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Heat Transfer Characteristics of a Two-Phase Closed Thermosyphons Using Nanofluids Based on SiC Nanoparticles

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ABSTRACT

The main goal of the present study was to investigate of the thermal conductivity and heat transfer characteristics of two-phase closed thermosyphon (TPCT) with SiC/water nanofluids. The outer diameter and length of the TPCT were of 10 and 300 mm, respectively. The laser pyrolysis and TEM techniques were used for synthesis and characterization of the nanoparticles. The mixtures of water and nanoparticles were prepared using a double ultrasonic homogenizer. The measurement of thermal conductivity of SiC/water nanofluids were investigated between 20 °C and 50°C, for two weight concentrations (0.5 and 1.0 wt%).%). The results show that the thermal conductivity of SiC/water nanofluids increases with the increasing of weight concentration of the nanoparticles and temperature. Also, effects of operating temperature and nanoparticles concentration on the heat transfer characteristics of TPCT were considered. The nanofluids based on SiC nanoparticles enhance heat transfer characteristics of TPCT compared with TPCT using water.

Keywords: Nanofluids, Thermal conductivity, Two-phase closed thermosyphon, Thermal performances.

1. INTRODUCTION

Silicon carbide is an important non-oxide material with excellent thermo-physical properties being used in various mechanical and thermal applications. The high thermal conductivity, low thermal expansion coefficient, chemical and thermal stability, high melting point and high erosion resistance make SiC a perfect candidate for high power, high temperature electronic devices, radiant heater tubes, heat exchangers, as well as abrasion and cutting applications [1, 2].

In the last decade, researchers were focusing on the measurement of both thermal conductivity and viscosity of the silicon carbide [1, 3-8]. Also, few studies were performed on heat transfer characteristics of the two-phase thermosyphon using silicon carbide [9-11].

Li et al. [1] studied the stability and the thermal conductivity of EG-based SiC nanofluids at various volume concentrations and temperatures. EG-based SiC nanofluids were made by the two-step method. Thermal conductivity SiC/EG nanofluids was investigated within the range of the temperature of 20 °C to 50°C, for five volume concentrations (0.2, 0.4, 0.6, 0.8 and 1.0 vol.%). The results showed an enhancement up to 16.21% in thermal conductivity of nanofluids at 50 °C and 1.0 vol.% nanoparticles compared to base fluids and theoretical model.

Singh et al. [3] investigated thermal conductivity and viscosity of water-based SiC nanofluids. Mean size of SiC particles was 170 nm. Thermal conductivity of the fluid was measured within the range of the volume concentration of 1.0% to 7.0%, for three temperatures (23, 50 and 70 °C). Viscosity of the nanofluids (1.8, 3.7, and 7.4 vol.% particle) were measured as a function of temperature ranging from 15 °C to 55 °C. The authors founded an enhancement in thermal conductivity of approximately 28% at a concentration of nanoparticles of 7.0 vol.% and in ambient conditions. Also, the highest viscosity (2.94 cP) was observed at 15 °C for the nanofluid with 7.4 vol.% loading. The effect of average particle sizes on basic macroscopic properties and heat transfer performance of α-SiC/water nanofluids was investigated by Timofeeva et al. [4]. The average particle sizes were varied from 16 to 90 nm. The results showed that high thermal conductivities and low viscosities were obtained in the case of nanofluids with larger solid particle sizes. This statement is based on the fact that the interfacial area between solid and liquid is smaller in the case the larger particles. The same research team [5] investigated the thermo-physical properties (thermal conductivity and viscosity) and turbulent flow heat transfer characteristics of α-SiC/EG-H_2O (50:50). In this study, the measurements were performed for various diameters of particles (16-90 nm).

Lee et al., [6] studied both viscosity and thermal conductivity of β-SiC/water nanofluids. The viscosity SiC/water nanofluids was investigated within the range of the temperature of 28 °C to 72°C for volume concentrations in range 0.001- 3.0%. The thermal conductivity was measured within the range of the temperature of 22 °C to 23.5°C for the same volume concentrations. The results showed that the increase of the relative thermal conductivity and relative viscosity was approximately 7.2% and 102% respectively at a concentration of nanoparticles of 3.0 vol.%.

Manna et al. [7] studied the thermal conductivity of the SiC/water nanofluids as a function of particle concentration and particle size. The experiments were conducted within the range of the volume concentration of 0.1 to 0.8 vol.%. The results showed that the thermal conductivity ratio of nanofluid significantly increase up to 12% with only 0.1 vol. % nanoparticles and decreases with particle size.

Studies concerning the fabricate SiC nanofluids with different SiC crystalline phases (α-SiC and β-SiC) in order to investigate comparatively physicochemical and thermo-physical properties of SiC nanofluids in H_2O /EG mixture (50/50 wt% ratio) were performed by Nikkam et al. [8]. Their results indicated that nanofluids based on α-SiC nanoparticles have better thermo-physical properties compared with nanofluids based on β -SiC nanoparticles. Thus, a thermal conductivity enhancement of 20% and an increase viscosity of 14% were obtained for nanofluids containing 9.0 wt% of particular type of α-SiC nanoparticles.

Concerning the use of nanofluids in heat pipes, studies in this field were performed by Wang et al. [9] and Yao et al. [10]. Researches in which SiC nanofluids were used as working fluids in thermosyphons or heat pipes are limited. Thus, Abbasi et al. [11] experimentally investigated the effect of β-SiC/water nanofluids on thermosyphon efficiency enhancement. The mean diameter of β-SiC nanoparticles was 50 nm. The inner diameter and the length of the copper TPCT were 28 mm and 1500 mm respectively. The experiments were performed within the range of the input power 100-300 W, for four volume concentrations (0.5, 1.0, 1.5, and 2.0 vol.%). The results showed that the efficiency of TPCT for 2.0 vol% SiC/water nanofluid is of 1.11 times higher than that with pure water.

Ghanbarpour et al. [12] investigated the thermal performances of heat pipes using α-SiC/water nanofluid. Also, the authors measured thermo-physical properties (thermal conductivity, viscosity, density and specific heat) for three concentrations of nanoparticule (0.35, 0.7 and 1.0 wt.%). The inner diameter and the length of the copper heat pipes were 6.36 mm and 250 mm respectively. The evaporator and condenser sections of the heat pipe were 50 mm and 50 mm long, respectively. Their results showed that the thermal resistance was reduced by 30% for the heat pipes with1.0 wt.% SiC nanoparticles. Also, the results indicated that the maximum heat removal capacity of the heat pipe increases by 29% for 1.0 wt.% SiC nanoparticles.

Thermal performances of heat pipes using nanofluids based on SiC particles were investigated by Kim et al. [13]. In this study, volume concentrations of nanoparticles of 0.01% and 0.1% respectively were considered. The diameter and the length of the stainless steel heat pipes were 19 mm and 1000 mm respectively. The authors founded that the heat pipes using nanofluids based on SiC nanoparticles not have the higher thermal performances than the heat pipes using water as working fluid.

The main goal of the study is to prepare and to investigate the effects of the temperature and weight concentration on the thermal conductivity and thermal performances of SiC/water nanofluids used in two-phase closed thermosyphon. The SiC nanoparticles were obtained by the laser pyrolysis technique. Thermal conductivity of SiC/water nanofluids was investigated within the range of temperature from 20 °C to 50 °C. Also, effects of the operating temperature and of the nanoparticles concentration on the thermal performances of TPCT were studied.

2. EXPERIMENTAL PROCEDURE

2.1 Nanofluid preparation

The laser pyrolysis technique was used for synthesis of nanoparticles. The laser pyrolysis method requires the presence of a sensitizer (laser energy transfer agent) besides the nanoparticles precursors. For the synthesis of the nanopowder, a mixture of silane and acethylene was used. Also, a Coherent CO_2 pulsed laser with 400W nominal power, working at 10.59 μm was used for the synthesis of the nanopowders (80 KHz frequency and a duty factor around 60%).

The SiC nanoparticles have been characterized using TEM technique. TEM image of SiC nanoparticles is shown in Figure 1.

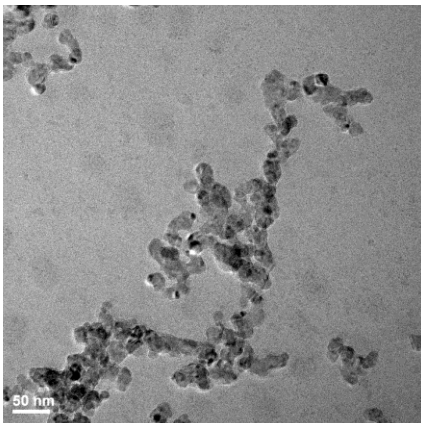

Figure 1. TEM image of SiC nanopaticles

As depicted, some nanoparticles are arranged in ramified/chained aggregates or small clusters. Their sizes are in more or less correlated with the mean crystallite sized extracted from X-ray measurements, generally under 25 nm for both samples. The aggregation of these nanoparticles can be explained by the welding of hot fresh nanoparticles due to their collision in the crowded laser pyrolysis flame.

In this study, homogeneous and stable water-based SiC nanofluids with different weight concentrations were prepared. For the aqueous nanofluid preparation, the low viscosity dry carboximethylcellulose white powder (CMCNa) was mixed with SiC nanopowder and introduced in very small portions in the vessel containing 250 ml distilled water under the action of a strong ultrasonic homogenizer (Hielscher UIP 1000hd endowed with a 22 mm diameter sonotrode having a 1000 W nominal power and working at 20 kHz frequency) with a supplementary mechanical mixing using a vibrating thin rod terminated with a orthogonally positioned toroidal spiral. After introducing the powders, the rod was removed and the ultrasonical treatment was continued for another hour, without external cooling. The powders concentration in distilled water was 0.5 wt.% and 1.0 wt.% respectively. Following this procedure, no settlement of nanoparticles was observed after 6 months.

2.2 Experimental setup and procedure

Thermal conductivity of the water-based SiC nanofluids was measured using a KD 2 Pro Thermal Properties Analyzer (accuracy of ±5%). The measurement principle of KD 2 is based on the transient hot-wire technique. The analyzer consists of a thermal probe, a thermo-resistor and a microprocessor to control and measure the conduction in the probe. The diameter and length of the thermal probe were 1.3 mm and 60 mm respectively. Before measurements, the thermal conductivity of the distilled water at the room temperature of 293 K was measured. Thermal conductivity of the water was 0.600 W/mK, which is in good agreement with the value in literature of 0.598 W/mK.

The installation for determination of the thermal performances of TPCT is shown in Figure 2. The dimensions and the material of TPCT as given in Table 1:

Table 1. Dimensions of the TPCT

Dimensions of the TPCT [mm]	Present study
Length	305
Diameter (outer)	10
Thickness	1
Evaporator	121
Adiabatic section	54
Condenser	130
Material	Copper

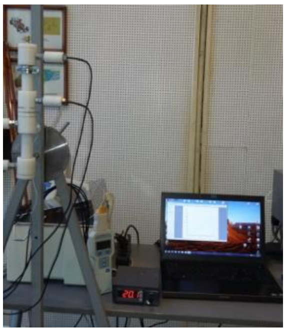

Figure 2. The experimental set-up for measuring the thermal performance of the TPCT

The measurement of the temperatures on evaporator, adiabatic and condenser sections were performed with five thermo-resistances, type –P-1000 (uncertainty: ±0.1°C). The thermo-resistances were placed on TPCT as follows: two on the evaporator, one on the adiabatic section and two on the condenser. To keep the temperature at constant value on evaporator section is performed with a thermostatic bath, type GD 120-S26 (operating range of -15 °C to 120 °C and ±0.1°C accuracy). Also, to keep the temperature and the mass flow rate of the cooling water at constant value on condenser is performed with a thermostatic bath Haake C10 – P5/U (operating range of 25–100 °C and ±0.04 °C accuracy). All the measurements (the inlet and outlet temperatures from evaporator and condensers sections and the mass flow rates of the cooling water) were performed at an inclination angle of 90° (vertical) and a filling ratio of 25%.

2.3 Data reduction

The heat transfer rate was defined as:

$$\dot{Q} = \dot{m} \cdot c_p \cdot \left(T_{C2} - T_{C1}\right) \quad [W] \tag{1}$$

The thermal resistance was computed by the Equation [14]:

$$R = \frac{T_{Eave} - T_S}{\dot{Q}} \quad \left[\frac{K}{W}\right] \tag{2}$$

Also, the temperature difference was defined as:

$$\Delta T = \frac{T_{E1} + T_{E2}}{2} - \frac{T_{C1} + T_{C2}}{2} \quad [K] \tag{3}$$

The vapor temperature, T_S, was measured on adiabatic section.

3. RESULTS AND DISCUSSIONS

3.1 Influence of the CMCNa concentration on thermal conductivity

In order to establish the optimal amount of surfactant, the low viscosity CMCNa solutions in distilled water were prepared in conditions similar, with concentrations of 3.0, 6.0 and 10 g /l, because it assume that to the viscosity of the nanofluid contributes to both nanoparticles and surfactant (even if a part was bound nanoparticle). Also, for comparison a suspension of 3 g/l of medium viscosity CMCNa was prepared.

The thermal conductivity of the distilled water with surfactant (CMCNa) was shown in Figure 3. As shown in Figure 3, thermal conductivity of the water+CMCNa (low viscosity) decreases with the increase of surfactant concentration. Also, it can be seen that the thermal conductivity value of the medium viscosity CMCNa was less than the low viscosity CMCNa for the same concentration. Following the measurements, the concentration of the surfactant for each type of nanofluids was established to 3g/l.

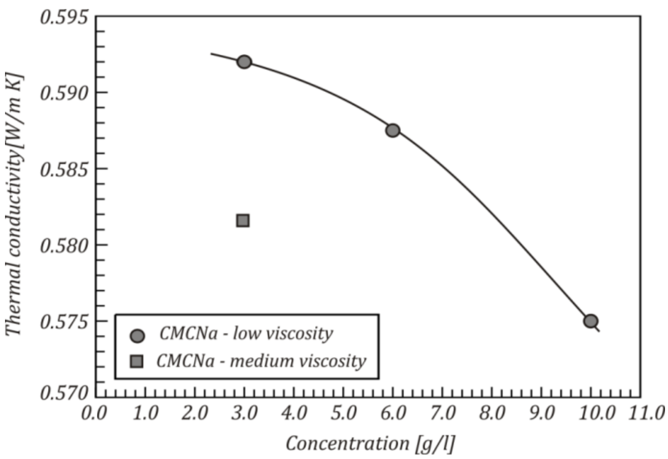

Figure 3. The effect of the surfactant concentration on thermal conductivity

The results similar were founded by Tavman and Turgut [15]. They studied the effect of the sodium dodecylbenzenesulfonate (SDBS) used as surfactant on the thermal conductivity and founded that the thermal conductivity of the SDBS – water mixture decreases with the increasing SDBS ratios. Also, Zhou et al. [16] measured the thermal conductivity of the various surfactants with different concentrations in pure water and in nanofluids. They founded that the thermal conductivity ratio of the sodium dodecylbenzenesulfonate (SDBS) decreases slowly with increase of the SDBS concentration from 0.03 wt% to 0.2 wt%, and then decreases very quickly with increase of the SDBS concentration. Also, the thermal conductivity ratios of the SDS and CTAB surfactants had the same trend as SDBS surfactant, namely the thermal conductivity ratio decreases with the increase of the surfactant concentration.

3.2 Influence of the temperature on thermal conductivity of the nanofluids

In the current study, the measurement of the thermal conductivity was performed for values of temperatures between 20 °C and 50 °C and weight concentrations of SiC nanoparticles of 0.5 and 1.0%.

The effects of temperature and nanoparticles concentration on the thermal conductivity of SiC/water nanofluids were shown in Figure 4.

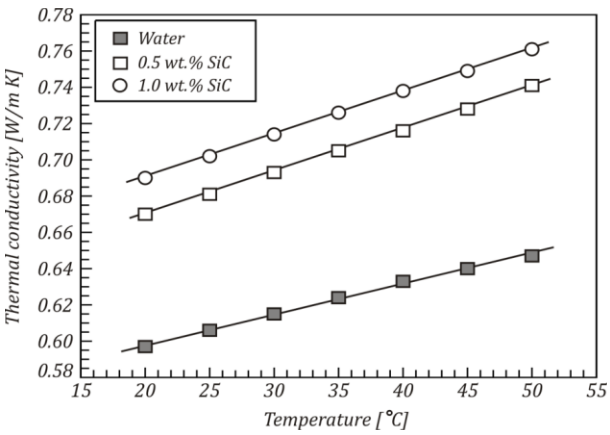

Figure 4. The thermal conductivity versus temperature at various weight concentrations

As shown in Figure 4, for all studied cases, the thermal conductivity of nanofluids linearly increases with the increase of the temperature and weight concentration. The maximum relative thermal conductivity $\left(100\left(k_{nf}-k_w\right)/k_w\right)$ was 17.62% for a concentration of 1.0 wt% and a temperature of 50 °C. At this temperature, the relative thermal conductivity for a concentration of the nanoparticles of 0.5% was 14.53%. The results in this study are similar with those found in literature [1, 3, 6].

The obtained results for the thermal conductivity of the SiC-water nanofluids with weight concentrations of 0.5 wt% and 1.0 wt% respectively in within range 20-50 °C were compared with those from literatures as shown in Table 1. As shown in Table 2, the thermal conductivity of nanofluids, for all experimental data, was higher than the thermal conductivity of the base fluid. The enhancement of the thermal conductivity of the nanofluids depends on many factors: the preparation method, the base fluid, the nanoparticles concentration, the particle size, presence or absence of the surfactants.

Table 2. Experimental thermal conductivity in comparison with the literatures

Ref.	Concen-tration	Nanofluid	Tempera-ture	Maximum increase in thermal conductivity (%)
Present study	0.5-1.0 wt%	SiC/ water	20-50 °C	17.62%
Li et al. [1]	0.2-1.0 vol%	SiC/EG	20-50 °C	16.21%
Singh et al. [3]	1.8- 7.0 vol.%	SiC/ water	15 -55 °C	28%
Timofeeva et al. [5]	4.0 vol%	α-SiC/ /EG-H_2O	Not reported	~ 17%
Lee et al., [6]	0.001- 3.0 vol.%.	β-SiC/ water	22 - 23.5°C	7.2%
Manna et al. [7]	0.1 to 0.8 vol.%.	SiC/ water	Room tempera-tures	26%
Nikkam et al. [8].	9.0 wt%	α-SiC/ EG-H_2O	20 °C	20%
Xie [17]	0.8-4.2 vol%	SiC 26/ EG SiC 26/ water	4 °C	15.8%
	1.0-4.0 vol%	SiC600/ EG SiC600/ water	4 °C	22.9%

3.3 The thermal performances of the TPCT

The heat transfer rate transferred to the coolant water was calculated as inlet and outlet temperature difference from condenser section, taking into account the water mass flow rate and specific heat (see Eq. 1). Figure 5 shows the heat transfer rate of the TPCT using water and SiC/water nanofluid with two weight concentrations of nanoparticles (0.5 – 1.0%).

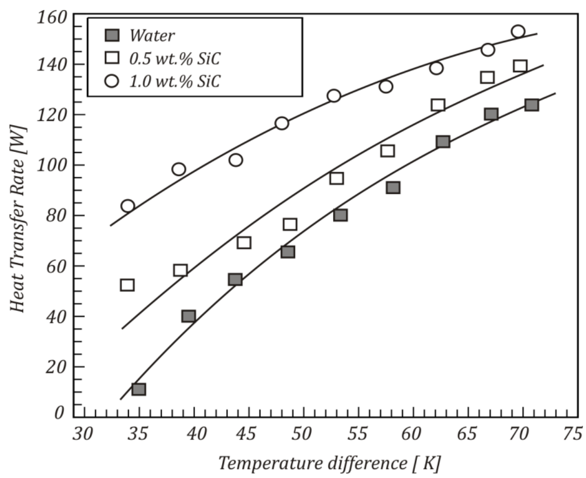

Figure 5. Heat transfer rate of the TPCT for water and nanofluids with various SiC nanoparticles

As shown in Figure 5, the heat transfer rates of the TPCT using nanofluids were much higher than those of the base fluid. Also, it can be seen that the heat transfer rate of the

TPCT increases significantly with the increase of both the operating temperature and nanoparticles concentration. The heat transfer rate increases up to 24.4% for the TPCT with SiC/water nanofluid at a weight concentration of 1.0 % compared with that of the TPCT using water, in conditions of TPCT operation at maximum temperature differences. At the same the temperature difference and a concentration of nanoparticles of 0.5 wt.%, the enhancement of the heat transfer rate in TPCT was 18.5%.

The thermal resistance of the TPCT at various operating temperatures of the TPCT with water and SiC/water nanofluids is shown in Figure 6.

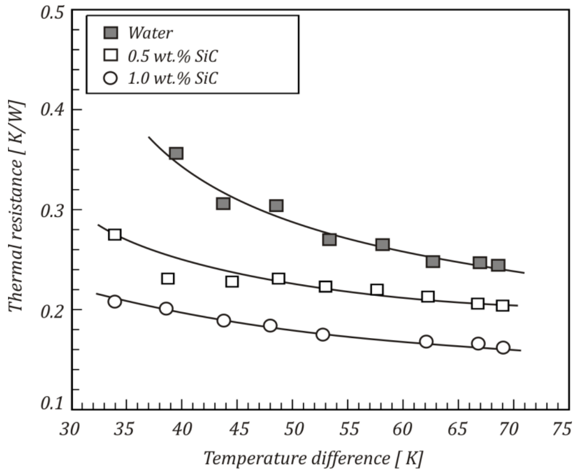

Figure 6. Thermal restistance of the TPCT for water and nanofluids with various SiC nanoparticles

As shown in Figure 6, the thermal resistance of the TPCT decreases with the increase operating temperature of the TPCT, and the thermal resistance for TPCT using water at various temperatures differences was much higher than the thermal resistance for TPCT using SiC/water nanofluids. Also, it can be seen that the increases of the nanoparticles concentration decrease the thermal resistance of TPCT using SiC/water nanofluids thus providing a better performance. Thus, the thermal resistance decreases up to 32.8% for the TPCT with SiC/water nanofluid at a weight concentration of 1.0 % compared with that of the TPCT using water, in conditions of TPCT operation at higher temperature differences. At the same the temperature difference and a concentration of nanoparticles of 0.5 wt.%, the average reduction of the thermal resistance in TPCT was 16.6%.

4. CONCLUSIONS

In this study, thermal conductivity and heat transfer characteristics of the TPCT using SiC/water nanofluids were experimentally investigated. The measurements were performed for two weight concentrations of SiC nanoparticles (0.5 and 1.0 %). The laser pyrolysis and TEM techniques were used for synthesis and characterization of the nanoparticles. In order to ensure long-term stability of the suspension was used a surfactant (CMCNa). The experimental results showed that the thermal conductivity of nanofluids based on SiC nanoparticles increases with increasing weight concentration of nanoparticles and temperature. Also, effects of operating temperature and nanoparticles concentration on the thermal performances of TPCT were investigated. Current results indicate that the heat transfer rate of the TPCT using SiC/water nanofluids increases with the increasing weight concentration of nanoparticles and the operating temperature. Also, the thermal resistance of the TPCT decreases significantly when using SiC/water nanofluids in TPCT.

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NOMENCLATURE

c_p	specific heat, J. kg^{-1}. K^{-1}
$\dot{m}$	mass flow rate of the cooling water, kg. m^{-3}
Q	heat transfer rate, W
R	thermal resistance, K. W^{-1}
T_{C1}, T_{C2}	inlet and outlet temperatures from condenser section, K
T_{E1}, T_{E2}	inlet and outlet temperatures from evaporator section, K
T_S	vapor temperature, K

Subscripts

nf	nanofluid
w	water