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Evaluation of the Thermal Performance of Hybrid Nanofluids in Pulsating Heat Pipe

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ABSTRACT

The present article performed experimental and numerical investigations to evaluate the thermal performance of hybrid nanofluids in PHP under heat input and filling ratio of 10 W – 100 W and 50 % - 60 %, respectively. The thermal performance results of PHP incorporated with hybrid nanofluids were compared with water. Water has low thermal conductivity value which is not favourable for an efficient heat transfer in a cooling device. Several studies have shown that hybrid nanofluid as a promising working fluid for thermal performance enhancement of the heat transfer device. The present study uses Al_2O_3-CuO hybrid nanofluid and SiO_2-CuO hybrid nanofluid with mass concentration of 0.1 %. The thermal performance of PHP was studied with respect to the start-up mechanism, steady-state evaporator temperature, thermal resistance and the formation of two-phase flow. From the experiment results, PHP filled with SiO_2-CuO hybrid nanofluid obtained the lowest thermal resistance value of 0.27 °C/W. Thermal resistance was improved by 55 % when PHP was charged with SiO_2-CuO hybrid nanofluid compared to water. The optimal filling ratio of PHP is found to be 60 % at all the heat input and working fluid tested. Incorporating hybrid nanofluids in PHP have seen to expedite the start-up mechanism and also showed lower steady-state evaporator temperature and thermal resistance values.

Keywords:
Hybrid nanofluid; Pulsating heat pipe; Thermal performance

1. Introduction

In this digitalized era, consumer uses high performance miniaturized electrical device to cater for their daily life needs. This high-performance device produced a very high heat flux which could cause overheating and deterioration of performance if the heat is not efficiently dissipated. The advancement of the manufacturing and semiconductor industries had made it possible to produce million transistors on a microchip. This leads to high heat flux dissipation out of the microchip when being used in an electrical device. Heat pipe is one of the famously known heat transfer devices to remove high heat flux out of an electrical device. Pulsating heat pipe (PHP) is a unique kind of heat pipe owing to its wickless structure. PHP is very different than conventional heat pipes. This is

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because the transport mechanism in PHP relies solely on the temperature and pressure indifference which are powered thermally. Therefore, a mechanical pump is not required in PHP. Nanofluid has shown positive results to improve the thermal performance of heat transfer devices [1-2]. It has been used vastly by researchers due to the high thermal conductivity of the nanoparticles [3-6]. Nazari *et al.,* [7] perform an investigation using graphene oxide nanofluid in PHP. The experimental study is conducted with different nanofluid mass concentrations of 0.25 % to 1.5 %. From the results, PHP charged with lower nanofluid concentration exhibited the best thermal resistance value. It is also observed that addition of nanoparticles in base fluid enhance the heat transfer by up to 40 % in relative to water as the working fluid. Parsaiemehr *et al.,* [8] studied the turbulent flow and heat transfer of Al_2O_3 nanofluid in a rectangular ribbed channel. The turbulent flow simulated at Reynolds number ranged from 150000 – 30000. Based on the results, the maximum heat transfer was obtained by 2.37 times when Reynolds number is simulated at 15000 and an attack angle of 60° when incorporated the Al_2O_3 nanofluid in the rectangular ribbed channel.

However, nanofluid characteristics were reported does not meet all the desired traits of an efficient working fluid [9]. Recently, hybrid nanofluids have grabbed attention owing to the ideal thermal properties that can meet for specific heat transfer application [10]. Hybrid nanofluid is defined by a base fluid that is dispersed with two or more kind of solid nanoparticles. Sundar *et al.,* [11] performed investigations on the enhancement of a circular tube using MWCNTs-Fe_3O_4/water hybrid nanofluid. The author reported the hybrid nanofluids have improved in thermal performance in comparison to the single-particle nanofluids. On the other hand, Rosdzimin *et al.,* [12] conducted a numerical study of forced convective heat transfer on Al_2O_3-Cu hybrid nanofluid. It is reported that the heat transfer coefficient was greatly improved as the concentration of the hybrid nanoparticles was increased. The numerical model was validated and found coherent with the experimental results.

Several studies have shown the efficacy of hybrid nanofluid as a working fluid for thermal performance enhancement of heat transfer devices. However, further studies are required to explore and understand the reason for heat transfer improvement using the novel hybrid nanofluid. There are very few studies on thermal enhancement of heat pipes using hybrid nanofluid can be found in the literature [6–9]. Therefore, the present study put an effort by filling the gap in this area through experimental and numerical investigations on PHP charged with Al_2O_3-CuO hybrid nanofluid and SiO_2-CuO hybrid nanofluid with mass concentrations of 0.1 %.

2. Methodology

2.1 Schematic Diagram of PHP

The schematic diagram of the experimental setup is depicted in Figure 1. It consists of a computer, data logger, vacuum pump, control panel, and power supply. These types of equipment are used in order to conduct the experimental investigations on a four turns PHP which is made up of copper material. The inner and outer diameter of PHP is given by 2 mm and 3 mm respectively. The evaporator region is equipped with five heating coils for heating purposes. The adiabatic section is insulated with glass wool to ensure no heat loss, while the condenser section is kept exposed to room temperature with natural convection. Seven K-type thermocouples with accuracy of ±0.5 °C are installed at each sections in order for determination of temperature. The vacuum pump is initially used to create vacuum pressure in PHP up to 0.01 mbar. Then the charging valve is utilized to inject the working fluid into PHP. Control panel is adjusted in order to manipulate the heating power supply to the evaporator region. The data logger is used to collect data from the thermocouples at each section and send it to the computer every 2 seconds. The heating power is increased once the temperatures given at each sections reaches steady state. The present experimental investigations of PHP is conducted using Al_2O_3-CuO hybrid nanofluid, SiO_2-CuO hybrid nanofluid and water under heat input of 10 W to 100 W at 50 % to 60 % filling ratio of PHP.

Preparation of hybrid nanofluids is firstly conducted using an ultrasonic bath with a duration of 360 minutes. Firstly, a magnetic stirrer is utilized by preparing individual single-particle nanofluid with duration of 30 minutes. Then both single-particle nanofluid is combined together and stirred again in the magnetic stirrer for another 30 minutes before going through the ultrasonication process. For example, to prepare Al_2O_3-CuO hybrid nanofluid, Al_2O_3 nanofluid and CuO nanofluid is prepared separately before mixed it together to form the hybrid nanofluid. Eq. (1) is used to prepare the hybrid nanofluids at particle mass concentration of 0.1 %. Sedimentation analysis is conducted to evaluate the stability of the hybrid nanofluids and it is found that the hybrid nanofluids remain homogenous for up to 7 days without sedimentation.

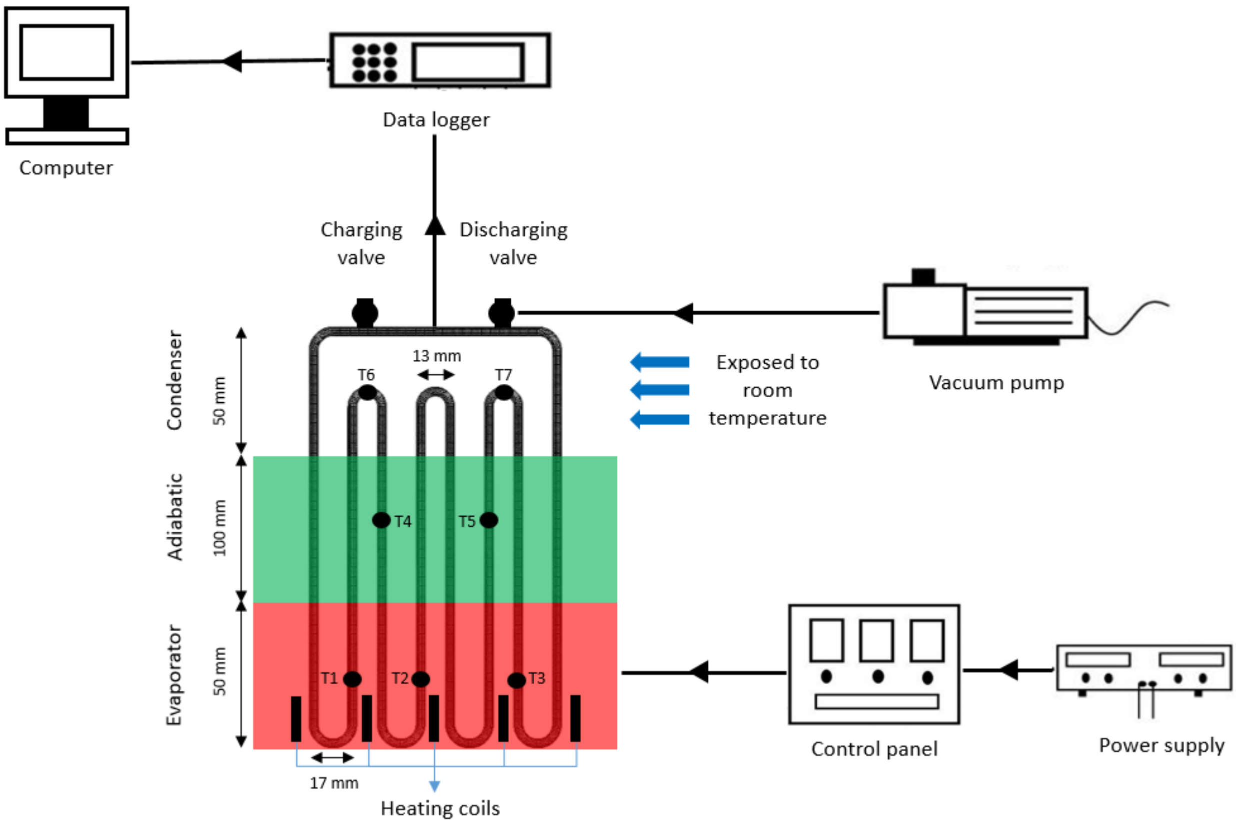

Fig. 1. Schematic diagram of the experimental setup

$$\%mass \cdot concentration = \frac{W_{np}}{W_{bf} + W_{np}} \times 100 \quad (1)$$

2.2 Numerical Methodology

The present numerical study is conducted using ANSYS Fluent software. A 3D four turns PHP is modelled according to the dimensions of the experimental rig. K-epsilon turbulence model is incorporated and the simulations are treated as transient. PISO is used for pressure velocity coupling because of its suitability for transient flow problem. Lee's model is utilized in consideration of the evaporation and condensation phenomena in PHP. VOF model is employed since PHP is a two-phase flow problem and it is able to track the interfaces of two or more immiscible phases. Eqs. (2) and (3) are solved in the simulations to ensure the interfaces can be successfully traced. Hexahedral meshes in generated throughout the domain owing to the accuracy of the end results as compared to tetrahedral meshes. Consideration of thermal conductivity and viscosity of hybrid nanofluids are taken in the present numerical study. The thermal conductivity and viscosity values of hybrid nanofluids are evaluated experimentally in the present study at temperature ranged of 50 °C to 80 °C as shown in Table 1. Timestep of 10^{-4} seconds is used which gives a total simulation time of 6 seconds for all the study parameters.

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla.\left(\alpha_q\rho_q v\right)=S_{\alpha q}+\sum_{p=1}^{n}\left(\dot{m}_{pq}-\dot{m}_{qp}\right)\right] \quad (2)$$

$$\frac{\partial}{\partial t}\left(\rho\vec{v}\right)+\nabla.(\rho v v)=-\nabla p+\nabla.\left[\mu\left(\nabla v+\nabla v^T\right)\right]+\rho g+F \quad (3)$$

Table 1
Measured thermal conductivity and viscosity of hybrid nanofluids and water at the temperature range of 50 °C to 80 °C

Temperature (°C)	Al_2O_3-CuO/water		SiO_2-CuO/water		Water	
	Thermal conductivity (W/m.k)	Viscosity (cP)	Thermal conductivity (W/m.k)	Viscosity (cP)	Thermal conductivity (W/m.k)	Viscosity (cP)
50	0.76	0.69	0.70	0.64	0.64	0.59
60	0.78	0.65	0.72	0.60	0.66	0.45
70	0.80	0.62	0.74	0.55	0.68	0.38
80	0.81	0.58	0.76	0.49	0.69	0.36

3. Results

3.1 Start-up Mechanism

Start-up mechanism is an essential analysis conducted in the determination of pulsations in PHP. The success heat transfer mechanism of PHP depends heavily on the onset of pulsations. Start-up mechanism is defined as the start of two-phase liquid-vapour slugs flow in PHP. When start-up has been achieved, the fluid will be able to flow passively in PHP due to the temperature and pressure difference in the condenser and evaporator section. Figure 2 illustrates the start-up mechanism of PHP charged with water under heat input of 40 W at filling ratio of 50 % and 60 %. From the results, PHP filled with water have achieved pulsations under heating power of 40 W. The pulsations shown by PHP at 60 % filling ratio is more vigorous in relative to PHP at 50 % filling ratio. Furthermore, the temperature difference between the evaporator and condenser section for PHP at 60 % filling ratio exhibited much smaller gap as compared to PHP at 50 % filling ratio. Smaller temperature difference will lead to a better thermal resistance value of PHP. On the other hand, the steady-state evaporator temperature of PHP at 50 % filling showed higher value at 151 °C, whereas PHP at 60 % filling ratio obtained lower steady-state evaporator temperature of 135 °C.

Figure 3 depicted the start-up of PHP charged with Al_2O_3-CuO hybrid nanofluid under heat input of 20 W at a filling ratio of 50 % and 60 %. It is observed that the start-up period can be attained earlier when PHP is charged with Al_2O_3-CuO hybrid nanofluid as the working fluid in comparison to water. Moreover, the heating power required in order to start the pulsations in PHP charged with Al_2O_3-CuO hybrid nanofluid is lower at 20 W. The steady-state evaporator temperature shown the value of 117 °C and 115 °C for PHP at 50 % and 60 % filling ratio respectively. It is calculated, the steady-state evaporator temperature is enhanced by 22 % when PHP charged with Al_2O_3-CuO hybrid nanofluid compared to water. This shows that the suspension of hybrid nanoparticles in the base fluid water has seen to result in the improvement of thermal performance of PHP. In addition, PHP with Al_2O_3-CuO hybrid nanofluid presented smaller gap of temperature difference between evaporator and condenser section in comparison to PHP filled with water.

Likewise, PHP charged with SiO_2-CuO hybrid nanofluid at a filling ratio of 50 % and 60 % required lower heating power in order to start-up pulsations at 20 W as shown in Figure 4. This is due to the SiO_2-CuO hybrid nanoparticles dispersion which augmented the thermal conductivity of the base fluid water. Due to this reason, the heat transfer can be greatly enhanced and more heat can be absorbed and dissipated much efficiently. Furthermore, using hybrid nanofluids in PHP have promoted more nucleation sites which are essential for bubbles growth and development in PHP. Therefore, the passive pulsations of liquid vapor slugs flow in PHP charged with hybrid nanofluids can be obtained quicker in comparison to water as the working fluid in PHP. The steady-state evaporator temperature of PHP filled with SiO_2-CuO hybrid nanofluid is obtained at 105 °C which is lower by 10 °C and 30 °C in relative to Al_2O_3-CuO hybrid nanofluid and water respectively at 60 % filling ratio. Additionally, the temperature difference between the evaporator and condenser section presented smaller gap for PHP incorporated with SiO_2-CuO hybrid nanofluid in comparison to Al_2O_3-CuO hybrid nanofluid and water. Based on the results shown from Figures 2, Figures 3 and Figures 4, the temperature difference between the evaporator and condenser region is smaller for hybrid nanofluids and exhibited lower evaporator temperature in comparison to water.

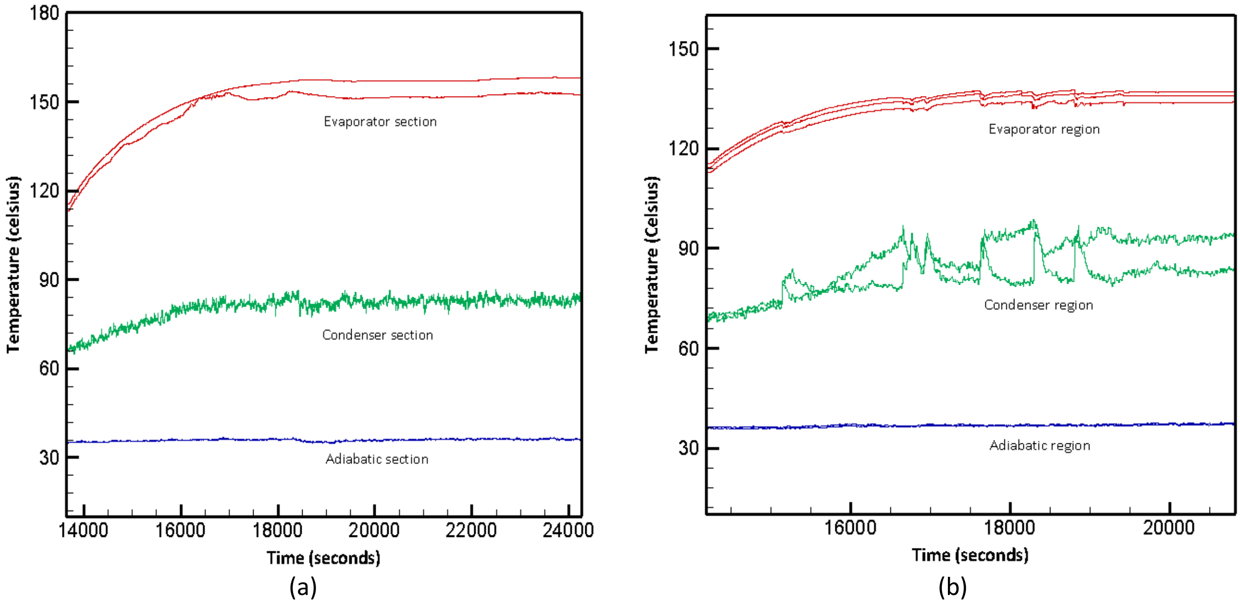

Fig. 2. Start-up mechanism of PHP charged with water under heat input of 40 W at filling ratio of (a) 50 % (b) 60 %

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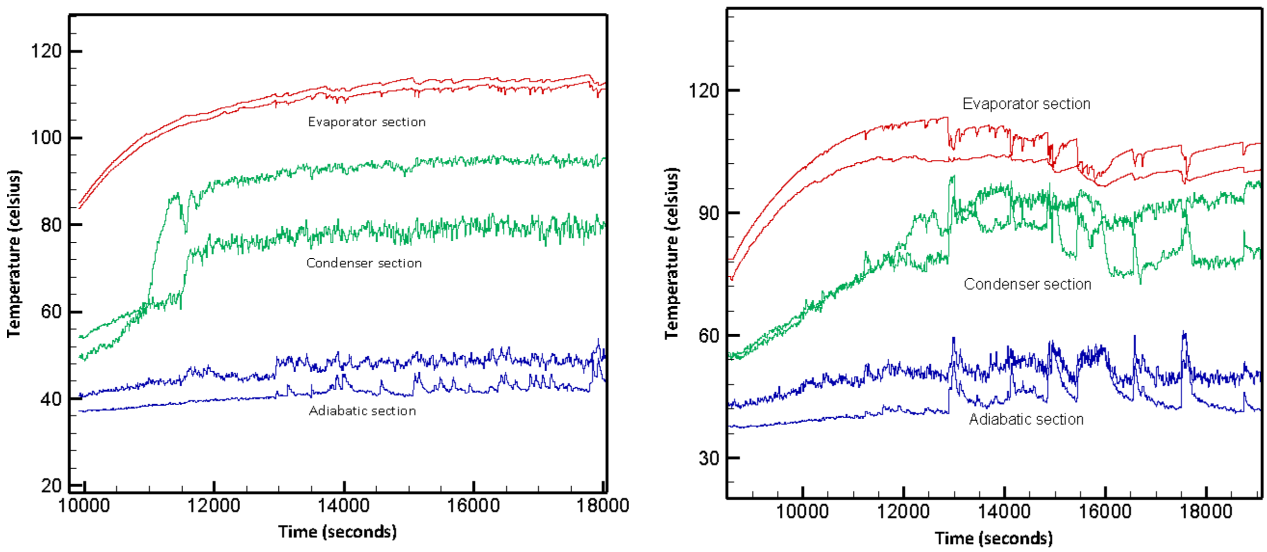
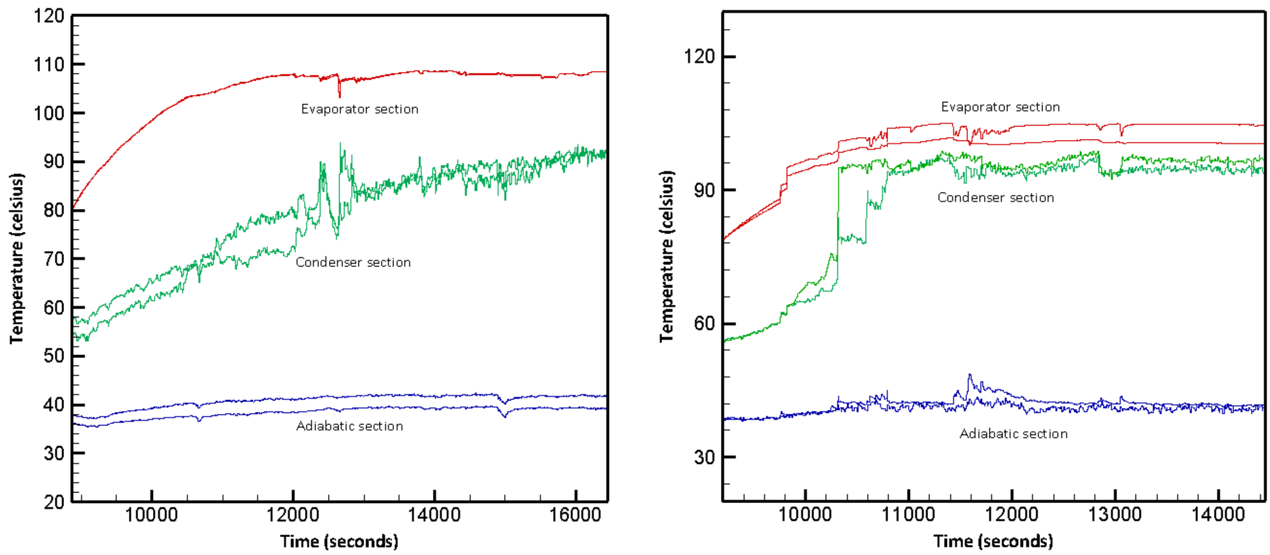


(a) (b)

Fig. 3. Start-up mechanism of PHP charged with Al_2O_3-CuO hybrid nanofluid under heat input of 20 W at filling ratio of (a) 50 % (b) 60 %



(a) (b)

Fig. 4. Start-up mechanism of PHP charged with SiO_2-CuO hybrid nanofluid under heat input of 20 W at filling ratio of (a) 50 % (b) 60 %

3.2 Thermal Resistance

The thermal performance of PHP in the present experimental investigation of PHP is determined by using thermal resistance. Eq. (4) illustrates the thermal resistance equation, whereby T_e and T_c are the average steady-state temperature of the evaporator and condenser sections, respectively. The heat input supply to the evaporator section is denoted by Q.

$$R = (T_e - T_c) / Q \tag{4}$$

Figure 5 depicts the thermal resistance of PHP charged with hybrid nanofluids and water under heating power of 10 W to 100 W at a filling ratio of 50 % and 60 %. It is presented that the SiO_2-CuO hybrid nanofluid exhibited the lowest thermal resistance under all heat input and filling ratio tested compared to Al_2O_3-CuO hybrid nanofluid and water. The graph indicates that SiO_2-CuO hybrid nanofluid is the best working fluid for enhancement of thermal performance of PHP subsequently Al_2O_3-CuO hybrid nanofluid and water. Furthermore, it is also shown 60 % is the optimal filling ratio of PHP owing to the lower thermal resistance value in relative to PHP at 50 % filling ratio. The thermal resistance of PHP charged with SiO_2-CuO hybrid nanofluid improved by 55 % as compared to water under heating power of 100 W at 60 % filling ratio. The lowest thermal resistance obtained is 0.27 °C/W for PHP charged with SiO_2-CuO hybrid nanofluid at heat input of 50 W at 60 % filling ratio. Al_2O_3-CuO hybrid nanofluid presented higher viscosity than SiO_2-CuO hybrid nanofluid, hence contributes to higher thermal resistance value. This is because the fluid flow in PHP is resisted by the shear forces existed in the walls of PHP, therefore heat cannot be efficiently absorbed and dissipated [13-14].

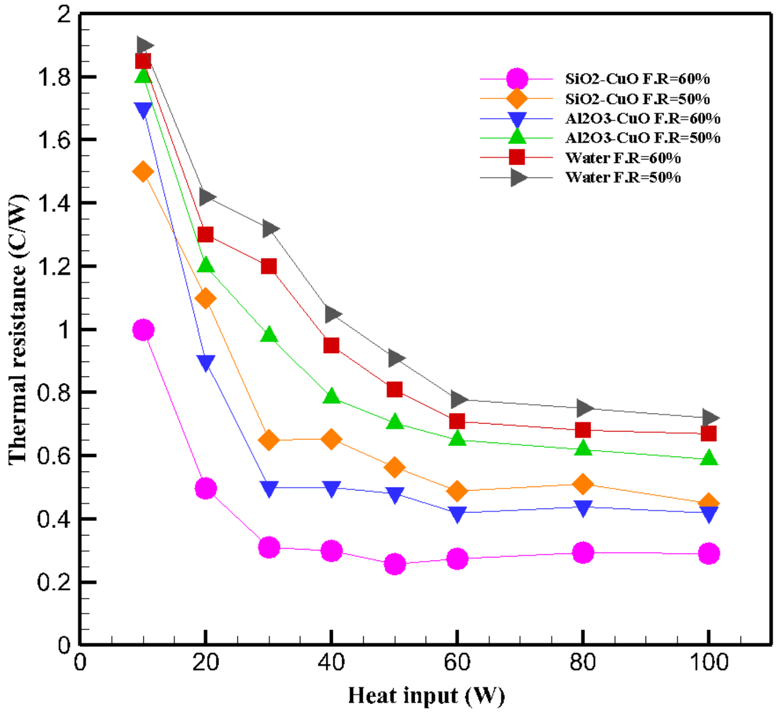
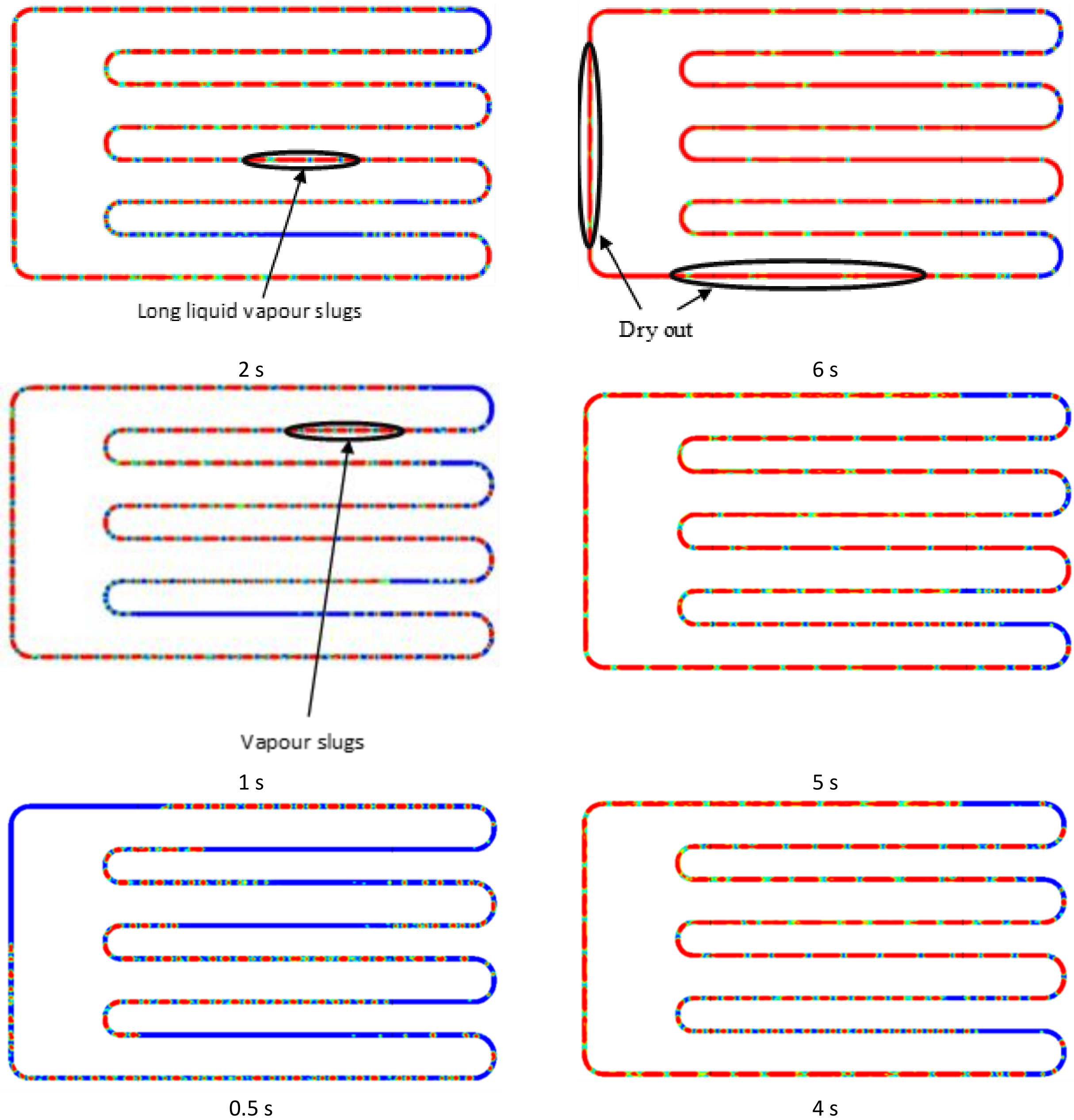


Fig. 5. Thermal resistance of PHP charged with hybrid nanofluids and water under heat input of 10 W to 100 W for 50 % and 60 % filling ratio

3.3 Numerical Results on The Formation of Bubbles in PHP

Numerical investigations are conducted for PHP charged with hybrid nanofluids and water under heat input of 100 W at 60 % filling ratio as shown in Figures 6, 7, and 8. The volume fraction contour can help to give an insight into the formation and development of vapour bubbles into vapour slugs in PHP. The red and blue colour in the volume fraction contour represents the vapour and liquid phase respectively. The simulation was treated as transient case with total simulation time of 6 s. The boundary condition for the evaporator section is supplied with constant temperature correspond to the steady-state evaporator temperature obtained from the experimental study. Adiabatic and condenser section is supplied with zero heat flux and natural free convection with value of 25 W/m^2k respectively. At simulation time of 0.1 s, it can be observed only tiny vapour bubbles appeared in the PHP charged with hybrid nanofluids and water. As time progressed, the vapour bubbles are seen to coalescence among each other which formed vapour slugs. It is shown that PHP charged with hybrid nanofluids attained faster vapour slugs formation at 0.5 s as compared to water at 1 s. This shows that consideration of augmentation of thermal conductivity of the hybrid nanofluids in the present numerical study has expedited the process of nucleate boiling in PHP. The evaporation of the hybrid nanofluids took place much quicker due to better heat transfer rate as compared to water. It is also shown that the vapour slugs formed into long vapour slugs at simulation time of 2 s, 3 s, and 4 s for working fluid of water, Al_2O_3-CuO hybrid nanofluid and SiO_2-CuO hybrid nanofluid respectively. A dry out phenomenon is seen to occur for PHP filled with water, while this event did not occur in PHP charged with hybrid nanofluids. This indicates that hybrid nanofluids are suitable for high heating power application since it can dissipate heat at much greater rate than water. Whereby, PHP filled with water went through dry out phenomena because of accumulation of heat that is not being removed efficiently from the condenser section. The results and phenomenon observed in the present numerical investigations are also reported by previous researchers in the study of two-phase flow in heat pipes [15-17].



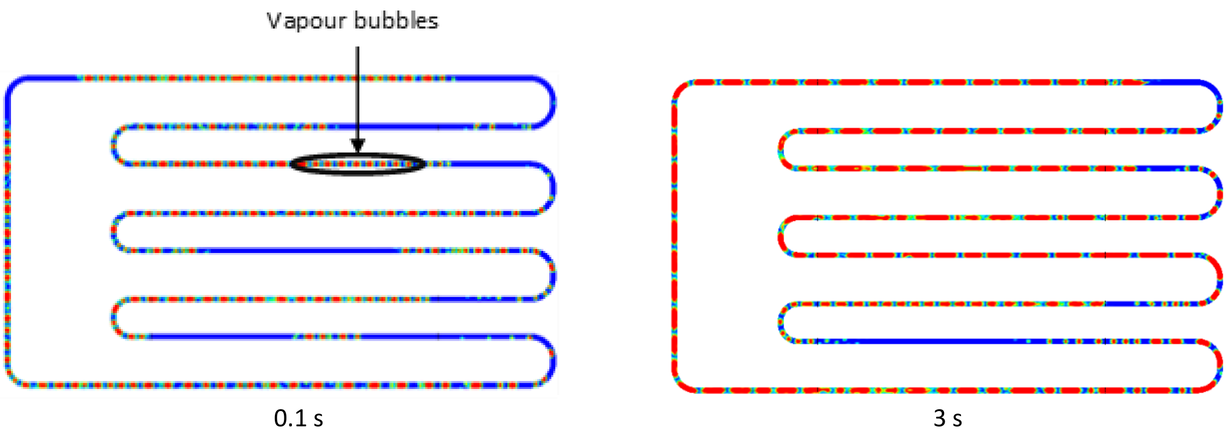
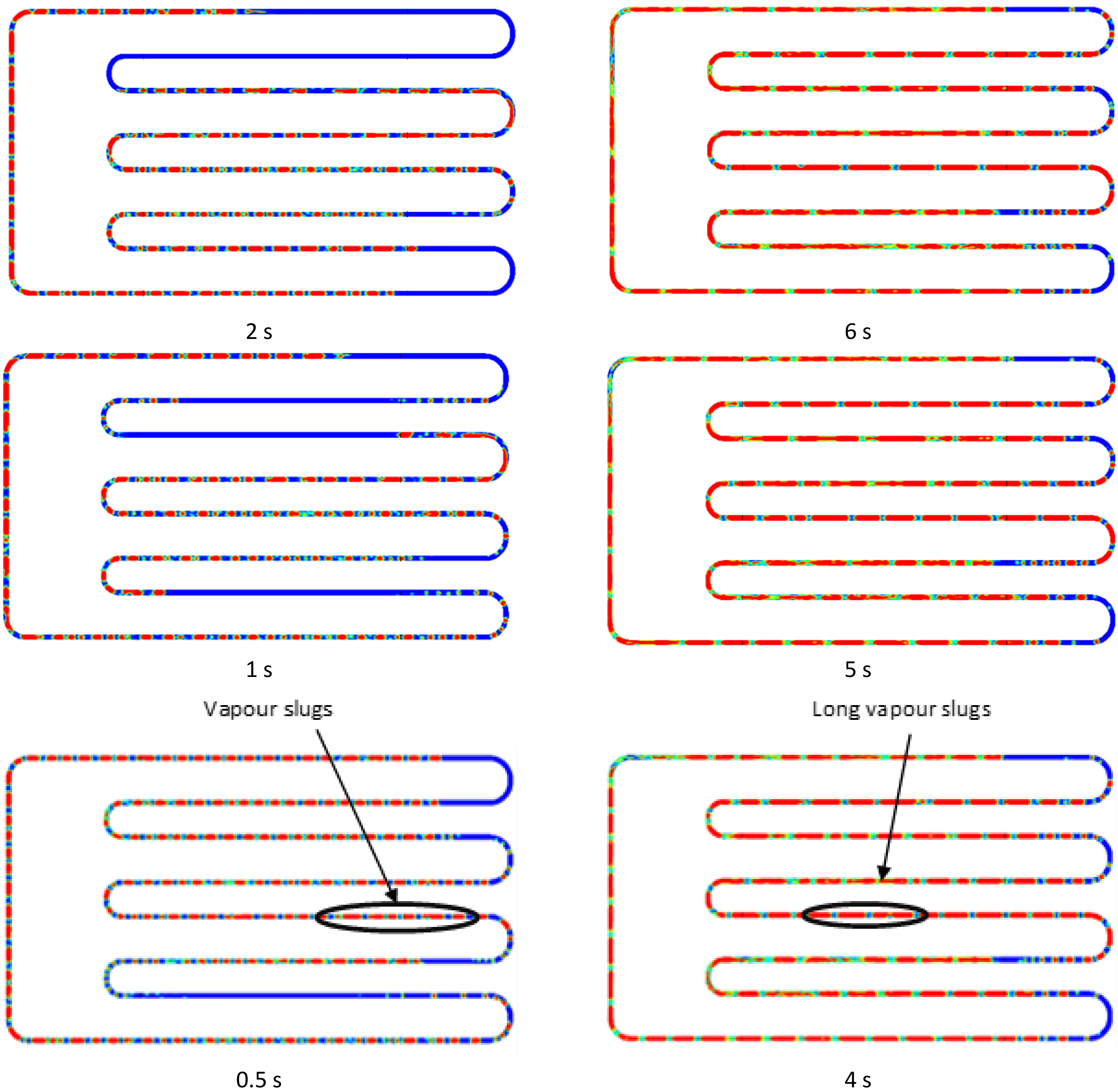


Fig. 6. Volume fraction contour of PHP charged with water under 100 W heat input at 60 % filling ratio



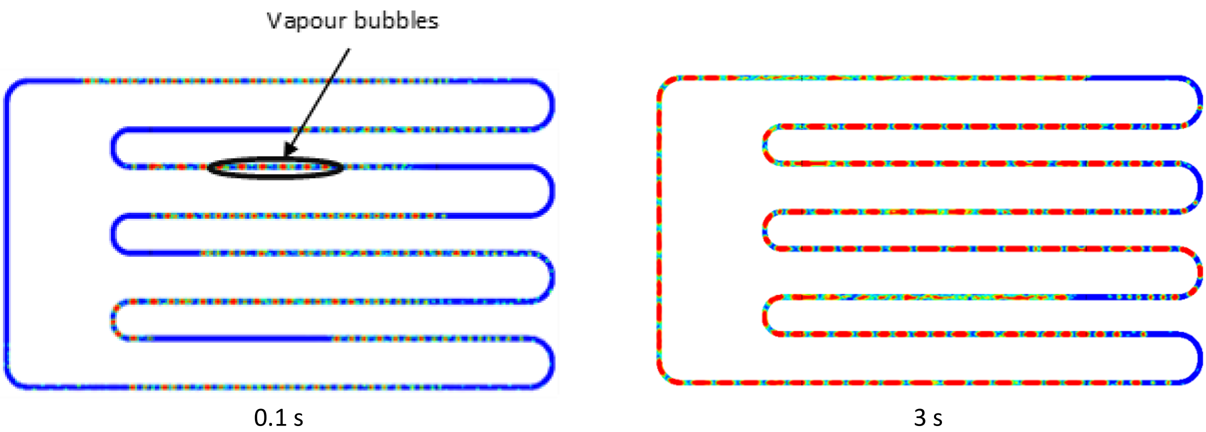
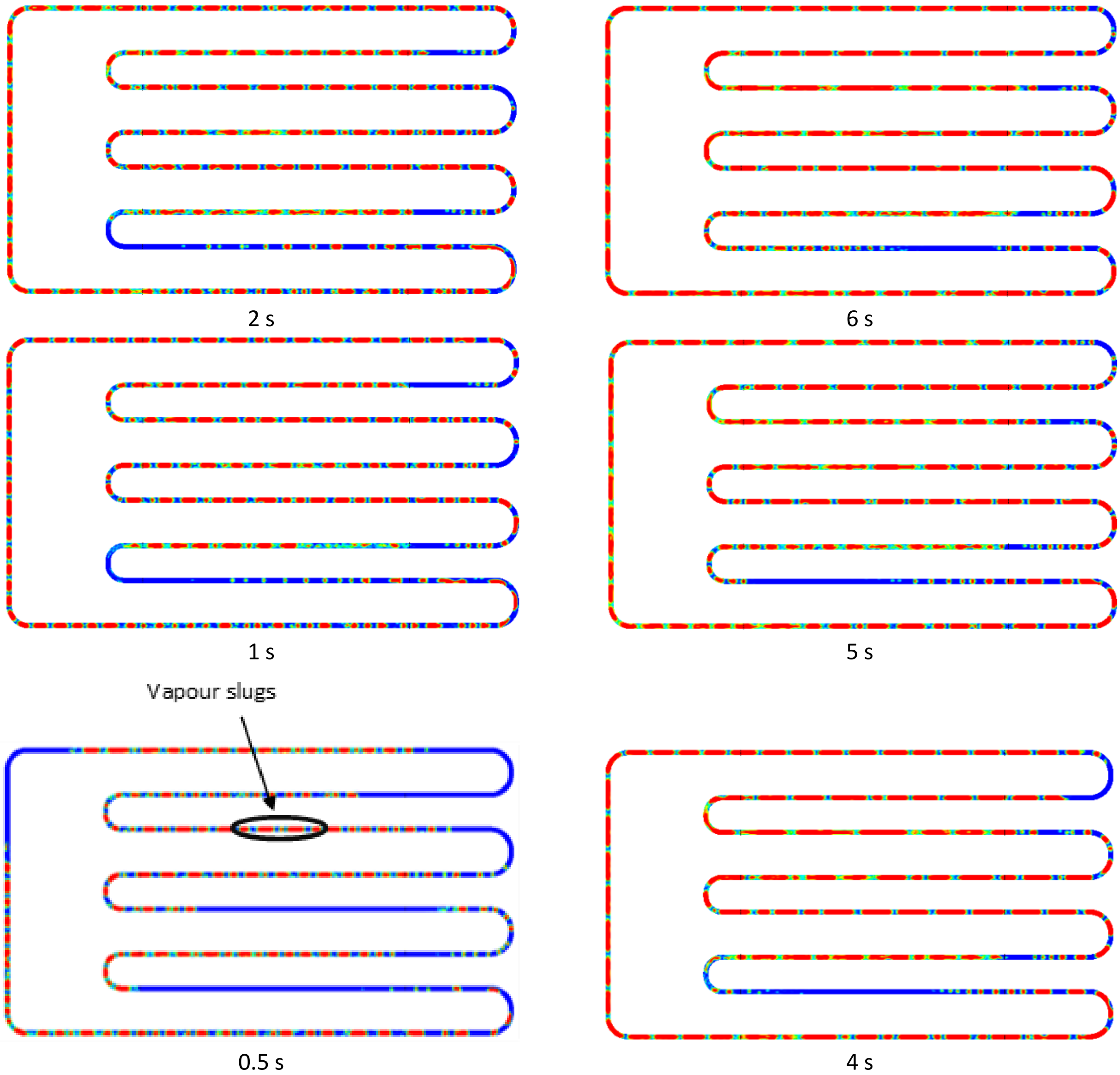


Fig. 7. Volume fraction contour of PHP charged with SiO_2-CuO hybrid nanofluid under 100 W heat input at 60 % filling ratio



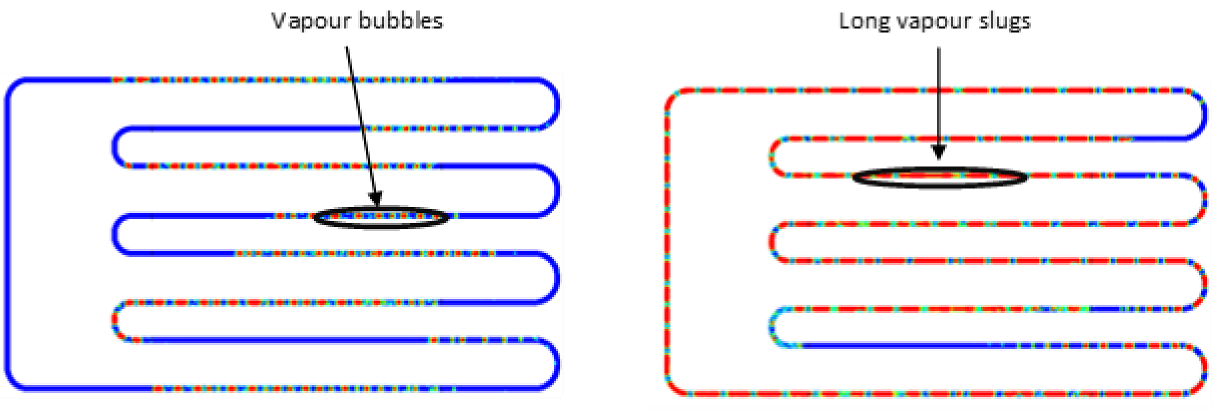


Fig. 8. Volume fraction contour of PHP charged with Al_2O_3-CuO hybrid nanofluid under 100 W heat input at 60 % filling ratio

4. Conclusions

The present experimental and numerical investigations on PHP charged with hybrid nanofluids and water is evaluated in terms of the start-up mechanism, steady-state evaporator temperature, thermal resistance, and two-phase flow formation in PHP in which can be deduced as follows:

i. The start-up mechanism can be achieved faster when hybrid nanoparticles are suspended in the base fluid water. Moreover, the steady-state evaporator temperature is shown much lower for PHP charged with hybrid nanofluids than water.
ii. The temperature difference between the evaporator and condenser sections exhibited smaller gap when PHP is filled with hybrid nanofluids. The SiO_2-CuO hybrid nanofluid showed the smallest temperature gap in comparison to other working fluid.
iii. SiO_2-CuO hybrid nanofluid has the lowest thermal resistance value of 0.27 °C/W and presented an enhancement of 55 % in relative to water.
iv. It is shown that the Al_2O_3-CuO hybrid nanofluid has the highest thermal conductivity value, however, the thermal performance of PHP is deteriorated due to its large viscosity value.
v. 60 % is the optimal filling ratio of PHP for all the working fluid tested at all the study parameters. The temperature difference of evaporator and condenser sections exhibited a smaller gap for PHP at 60 % filling ratio, hence leads to better thermal performance compared to PHP with 50 % filling ratio.
vi. In the numerical investigations, the dry out phenomena are observed when PHP is incorporated with water, whereas this phenomenon did not occur when PHP is filled with hybrid nanofluids. This designates that the hybrid nanofluids suitable for high heating power applications.

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