Enhancement of the Thermal Performance of a Single Turn Pulsating Heat Pipe by Adding Micro-Coppers into the Base Fluid

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ABSTRACT: *In this research, a series of experimental and numerical studies on the thermal performance of a single-turn Pulsating Heat Pipe (PHP) using distilled water as base fluid and distilled water including micro-coppers were performed. Thermal resistance, average temperatures of the hot region (evaporator), average temperatures of the cold part (condenser), and two-phase flow regime of the system were investigated at the different filling ratios, at input powers (20, 30, 40, 50 and 60W), at a concentration of micro-coppers (0.0625 g/mL). The oscillating heat pipe was fabricated with a copper capillary tube by choosing the internal and external diameters of 4 mm and 6 mm, respectively. Experiments showed adding micro-coppers into base fluid improves the main mechanism of the PHP based on the oscillating motion of vapor plugs and liquid slugs. The lowest thermal resistance of the system at a filling ratio of 40%, at a concentration of micro-coppers (0.0625 g/ml), at heat input (60 W) was 0.95 deg C/W. Meanwhile, CFD results illustrated adding micro-coppers into base fluid increases the turbulence intensity of the system especially in the evaporator up to 45% which enhances the heat transfer through the PHP in comparison to base fluid.*

KEYWORDS: *Experimental findings; Micro-coppers; Filling ratio; Numerical simulation; Uncertainty analysis.*

INTRODUCTION

With the development of technology, electronic devices are encountering significant changes in their form, dimension, and efficiency. Today, requests for flexible electronics, such as display panels and wearable instruments are dramatically increasing [1-3]. Heat consumption in electronic machines would force the systems to experience a huge reduction in performance. Pulsating Heat Pipes (PHPs) that were introduced by Akachi, have been displaying

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noticeable potential on heat exchange, heat recovery and cooling processes [4, 5]. A pulsating heat pipe is a device with high efficiency in heat transfer that operates by excited pulsating motion created by the cyclic phase change of working fluids [6]. Removing wicks in the structure of PHPs makes them simpler and cheaper in comparison to the conventional types and they can also be fabricated into various models like open loop, closed loop, and closed loop with check valve, etc. Because of the mentioned advantages, PHP has reached remarkable attention throughout the world [7-9]. The main mechanism of a PHP is based on the oscillating motion of vapor plugs and liquid slugs. Hence, forming a meniscus in a capillary tube is a determinative factor that shows the system is operating as a PHP and it depends on the ratio of gravitational force and surface tension force [10].

Nanofluids with high thermal conductivities have been presented as appropriate working fluids that could be significantly able to improve the heat transfer performance of thermal devices. Nanofluids are fluids including solid particles on 1–100 nm scale that disperse in the base fluid. Nazari et al. presented an experimental evaluation of the thermal performance of a pulsating heat pipe containing a graphene oxide Nanofluid. The results displayed that the thermal conductivity of the device is enhanced by using a graphene oxide sheet, as well as decreasing the thermal resistance of the PHP up to 42% [11]. *Zhou et al*. experimented with the heat transfer efficiency of an oscillating heat pipe including nanofluids with graphene. Empirical results indicated that the heat transfer of the PHP was increased by utilizing graphene nanofluids. From the research, the optimum range of nanofluid concentrations was about 2-13.8% [12]. *Sarafraz et al.* propounded the experiments on a copper heat pipe including alumina-glycol nanofluids. The results demonstrated adding surfactant leads to an improvement in the thermal performance of the pulsating heat pipe [13]. *Suresh et al.* investigated the effect of the filling ratio on the thermal characteristics and performance of a pulsating heat pipe experimentally and numerically. Findings indicated that the thermal resistance of the system declines rapidly by increasing the input power from 20 to 40W while it decreases gradually from 40 to 80W [14]. Furthermore, Riehl et al. did experimental research on a PHP with copper nanofluid. The study pointed by adding copper nanoparticles in base fluid (water), the number of nucleation sites that will augment was advantageous for forming a bubble [15]. *Mohammadi et al*. measured the thermal resistance of a four-turn PHP with Ferrofluid at different input powers (35- 85W), at different nanofluid volumetric concentrations (2 and 7%). The findings indicated utilizing nanofluids reduces the thermal resistance of the system in comparison to base fluid [16]. Recently, *Zufar et al*. presented experimental and numerical evaluations on the thermal performance of a PHP with hybrid nanofluids. The start-up oscillation, average evaporation part temperatures, thermal resistance, two-phase flow regime, and non-linear temperature analysis were studied with respect to input powers and filling ratio of 10-100 W and 50-60%, respectively [17]. *Noh et al.* performed a simulation on the thermal performance of a PHP with a numerical approach. Results from the research demonstrated that the thermal efficiency of the system is optimized while the merit number is maximized [18]. *Wang et al.* presented a numerical simulation of flow and heat transfer in oscillating heat pipes. Results indicated that the simulation could predict the heat transport capability of PHP successfully [19].

Based on the above literature, utilizing working fluid like nanofluid or mono-nanofluid to improve thermal efficiency of the oscillating heat pipe has been vastly studied. To the authors' best knowledge, no experimental or numerical research has investigated using working fluid with microparticles like micro-coppers in PHPs. Accordingly, this study evaluated the effect of micro-coppers on the thermal performance and flow regime of a single-turn pulsating heat pipe experimentally and numerically.

EXPERIMENTAL SECTION

Experimental set-up

The schematic diagram of the experimental setup with a data logger, a PHP, a vacuum pump, and a power supply is shown in Fig. 1. The PHP comprises three main sections like the condenser, the adiabatic section, and the hot part (evaporator). Meanwhile, the lengths of the evaporation part, the adiabatic section, and cold side are 50mm, 100mm, and 50mm, respectively. The copper cold side (condenser) is located at the upside of the PHP and a water bath with the size of $250\times120\times60$ mm^3 is set for cooling purposes by water at the temperature of 20 °C.

The copper evaporation part is placed at the bottom of the device and connected to DC power supply (model: DELTA MST) that supplies input power from 20 W to 60 W. The evaporator is covered by glass wool as an insulator

Table 1: Physical properties of distilled water at atmospheric pressure [20]

Working Fluid	Surface tension $\sigma \times 10^3 (\frac{N}{m})$	$\frac{dP}{dT_{sat}} \times 10^3 (\frac{Pa}{c})$	Dynamic viscosity ν_f $(mPa.s)$	Liquid specific heat C_{pl} $(kj/kg.c)$	Liquid density ρl (kg/m^3)	Boiling point $T_s(c)$
Distilled water	72.8	1.92	1.01	4.18	998	100

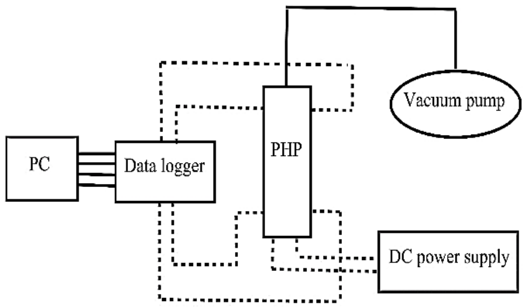


Fig. 1: Schematic diagram of the PHP experimental set-up

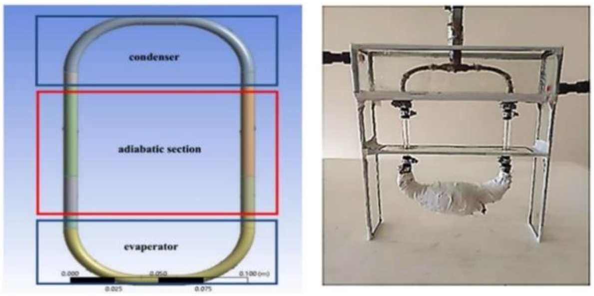


Fig. 2: The simulation model and experimental PHP

to reduce waste of heat to the environment. Furthermore, a glass adiabatic side is embedded between condensation and evaporation sections.

Before injecting the working fluid, a vacuum pump was utilized to evacuate the PHP. Then, the device was filled with working fluid (distilled water as base fluid and distilled water including the concentration of micro-coppers 0.0625g/mL). The physical properties of the working fluid are presented in Table 1. From Table 1, the critical diameter of distilled water is 1.75-4.85mm [20]. The single-turn pulsating heat pipe has been built with internal and external diameters of 4mm and 6mm, respectively. Collecting the Temperature of each part (condenser and evaporator) at different heat inputs (20-60 W) was done via a data logger (model: DATA LOGGER ®). Four K-type thermocouples were connected to monitor temperatures; two of them were placed in the evaporation part (T_{e1} and T_{e2}) and the rest were put in the condenser (T_{c1} and T_{c2}).

CFD SIMULATION OF THE PULSATING HEAT PIPE

Physical Model

To simulate the internal flow regime of PHP, a 3D physical model was designed in OPEN FOAM software. The properties of the working fluid (Distilled water as base fluid and the base fluid including micro-coppers) were determined. The experimental PHP and simulation model with three main parts of evaporator, condenser, and adiabatic section are depicted in Fig. 2.

Computational setup

The main equations like energy, momentum, and continuity equations in the VOF model were applied to study the motion of the working fluid. The viscous model was chosen as the K-epsilon model. It is considered that Water vapor is primary and water as a secondary fluid. A Discrete Phase Model (DPM) was turned on by defining the properties of injection (micro-coppers).

To evaluate the impact of surface tension, the Continuum Surface Force (CSF) model was activated. The value of surface tension of 0.072N/m was assigned by considering wall and jump adhesion. As respect to empirical research, input powers not over 60W were applied in the evaporation section. Insulation boundary condition was considered in the adiabatic section.

Solution method

For this simulation, the filling ratio of PHP was assigned to 40%. By considering the operating temperature of 298.15 K, the pressure velocity coupling was set as SIMPLE. Energy, momentum, and volume fractions were taken as second-order upwind. The relaxation factors for density, pressure and momentum were applied 1, 0.3, and 0.7, respectively. All velocity components were provided in the condensation part as 0 m/s and relative pressure as 0 KPa. In all domains, the walls are in no-slip condition.

Fig. 3: Thermal resistance of the system without microparticles as a function of heat input for different filling ratio

Fig. 4: Thermal resistance of the PHP against heat input and filling ratio at concentration of 0.0625 g mL^{-1}

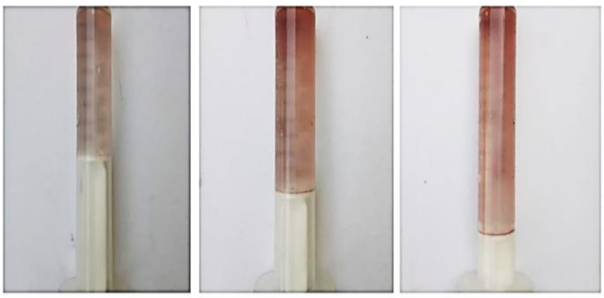


Fig. 5: syringes of distilled water including micro-coppers at a concentration of 0.0625 g mL^{-1}

RESULTS AND DISCUSSIONS

Experimental Investigations on the Influence of filling ratio

To investigate the effect of the filling ratio, experiments were carried out by changing FR to 40%, 50%, and 60% and the findings are demonstrated in Fig. 3.

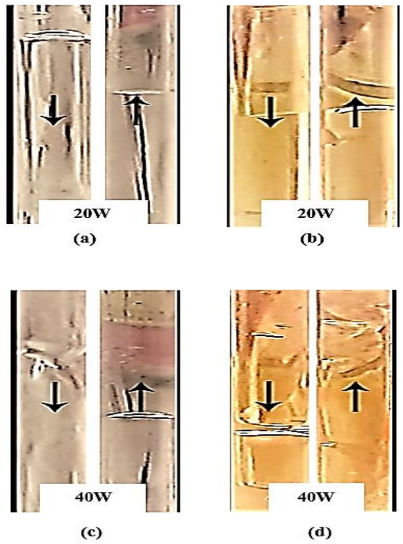


Fig. 6: Flow regimes of the system at a filling ratio of 40%, for the PHP: (a) and (c) without micro-coppers, (b) and (d) with micro-coppers

For FR=60%, a larger volume of the PHP is filled by working fluid, so fewer bubbles might form in the system at lower heat inputs. Then, bubble pumping action and oscillating movement through the PHP is decreased. Although, for FR=40% at lower input powers, more bubbles could generate and move easily inside the device as compared to FR=60%.

The PHP including micro-coppers

As it is exhibited in Fig. 4, Similar to results obtained for PHP without microparticles, experimental results demonstrate that the thermal resistance of the system with micro-coppers decreases by enhancing input power to the evaporator. From the findings, the system with micro-coppers experienced the maximum and minimum values of thermal resistance, as 0.64degC/W and 2.48degC/W, respectively. Fig. 5 displays the syringes of distilled water as base fluid, including micro-coppers at a concentration of 0.0625 g/mL, at different filling ratios (40, 50, and 60%). Flow regimes of the PHP with micro-coppers and without are visualized in the adiabatic section in Fig. 6. From the results, adding micro-coppers distributes the heat flux throughout the PHP smoothly so it reduces the risk of encountering drying out in the system especially at higher heat inputs. Physical properties of micro-coppers is illustrated in Table 2 [21]. Experimental data indicate that the thermal resistance of the PHP with distilled water as base fluid and the fluid including

Table 2: Physical properties of the micro-coppers at atmospheric pressure [21]

Microparticles	Density (kg/m^3)	Thermal conductivity (W/K.m)	Melting point (k)	Boiling point (k)	(Sizeμm)
Copper	8960	401	1357	2835	45

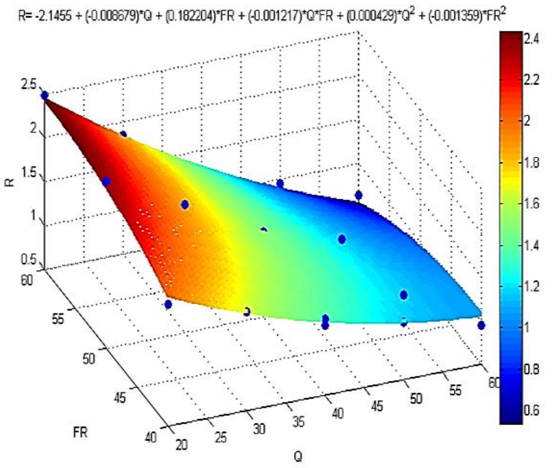


Fig. 7: The figure of the system from Matlab

micro-coppers decreases by increasing input power. Thermal resistance is used as an important factor to evaluate the performance of PHP. Thermal resistance is obtained from Eq. (1)

$$R_{PHP}=\frac{T_{avg,e}-T_{avg,c}}{Q} \quad (1)$$

Where R_{PHP} is the average thermal resistance, $T_{avg,e,}$ and $T_{avg,c}$ are the average evaporator and condenser temperatures, respectively. The average temperatures are achieved by using Relation (2)

$$T_{avg}=\frac{1}{2}\sum_{i=1}^{2} T_i \quad (2)$$

It would be assumed the Sedimentation of some microparticles (micro-coppers) inside the PHP especially the evaporator might generate many active nucleate parts that improve the boiling heat transfer. Meanwhile, adding micro-coppers to distilled water enhances the surface-to-volume ratio and would increase the heat transfer area.

Correlation

For the system with different values of filling ratio (40%, 50% and 60%), A novel experimental equation is presented to predict the thermal resistance. By using the technique of curve-fitting, the relation in terms of independent variables like filling ratio and heat input is as Equation (3)

$$R^{-0.51}{}_{Pre}=1.082-6.51\times Q-0.061\times FR+1.8\times FR\times Q+9.2\times Q^2$$
$$+1.052\times FR^2 \quad (3)$$

Where, *FR* is the filling ratio in (%) and *Q* is heat input in (W). Furthermore, Fig. 7 displays a diagram for the system with different values of filling ratios (40%, 50% and 60%) and the various number of heat inputs (20, 30, 40, 50, and 60)W obtained from a code which has written in Matlab software as follows:

$$R=-2.1455-0.008679\times Q+0.182204\times FR-0.001217\times FR\times Q$$
$$+0.000429\times Q^2-0.001359\times FR^2 \quad (4)$$

Optimization

By applying the technique of curve-fitting on experimental data, optimized values of heat input and filling ratio were derived to achieve the best thermal resistance of the single turn pulsating heat pipe containing distilled water and the system including base fluid with micro-coppers. The most important scope is to obtain the maximum thermal performance of PHP by optimizing different parameters as they are shown in Tables 3 and 4. From findings in Figs. 8 and 9, it would be predicted that the PHP can experience the minimum values of thermal resistance at the highest value of heat input (60W).

Uncertainty analysis

Each experimental research has errors, so data uncertainty needs to be considered. Holman method was applied to calculate the uncertainties of the measurement design characters [22]. The uncertainty of a K-type thermocouple was given by 0.1 k. In this experiment, the input power gained by the current and voltage having an accuracy of 0.03 A and 0.3 V, respectively. The equation (5) calculates the uncertainty of input power as follows:

$$\frac{\delta R_{PHP}}{R}=\sqrt{\left(\frac{\delta T_e}{T_e-T_c}\right)^2+\left(\frac{\delta T_c}{T_e-T_c}\right)^2+\left(\frac{\delta Q}{Q}\right)^2} \quad (5)$$

The maximum uncertainty of the thermal resistance that was calculated using equation (5) is about 8%.

Numerical simulation compared with experimental results

Water volume fractions of the PHP containing base fluid at different input powers of 20W and 50W, at a filling ratio of 40%, are depicted in Fig. 10. By considering bubble dynamics, coupling latent heat advantage with

Table 3: Minimum values of thermal resistance from the curve-fitting for the system without micro-coppers

Number	Thermal Heat Input	Filling Ratio	Thermal Resistance	Desirability
1	60.000	40.000	1.046	1.000
2	60.000	60.000	0.857	1.000
3	60.000	50.000	0.964	1.000
4	60.000	54.625	0.917	1.000
5	60.000	42.500	1.029	1.000
6	60.000	52.500	0.939	1.000
7	60.000	55.375	0.909	1.000
8	60.000	45.375	1.006	1.000
9	60.000	57.500	0.886	1.000
10	60.000	57.026	0.891	1.000
11	60.000	47.869	0.984	1.000
12	60.000	54.033	0.923	1.000
13	60.000	55.177	0.911	1.000
14	60.000	50.877	0.955	1.000
15	60.000	53.483	0.929	1.000
16	60.000	46.029	1.000	1.000
17	60.000	43.738	1.019	1.000
18	60.000	51.763	0.947	1.000
19	60.000	53.045	0.933	1.000

Table 4: Minimum values of thermal resistance from the curve-fitting for the system with micro-coppers

Number	Filling Ratio	Heat Input	Thermal Resistance	Desirability
1	60.000	60.000	0.651	0.993
2	59.926	60.000	0.654	0.992
3	60.000	59.845	0.654	0.991
4	59.613	60.000	0.667	0.990
5	59.999	59.999	0.649	0.990
6	60.000	59.664	0.658	0.989
7	60.000	60.000	0.652	0.988
8	59.966	60.000	0.654	0.986
9	58.948	60.000	0.694	0.985
10	60.000	59.290	0.667	0.984
11	60.000	59.976	0.647	0.982
12	60.000	60.000	0.643	0.973
13	56.274	60.000	0.793	0.967
14	40.000	60.000	0.921	0.943
15	40.125	60.000	0.923	0.943
16	40.000	59.848	0.923	0.942
17	51.010	60.000	0.932	0.941
18	40.000	60.000	0.920	0.941
19	50.805	60.000	0.936	0.941
20	40.829	60.000	0.936	0.940

sensible heat transport into a liquid plug makes the system ready to get better oscillating mode. From the CFD findings, at lower heat input of 20W, fewer bubbles can be able to be formed in the device, but for the system at higher heat input of 50W more bubbles would generate and move easily through the PHP.

Fig. 11 illustrates adding micro-coppers to distilled water at filling ratio of 40%, at the concentration of micro- coppers 0.0625 g/mL, at heat input of 60W improves the main mechanism of the PHP based on the oscillating movement of vapor plugs and liquid slugs.

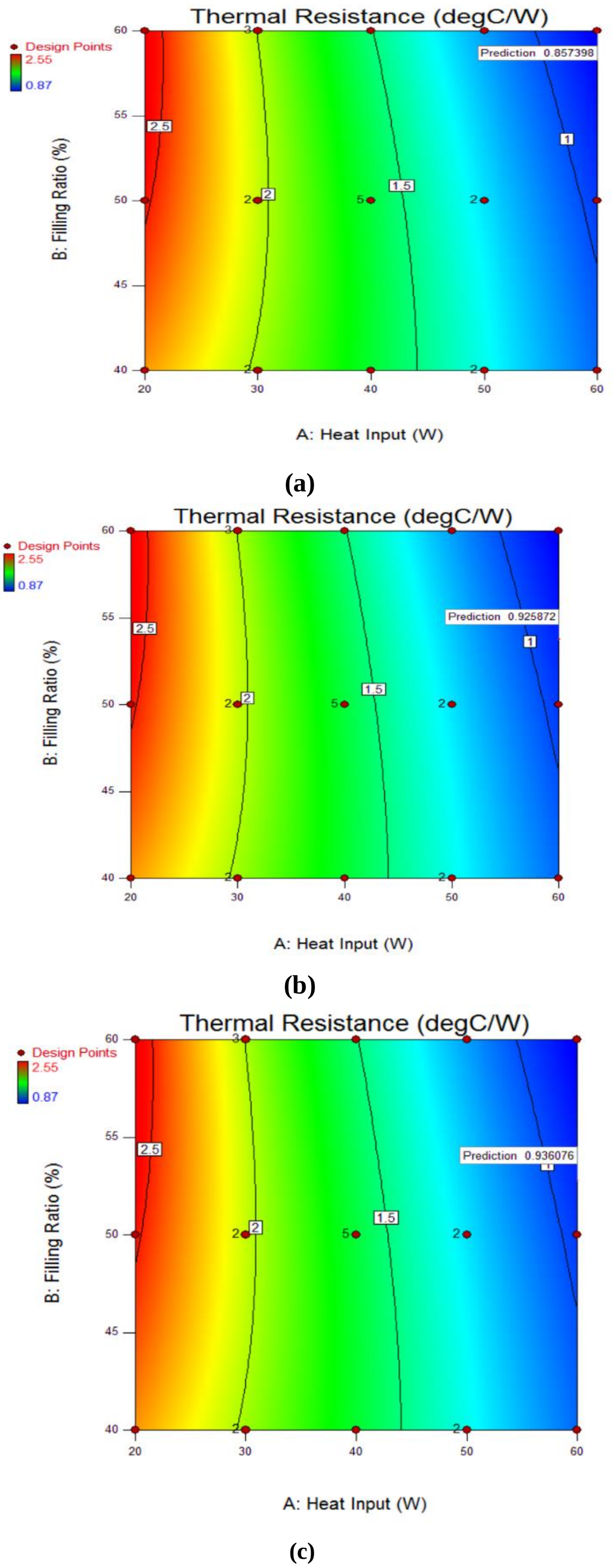


Fig. 8: Optimal graphs of the thermal resistance for the system without micro-coppers

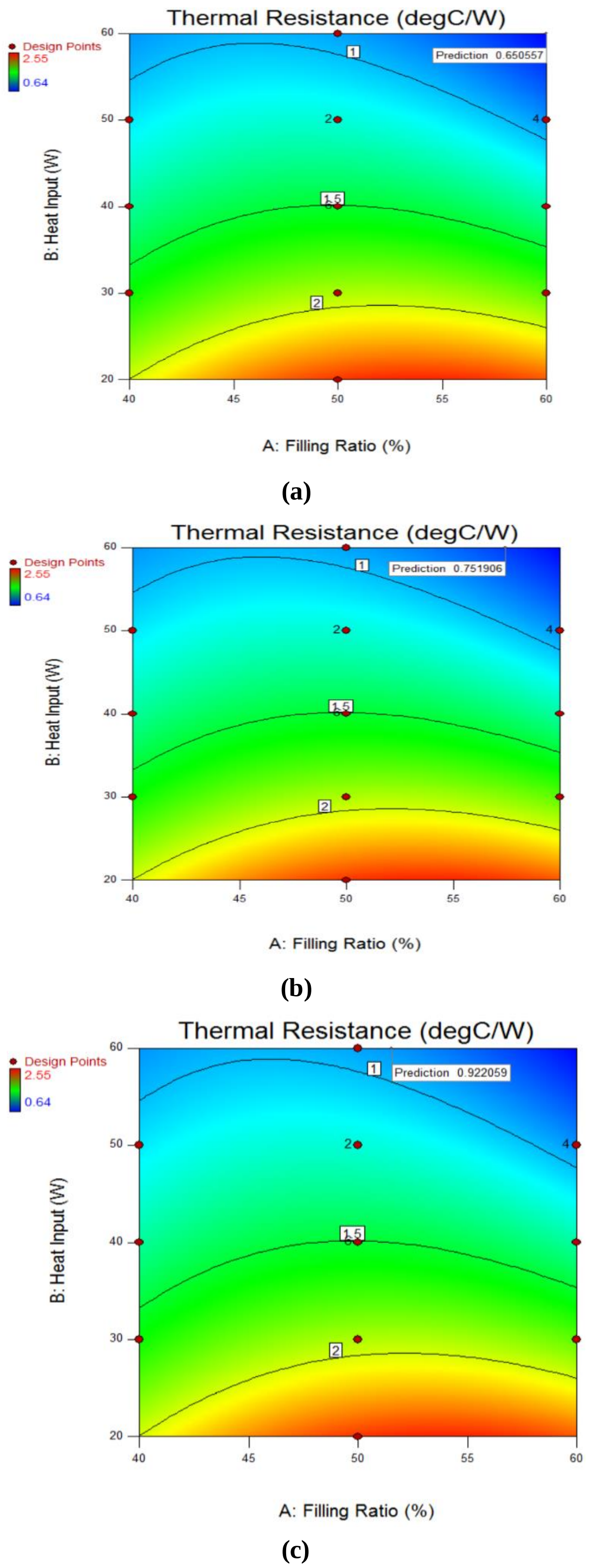
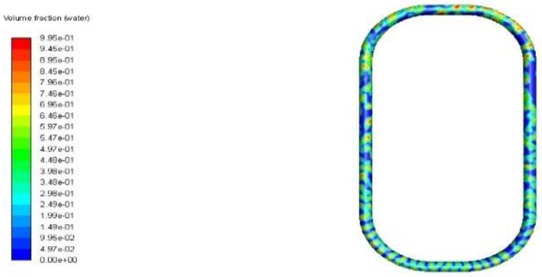
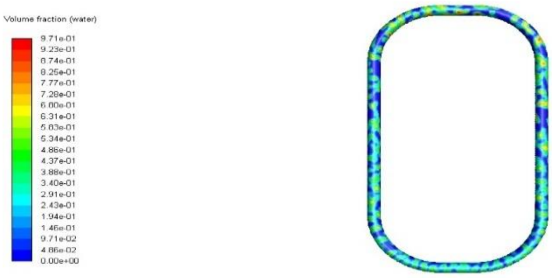


Fig. 9: Optimal graphs of the thermal resistance for the system with micro-coppers

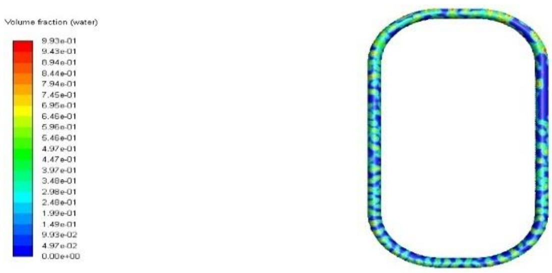


(a)

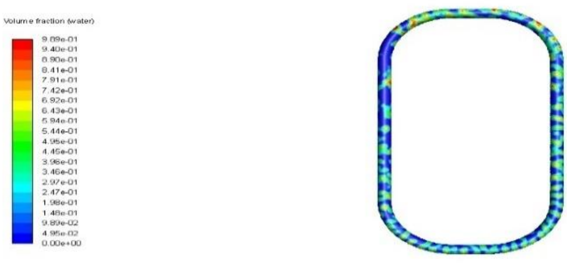


(b)

***Fig. 10:** Water volume fractions of the PHP without micro-coppers at heat inputs: (a) 20W (b) 50W*



(a)



(b)

***Fig. 11:** Water volume fractions of the PHP at heat input of 60W: (a) without micro-coppers (b) with micro-coppers*

From CFD results in Fig. 12, it is illustrated that adding micro-coppers into base fluid increases the turbulence of the system, especially the evaporator and enhances the heat transfer through the PHP in

***Fig. 12:** Particle ID for the PHP at concentration of micro-coppers 0.0625 g mL^{-1}, at filling ratio of 40%*

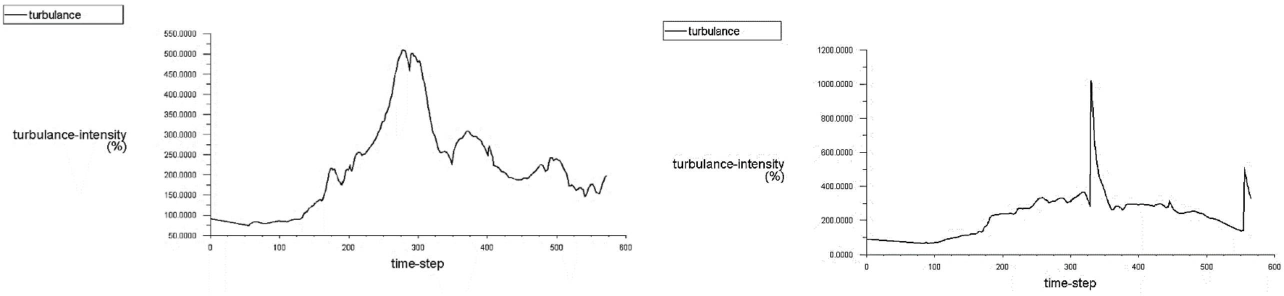
Comparison to base fluid. As it is displayed in Fig. 13, existing micro-coppers keep raising the turbulence of the system especially at higher time steps (or flow time) that support the oscillating motion of the device appropriately.

Fig. 14 depicts surface heat fluxes of the system including micro-coppers or without at input power 60W. It is assumed adding micro-coppers to the base fluid enhances the surface to volume ratio that it rises up the heat transfer area.

Temperature variations of the PHP with or without micro-coppers in the hot part (evaporator), at heat input 20W, at a filling ratio of 40% are shown in Fig. 15. To emphasize the exactness of experiment method, the experimental findings were validated by comparing data of the thermal resistance for the PHP at concentration of micro-coppers (0.0625 g/mL), at the filling ratio of 40% with the simulation results in Fig. 16. Whole results were evaluated at heat inputs (20, 30, 40, 50 and 60 W), for the same working fluid (distilled water including micro-coppers). The average error between the data gained by the experiment and CFD results is 13.2 %.

CONCLUSIONS

In this study, experimental research and Computational Fluid Dynamics (CFD) were utilized to investigate the flow regime of the single turn pulsating heat pipe including distilled water as base fluid with or without micro-coppers. The study was performed for the PHP at a concentration of micro-coppers (0.0625 g/mL), at different heat inputs

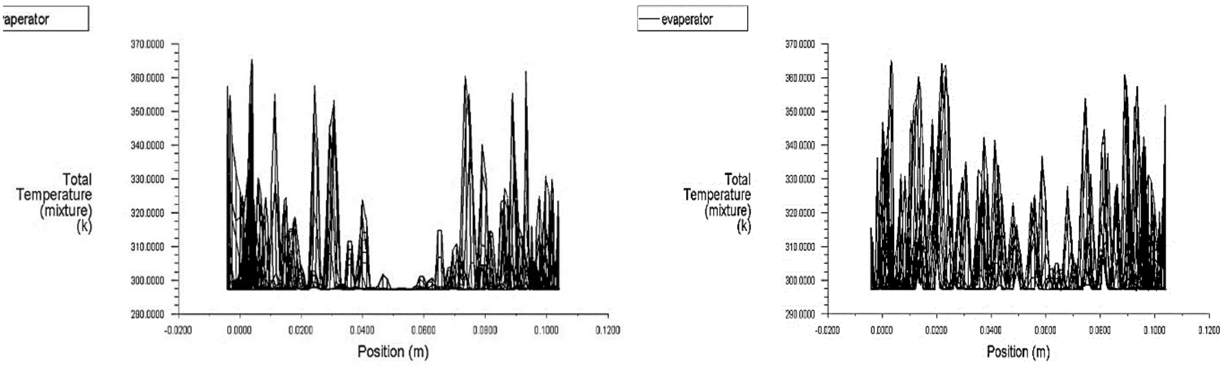


(a) (b)

Fig. 13: Turbulence intensity of the PHP at filling ratio of 40%, at heat input of 30W (a) without micro-coppers (b) with micro-coppers

(a) (b)

Fig. 14: Surface heat fluxes of the PHP at heat input 60 W: (a) without micro-coppers (b) with micro-coppers



(a) (b)

Figs. 15: Temperature variations of the evaporation section at heat input 20W: (a) without micro-coppers (b) with micro-coppers

(20W, 30W, 40W, 50W, 60W). The results achieved in this work are presented as follows:

1) The experimental findings indicate that the thermal resistance of the PHP with distilled water as base fluid and the fluid including micro-coppers decreases by increasing input power.

2) Experiments display adding micro-coppers into base fluid improves the main mechanism of the PHP based on the oscillating motion of vapor plugs and liquid slugs.

3) The lowest thermal resistance of the system at the filling ratio of 40%, at the concentration of micro-coppers (0.0625 g. mL^{-1}), at heat input (60W) was 0.95 degC. W^{-1}.

4) CFD findings indicate surface heat fluxes of the system with micro-coppers are more than those of without particles.

5) From CFD results, existing micro-coppers keep raising the turbulence of the system especially at higher time steps (or flow time) that supports the oscillating motion of the device appropriately.

Fig. 16: Validation of experimental data with CFD results for the PHP at a concentration of micro-coppers 0.0625 g m/L, at a filling ratio of 40%

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