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Enhancement of Heat Transfer Performance of a Heat Pipe by Using Calcium Magnesium Carbonate-Ethylene Glycol/Water Nanofluid with Sodium Dodecylbenzene Sulfonate

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Abstract

In this paper, the effect of using $CaMg(CO_3)_2$/Ethylene Glycol-water (50:50%) as a working fluid on the thermal performance of thermosyphon heat pipe was experimentally studied. Nanofluid was prepared by two-step method using 2% concentration of $CaMg(CO_3)_2$ nanoparticle and 0.05% surfactant (Sodium dodecylbenzene sulfonate). For the experimental set-up, a straight copper pipe of one-meter length was used. The inner diameter of the pipe is 13 mm, and the outer diameter is 15 mm. Experiments were conducted at three different cooling water mass flow rates (5, 7.5, and 10 g/s) and different heating powers (200, 300, 400 W) to test heat pipe performance. It was observed that the $CaMg(CO_3)_2$ nanofluid reduced the average wall temperature of the heat pipe according to the base fluid. Furthermore, the efficiency and thermal resistance of the heat pipe were investigated separately for EG/water and $CaMg(CO_3)_2$ nanofluid. The maximum heat transfer enhancement was obtained as 9.55% under 400 W heating power and 10 g/s cooling water mass flow rate conditions and the maximum improvement in thermal resistance was observed as 21% at 200 W and 10 g/s cooling mass flow rate. Viscosity and specific heat of base fluid and $CaMg(CO_3)_2$ nanofluid were also determined and compared to each other.

Keywords

nanofluid, $CaMg(CO_3)_2$, EG/water, heat pipe, heat transfer enhancement

1 Introduction

The heat pipe is a kind of passive heat transfer device with effective thermal conductivity. The most important aspects of the heat transfer applications are efficient and speed heat transfer with small temperature differences [1]. Heat pipes with high thermal conductivity meet these needs and are therefore used in plenty of applications (cooling, aerospace applications, fuel cells, solar thermal systems, etc.). Amongst the different technologies and methods, a heat pipe is a charming selection because of its low cost, weight, simple design and energy-efficient [2]. There are different types of heat pipes. Thermosyphon is one of them. In general, a thermosyphon type heat pipe consists of an insulated pipe and a working fluid circulated within this pipe. The heat pipe parts are the evaporator section, adiabatic section and condenser section. In the case of heat input from the evaporator zone, the working fluid passes from the liquid phase to the vapor phase and carries the heat energy from one region to another with the effect of the vacuum and natural convection. The fluid goes into the liquid phase under the influence of the lower temperature at the condensation area and it reaches back to the evaporator area due to the effect of gravity [3]. This process also occurs periodically when heat input to the system is to be continuous.

Conventional fluids are commonly used in heat pipes as working fluids such as water, motor oil and ethylene glycol. Although various techniques have been used to enhance heat transfer, conventional fluids with weak heat characteristics restrict the increase in thermal performance of the system and in particular impose a significant limitation on the performance improvement and the compactness of heat exchangers [4]. In order to eliminate this disadvantage, solid particles with a particle size of less than 100 nm and having high thermal conductivity are added to a suspension, which is called nanofluid.

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The main purpose of the nanofluid is to achieve the highest thermal conductivity capacity at the lowest possible nanoparticle concentration. Due to their molecular structure, nanoparticles contact a larger area than conventional fluids. Nanoparticles increase the thermal capacity and stability of the fluid more than the microparticles and reduce the erosion and pumping power in the channel.

Many researchers [5–11] used different nanofluids as working fluid in a thermosyphon type heat pipe and obtained enhancement in the thermal performance of thermosyphons. Nanofluids also have been using in different types of heat exchangers. Khanlari [12] investigated the effect of utilizing Al_2O_3/deionized water (DW) in the efficiency of parallel flow tube-type heat exchanger and counterflow tube-type heat exchanger. The results demonstrated that Al_2O_3–SiO_2/deionized water hybrid nanofluid provides a maximum enhancement of 25%, 60% and 67% of the overall heat transfer coefficient at 0.5%, 1% and 1.5% nanoparticle ratio, respectively. Khanlari et al. [13, 14] also analyzed the effects of using kaolin/deionized water nanofluid as working fluids in the plate heat exchanger and counter flow concentric tube (CFCT) heat exchanger and parallel flow concentric tube (PFCT) heat exchanger. Their results showed that kaolin/deionized water nanofluid caused maximum improvement of 18%, 37% and 12% in heat transfer rate CFCT and PFCT heat exchangers respectively, Said et al. [15] used CuO/water as heat transfer fluid in shell and tube heat exchanger. Their experimental results demonstrated an increase in the heat transfer coefficient and convective coefficient by 7% and 11.39%, respectively. Many parameters have a great role in the heat performance of a nanofluid. Some of them are concentration, size and shape of nanoparticle, type of surfactant and base fluid, nanofluid temperature, etc. Huminic et al. [16] investigated nanoparticle concentration of Fe_2O_3/water nanofluid on the thermal performance of thermosyphon type heat pipe. They prepared different concentrations of 0%, 2% and 5.3% nanofluids by volume and obtained an increase of heat transfer rate of 42% for Fe_2O_3/water nanofluid concentration of 5.3% for an inclination angle of 90°. Kamyar et al. [17] conducted thermal performance tests of a two-phase closed thermosyphon by using Al_2O_3 and $TiSiO_4$ nanofluids. They studied different nanoparticle concentrations (0.01%, 0.02%, 0.05% and 0.075%) and different ranges of heating powers from 40 W to 210 W. They found that thermal resistance decreased by 65% and 57% using Al_2O_3 (0.05 vol%) and $TiSiO_4$ (0.075 vol%) nanofluids, respectively. Lanjewar et al. [18] prepared CuO-polyaniline (PANI) nanocomposite based nanofluid at different concentrations and investigated its thermal performance in a vertical helically coiled heat exchanger. They obtained a 37% increase in heat transfer coefficient when they used CuO-PANI nanocomposite based nanofluid with 0.2 vol. %. Kim et al. [19] presented a study about the effect of nanoparticle size on the enhancement of nanofluid thermal conductivity. They prepared ZnO-water nanofluid at 3% by volume of zinc oxide nanoparticle size and observed enhancement by 14.2%, 11.5% and 7.3% in thermal conductivity when using 10 nm, 30 nm, and 60 nm nanoparticles, respectively. Many other studies show that the thermal performance of a nanofluid increase when particle size decreases [20–22]. In addition, studies show that the rate of thermal conductivity improvement of hybrid nanofluids compared to base fluids is higher than mono nanofluids [23]. The addition of a surfactant into a nanofluid improves the performance of the nanofluid. A surfactant may prevent the suspension from coagulating either by steric stabilization or by a combination of steric and electrostatic stabilization [24, 25]. Surfactants can be used to reduce the surface tension of heat pipes [26]. Sözen et al. [27] investigated the effects of TiO_2/deionized water nanofluid with the use of the different types of surfactants on the thermal performance of a two-phase closed thermosyphon at various conditions. They used Triton X-100 and sodium dodecylbenzene sulfonate (SDBS) as surfactants. They observed that the thermal resistance decreased by 43.26% when using TiO_2 nanofluid with SDBS compared to water. Yang et al. [28] studied the effect of different surfactants (polyacrylic acid, cetyl trimethyl ammonium bromide, and SDBS) on the stability of a-Al_2O_3 nanofluids. They reported that the stability of nanofluid increased with using a surfactant. However, it was found that the dispersion of Al_2O_3 suspensions decreased with increasing surfactant concentration. The addition of nanoparticles and surfactant to the base fluid causes an increase in viscosity of the overall fluid so the power required to pump the nanofluids and pressure drop increase [29]. It is necessary to determine the optimal nanoparticle concentration and surfactant, which provide minimum viscosity and high thermal conductivity for nanofluids.

The mixture of ethylene glycol and water has wide usage as heat transfer fluids in cold areas such as Canada, Alaska, Northern Europe and Russia for building heating systems, automobiles, and heat exchangers. Commonly used mixtures are 40:60% and 50:50% of ethylene glycol and water [30]. Calcium magnesium carbonate is an anhydrous carbonate mineral, commonly known as dolomite, with the molecular formula $CaMg(CO_3)_2$. It is quite widespread in the world. Dolomite is therefore an easy to find and inexpensive mineral. In the present study, $CaMg(CO_3)_2$-ethylene glycol/water (50% wt) nanofluid was prepared at the rate of 2% (wt.) nanoparticle concentration by two-step method. SDBS was used as a surfactant. Viscosity and specific heat of $CaMg(CO_3)_2$ nanofluid were experimentally determined and then obtained results were compared with the base fluid. The thermal performance of $CaMg(CO_3)_2$-ethylene glycol/water nanofluid in thermosyphon heat pipe was also investigated.

2 Materials and method

$CaMg(CO_3)_2$ nanofluid was prepared by using two-step method. In the first stage, $CaMg(CO_3)_2$ nanoparticles were obtained by using ball milling. $CaMg(CO_3)_2$ particle size was measured by nanoparticle size analyzer (Malvern Zetasizer Nano ZS). The $CaMg(CO_3)_2$ particles in the nanoscale were dispersed into the base fluid at 2% by mass. Ethylene glycol-water (50% wt.) was used as base fluid. 0.5% by mass of surfactant was added. The sodium dodecylbenzene sulfonate ($C_{18}H_{29}NaO_3S$), an anionic surface active agent, was used as a surfactant. Ultrasonication was applied for three hours to prepare a stable mixture. The stability of the prepared nanofluid was determined by zeta potential measurement. Zeta potential was measured for $CaMg(CO_3)_2$ nanofluid by a Malvern Zetasizer Nano ZS. Viscosity measurements were made with Brookfield DV-III rheometer. Viscosities of base fluid and nanofluids were measured at different temperatures (20 °C, 40 °C, 50 °C, 60 °C and 70 °C). Specific heat capacity was measured by using Differential Scanning Calorimeter (DSC 4000, Perkin Elmer).

The thermal performance of nanofluid was experimentally investigated in a thermosyphon heat pipe. The schematic view of the experimental setup is illustrated in Fig. 1. In this study, a straight copper tube with an inner diameter of 13 mm, an outer diameter of 15 mm and a length of 1000 mm (400 mm of evaporator while 200 mm of adiabatic section and the remaining 400 mm of condenser) was used as the heat pipe. An electrical heater comprising of a Ni-Cr wire with a 1500 W nominal power heated the evaporator section. The heater was insulated by glass wool to prevent heat leakages along the heat pipe wall. The input power was set as 200, 300 400 W in the experiments. The condenser section of the heat pipe was equipped with a cooling water system (i.e., cooling jacket). The heat was drowned out from the condenser utilizing the circulation of the cooling water in the jacket. A flow meter was used to set the desired cooling water mass flow rate.

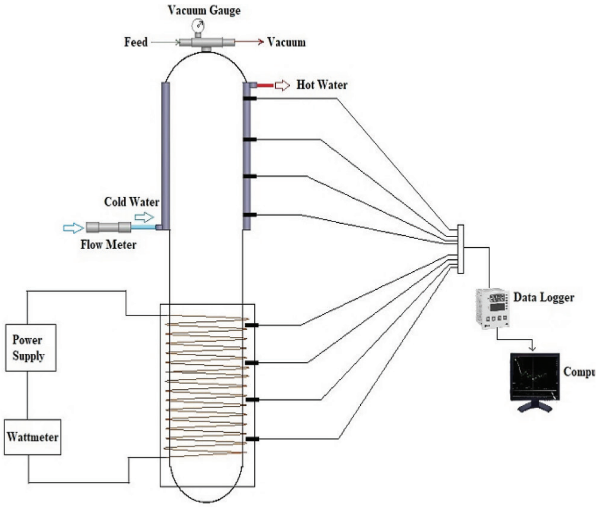


Fig. 1 Schematic view of the experimental test setup

The temperature values are monitored by the distributed K-type thermocouples (10 pieces) along the heat pipe wall. Four of these are placed on the evaporator and four of them are mounted on the condenser section, and two of them are placed on the input and the output of the cooling water. Data from thermocouples were recorded. In all experiments, the heat pipe was placed horizontally at a 90° angle.

3 Results and discussion

The average particle size of $CaMg(CO_3)_2$ was measured as 24.54 nm. Zeta-potential of $CaMg(CO_3)_2$ nanofluid was found as 23 mV. Nanofluids are considered to be physically stable when the zeta-potential is greater than or equal to 20 mV in either the positive or negative value [31]. Thermophysical properties of nanofluid have a specific role in the thermal performance of heat pipes. In this study, the viscosity and specific heat of nanofluids were determined and compared to ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) data. Viscosities of base fluid and nanofluid were given in Fig. 2. A comparison between the experimental result and the presented result in ASHRAE [32] has been made to determine the accuracy of the results for the viscosity of the EG/water mixture. It is found that the average difference does not exceed 4% between present data and ASHRAE. The viscosity of base fluid increase with the use of nanoparticles and surfactant [33]. However, it has an unfavorable effect on heat pipes. Lower viscosity provides the appropriate thermal performance of the heat pipe. $CaMg(CO_3)_2$ nanoparticles (24 nm) only increased the viscosity of the nanofluid by 2.8% at 20 °C.

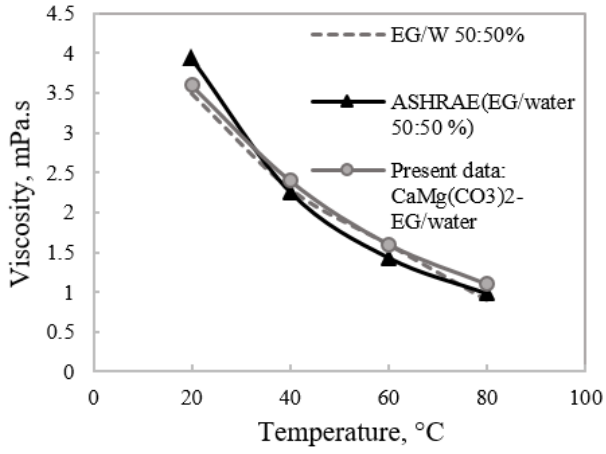


Fig. 2 Experimental viscosity results and ASHRAE [32] data of base fluid

Specific heat is another thermophysical property that affects the thermal performance of nanofluid, and thereby heat pipe was also determined. ASHRAE data and measured the specific heat of EG/water and $CaMg(CO_3)_2$-ethylene glycol (EG)/water nanofluid at 20 °C were given in Table 1 [32]. Specific heat of $CaMg(CO_3)_2$ nanofluid is bigger than EG/water so heat retention and heat carrying capacity of $CaMg(CO_3)_2$ nanofluid are higher than base fluid.

Heat transfer rate (Q_c) was calculated by using the water mass flow rate, the specific heat of the water and the inlet and outlet cooling water temperature difference in the condenser,

$$\dot{Q}_c = \dot{m}c(T_{out} - T_{in}) \,. \tag{1}$$

Q_e is the heating power applied to the evaporator section; 200 W, 300 W and 400 W. The thermal resistance of heat pipe is given by;

$$R = \frac{\Delta T}{\dot{Q}_e} \,. \tag{2}$$

ΔT is temperature difference between mean temperatures of the evaporation and condensation section. ΔT is defined as:

$$\Delta T = \frac{T_{e1}+T_{e2}+T_{e3}+T_{e4}}{4} - \frac{T_{c1}+T_{c2}+T_{c3}+T_{c4}}{4} \,. \tag{3}$$

Efficiency is;

$$\eta = \frac{\dot{Q}_c}{\dot{Q}_e} \,. \tag{4}$$

The distribution of temperature along the heat pipe wall was recorded and utilized for efficiency calculation. The temperature distribution of the thermosyphon heat pipe wall was illustrated for EG/water (50:50) and $CaMg(CO_3)_2$ nanofluid with the $CaMg(CO_3)_2$ nanoparticle mass fraction of 2% and SDBS fraction of 0.5% at a heating power of 200 W and cooling water mass flow rates of 5 g/s, 7.5 g/s and 10 g/s in Fig. 3.

As it can be seen in Fig. 3, the temperature of heat pipe wall is dramatically decreasing while passing from evaporator to the condenser section. Nanofluid employment instead of ethylene glycol/water as working fluid significantly reduced the mean temperature of the heat pipe wall. The average wall temperatures in the evaporator section at the conditions of 200 W heating power and 10 g/s mass flow rate were 92 °C and 77.5 °C when EG/water and 2% concentration of $CaMg(CO_3)_2$ nanofluid were used respectively. It was shown that the average temperature decreased by 14.5 °C. $CaMg(CO_3)_2$ nanofluid enhances boiling heat transfer of heat pipe according to EG/water. Nanoparticle interactions with bubbles and highly conductive nanoparticles provide that the boiling temperature of nanofluid is lower than of base fluid type. Furthermore, because of the increase in the cooling water mass flow rate, the average wall temperatures in the evaporator and condenser sections decreased.

In a similar way, temperature changes along the heat pipe wall for 300 W and 400 W heating powers could be seen in Fig. 4 and Fig. 5, respectively. The same trend in temperature distributions could also be seen in these figures.

Table 1 Specific heat results and ASHRAE [32] data of base fluid at 20 °C

	Specific Heat (J/g °C)
ASHRAE-EG/water (50:50%)	3.28
EG/water (50:50%)	3.32
$CaMg(CO_3)_2$ nanofluid	3.74

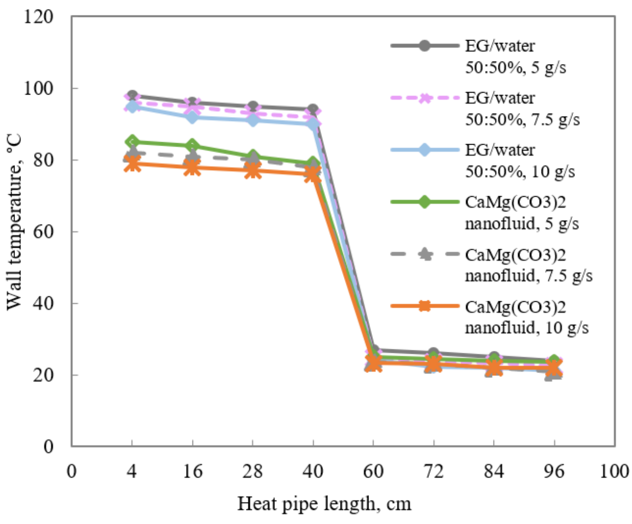


Fig. 3 The variation of wall temperature along the heat pipe (200 W)

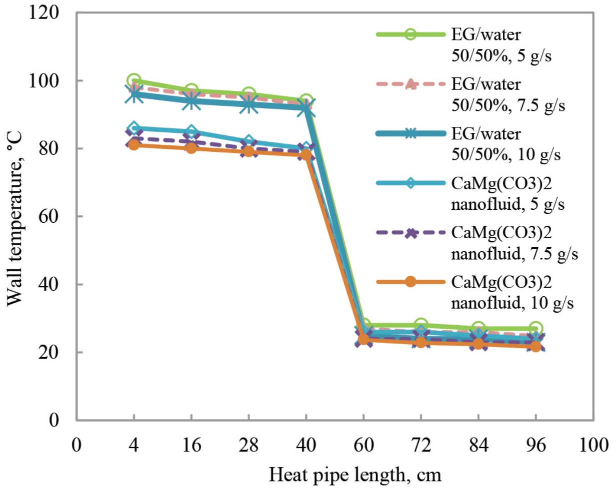


Fig. 4 The variation of wall temperature along the heat pipe (300 W)

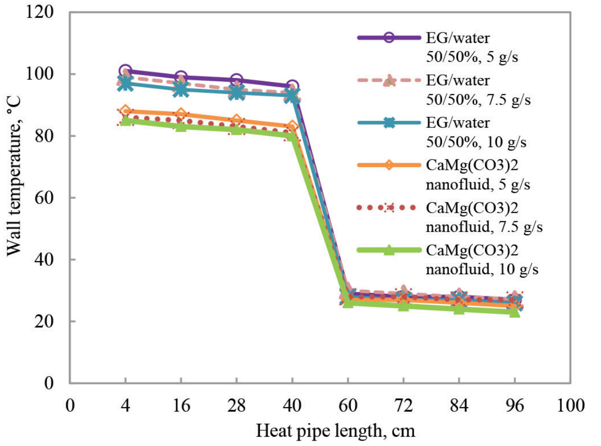
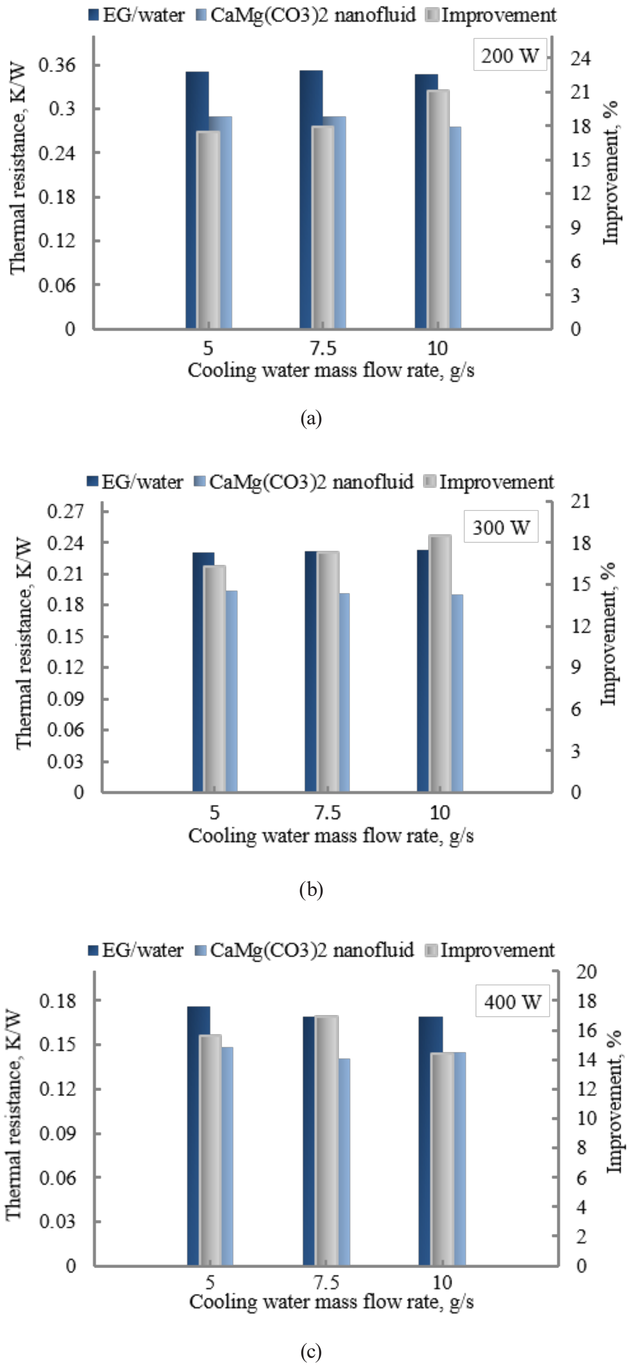


Fig. 5 The variation of wall temperature along the heat pipe (400 W)

the evaporator section was found to be 85.8 °C in the case of using CaMg$(CO_3)_2$ nanofluid at a concentration of 2%. The average wall temperature difference is 12.8 °C.

The thermal resistance of the heat pipe was also investigated in this study for the base fluid and CaMg$(CO_3)_2$ nanofluid. Fig. 6 shows thermal resistances of heat pipe for heating powers of 200, 300, 400 W when using EG/water and CaMg$(CO_3)_2$ nanofluid. By using nanofluid as a working fluid in the heat pipe was decreased the thermal resistance of the heat pipe. While the thermal resistance of EG/water was 0.348 K/W, the thermal resistance of CaMg$(CO_3)_2$ nanofluid was found to be 0.274 K/W at 200 W heating power and 10 g/s mass flow rate of the cooling water. At these conditions, the maximum thermal resistance improvement was obtained as 21%. Large bubbling nucleation prevents heat transfer from solid to liquid. Nanoparticles in nanofluid decrease the wettability related to the solid-liquid contact angle. Thus, the size of the bubble nucleation reduces and the thermal resistance decreases according to the base liquid [34]. The thermal resistance of the heat pipe is reduced with increasing heating power for both working fluids. Because of low heating power, boiling does not occur on all heat transfer surfaces. In this case, heat transfer occurs by natural convection. Therefore, as can be seen in Fig. 6 thermal resistance is high at the low heating powers. As the heating power increases, the boiling in the surface increases. Therefore, the heat transfer takes place with both natural convection and phase change and causes the thermal resistance to decrease [35].



(a)

(b)

(c)

Fig. 6 Thermal resistance values of the heat pipe at different heating powers; (a) 200 W; (b) 300 W; (c) 400 W

The efficiency of the thermosyphon heat pipe at different heating powers and cooling water mass flow rates were given in Fig. 7 for EG/water and $CaMg(CO_3)_2$ nanofluid.

The efficiency of the heat pipe was higher for all operating conditions when using $CaMg(CO_3)_2$ nanofluid as a working fluid. For 200 W heating power, the maximum efficiency was observed as 62.4% for $CaMg(CO_3)_2$ nanofluid and 59.5% for EG/water in 7.5 g/s cooling water mass flow rate condition. Thus, an increase of 4.87% has occurred in the efficiency of the heat pipe. The maximum enhancement ratio in the thermal efficiency was obtained as 9.55% under 400 W heating power and 10 g/s cooling water mass flow rate conditions. As the heat transfer rate increases, the efficiency of the thermal system increases. It was seen that $CaMg(CO_3)_2$ nanofluid has good heat transfer capability when compared to EG/water working fluid because of metal nanoparticles containing.

4 Conclusion

Heat transfer enhancement of a heat pipe using $CaMg(CO_3)_2$ nanofluid as a working fluid has been investigated experimentally under various operating conditions. EG/water (50:50%) and SDBS were used as base fluid and surfactant to prepare $CaMg(CO_3)_2$ nanofluid. $CaMg(CO_3)_2$ nanoparticles were obtained as 24 nm by ball milling. Viscosity at different temperatures and specific heat of $CaMg(CO_3)_2$ nanofluid and EG/water were measured. The viscosity increased by only 2.8% at 20 °C after adding $CaMg(CO_3)_2$ nanoparticles and surfactant. The specific heat of $CaMg(CO_3)_2$ nanofluid was found to be higher than EG/water. Temperature distribution along the heat pipe wall, thermal resistance and efficiency of heat pipe were determined for each working fluid and the following conclusion have been made;

- $CaMg(CO_3)_2$ nanofluid showed higher performance in heat pipe compared to EG/water. When $CaMg(CO_3)_2$ nanofluid was used in the heat pipe under optimum conditions, the average wall temperature of the evaporator section was measured as 14.5 °C lower than EG/water at 200 W heating power and 10 g/s cooling water mass flow rate. The use of the $CaMg(CO_3)_2$ nanofluid provided a narrower range of wall temperature distribution than a mixture of EG/water.

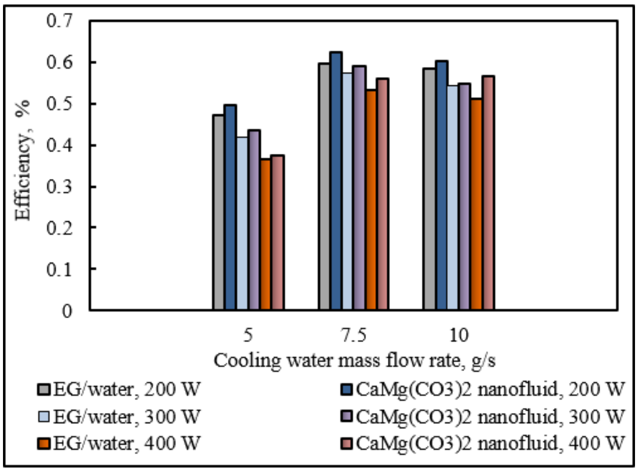


Fig. 7 The efficiency of the heat pipe under varying operating conditions

- The thermal resistance of heat pipe declined with the use of $CaMg(CO_3)_2$ nanofluid according to EG/water. The improvement of thermal resistance at the rate of 21% was obtained when nanofluid was used under 200 W heating power and 10 g/s cooling water mass flow rate conditions.
- The heat pipe efficiency enhanced by 9.55% at 400 W heating power rate and 10 g/s cooling water mass flow rate when using $CaMg(CO_3)_2$ nanofluid compared to EG/water. Adding $CaMg(CO_3)_2$ nanoparticles to a mixture of EG/water provided enhancement of its thermal performance.

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Nomenclature

η:	Thermal efficiency
$\dot{Q}_c$:	Heat transfer rate (condenser), W
$\dot{Q}_e$:	Heating power, W
$\dot{m}_{water}$:	Mass flow rate of water, g/s^{-1}
c:	Specific heat capacity, J/g.s
ΔT:	Temperature difference, °C
T_e:	Wall temperature of evaporator, °C
T_c:	Wall temperature of condenser, °C
R:	Thermal resistance, $°C/W^{-1}$

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