evaporator and the adiabatic sections were smaller for high heat loads when nano fluid was used. In this case, the film evaporation effect is more predominant than the nucleate boiling, which directly affects the pulsating flow.

5.1.1 Reasons for improved heat transfer with nanofluids

The heat transfer capacity of the nanofluids showed better results than the base fluid [21, 24, 25, 41]. Reihl**[**21] reasoned that the improvement in thermal behavior of the device was because of the fact that the amount of fluid is always constant in case of nanoparticles. The increase in heat transfer with nanofluid is also because of the large surface area[25], which increases the heat conduction between the base fluid and the particles; the small size of the particles and their speed of Brownian motion, which makes the micro-convection heat movement quick[41] (which was in contradiction to the studies made by Eapen et.al. [43] and the increased thermal conductivity [25,41]). Also the size of nano particle powder being close to phonon, thus the nano-powder particle penetrates the based fluid to form a short circuit and reduces the thermal resistance [41]. The thermal resistance of PHP with nanofluid as the working fluid greatly decreased [41] in comparison to the base fluid; but it increased in case of silica nanoparticles [26].The thermal resistance of a PHP depends on the filling ratio, lowering of filling ratio led to a smaller resistance. The total resistance can be calculated as [25]:

$$R = 2R_{wall} + R_{l-v} + R_{evap} + R_{cond} \qquad (3)$$

Where R_{wall}, R_{l-v}, R_{evap}, R_{cond} are conductive resistance in the pipe wall, the thermal resistance in the two phase flow along the heat pipe length and the thermal resistance at the evaporator and that at the condenser respectively.

5.1.1.1 Effect on R_{wall}

Generally $R_{wall}$is small and independent of the working fluid used.

5.1.1.2 Effect on R_{l-v}

Mainly theheat transfer in this section occurs due to convection, and thus depends upon the thermophysical properties of the working fluid viz. thermal conductivity, heat capacity and dynamic viscosity of the fluid.The presence of nanoparticles in water increases the thermal conductivity (k) of the working fluid. The nanoparticles can absorb liquid molecules, and cause the formation of molecular nanolayer on the surface of nanoparticles [44, 45], which has a thermal conductivity higher than that of the bulk liquid and can intensify the heat transfer in the interior of the fluid; the addition of nanoparticles to base fluid changes the heat capacity (ρCp) of the base fluid; the dynamic viscosity (μ) of the fluid is also varied due to the addition of nanoparticles. For a nanofluid having a higher viscosity than base water, the increased viscosity means lower flow rate and thus less heat can be transferred by the fluid in the OHP; in addition to the above thermophysical parameters, nanoparticles migration motion and its induced microconvection in the aqueous suspension were also assumed to enhance the convective heat transfer of the working fluid.However, the effect of these factors will be small as the concentration of the nanofluid used by the various researchers is very low. [26].

5.1.1.3 Effect on R_{evap} and R_{cond}

The thermal resistancesR_{evap} and $R_{cond}$are greatly influencedby the inner surface conditions. The thermal resistance due to nucleate boiling at the evaporator is given by [46]:

$$R_{evap} = \frac{1}{hA_s} = \frac{1}{2N_a D_b^2 \sqrt{f}\sqrt{\pi K \rho C_p A_s}} \qquad (4)$$

where, Na, Db, f, k, ρ, cp are the surface active nucleation site density, bubble release diameter, bubble release frequency, liquid thermal conductivity, density and specific heat, respectively. Considering that the variation of product (kρcp) due to the addition of nanoparticles be less than 1.1%, and the increase of surface heat transfer area at the evaporator (Ae) due to the deposition of nanoparticles be less than 2.1%, then the above equation simplifies [26] to

$$R_{evap} \propto \frac{1}{N_a D_b^2 \sqrt{f}} \quad (5)$$

Wang and Dhir[47]correlated their experimental data to give the expression of surface active nucleation site density as follows,

$$N_a \propto N_c \left(1 - Cos\theta\right)\left(T_w - T_{wsat}\right)^6 \quad (6)$$

where, Nc is the micro-cavity density on the surface, θ is the surface contact angle, and (T_w-T_{sat}) is the wall superheat. It is clear from Eq.(6) that decreasing contact angle θ (or increasing surface wettability) tends to decrease the active nucleation site density and deteriorate the boiling heat transfer at the evaporator. Fig 6 shows that the surface contact angle at the evaporator decreased from $65^0$for the clean surface to $29^0$and 54^0 for the silica and alumina nanoparticle-deposited surfaces, respectively. The surface contact angle at the evaporator decreased after the deposition of nanoparticles, thus thermal performance of the SiO_2nanofluids-charged PHP deteriorated. For the silica nanoparticle the average size of the agglomerates was about 2-3 μm, which was of the same magnitude as the clean surface cavities. Thus the micro cavity density decreased, as the silica nano particles crammed into the surface cavities and thus deteriorated the nucleate boiling heat transfer. [26].

The deposition of nanoparticles on the condenser surface may also affect the resistance of condenser,$R_{cond.}$ As in case of silica, the deposition was appreciable, hence the thermal resistance increased [26] while the deposition of alumina nanoparticle was negligible, hence it did not affect $R_{cond.}$. Also the size of alumina nanoparticle agglomerates deposited on the boiling surface was several ten to hundred nano-meters (measured by the AFM) [26], which were one to two orders of magnitude smaller than the cavities of clean surface. As a result, when the smaller alumina nanoparticles deposited on the clean surface, they created more new active nucleation sites by splitting a single nucleation site into multiple ones (i.e., Na is increased) , and thus enhanced the boiling heat transfer.

5.2 Effect of nanofluid on flow pattern

There are four types of flow pattern in a PHP: slug flow, annular flow, bubble flow and disperse flow. The annular flow occurs at low temperature, low thermal conductivity, fluid, and high aspect ratio (Le/D). The heat flux of the slug flow is better [25] than the annular flow, the heat flux of the bubble flow is higher than the slug and annular flow, and the best heat flux is dispersed flow. It occurs at a high temperature and a low aspect ratio. With the same fluid, the flow pattern at the inner tube changes from annular flow to slug, bubble, or dispersed flow when the operating temperature is increased.

Bhuwakietkumjohn and Rittidech[12] compared the flow behavior of working silver nanoparticles in ethanol with the base fluid. When the heat source temperature was low (85^0C), annular flow with very few nucleation sites appeared and slug flow with more nucleation sites was observed in the lower part of the evaporator. Slug flow and annular flow dominated the lower and middle parts of the evaporator. As the temperature was increased to 105^0C, slug flow and bubble flow with more nucleation sites were observed in the lower part of evaporator. Bubble flow and slug flow dominated the middle and upper part of the evaporator. On further increasing the temperature to 125^0C dispersed bubble flow with very few nucleation sites appeared in the lower part of the evaporator. The flow behavior was the same for both the fluids. But considerable increase in the heat could be observed. For evaporator length of 50mm, the flux increased 50, 32 and 55% for 85, 105 and 125^0C respectively. The vapor slug length reduced by 1.5 times to 1.8 times while the velocity of the vapor plug increased by 2.3 times to 1.87 times by the use of nanofluid, as the temperature increased from 85^0C to 125^0C. When the evaporator length was increased to 100mm, the flux increased by 3.44 times at 85^0C while the increase was 2.8 times for 105 and 125^0C respectively. As vapor slug length increased to 0.041m which was 0.0034m at 85^0C, but it decreased from 0.0995 to 0.036 and from0.907 to 0.028m at 105 and 125^0C. Similarly the slug velocity decreased from 0.1873m/s to 0.0434 m/s at 85^0C, while it increased from 0.0068m/s to 0.0566m/s and from0.0091 to 0.0625 m/s at 105 and 125^0C.

5.3 Effect of nanoparticle size on startup of a PHP & thermal resistance of PHP/OHP

For both PHPs either charged with pure water or nanofluid, there exists a startup heat input. When the heat input is less than this required startup, no oscillating motions are observed and the temperature difference between the evaporator and condenser increases linearly as the power input is increased. When the temperature is higher than the point when the temperature fluctuations are observed, temperature oscillations start and the temperature acquires a steady value. This indicates that the oscillating motion has started and PHP starts to function. This point is called the startup temperature. The startup condition is very important for the stable oscillating motion occurring in a PHP. The PHP startup depends on many factors such as the wall temperature variation, heat flux level, physical properties of working fluid, heating and cooling modes, transient heat transfer process, initial temperature, and so on [48].

Ma et.al.[20]studied the effect of nanoparticles on startup of the PHP and found that the heat resistance was same as that obtained with base fluid as the working fluid, before the heat input reached the startup i.e. when there was no oscillations. When the evaporator is at the bottom, the nanoparticles stay in the evaporator section. Once the oscillating motions starts and the nanoparticles are well mixed, the thermal resistance reduces significantly.

Ji etal. [4] investigated the effect of four different particle sizes of Al_2O_3viz. 20 µm, 2.2 µm, 80 nm, and 50 nm and the base fluid water on the startup temperature and thermal resistance of a PHP/OHP. When the particle size became smaller, the startup temperature decreased. For the largest particles of 20 µm tested herein, the startup temperature was 48.5 ^{0}C, while for the 50 nm particles the startup temperature was 40.6 ^{0}C. As the particle size reduced from 20 µm to 80 nm, the heat transport capability increased or the thermal resistance decreased. But if the particle size further decreased less than 50 nm, the thermal resistance could not be further reduced, i.e., there exists an optimal particle size for the maximum heat transport capability. Among four particles of 20 µm, 2.2 µm, 80 nm, and 50 nm tested herein, 80 nm particles resulted in the best heat transport capability for the OHP investigated herein, the thermal resistance was 0.113 ^{0}C/W at 25 ^{0}C and a power input of 200 W.

By using Al_2O_3 nanofluid of particle size 45 nm in de-ionised water base with filling ratio 50% in a PHP using copper tubes of 6 turns and inner diameter 1.4 mm, Bhawna et al (49) investigated the effect of Al_2O_3nano particle concentration on the thermal resistance of PHP at different orientations. Fig. 7 shows the experimental results at vertical orientation. It was found that as the concentration increased from 0.25% to 1% the thermal resistance reduced in comparison to DI water, but as the concentration increased from 1.5% to 5.0%, the thermal resistance was more than that of water. Thus the optimum concentration of Al_2O_3 was 1.0%.

5.4 Effect of nanoparticle shape on thermal resistance of PHP/OHP

Ji et al. in 2011[28] tested the effect of shape of alumina nanoparticle. The nanoparticles of boehmite alumina with different shapes, platelet(P1), blade(P2), cylinder(P3) and brick(P4) were studied for varying concentration, 0.3,1, 3 and 5 vol%. A binary mixture of ethylene glycol and DI water (50/50 by volume) was used as the base fluid. The optimum concentration varied with the shape of the particles. For the PHPs charged with platelet, blade and brick,the optimum volume fraction was about 0.3% while for the PHP charged with cylinder; the optimum fraction was 1%. At operating temperature 20 ^{0}C for input power less than 100 W, heat transfer enhancement from the highest to lowest is: P3> P2 > P1 > P4 and for input power more than 125 W sequence of heat transfer enhancement from the highest to lowest becomes: P4 > P3 > P1> P2 for the optimum concentration. But overall cylinder shape gave the best performance.

5.5 *Effect of nanofluid concentration on PHP:*

Bhawna etal.[49] investigated the effect of concentration of Al_2O_3nanofluid on 6 turn copper PHP (i.d1.45mm , o.d2.45 mm) by varying the concentration from 0.25% to 2.5%(fig. 7) at a filling ratio of 50%. It was found that a minimum resistance is obtained at 1.0% concentration. At an input power of50 W, the resistance of PHP decreased from 1.112 for DI water to 0.8045 ^{0}C/W for 1.0% of nanofluidat the heat load of 40W . As the concentration of nanofluid further increased from 1.25% to 2.5%, a reverse effect was obtained. Similar result was obtained by Lin et al.[24] for silver nanofluid ;Qu et al.[11] for alumina nanofluid, etc. As the concentration of the nanofluid increases, the heat conduction coefficient also increases. But in comparison to 1.25%, 1% concentration fluid gave better results. This is because of the fact that higher concentration makes the higher viscosity which makes the bubble difficult to produce and the force of friction causes obstruction of the liquid slug with tube wall becomes larger, so obstruction is relatively greater when the bubble is promoted and influences the whole efficiency of the heat transfer.

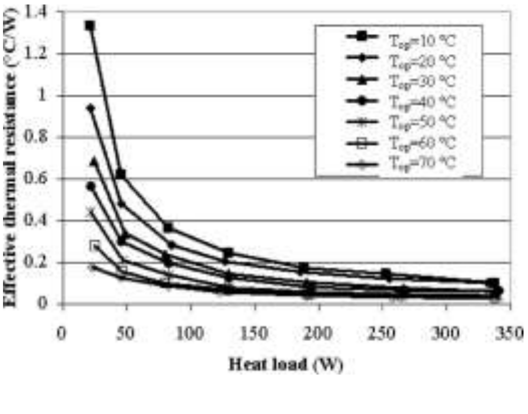

Fig 3Thermal resistance at various heat loads and operating temperatures[20]

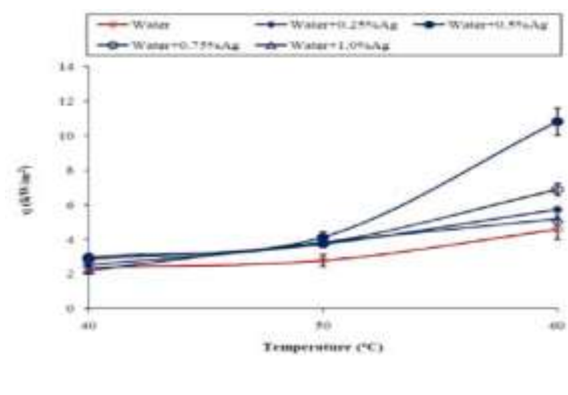

Fig 4 The operating temperature effect on the heat transfer rate of CLOHP/CV at an aspect ratio of 25 [25].

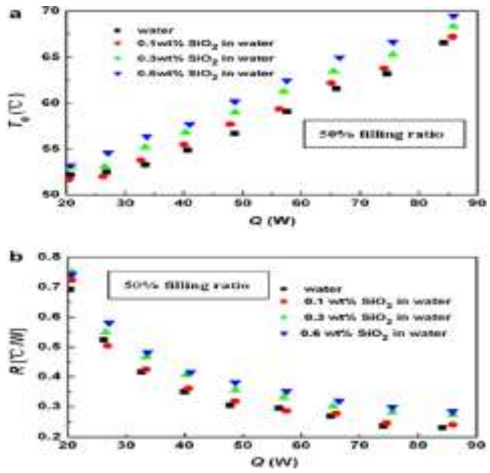

Fig. 5 Thermal performance of the PHP/OHP charged with SiO_2/water nanofluids at different mass concentration(a) Average evaporator temperature; (b) overall thermal resistance[26].

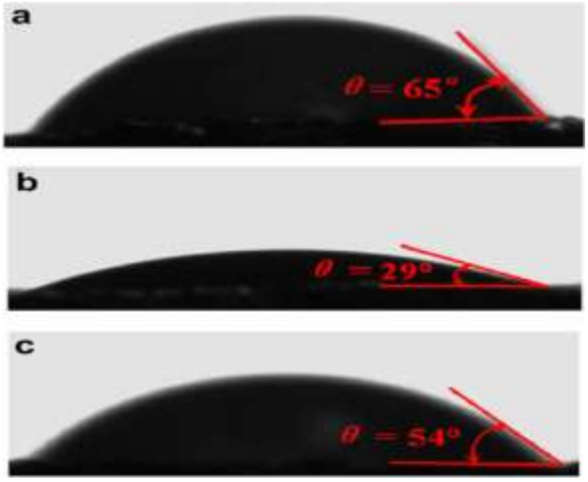

Fig 6Static contact angles of droplet on different surfaces: (a) pure water droplet on clean surface boiled in pure water, $\theta = 65^0$; (b) SiO_2/water nanofluid droplet on silica nanoparticles-deposited surface at the evaporator, $\theta = 29^0$; and (c) Al_2O_3/water nanofluid droplet on alumina nanoparticles-deposited surface at the evaporator, $\theta = 54^0$[26].

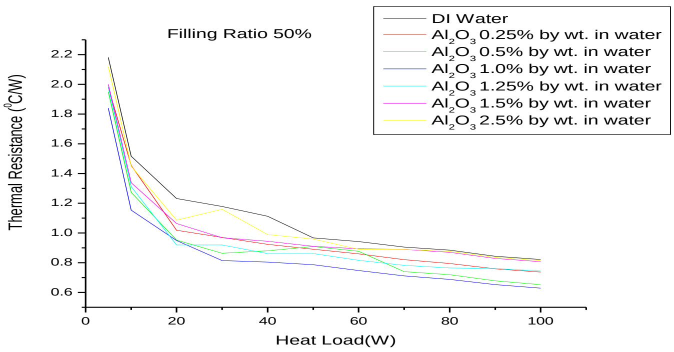

Fig 7 Effect of concentration of Al_2O_3 on thermal resistance of PHP at FR 50%[49]

VI. Conclusions & Future Scope

From the above discussion it can be said that nanofluids are potential fluids to be used as working fluid in PHP/OHP because of the following reasons:

1. Presence of nano particles can affect the startup temperature of the PHP. However, the startup temperature depends on the particle size.
2. When the nanoparticle size is reduced, the thermal conductivity of the nanofluid increases. However, the nanoparticles may agglomerate, settle, or coalesce to the walls with long-term operation of the nanofluid PHP. Preliminary long-term testing of the prototype device showed that the heat transfer performance remained the same over a period of at least six months.
3. Lower operating temperatures and greater pulsations of amplitudes can be obtained with the use of nanofluids in PHP.
4. Enhanced nucleation sites and reduced bubble diameter can be obtained.
5. The surface wettability or the contact angle of the nanoparticles with the surface plays an important role in selection of the nanofluid.
6. Among the four shapes(cylinder, blade, plate and brick) studied so far, the cylindrical shape gives the best result.

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Table: Work done on PHP/OHP with nanofluid as the working fluid

Investigator	Type (Closed/Open)	Material	Diameter & Parallel channels	Nanofluid	Filled Ratio	Q(W)	Conclusion & comments
Ma et.al.(2006) [8]	Closed	Alloy 122 Copper	i.d. =1.65mm, o.d.=3.18mm with 12 turns	HPLC grade water with diamond nanoparticles (20-50 nm)	50%	0 to 336 W	Temperature difference between the evaporator and condenser with nanofluid was quite less than that for base fluid.
Ma et.al.(2006) [20]	Closed	Alloy 122 Copper	i.d. =1.65mm, o.d.=3.18mm with 12 turns	1.0 vol% diamond nanoparticles (5–50 nm)	50%	0 to 336 W	a thermal resistance of 0.03°C/W was reached at 336 W
Reihl (2006) [21]	open	copper	i.d.1.5mm	CuO (5%) in water			Nanofluid seems to improve the device thermal behavior, especially because the amount of fluid is always constant (lower evaporator temperatures)
Park & Ma(2007) [22]	closed			1.0 vol% CuNi particles in HPLC grade water	10-90%		Optimum filling ratio was 50%
Chiang et.al. (2007) [23]	closed			Diamond nano fluid (0.5 wt%)	10-90%		Optimum filling ratio depends on structure, for 36 port-50% & for 26 port 20%.
Lin et.al. (2008) [24]	closed	copper	i.d.2.45mm, o.d.3mm with 5 turns	Silver nano particle (20nm) in water	20%, 40%, 60%, 80%.	5-85W	Optimum FR 60%. For 85 W power, thermal resistance of evaporator and condenser decreases by 7.79 & 0.093 ^{0}C/W.
Wannapakhe et.al.(2009) [25]	Closed with check valve	copper	i.d. 2mm with 40 turns	Silver nanoparticles (0.25, 0.5, 0.75 & 1 % w/v) in H_2O	50%		Best inclination angle was 90^0; silver nano fluid increases heat by more than 10%.
Bhuwakietkumjohn & .Rittidech (2010) [12]	Closed with check valve	glass	i.d. 2.4 mm	Silver nanoparticle in ethanol	50%		When velocity of slug increases, its length decreases & heat flux rapidly increases. Nanofluid gave higher heat flux than base fluid.
Qu et.al (2010) [11]	closed	Stainless steel	i.d.2mm,o.d. 3mm with 6 turns	Al_2O_3 nanoparticles(0.1% , 0.3%, 0.6%, 0.9% , 1.2% by wt)(56nm) in water	50%, 60%, 70%	20 W-140W	Optimum concentration of nano fluid=0.9wt%; maximal decrease of thermal resistance was 0.14 ^{0}C/W at 70%FR when q= 58.8 W.
Qu & Wu(2011) [26]	closed	Stainless steel	i.d.2mm, o.d.3mm with 6 turns	Al_2O_3 nanoparticles (0-1.2wt% wt)) & SiO_2 (0-0.6wt%) in water	50%	20 W-140W	For Al_2O_3, optimum conc. 0.9%; For SiO_2 nanofluid, the thermal resistance & evaporator wall temperature increased.
Reihl (2011)[27]	open	copper	i.d.1.5mm	Copper nanoparticles (5wt%) in water	50%	0-60W	Overall improvement of the device by use of nanofluid.
Ji et al. (2011) [4]	closed	copper	i.d 1.65 mm and o.d. 3.18 mm with 6 turns	Al_2O_3 nanoparticles (50nm, 80nm, 2.2μm, 20 μm) in water.	50%, 60%, 66%, 76%	0-200W	when the particle size becomes smaller, the startup temperature decreases 80 nm Al2O3 particles, the OHP can achieve the best heat transfer performance.
Ji et. al. (2011) [28]	closed	copper	i.d 1.65 mm and o.d. 3.18 mm with 6 turns	Al_2O_3 nanoparticles (cylindrical, brick, blade, platelet) in ethylene glycol &water (50/50 by volume).	50%	0-250W	Best performance was achieved by cylindrical particles.

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