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Analysing the Thermal Performance of Heat Pipe Using Copper Nanofluids

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ABSTRACT

Heat pipes are heat transfer device that do not need external power; as a result, they are used in various thermal systems. Enhancing the performance of heat transfer device is a continues effort. Thus, this study investigates the effect of copper nanofluid on the thermal performance of cylindrical heat pipe (HP) that has screen mesh wick for heat transfer applications. The copper HP consists of 350 mm length and 12.7 mm outside diameter. To investigate its thermal performance mathematical model is developed. Demineralized water based 20 nm copper nanofluids with 0 to 4% particle concentrations were considered in the study. Simulation was done at 100 W heat input and results showed that when the particle concentration increases the evaporator wall temperature drops. At 4% particle concentration nanofluid the HP thermal resistance reduced by 17.5% compared to when the HP uses demineralized water. Furthermore, for a given particle concentration as the heat input increases the temperature change between the evaporator and the condenser increases. The outcome of the investigation can be input to the design of solar heat exchangers that use HPs filled with nanofluids.

Keywords: Heat pipe, copper nanofluids, thermal performance, particles concentration.

1. Introduction

Energy should be properly and efficiently utilized. HPs are efficient heat transfer device; they can be used in various thermal applications such as energy storage, waste heat recovery, electronic cooling, and solar thermal energy technologies. They are very effective in transferring heat at considerable rates and distances with a minimum temperature lose, easy to fabricate, simple to control and do not need external pumping power [1]. There are different types of design, setup and working fluid depending on their application. Use of nanofluids as working fluids is one of the opportunities to improve the heat transfer characteristics of heat exchangers in solar technologies. Like other heat exchangers HP performance depends on several factors including its diameter, length, material type, wick structure, working fluid, fin arrangement, operating conditions, shape,

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orientation, and ambient temperature [2]. In the past few decades, several analytical as well as experimental studies were conducted and significant improvements were achieved. Loh *et al*., [3] investigated the effect of inclination angles and different wick structures on HP performance. Mohamed *et al*., [4] analyzed the effect of wick structure permeability and thickness using water and methanol as a mediums of heat transfer on L-shape HP performance. Li *et al*., [2] fabricated a HP with a sintered-grooved composite wick and studied its performance experimentally using water as a working fluid.

With regard to working fluids, many researches have been done. For instance, Jahanbakhsh *et al*., [5] experimentally examined a HP performance which is used as a solar collector and water-ethanol solution is used as the working medium. They concluded that the smaller the heat flux, the higher is HP performance. A collector that used only a large wickless HP was studied numerically and experimentally by Wei *et al*., [6]. Azad [7] compared experimentally three different kinds of HP solar collectors' performance at the same working conditions. Recently, Naghavi *et al*., [8] designed a solar collector system using evacuated tube HP for heating water with heat storage tank and investigated the performance experimentally. The heat transfer capability of CuO/DI water nanofluid in HPs that have sintered and mesh wick, respectively, were investigated by Kumaresan *et al*., [9]. They observed that the HP thermal resistance with the sintered wick reduced by 13.9% relative to the HP with mesh wick. Up-to-date studies [10,11] showed that there has been increasing interest in nanofluid and its use in HP heat performance enhancement. This is because, HP heat transfer capability relies on the heat transfer medium characteristics [12]. In these papers, the experimental results revealed that use of nanofluids as a working fluid improved the heat transfer effectiveness of the HP by reducing thermal resistance of saturated porous media. According to this review the use of nanofluids in a HP significantly enhances its heat transfer performance. In general, the aforementioned literature reviews showed that there are continues efforts to improve the performance of HPs using different nanofluids and the improvement is not yet fully addressed. Therefore, this paper investigates numerically the thermal performance of cylindrical HP using copper water nanofluids. For comparison purpose the HP performance with demineralized water as a working medium is presented.

2. Methodology

HP consists of three major components: a sealed cylindrical pipe, screen mesh wick, and a working fluid. The schematic diagram of a typical HP is shown in Figure 1. The most commonly used material copper was used as HP. The wick is composed of 2 layers of screen wire mesh and assumed to be copper with 0.45 porosity and each 0.5 mm thickness. To investigate the performance pure metal nanofluids (Cu-water) with different percentage particles concentrations were considered. The HP is 350 mm long, (with a circular section of 12.7 mm outer diameter and 0.71 mm wall thickness). As indicated in Figure 1 the length of the HP consists of three parts: evaporator (100 mm), adiabatic section (100 mm), and condenser (150 mm). Table 1 shows the thermal properties of the base working fluid and copper nanoparticles.

Table 1
Thermophysical properties of water and Cu-nanoparticles

Physical properties	k(W/m K)	Cp(J/kg K)	ρ(kg/m3)
Pure water	0.613	4179	997.1
Copper	400	385	8933

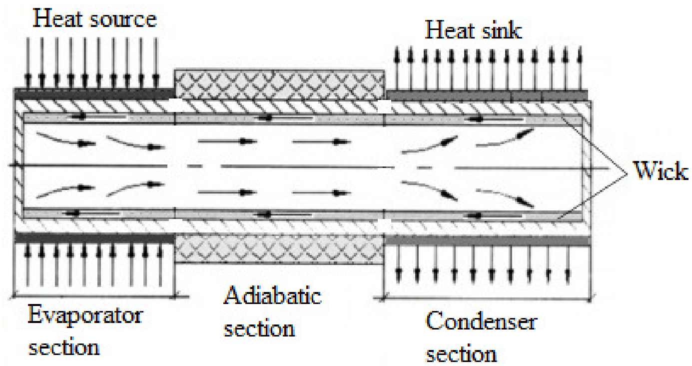

Fig. 1. A schematic representation of a HP

The mathematical model requires extra information of the wick and the nanofluid, and they can be predicted from empirical correlations. Furthermore, after assessing various available empirical correlations that are obtained from different technical literature, the following were selected.

The HP temperature distribution depends on the wick effective thermal conductivity and can be estimated as [13]

$$k_{eff} = \frac{k_{nf}[(k_{nf}+k_s)-(1-\varepsilon)(k_{nf}-k_s)]}{[(k_{nf}+k_s)+(1-\varepsilon)(k_{nf}-k_s)]} \tag{1}$$

The nanofluids thermal conductivity that consider nanolayer deposition on the surface of the nanoparticle is estimated as [14]

$$k_{nf} = \frac{k_{pe}+2k_b+2(k_{pe}-k_b)(1-\beta)^3\phi}{k_{pe}+2k_b-(k_{pe}-k_b)(1-\beta)^3\phi}k_b \tag{2}$$

$$k_{pe} = \frac{[2(1-\gamma)+(1+\beta)^3(1+2\gamma)\gamma]}{-(1-\gamma)+(1+\beta)^3(1+2\gamma)}k_p \tag{3}$$

$$\gamma = \frac{k_{layer}}{k_p} \ and \ \beta = w/\mathrm{r_p} \tag{4}$$

The heat transfer on the outer side of the condenser that uses water for cooling depends on the heat transfer coefficient, *h*. To get the *h* value first the Nusselt number is calculated from Eq. (5) correlation [15] and then *h* was calculated using Eq. (6).

$$Nu = 0.3 + \frac{0.62\mathrm{Re}_{Dh}^{1/2}\mathrm{Pr}^{1/3}}{[1+(0.4/\mathrm{Pr})^{2/3}]^{1/4}}\left[1+\left(\frac{\mathrm{Re}_{Dh}}{282000}\right)^{5/8}\right]^{4/5} \tag{5}$$

$$h = \frac{Nu * k_l}{D_h} \tag{6}$$

The HP temperature depends on the geometries and its thermal properties, effective thermal conductivity of the wick and on the cooling water heat transfer coefficient and bulk temperature. Furthermore, the HP wall temperature along the length is predicted as [16]

$$T_{wall}(x)=\begin{cases} T_b+\dfrac{Q}{2\pi L_c}\left[\left(\dfrac{\ln(R_o/R_w)}{k_w}\right)+\dfrac{\ln(R_w/R_v)}{k_{eff}}\left(1+\dfrac{L_c}{L_e}\right)+\dfrac{1}{hR_o}\right] & 0\le x\le L_e \\ T_b+\dfrac{Q}{2\pi L_c}\left[\left(\dfrac{\ln(R_o/R_w)}{k_w}\right)+\dfrac{\ln(R_w/R_v)}{k_{eff}}+\dfrac{1}{hR_o}\right] & L_e\le x\le L_e+L_a \\ T_b+\dfrac{Q}{2\pi hR_oL_c} & L_e+L_a\le x\le L \end{cases} \quad (7)$$

One of the parameters that shows the thermal performance of a HP is thermal resistance which is given by

$$R=\frac{T_e-T_c}{Q} \quad (8)$$

3. Results and Discussion

The nanofluids considered for this study is copper-water base nanofluid and the copper nanoparticles are 20 nm size. The effective thermal conductivity improvement of the nanofluid is simulated in the range of 0 to 4% particle concentration and as shown in Figure 2 the thermal conductivity enhancement is increasing as the particle concertation increases and at 4% concentration the enhancement is 23% compared to demineralized water.

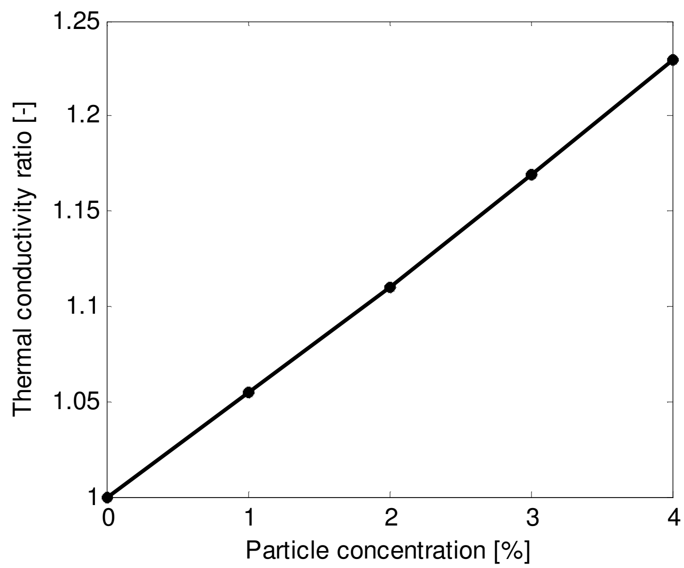

Fig. 2. Effective thermal conductivity variation with respect to particle concentrations

The temperature distribution of the HP wall along its length for different particle concentrations at 100 W heat input was simulated. As can be seen in Figure 3 when the particle concentration increases the evaporator wall temperature drops; because as mentioned in Figure 2 the thermal conductivity of the nanofluids increases and it becomes a better heat transfer medium. The same is true in the adiabatic section. However, all the temperatures merge to one value in the condenser section in all cases because of the cooling effect.

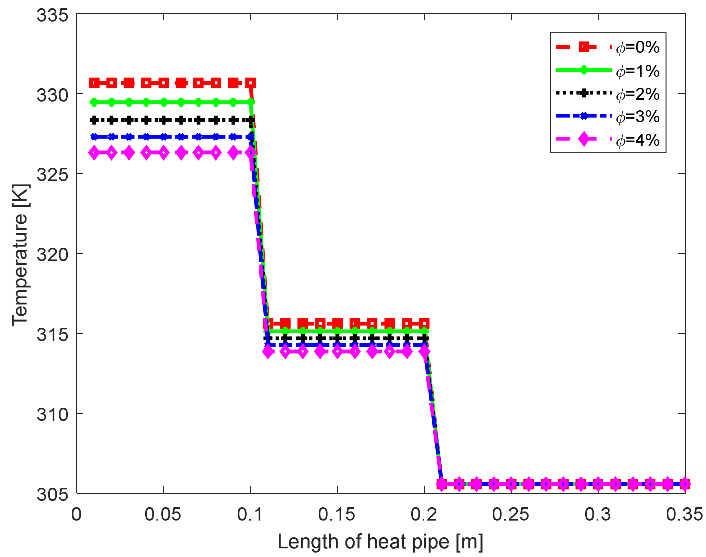

Fig. 3. Temperature distribution of the HP along its length for different particle concentrations

The HP thermal resistance is simulated by varying the nanofluids concentration at 100 W heat input. As depicted in Figure 4 the thermal resistance declines as the particle concentration increases. At 4% volume concentration the reduction in thermal resistance is 17.5% compared to the demineralized water. Thus, the thermal performance of the HP has been enhanced by the presence of the nanoparticles inside the water. This is the consequence of thermal resistance reduction while improving the maximum heat load it can carry.

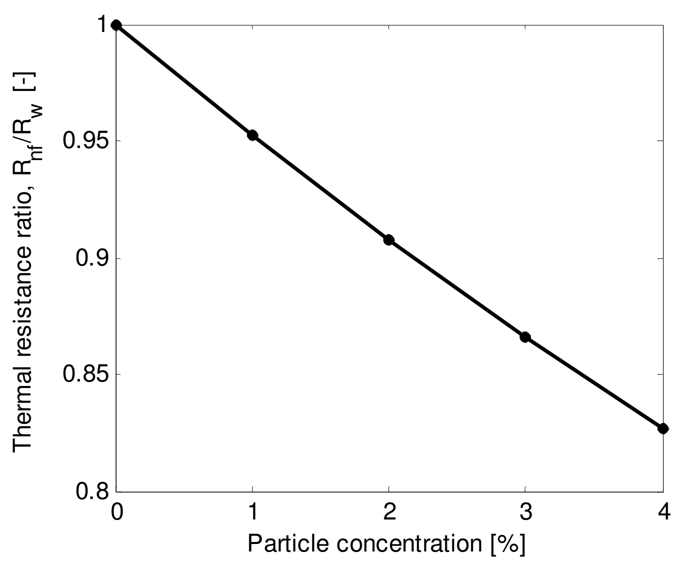

Fig. 4. Thermal resistance of the HP with respect to particle concentration

The potential of the temperature difference between the evaporator and the condenser is studied with respect to heat input for different particle concentrations. Depicted in Figure 5 for a given particle concentration as the heat input increases the temperature difference increases. However, at a given heat input when the particle concentration increases the temperature difference decreases. Its overall effect is enhancing the heat transfer ($Q = \Delta T / R$) because the decrease in thermal resistance is significant compared to the decrease in temperature difference.

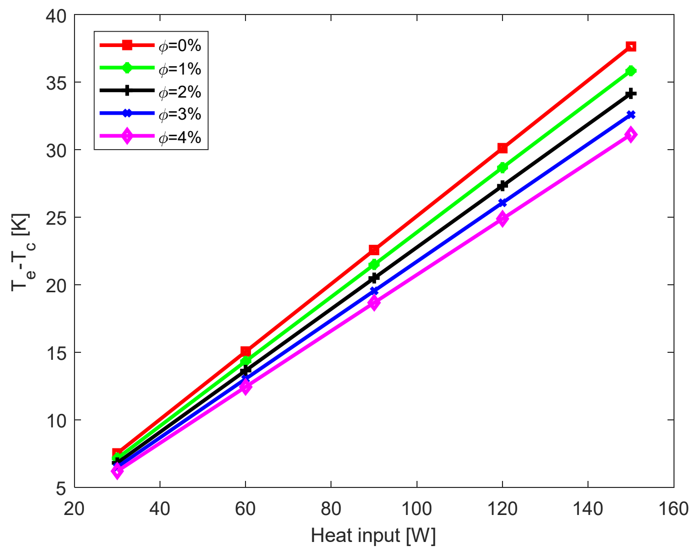

Fig. 5. Temperature difference variation with respect to heat input for different particle concentrations

4. Conclusions

Mathematical model of cylindrical HP with screen mesh is developed. The model was used to simulate the HP thermal performance. The demineralized water based 20 nm copper nanofluids with 0 to 4% particles concentration was considered in the study. The following are drawn from the simulation. Simulation was done at 100 W heat input and results showed that when the particle concentration increases the evaporator wall temperature drops. At 4% nanofluids concentration the HP thermal resistance reduced by 17.5% compared to when it uses demineralized water. Furthermore, for a given particle concentration as the heat input increases the temperature difference between the evaporator and the condenser increases. In general increasing the particles concentration will increase the heat transfer ($Q = \Delta T / R$) because the decrease in thermal resistance is significant compared to the decrease in temperature difference. Thus, it is recommended that HPs that are used in solar heating application to employ nanofluids with a limited amount of nanoparticles that have higher thermal conductivity to enhance heat exchange performance.

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