A REVIEW OF NANOFLUIDIC PULSATING HEAT PIPES: SUITABLE CHOICES FOR THERMAL MANAGEMENT OF ELECTRONICS

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ABSTRACT

Moving toward application of miniature and high performance chips in electronic fields, thermal management of these sensitive devices has become a challenging issue to direct heat transfer investigations. In this regard, Pulsating Heat Pipes (PHPs) have attracted attention, due to simplicity of structure, reliability, and low manufacturing cost. Moreover, working fluid has an important effect on PHP's performance. Having high thermal conductivity, nanofluids are outstanding substitutes for PHP's conventional working fluids. Focusing on recent advances on nanofluidic PHPs, this paper reviews operating principles and conducted experiments in this field. Furthermore, unsolved concerns regarding this field are mentioned.

Keywords: Thermal management, Pulsating Heat Pipes (PHPs), Nanofluid, Thermal conductivity.

1. INTRODUCTION

Due to huge amounts of heat generation in industrial grounds, there had been always a great demand for having robust and promising cooling devices in technological fields. Currently, thermal management of electronics has become an encouraging issue for researchers since proper treatment of high operating temperature and heat flux density of these miniature devices can improve their maintenance and performance (Dhinsa *et al.*, 2005; Karimi and Culham, 2004). To this end, an effective heat removal process is required, in order to maintain the chip's temperature low enough to allow its favorable efficiency.

Several methods such as conventional cooling with air or water, spray cooling, and jet impingement have been applied to dissipate heat from electronic devices (Karimi and Culham, 2004; Downs and James, 1987; Kim, 2007). The coolant needs to be small enough to be placed in restricted spaces, be able to work in the space when the gravitational force is absent, be cheap, has a high value manufacturing capability and low manufacturing complexities.

Consequently, two-phase thermal devices such as traditional heat pipes were introduced and employed as high performance coolant. Despite all the advantages of heat pipes, their performance was completely dependent to inclination angle and they could not operate in absence of gravitational field. Using wick structures, they could operate in the absence of gravity, but this method is very expensive and may cause problem in some situations (Mohammadi, 2010). In this regard, another kind of heat pipe, called Pulsating Heat Pipe (PHP), utilizing pulsating motion as its base mechanism, was put forward, first by Akachi (1990) in the 1990s. Having gravitational independent operation, owning simple fabrication process, and being cheap, it has emerged as one of the most operative thermal devices, which is capable

of removing the ultra-high heat fluxes that are produced in recent electronic devices.

PHP is a cooling device made of a long capillary tube, which forms a continuous structure and operates by the pulsation and phase-change of its working fluid. Application of heat load to the PHP, it benefits both sensible and latent heat transfer mechanisms and owns the potential to dissipate immense amounts of heat loads. It can function autonomous from operating orientation at large turn numbers (Charoensawan *et al.*, 2003). Contrary to old-style heat pipes, PHPs have wickless structure, which makes their design simple and high maintaining.

Researchers have shown that geometry and design material of PHP are key issues influencing its thermal behavior (Jamshidi *et al.*, 2011). Counting the geometry effects; number of turns, total length of the tube, tube diameter, and the height of whole system should be considered.

Furthermore, the kind of working fluid and its charging ratio has an impact on thermal performance. Therefore, finding the optimum functional fluid for PHP has become the center of challenge in many heat transfer investigations. A fluid with perfect thermal properties was desirable for this purpose.

Among all the experimented fluids, including water (Khandekar, 2004; Shafii *et al.*, 2010; Wilson *et al.*, 2011), acetone (Wilson *et al.*, 2011), refrigerants (Khandekar, 2004; Naphon *et al.*, 2009), fluids with micro particles (Wang *et al.*, 2009-a), etc., homogenous dispersion of solid nanoparticles in the base fluid could significantly enhance its thermal properties. Choi (Choi and Eastman, 1995; Choi, 1995) was one of the forerunners of this field. It has been detected that the thermal conductivity of the nanofluids at different concentrations is more than that of the pure base fluid. Due to small size of the particles, they are not easy to choke the heat transfer passage (Qu *et al.*, 2008).

There are few reviews on performance of heat pipes in the literature. Sobhan *et al.* (2007) proposed a review on micro heat pipes

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experimental and theoretical aspects. Also, the design effects of this kind of heat pipes were reviewed. In 2007, Launay et al. (2007) reviewed operational parameters of a loop heat pipe thoroughly. Furthermore, Zhang and Faghri (2008) presented an exhaustive review on developments and unsolved issues in PHPs. They reviewed investigations on flow visualization, heat transfer characteristics, and theoretical modeling of PHPs up to 2008.

To the authors' best knowledge, there is not any review on performance of nanofluid charged PHPs, so in this paper, an exhaustive review on recent research advances on thermal performance of PHPs that are charged with nanofluids will be represented. Effects of concentration of nanofluid, charging ratio, inclination angle, and operating pressure on thermal performance of PHPs will be described. Advances in visual investigation of nanofluid PHPs will be demonstrated. Besides, a tabular review (Table 1) will depict the results of nanofluid charged PHPs' experiments. Unsolved concerns in this field that are not investigated so far will be mentioned.

2. STRUCTURE

A PHP is consisted of a long capillary tube, which is meandered into a number of turns, and it is mainly divided into three major parts: an evaporating section, a condensing section, and an adiabatic section (Arabnejad *et al.*, 2010). At a specific heat load, increment of PHP's turn number leads into transferring less amount of heat each turn. Therefore, the dry out is avoided and thermal resistance of the PHP decreases. Although, if the heat transfer contribution of each turn is not high enough to generate the oscillating motion, the performance of PHP degrades. As a result, an optimal number of turns exists for PHP (Charoensawan *et al.*, 2003).

In forced convection heat transfer, an external force is needed to make the fluid circulate in pipes. However, in a PHP, the designation and geometry shape are in a way that the pumping process occurs spontaneously. To this end, the inner diameter of the tube should not exceed a maximum allowable amount obtained from Eq. (1).

$$D_{max} = \sqrt{\frac{Bo_{crit} \sigma}{g(\rho_l - \rho_v)}} \quad (1)$$

In which Bo is dimensionless Bond number, σ is surface tension of the fluid, g is acceleration of gravity, and ρ is density.

Finding the maximum allowable inside diameter of the tube, Khandekar et al. (2002) used a critical Bond number of 2, while Shafii et al. (2001) used the value of 1.84. If the inner diameter exceeds the maximum suggested diameter, the liquid and vapor phases' stratification occurs and the device's heat transfer mechanism changes to a simple thermosyphon. In this case, the nucleate pool boiling is the main heat transfer mechanism. In this regards, internal diameters of less than 5 mm are recommended in order to have good thermal performance of the PHPs (Shafii *et al.*, 2001).

PHPs are classified in two types:

- Open-Loop PHP (OLPHP): In which the ends of pipe are not connected and they are sealed.
- Closed-Loop PHP (CLPHP): In which the ends of pipe are connected and the working fluid can circulate in it completely (Shafii *et al.*, 2002).

Also, CLPHPs may be consisted of one or more check valves in their structure, in order to avoid flow reversion. These types of PHPs are called Closed Loop Pulsating Heat Pipe with Check Valve (CLPHP/CV). CLPHP/CVs have shown better thermal performance in comparison to other types (Wannapakhe *et al.*, 2009). However, difficulties in their manufacturing, especially in small scales, reduce their application. Figure 1 shows different kind of PHPs.

Fig. 1 Different kind of PHPs.

The desired input heat power is applied to PHP from the evaporating section by various methods. Wrapping the evaporator by Nickel-Chrome wire and electrically heating the system is a common way. In this method, the heat load is measured indirectly by controlling the voltage (V) and current (I). Different kinds of heaters may also be used. Using hot water bath is another technique to introduce PHP with the heat flux. It should be noted that in most of the PHPs, the evaporator and adiabatic section are thermally insulated in order to minimize heat loss from the system.

The heat transferred by the PHP is dissipated from the condenser. Using a constant flow of coolant (air or liquid) or natural convection is a usual technique for this purpose. The temperature of fluid entering and leaving the condensation section is measured and recorded. Having the mass flow rate of the fluid (m), the temperature difference between the entrance and exit of the fluid (ΔT), and specific heat at constant pressure (C); the amount of transferred heat (q) can be calculated using Eq. (2).

$$q = mC\Delta T \quad (2)$$

3. OPERATIONAL MECHANISM OF A PHP

A PHP is first evacuated and then partially filled with the working fluid. Liquid slugs and vapor plugs are formed in the tube as a result of surface tension force in small diameter pipes (Mohammadi, 2010). It can be said that PHP's operating principle is based on continuous oscillating motion of its working fluid and its heat transport capability is due to its phase change and forced convection heat transfer. The thermodynamic phenomena in the PHP support the needed force of generation and perpetuity of the pulsating motion (Khandekar, 2004).

Since PHP is not an isothermal system, there is a temperature gradient between the evaporator and condenser. In addition, a temperature difference exists between the points of each turn. Therefore, an unsteady pressure difference, which is responsible for the oscillating motion in the PHP, is created. Heating the evaporating section and cooling the condensing section, the system also tends to reach an unsteady state (Mohammadi, 2010). Furthermore, in real systems there is always a tendency to generate chaos and increase the entropy (Mohammadi, 2010). Due to all mentioned factors, a perpetual oscillating flow is formed in the PHP.

The vapor plug is not in direct contact with the internal surface of the pipe, as it is surrounded by a thin film of liquid. Also, the surface tension force makes the liquid slugs form a meniscus shape. Working fluid properties and mutual effects of wall and fluid are responsible for the thickness of the liquid film and the curvature angle between the liquid slugs and the inner wall. Besides, the gravity effects should be considered too (Mohammadi, 2010).

4. THEORETICAL APPROACH

The efficiency of a PHP is considered by its thermal resistance, heat transport coefficient, or the temperature difference between evaporator and condenser. As much as thermal resistance or temperature difference is smaller, or heat transport coefficient is higher the system is able to dissipate the heat applied to the evaporator more effectively. It should be mentioned that heat transport coefficient is inversely related to thermal resistance. Equation (3) introduces a way of computing thermal resistance:

$$R = \frac{T_{evp} - T_{con}}{Q} \quad (3)$$

In which R is thermal resistance, T_{evp} is evaporator's temperature, T_{con} is condenser's temperature, which are measured when the system reaches its steady state, and Q is the input power, exerted to the PHP. In almost all experiments, the temperatures are measured in different parts of the evaporating or condensing section. In this case, the average temperature in each section is used.

Existence of nanoparticles in the working fluid of PHPs causes an enhancement in convective heat transfer, due to particle migration. Besides, modification in surface condition of the PHP is likely to influence thermal resistance. Qu et al. (2010) performed the following analysis for investigating the effects of nanofluids. To analyze thermal resistance more accurately, it can be written as Eq. (4).

$$R = 2R_{wall} + R_{l-v} + R_{evp} + R_{con} \quad (4)$$

Where R is the overall thermal resistance, R_{wall} is the conductive thermal resistance in the pipe wall, R_{l-v} is the thermal resistance in the two-phase flow along the heat pipe length, R_{evp} and R_{con} are thermal resistances caused by evaporation and condensation at the evaporator and condenser, respectively.

Since the conductive thermal resistance in the pipe wall (R_{wall}) is negligibly small and independent to the nanofluid type, it can be ignored in the Eq. (4). The convective heat transfer of the PHP and thermal conductivity of the working fluid are improved by addition of nanoparticles to the base fluid. Besides, the pulsating motion in the tube prevents the particles from agglomeration and deposition (Ma et al., 2006). Therefore, R_{l-v} decreases. However, due to small concentration of nanoparticles, this reduction is very small.

Surface condition has an important impact on R_{evp} and R_{con} . The thermal resistance of evaporation can be defined as Eq. (5) (Qu and Wu, 2011).

$$R_{evp} = \frac{1}{hA_{evp}} \quad (5)$$

In which h is the evaporation heat transfer coefficient and A_{evp} is the heat transfer area at the evaporator.

On the other hand, nucleate boiling happens in the evaporating section. Hence, the thermal resistance due to boiling in the evaporator can be shown in Eq. (6) (Qu et al., 2010; Mikic and Rohsenow, 1969).

$$R_{evp} = \frac{1}{2Nd^2\sqrt{f}\sqrt{\pi k_1\rho_1c_1}} \quad (6)$$

In the previous equation, N is the active nucleation site density, which is dependent to surface condition. d , f , k_1 , ρ_1 , and c_1 are bubble release diameter, bubble release frequency, thermal conductivity of the working fluid, its density and specific heat, respectively.

It can be claimed that if the size of surface cavities are one or two orders of magnitude larger than the nanoparticles' size, sedimentation

of nanoparticles on the cavities leads into generation of more new nucleation sites and the thermal resistance decreases (Das et al., 2008). Besides, bubble release diameter and bubble release frequency are influenced by the irregular nanopores formed between the deposited nanoparticles, which affect the surface roughness (Qu et al., 2010).

The heat loss can also be calculated from Eq. (7), having transferred heat (q) and applied heat (Q).

$$\text{Heat loss} = Q - q \quad (7)$$

5. NANOFLUIDS

In recent years, nanofluids have drawn researchers' attention, due to their considerable thermal conductivity. Homogenous suspension of the nanoparticles to the base fluid improves thermal properties of the solution. It is an important issue to find an appropriate method of nanofluid preparation, since an effective method is able to improve thermal properties of the fluid, due to inhibition of instability, chemical change of the fluid, and sedimentation of nanoparticles.

Homogenous dispersing of nanoparticles in the base fluid is an important concern. In absence of an efficient stabilizing method, nanoparticles settle down in the motionless base fluid (Wilson et al., 2006). In this regards, two major methods are applied: single-step and two-step. The first method (single-step), named Vacuum Evaporation onto a Running Oil Substrate (VEROS), was introduced by Akoh and coworkers (1978). It uses direct evaporation approach as its mechanism. Contrary to the base clue of this technique, it is hard to take apart particles from the base fluid (Wang and Mujumdar, 2007). VEROS was revised by Eastman et al. (1997). They condensed copper vapor into nanoparticles, using low vapor pressure liquid. Reduction $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ with $\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$ in ethylene glycol in presence of microwave irradiation, Zhu and coworkers (2004) prepared copper nanofluid by a similar method. In addition, in one-step method, the size of particles can be controlled and the agglomeration of nanoparticle is reduced (Kebinski et al., 2005).

Mixing available nanopowders and the base fluid, two-step procedure is proposed. Fabricating a homogeneous nanofluid, as well as using ultrasonic bath, controlling the pH of the solution, and using surfactants are also common in this technique (Wannapakhe et al., 2009). Surfactants (surface active agents) are added to the solution in order to avoid clogging of particles. These kinds of dispersants are able to enhance heat transfer performance of the fluid (Putra et al., 2003). They should be chosen regarding the properties of solution and nanoparticles. The two-step method is more suitable for oxide nanoparticles than for the metallic particles. In this technique the surface properties of the particles are influenced (Wang and Mujumdar, 2007). It is highly recommended to conduct a thorough investigation in order to study the effects of nanofluid's preparation procedure on the thermal performance of the PHPs.

The stability of suspension also depends on nanoparticles' kind. Preparing water-copper oxide and water-titanium oxide nanofluids at the same situation, Qu et al. (2008) observed different settling behavior. They pointed out that sedimentation of copper oxide nanoparticles occurred faster than that of the titanium oxide nanoparticles.

Measuring the thermal conductivity of the nanofluid, transient hot wire method is a common technique (Kestin and Wakeham, 1978). Also, the steady-state parallel-plate method (Wang et al., 1999) and the temperature oscillation method can be used (Das et al., 2003).

Transient hot wire method cannot be applied directly, since nanofluids are electrically conductive (Wang and Mujumdar, 2007). Therefore, the wire is coated with an epoxy adhesive in a modified hot-wire method (Nagasaka and Nagashima, 1981).

Maxwell (1881) suggested a model for thermal conductivity of solid-liquid mixture, which is valid at low solid concentrations. In this model, the effective thermal conductivity is defined by Eq. (8).

$$k_{eff} = \frac{k_p + 2k_b + 2(k_p - k_b)\phi}{k_p + 2k_b - (k_p - k_b)\phi} k_b \quad (8)$$

Where k_p is the thermal conductivity of the particle, k_b is the thermal conductivity of the base fluid, and ϕ is the particle volume fraction of the suspension. Bruggeman (1935) proposed a model for spherical particles without any limitation on concentration. This model is as Eq. (9).

$$\phi \left(\frac{k_p - k_{eff}}{k_p + 2k_{eff}} \right) + (1 - \phi) \left(\frac{k_b - k_{eff}}{k_b + 2k_{eff}} \right) = 0 \quad (9)$$

By changing the nanofluid's type, thermal performance of the PHP is affected. Nanofluids exist in different types such as (Das *et al.*, 2006):

- Ceramic nanofluids
- Metallic nanofluids: Fluids that include metallic particles. They improve thermal conductivity significantly, especially at very low concentrations (Das *et al.*, 2003).
- Carbon Nano-Tube and Polymer Nano-Tube nanofluids (CNT & PNT)
- Magnetic nanofluids: They are consisted of Magnetic NanoParticles (MNP) and are useful fluids in medical fields, industrial fields, and electrical fields (Mohammadi, 2010). Also, they appeared as very efficient fluids at several applications such as heat pipes, sensitive switch nano-devices, microfluidic on-chip systems and nanogap-based NDA sensors (Chang and Lee, 2007).

Still, there are too many nanoparticles that are not tested in PHPs and their performance is indescribable. Examples for these nanoparticles are CNT, SiC, Fe, Ni, Zn, Zr, ZnO, CeO₂, etc. Plus, the kind of base fluid has a considerable impact on thermal behavior. Effect of changing the base fluid (alcohols, refrigerants, oils, and etc.) is not considered so much and most of the studies are focused on water as the base fluid up to now.

Also, Core-shell nanoparticles have attracted growing attention in chemical and biomedical applications, such as drug delivery (Choi *et al.*, 2003), cellular therapy (Zhang *et al.*, 2002), separation, and purification of biomolecules from the matrices (Tamer *et al.*, 2010). The surface properties of particles can change to desired ones by covering them with inorganic metallic or oxide surfaces such as SiO₂ and TiO₂, or organic polymers. As a result of coating nanoparticles with mentioned layers the redox reaction of the core is not affected, since the coating is chemically inactive. Also, the clogging of the nanoparticles is prevented through chemical reactions. It should be asserted that the thickness of the covering layer has an impact on magnetic properties in case of magnetic nanofluids (Rashdan *et al.*, 2010). On the other hand, the aim of coating nanoparticles is to make them more stable and easily dispersed (Baer, 2004). An example of suitable coating material is gold, due to its good catalytic activity properties (Wu *et al.*, 2010).

However, not all nanofluids are able to improve thermal performance. For example, Qu *et al.* (2011) found that charging a PHP with water-SiO₂ nanofluid at different concentrations, increased the thermal resistance of the PHP by maximum value of 23.7% in comparison to using pure water as the working fluid. They repeated the experiment for the water-Al₂O₃ nanofluid at the same operating situation. A maximum 25.7% reduction in thermal resistance was obtained this time. They justified these different performances by differences in thermal resistance due to the change of surface condition at the evaporating and condensing sections caused by nanoparticles' different sedimentation. The deposition of silica nanoparticles were

more serious in both evaporator and condenser, compared with alumina nanoparticles. The deposition of silica nanoparticles caused the surface nucleation sites to decrease. Then, thermal performance of the PHP degraded.

Using a specific nanoparticle, the size and the shape of the particles are effective features in thermal performance. Ji *et al.* (2011-a) inspected four sizes of Al₂O₃ particles, including 50 nm, 80 nm, 2.2 μ m, and 20 μ m. Figure 2 displays SEM images of Al₂O₃ particles with different average diameters.

Fig. 2 Alumina particles with average diameters of (a) 20 μ m, (b) 2.2 μ m, (c) 80 nm, and (d) 50 nm (Ji *et al.*, 2011-a).

It was detected that charging the PHP with fluids containing smaller size nanoparticles improves the heat transfer capability of the PHP. Moreover, the optimum particle size found to be 80 nm.

In addition, effect of nanoparticles' shape was investigated by Ji *et al.* (2011-b). They studied four types of alumina nanoparticles with shapes of platelet, blade, cylinder, and brick, respectively. The shape of nanoparticles is shown in Fig. 3.

Fig. 3 Al₂O₃ nanoparticles: (a) Platelets, (b) Blades, (c) Cylinders, (d) Bricks (Ji *et al.*, 2011-b).

Heat transport capability of the PHP was enhanced when it was charged with nanofluid, regardless to its shape. For different shapes of nanoparticles, the best performance occurred at different concentrations. The best thermal efficiency was achieved in the cylinder shape nanoparticle PHP at 0.3% volume fraction, while the

lowest heat transfer performance occurred at brick shape nanoparticle PHP.

Up to this point, only a few investigations have been conducted to determine the effect of particle size and shape, and particle type on the thermal performance of the PHPs. Therefore, the mentioned debatable issues require further consideration.

6. VISUAL APPROACH

It is desirable for researchers to study the operational mechanism and flow pattern of the PHP visually. A number of PHPs are made of glass, entirely or partially, so that their inside is visible. The main flow regime of fluid in the tube, the exact time of startup and dry out of system, the boiling process, and the oscillation of flow are observable at visual experiments. Kahndekar (2004) studied the flow pattern inside a PHP. His results are stated below:

Instantly after the PHP is filled with working fluid, vapor plugs form in an indiscriminate arrangement. In this case, the surface tension is the prevailing force inside the tube. PHPs are mainly driven by the heat input which is applied to them; hence a minimum heat power is required so as to the system can startup its function. When the input power is less than startup power, vapor plugs are remained inert and no oscillation is detected. It should be asserted that as the evaporator temperature is increased at this stage, a group of bubbles are generated at the evaporating section. As the input heat flux exceeds the startup power, unsystematic pulsating motion is commenced, while the flow pattern is capillary slug flow. At this point, the thermal performance of the PHP is not satisfactory. Additional increment of input power leads into stable pulsating motion in the system. Yet, the global slug flow is observable in the PHP. A further increase in heating power makes the working fluid move faster in the tube and sets the flow direction fixed. Furthermore, the flow pattern starts to change from slug flow to semi-annular/annular flow and the thermal resistance of the system is reduced dramatically. This transition is shown in Fig. 4. This decrease in thermal resistance leads into reverse transition to slug flow. At higher input powers, the unstable slug flow is once more observed because of shrinking size of bubbles. At very high input heat flux, the PHP experiences dry out, which degrades its performance. The exact time of each phenomenon is completely related to the working fluid and its charging ratio and the shape of the PHP (Khandekar, 2004).

Fig. 4 Transition of flow pattern inside one turn of the PHP due to increment of input power (Khandekar, 2004).

A visual experimental investigation of three PHPs with different number of turns, charged with water and water-diamond nanofluid at two different concentrations and 50% charging ratio was conducted by Wilson et al. (2008). Neutron radiography method was adopted to image the flow patterns in the tubes. It was observed that the oscillation of the flow happened before start of temperature oscillation. Increment

of the heat input, the velocity of the fluid was increased in the tube. Also, the frequency and amplitude of the oscillation were higher for the PHP charged with pure water, compared to those of the nanofluid charged one. Finally, neither nucleation nor vapor bubble collapse were detected in this experiment.

Li et al. (2011) conducted an experimental test with a quartz glass made PHP. By increment of the input heat flux, they observed column flow, slug flow and annular flow in the tube, respectively. Vapor columns length in water-SiO₂ nanofluid PHP was less than that of the DI water charged one, thus some nanofluid vapor columns shrunk into small bubbles. Using an infrared imaging system, Fig. 5 manifests the transition to slug flow and annular flow. They also reported that flow regime transition in nanofluid charged PHP was due to the nucleate boiling.

Fig. 5 Transition of: (a) bubbles to (b) slug flow regime, in the evaporator of the PHP charged with nanofluid (Li et al., 2011).

So far, many other visual experiments studying different aspects affecting the performance of nanofluid charged PHPs are required to have a comprehensive awareness of phenomena and flow patterns inside the tube. Besides, different nanofluids may have their specific flow characteristics and comparing flow patterns of different nanofluids is an important concern which is not solved yet.

7. STARTUP PERFORMANCE OF PHP

To begin PHP's function, a minimum heat input is required to start pulsating motion. Initially after applying a low heat input, liquid slugs cannot move in the tube and this results a temperature climb up in evaporating section. After a certain time (startup time), absorbed heat by the working fluid is adequate to commence low amplitude pulsating motions. Due to movement of working fluid, temperature of evaporating section falls. Finally, evaporator's temperature pulsates around a certain value (Xu and Zhang, 2005). However, in some experiments, the reduction in evaporator temperature does not happen (Xu and Zhang, 2005; Mohammadi et al., 2012a). It should be mentioned that increment of heat load, reduces the required startup time (Qu et al., 2008).

Experimenting water charged and nanofluidic PHPs, Qu et al. (2008) observed that using nanofluid in a PHP lessened the startup time, due to nanofluids' high thermal conductivity, which played a pivotal role in conduction heat transfer, great ability of bubble formation, which increased the interface between liquid plugs and tube wall, and the impact of nanoparticles on surface roughness of the inner wall. Also, it was pointed out that operating in vertical mode and inclination angles near it made the PHP capable of a faster startup.

Ji et al. (2011-a) investigated the startup temperature of different size of particles. They reported that all of the investigated particles could enhance the startup performance relative to distilled water. Furthermore, increment of particles' size increased the startup temperature of the system.

Charging PHP with ferrofluid, Mohammadi et al. (2012-a) studied the startup performance and observed enhanced startup of ferrofluid charged PHP compared to water charged one. It was pointed out that at low charging ratio, the startup performance of the PHP was enhanced using ferrofluid, while in other charging ratios; water charged PHP experienced a better startup performance. They justified this behavior according to capability of working fluid's stronger pulsation in lower charging ratio. In addition, ferrofluid's concentration had an impact on startup performance of the PHP. At high concentration, in which the viscosity was higher, startup behavior was deteriorated.

8. PHP PARAMETRIC STUDY

8.1 Effect of concentration of nanofluid

Concentration of the nanoparticles in the base fluid is an impressive factor in thermal resistance of the PHP. Modification of concentration of nanofluid results in different thermal properties. A considerable number of experiments have been conducted trying to study the effect of nanofluid's concentration on thermal performance of the system. Reviewing all the mentioned investigations in this field, it can be concluded that although thermal conductivity of the nanofluid increases as the nanoparticles' concentration grows, the thermal resistance of the PHP does not decrease continuously, due to increment of the viscosity. In this case, the movement of the fluid in the tube is more difficult. Besides, agglomeration of nanoparticles in the base fluid is more serious in higher concentrations (Qu, and Wu, 2011). In other words, there is an optimum concentration of the nanoparticles in the base fluid, which leads into the best performance of the system.

Lin et al. (2008), using silver nanofluid water solution, obtained the results illustrated in Fig. 6. They reported 100 ppm concentration as the best efficiency in their experiment.

Fig. 6 The effect of heat input on thermal resistance at 60% charging ratio (Lin et al., 2008).

Similarly, Wang et al. (2009-a) stated that in horizontal heat mode, using alumina nanofluid, the best concentration was 0.1wt%; meanwhile, when the working fluid was adopted to be FS-39E microcapsule fluid, the best concentration was 1wt%.

Qu et al. (2010) used alumina nanofluid with five different mass fractions of 0.1%, 0.3%, 0.6%, 0.9% and 1.2% in a six-turned PHP. They reported 0.9% concentration as the best one between the stated concentrations.

Mohammadi et al. (2012b) tested two different volumetric concentrations of ferrofluid in a PHP. They showed that in absence of magnetic field, lower concentration (2.5%) has a better thermal

performance as a result of its lower viscosity; vice versa, in presence of magnetic field, larger concentration (7%) has a better thermal performance due to its larger magnetism effects. Their results are presented in Fig. 7.

Fig. 7 Thermal resistance as a function of heat input for two different concentrations of ferrofluid (Mohammadi et al., 2012-b).

8.2 Effect of charging ratio

A PHP is partially charged with a working fluid. The proportion of the working fluid volume to the whole volume of the PHP is called charging ratio. Investigations done in this field have shown that in lower charging ratios, although the working fluid can circulate easily, application of high heat loads to the system leads into dry out of PHP, which deteriorates thermal performance. In addition, as the charging ratio decreases, sensible heat transfer decreases too. On the other hand, in higher charging ratios, due to lack of enough empty space in pipe, the degree of freedom of working fluid for performing oscillation motion is decreased (Jamshidi et al., 2011) and as a result pumping efficiency of working fluid will be decreased (Lin et al., 2008). Furthermore, in this case the number of generated bubbles is too small to form oscillating motion. However, as the charging ratio increases sensible heat transfer increases, and probability of dry-out decreases. Thus, the middle charging ratios are reported to be optimal in a PHP's operation.

Jamshidi et al. (2011) tested a water-silver nanofluid charged PHP and a water-titanium oxide nanofluid one at different charging ratios. They found that the PHP benefits both sensible and latent heat transfer in charging ratios between 30% and 80%. However, the value of optimum charging ratio for each nanofluid was different. These optimum values were reported to be 40% for water-titanium oxide nanofluid and 50% for water-silver nanofluid. They justified this difference with dissimilar thermophysical properties of mentioned nanofluids. Indeed, due to addition of surfactant, surface tension and resistance to flow for water-silver nanofluid was lower than that for water; which has similar properties to water-titanium oxide nanofluid at experiment's conditions. Therefore, the optimum filling ratio would be higher for water-silver nanofluid compared to water-titanium oxide nanofluid.

Lin et al. (2008) reported that water-silver nanofluid charged PHPs have better thermal performance at mid charging ratios (40% and 60%). In addition, they confirmed that due to transferring more sensible heat, heat transport capability of water-silver nanofluid charged PHPs at 60% charging ratio is much more.

Mohammadi et al. (2012-c) studied the effect of charging ratio on the thermal performance of water and ferrofluid charged PHPs in horizontal heat mode, in either presence or absence of magnetic field. In absence of the magnetic field, they reported 55% as the optimum charging ratio for both working fluids. It was pointed out that application of magnetic field to the PHP reduced the thermal resistance. In this case, the thermal resistance decreased as the charging ratio increased, since the dragging force of the magnets pulled the liquid slugs toward the evaporating section and consequently dry out was

inhibited. In addition, the sensible heat transfer was enhanced at higher charging ratios. Therefore, the best charging ratio was found to be 70%.

In a similar experiment, Mohammadi et al. (2012-d) performed experiments on thermal performance of an OLPHP using ferrofluid at different charging ratios, including 20, 40, 60, and 80%. They reported 60% charging ratio as the optimal one in distilled water charged case, while for ferrofluid with application of magnetic field at low and high input powers, the system experienced its lowest thermal resistance at 20% and 60% charging ratios, respectively. A kind of ferrofluid in which no stabilization procedure was performed on it to disperse nanoparticles in the base fluid was used. As a result, the nanoparticles were deposited in the motionless condition. It was claimed that powerful pulsating motion is needed to disperse nanoparticles in the PHP and at relatively low charging ratios such strong pulsation will happen since at these low charging ratios more free spaces exist for movement of the working fluid in PHP. Therefore in the case of ferrofluid with application of magnetic field at low heat inputs, 20% charging ratio was the best charging ratio. However, they showed that at high input powers due to occurrence of dry out thermal performance of 20% charging ratio declines. Part of their results is shown in Fig. 8.

Fig. 8 Thermal resistance vs. heat input for 20% and 60 % charging ratios (Mohammadi *et al.*, 2012-d).

Mohammadi et al. (2012-a) also investigated the effect of charging ratio on thermal performance and startup operation of a ferrofluid charged OLPHP. Strong pulsation was required in order to avoid nanoparticles' agglomeration, which could be guaranteed in low charging ratios, such as 20%. They also tested the PHP, while it was charged with distilled water. It was explored that the optimum startup performance of the PHP was obtained at moderate charging ratios (40% and 60%).

8.3. Effect of Inclination angle

For many applications, it is required for PHP to have the capability of working appropriate in every orientation. PHPs can work properly in horizontal mode, when their turn numbers are considerably increased (Charoensawan *et al.*, 2003). Unfortunately, just a few investigations have been conducted to determine the effects of inclination angle of the nanofluidic PHPs on their thermal performance. To summarize the outcomes of these few studies, it should be mentioned that in most of the cases thermal performance of PHPs is almost constant in a wide range of inclination angles (from vertical to angles close to horizontal), since thermally excited oscillating motion in the PHP can compensate absence of gravitational force in non-horizontal angles.

Testing the PHP at four different orientations, including horizontal, 30°, 60°, and 90° from the horizontal, Qu et al. (2008) found that the effect of inclination angle on the performance is relatively small, when the system is not oriented horizontally. At the horizontal heating mode, the thermal performance of the nanofluid charged PHPs degrades significantly.

Similar experiment was also carried out by Mohammadi et al. (2012-c), comparing ferrofluid and distilled water as the working fluids

of the PHPs, in presence and absence of the magnetic field. Parts of their results are depicted in Figs. 9 and 10, changing the inclination angle of the PHP from 0 to 90 degree with respect to horizontal axis, at 70% charging ratio and under different operating conditions.

Fig. 9 Thermal resistance as a function of inclination for distilled water (Mohammadi et al., 2012-c).

Fig. 10 Effect of inclination angle on thermal resistance of a ferrofluid charged PHP in presence of magnetic field (Mohammadi *et al.*, 2012-c).

Figures 9 and 10 indicate that for distilled water and ferrofluid with the application of magnetic field, thermal performance of PHP is constant in a wide range of inclination angle, while at horizontal orientation, thermal performance degradation happens. In addition, it was pointed out that magnetic force plays the role of the gravitational force at the horizontal orientation and considerable enhancements in thermal performance of PHPs (74.8% in the best case, in comparison to water charged PHP) are obtained by application of magnetic field (Mohammadi, 2010).

8.4 Effect of operating pressure

Effect of operating pressure on the thermal performance of nanofluidic PHPs is very important and this issue is not widely investigated so far, while it is claimed that the performance of nanofluid charged heat pipes is improved dramatically with the increment of the operating pressure, due to impact of pressure on thermo-physical properties of the working fluid (Liu *et al.*, 2010).

Mohammadi et al. (2012-a) conducted an experiment to study the effect of operating pressure on thermal performance of a ferrofluid charged OLPHP, applying the magnetic field. It was claimed that in presence of magnetic field, higher operating pressure led to better startup of system.

Table 1 presents a brief review of recent investigated nanofluid charged PHPs.

Table 1 Recent Investigations on Nanofluidic PHPs.

Researcher	structure	Tube diameter (mm)	Inclination angle (°)	Charging ratio (%)	Concentration	Working fluid	Results
Ma et al. (2006-a; 2006-b)-Wilson et al. (2006)	Closed loop	1.65	90	50	1% volume fraction	HPLC grade water and HPLC grade water-diamond nanofluid	1. Addition of nanoparticles to the base fluid could increase its thermal conductivity.
							2. Nanofluidic PHPs were able to remove high amount of heat flux effectively.
							3. The effect of operating temperature was studied. Thermal resistance decreased as a result of operating temperature increment.
Park and Ma (2007)	Closed loop	1.6		30, 40, 50, 60, 70, 80	1% volume fraction	HPLC grade water and HPLC grade water-CuNi nanofluid	1. Temperature difference between the evaporator and the condenser decreased, due to nanofluid utilization.
							2. When the filling ratio was equal to 50%, the lowest temperature difference between the evaporator and the condenser was achieved.
Lin et al. (2008)	Closed loop	2.45		20, 40, 60, 80	100ppm-450ppm	water and water-silver nanofluid	1. The efficiency of the PHP was deteriorated in both high and low filling ratios, due to bubble pulsation impediment and dry out, respectively. The optimum ratio was 60%.
							2. The 100-ppm concentration was better, since in that case the viscosity was lower.
Qu et al. (2008)	Closed loop	4.3	0, 30, 60, 90	55	1% volume fraction	water, water-TiO ₂ nanofluid, and water-CuO nanofluid	1. Nanofluids reduced the thermal resistance of the PHP and made it start up faster.
							2. The inclination angles of 30°, 60°, and 90° had negligible impact on thermal performance.

Wilson et al. (2008)	Closed loop	3	50	1% by volume for 12 turned PHP and 0.016% by volume for 8 turned PHP	water, water-diamond nanofluid	1. The flow characteristics of nanofluidic PHPs were visually investigated.
						2. No nucleation was observed during the experiment.
Wannapakhe et al. (2009)	Closed loop	2	50	0.25, 0.5, 0.75, and 1% w/v	water and water-silver nanofluid	3. The working fluid velocity was increased as a result of heat input and operating temperature increment.
						1. Using nanofluid, heat transfer capability increased at all concentrations.
Wang et al. (2009-a; 2009-b)	Closed loop	1.3	40, 50, 60, 70, 80	FS-39E microcapsule: 0.5, 1, 2 and 3 wt% water-Al ₂ O ₃ nanofluid: 0.1 and 0.5 wt%	water, FS-39E microcapsule fluid, and water-Al ₂ O ₃ nanofluid	2. The optimum orientation and concentration found to be vertical and 0.5% w/v, respectively.
						1. Both the nanofluid and microfluid improved heat transfer capability of the PHP under certain conditions.
Qu et al. (2010)	Closed loop	2	50, 60, 70	mass fractions at 0.1%, 0.3%, 0.6%, 0.9% and 1.2%	water and water-Al ₂ O ₃ nanofluid	2. At vertical heat mode thermal performance of FS-39E microcapsule fluid was better, while at horizontal heat mode Al ₂ O ₃ nanofluid was preferred.
						3. The best concentrations of Al ₂ O ₃ nanofluid and FS-39E microcapsule fluid were 0.1 wt% and 1 wt%, respectively.
Bhuwakietkumjohn and Rittidech (2010)	Closed loop	2.4	50		ethanol, ethanol-silver nanofluid	1. The maximal decrease of thermal resistance occurred at 70% filling ratio and 0.9% mass fraction when the power input was 58.8 W. The least thermal resistance was reported to be 0.14 °C/W. The change of the surface condition at the evaporator accounts for the heat transfer improvement.
						2. Deposition of nanoparticles was more serious at the evaporator.
						1. The silver nanofluid's heat transfer capacity was higher than pure ethanol.
						2. The flow pattern transformed from a bubble flow with slug flow and annular flow to a dispersed bubble flow.

Cheng et al. (2010)	Closed loop	rectangular cross-sections with hydraulic diameters ranging from 0.762 to 1.389	-90, 0, +90	0.1 vol% acetone-diamond, 0.1 and 1 vol% water-diamond nanofluid, 0.0003 vol% water-gold nanofluid	acetone, water, acetone-diamond, water-gold, and water-diamond nanofluids	1. Four flat plate PHPs were investigated and a theoretical model for thermal performance prediction of PHPs was presented.
						2. In higher input powers, the effect of orientation angle was negligible.
Jamshidi et al. (2009; 2011)	Closed loop	1.8	0, 5, 10, 20, 35, 60, 75, 90	500 ppm, 2000 ppm, 4000 ppm for water-silver nanofluid; 1000 ppm for water-TiO ₂ nanofluid	water, water-silver nanofluid, and water-TiO ₂ nanofluid	1. Using nanofluids, dry out occurred at higher input power.
						2. The orientation of the PHP had a little effect on thermal resistance, except for horizontal orientation.
Ji et al. (2011-a)	Closed loop	1.65	90	0.5 wt%	water and water-Al ₂ O ₃ nanofluid	3. Flow pattern changed from slug flow to annular at larger heat fluxes.
						4. At lower concentrations, the thermal performance degraded.
						5. The optimum filling ratio reported to be 40% for both pure water and water-titanium oxide, while the best performance of water-silver nanofluid PHP was achieved at 50% filling ratio.
Ji et al. (2011-a)	Closed loop	1.65	90	0.5 wt%	water and water-Al ₂ O ₃ nanofluid	1. The Al ₂ O ₃ particles added in the PHP caused startup of the oscillating motion occurs faster and affected the thermal behavior.
						2. Investigating the particle size effect, as the particle size became smaller, the startup temperature decreased.
						3. Optimum particle diameter for the steady state was reported to be 80 nm.

Ji et al. (2011-b)	Closed loop	1.65	90	50	0.3, 1, 3, and 5 vol%	mixture of Ethylene Glycol (EG) and deionized water and Al ₂ O ₃ in a mixture of EG and deionized water	<div>1. Heat transport capability of the PHP was enhanced when it was charged with nanofluid, regardless to its shape.</div> <div>2. Investigating the nanoparticles' shape effect, the best thermal efficiency was achieved in the cylinder shape nanoparticle PHP at 0.3% volume fraction, while the lowest heat transfer performance occurred at brick shape nanoparticle PHP.</div>
Qu and Wu (2011)	Closed loop	2	90	50	mass fractions at 0-0.6 wt% for silica nanofluids and 0-1.2 wt% for alumina nanofluids	water, water-Al ₂ O ₃ nanofluid, water-SiO ₂ nanofluid	<div>1. In comparison with pure water, addition of alumina nanoparticles to the base fluid reduced the thermal resistance, while existence of silica nanoparticles in the base fluid degraded the thermal performance. This different behavior is due to change of surface condition as a result of different nanoparticles deposition.</div> <div>2. The optimum concentration was found to be 0.9% for water-Al₂O₃ nanofluid.</div>
Riehl and Santos (2011)	Open loop	1.5	-90, 0, +90	50	5% mass fraction	water and water-copper nanofluid	<div>1. Using water-copper nanofluid, an improvement on thermal performance was observed.</div> <div>2. At high heat loads, nanoparticles improved nucleate boiling, while at lower heat loads, the effect of film evaporation was dominant.</div>
Li et al. (2011)	Closed loop	3.53	0	nanofluid: 45.4% DI water: 45.7%	0.268% volume fraction	DI water and DI water-SiO ₂ nanofluid	<div>1. The flow pattern of the nanofluid PHP changed from slug to annular by increment of the heat load. This transition is mainly due to boiling nucleation of nanofluids.</div> <div>2. The PHP appeared more efficient, while it was charged with nanofluid.</div>

Mohammadi et al. (2011; 2012-b)	Closed loop	2.2	0, 22.5, 45, 67.5, 90	25, 40, 55, 70	2.5% and 7% volume fraction	distilled water and water-based ferrofluid	<div><div>1. Thermal resistance was measured in presence of magnetic field.</div><div>2. Either in presence or absence of magnetic field, charging the PHP with ferrofluid enhanced its performance.</div><div>3. In the horizontal heating mode, while the magnetic field was applied, the best thermal performance was attained at higher charging ratio.</div></div>
Mohammadi et al. (2012-a; 2012-d)- Taslimifar et al. (2012-a; 2013)	Open loop	1.75	0, 22.5, 45, 67.5, 90	20, 40, 60, 80	1.25, 2.5, and 5	distilled water and water based ferrofluid	<div><div>1. Using ferrofluid as the working fluid decreased the thermal resistance of the system and improved the startup performance.</div><div>2. Application of magnetic field enhanced the performance of the PHP, while the optimal location of magnets is near evaporator.</div><div>3. Very high concentration degraded the performance of the PHP, due to higher viscosity.</div><div>4. Increment of charging ratio deteriorated the startup of ferrofluid charged OLPHP.</div></div>
Taslimifar et al. (2012-b)	Open loop	1.75	0, 90	20, 40, 60, 80	2.5	distilled water, silica coated ferrofluid, ferrofluid	<div><div>1. Silica coated ferrofluid improved thermal performance; however, thermal resistance of PHP charged with ferrofluid without nanoparticle coating was reported to be lower than that of the silica coated ferrofluidic one.</div><div>2. Application of magnetic field to ferrofluid charged PHPs enhanced thermal performance.</div></div>

9. FUTURE TRENDS

Some of the future guidelines have mentioned earlier. In the following, other important issues that are not solved yet are mentioned.

9.1 OLPHPs vs. CLPHPs

According to Table 1, most of researches on thermal performance of nanofluidic PHPs have investigated CLPHPs. It is a good idea to set the direction of some experiments to compare performance of OLPHP and CLPHP.

9.2 Numerical and theoretical approach

Just a few investigations have been conducted to associate numerical and analytical researches on PHPs and to the best knowledge of the authors, there are no numerical or analytical study on nanofluid charged PHPs. Consequently, this important issue needs further attention, and obtained results should be compared with the existing experimental data.

9.3 Geometry parameters

Effect of several design factors including number of turns, internal diameter of the tube, cross section of the PHP, and length of different sections of PHP has not been investigated thoroughly in nanofluid charged PHPs.

9.4 Wick structure

Although the main idea of PHP is based on wickless operation, equipping a PHP with wick structure may have an impact on its performance; since it eases the circulation of working fluid inside tube and bubble generation process (Zhang and Faghri, 2008). Investigating a water charged PHP with a sintered particle wick structure, Xu et al. (2009) claimed that both sensible and latent heat transfer were improved. It is highly inspiring to conduct experiments to study the effect of using wick in nanofluidic PHPs.

9.5 Coated nanofluids

As it was mentioned before, coating nanoparticles may affect their stability and dispersion process. This technique may have an impact on thermal characteristics of the nanofluid. Although a comparison between silica coated ferrofluid and ferrofluid without coating charged OLPHPs' thermal performance was conducted by Taslimifar et al. (2012-b), which its results are illustrated in Table 1; this issue needs further consideration in order to obtain an exhaustive perception of coating effects.

9.6 Phase change of nanofluids

In field of energy management, storage of energy in forms of sensible and latent heat is an important issue (Yu and Xie, 2012). A number of investigations have been conducted to study the phase change of nanofluids, as suitable potentials for storage of thermal energy; which are able to increase both cool storage rate and cool storage capacity (Liu et al., 2009; Wu et al., 2010). However, further study and experiment on nanofluids' phase change in PHPs is required since their phase change, as one important factor affecting heat transport capability of PHP, may have an impact on thermal performance of these cooling devices.

9.7 Nanofluid's oscillatory flow in the PHP

As mentioned in previous sections, visual approaches, although limited, have been performed to study flow pattern in nanofluidic PHP. However, in addition to flow regime studies, chaotic oscillatory flow and circulation of working fluid are required to be further investigated.

In fact, studying the vibration induced by the applied heat flux would assist us learn about amplitude of oscillation of nanofluids, direction of circulation and its variations, and the frequency of variations of temperature and pressure at evaporator. This issue has been investigated in few studies for a number of PHPs (Khandekar et al., 2010); experimentally (Soichi and Takashi, 2004) and by numerical modeling (Zhang and Faghri, 2003). Yet, is recommended to broaden experiments to nanofluidic PHPs since it is an unsolved aspect of nanofluid charged PHPs.

10. CONCLUSION

Nanofluid charged PHPs have proven to be high performance thermal devices and can be used as a substitute for low performance conventional electronic coolers. In the present study a complete review of recent research advances in Pulsating Heat Pipes (PHPs) charged with nanofluids was provided. Developments in visual investigation were mentioned. The effect of many factors affecting thermal performance of the PHPs was mentioned. It was pointed out that there is an optimum concentration for nanofluid charged PHPs. Every nanofluid charged PHP has its own optimum charging ratio. Most of nanofluid charged PHPs can operate independent of gravity in non-horizontal orientations. Unsolved issues in this research field were also reported to be used as a topic in further studies.

NOMENCLATURE

A	heat transfer area (m^2)
Bo	Bond number
C	specific heat ($\text{J/kg } ^\circ\text{C}$)
D	internal diameter of the pipe (m)
d	bubble release diameter (m)
f	bubble release frequency(Hz)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient ($\text{W/}^\circ\text{C m}^2$)
k	thermal conductivity ($\text{W/}^\circ\text{C m}$)
m	mass flow rate (kg/s)
N	active nucleation site density (m^{-2})
PHP	Pulsating Heat Pipe
q	transferred heat (W)
Q	heat load (W)
R	thermal resistance ($^\circ\text{C/W}$)
T	temperature ($^\circ\text{C}$)

Greek Symbols

ϕ	volume fraction
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

b	Base fluid
con	condenser

<i>crit</i>	critical
<i>eff</i>	effective
<i>evp</i>	evaporator
<i>l</i>	liquid
<i>max</i>	maximum
<i>p</i>	particle
<i>v</i>	vapor
<i>wall</i>	tube's wall

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