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Thermoelectric cooling of electronic devices with nanofluid in a multiport minichannel heat exchanger

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ABSTRACT

The performance of thermoelectric cooling of electronic devices with nanofluid in a multiport minichannel heat exchanger is experimentally investigated. The Bismuth Telluride ($BiTe_3$) thermoelectric cooler (TEC) with a ΔT_{max} of 67 °C is used to extract heat from the electronic devices, which is a power transistor. The power transistor in the circuit board usually operates with the electric power ranging from 20 W to 400 W which is considered as the input power to the TEC. The aluminum oxide (Al_2O_3)–water nanofluid with volume concentrations of 0.1% and 0.2% is used as the coolant to remove the heat from the hot side of the TEC. The Reynolds number is varied from 200 to 1000. The result showed 40% enhancement in the coefficient of performance (COP) of thermoelectric module for 0.2% of nanoparticle volume concentration. A 9.15% decrement in thermoelectric temperature difference between the hot and cold side has also been observed for nanofluids (0.2 vol.%), which enhanced the module cooling capacity. The enhancement in local Nusselt number is found to be 23.92% for 0.2% of nanoparticles volume concentration when compared with that of water at a Reynolds number of 1000 and at 400 W power input. The migration of nanoparticles due to temperature difference (thermophoresis) from the wall of the minichannel to the center is attributed to be the reason for the higher local Nusselt number at the entrance region. The thermal effectiveness of the cooling system increases with increase in volume concentration which makes the nanofluids as a promising coolant for electronic cooling applications.

1. Introduction

The modern electronic devices are featured with a very large integration of their components in a very limited space. The very large integration enables the present and future electronic devices to have ultra-high performance. But, such devices consume more power, thus, increases heat dissipation per unit area. The inadequate thermal management in these devices forces them to work at higher temperatures. The efficiency in the performance of such devices is lowered at higher operational temperatures, which raises challenges in its cooling. The latest electronic devices demand a cooling system with higher heat dissipation capability.

The nanoparticle dispersed liquids (nanofluids) have been recommended as a promising option for various heat transfer applications, due to the observed enhancement of thermal conductivities and heat transfer coefficients. A number of studies have been reported on the thermal and heat transfer characteristics of various nanofluids in the recent past [1–3]. Baby and Ramaprabhu [4] experimentally investigated the thermal conductivity of graphene–water nanofluid at very low volume concentrations. An enhancement in thermal conductivity by about 14% has been achieved at 25 °C at a very low volume fraction of 0.056% which increases to about 64% at 50 °C. Godson et al. [5] experimentally measured the thermal conductivity of silver-water nanofluids. A minimum and maximum enhancement of 27% and 80% at 0.3 vol.% and 0.9 vol.% are respectively observed at an average temperature of 70 °C. Ghanbarpour et al. [6] experimentally studied the thermal conductivity of Al_2O_3–water nanofluids and observed 87% enhancement at 293 K for 50 wt.%.

Recently, minichannel heat sink is widely applied in electronic cooling applications [7–9]. The enhancement in the heat transfer coefficient is remarkable with use of minichannel heat exchanger. Sohel et al. [10] experimentally investigated enhancement of heat transfer of a minichannel heat sink using Al_2O_3–water nanofluid with 0.1–0.25% volume concentration. The heat transfer coefficient was found to be improved up to 18% and thermal resistance was

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Nomenclature

A	area of cross section (m^2)
C_p	specific heat (kJ/kg K)
D_h	hydraulic diameter (m)
h	convective heat transfer coefficient (W/m^2 K)
H	height of the channel (m)
I	current (A)
k	thermal conductivity (W/m K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
m	mass (kg)
n	number of channels
P_p	pumping power (W)
Pr	Prandtl number
Re	Reynolds number
$\dot{V}$	volume flow rate (m^3/s)
T	temperature (°C)
V	voltage (V)
v_m	mean velocity (m/s)
W	width of the channel (m)
x	section of the minichannel (m)
Δp	pressure drop (Pa)
Δt	time taken (s)
ΔT	thermoelectric temperature difference (°C)

Greek symbols

φ	volume fraction (%)
μ	dynamic viscosity (mN s/m^2)
ρ	density (kg/m^3)
ε_{th}	thermal effectiveness

Subscript

c	cold side
ch	channel
f	base fluid
h	hot side
i	node
in	inlet
L	liquid
nf	nanofluid
P	input power
p	nanoparticle
w	wall

lowered by 15.72%. The heat sink base temperature was lowered by 2.7 °C. Ijam et al. [11] investigated the heat transfer performance and flow properties of nanofluid cooled minichannel heat sink. Two types of nanofluids were examined mathematically, Al_2O_3 and TiO_2 dispersed in water with 0.8–4% volume concentration. The improved cooling of 17.32% for Al_2O_3–water and 16.53% for TiO_2–water were achieved. Xie et al. [12] numerically investigated a minichannel heat sink with the bottom size of 20 mm × 20 mm for pressure drop, thermal resistance and maximum allowable heat flux. A nearly optimized configuration of heat sink was found which can cool a chip with heat flux of 256 W/cm^2 at the pumping power of 0.205 W. Moraveji et al. [13] numerically investigated the effect of nanoparticle volume fraction on the convective heat transfer coefficient of minichannel with 20 × 20 mm bottom. TiO_2 and SiC dispersed in water with volume fraction between 0.8% and 4%. The results showed that the heat transfer coefficient became greater with increasing nanoparticle concentration and Reynolds number.

The determination of pressure drop and friction factor of nanofluid flowing in the minichannel is very essential in the evaluation of its performance and pumping power. Caney et al. [14] experimentally inspected the validity of the classical correlations of frictional pressure drop for minichannels. It is proved that the classical correlations meant for conventional size channel can be applied for minichannel. Dai et al. [15] proposed a general threshold to subdivide a flow in a smooth or a rough micro- and mini-channel in terms of relative roughness. It is concluded that when the relative roughness is less than 1%, the roughness had little effect on flow characteristics, while for the relative roughness is larger than 1%, the friction factor and critical Reynolds number deviates from the prediction values. Haghighi et al. [16] shown that the classical correlations developed for pure fluids such as the Shah correlation (for heat transfer) and the Darcy equation (for pressure drop) are valid for the tested nanofluids.

The thermoelectric cooler has been recently applied to electronic cooling with its advantages of precise temperature control, vibration free and compactness. The heat load and temperature at both sides of the TEC can be controlled by adjusting the current flow. The temperature at the cold side of the TEC is mostly below ambient. The studies show that the thermoelectric cooler improves the thermal performance of cooling devices. Chang et al. [17] experimentally investigated effects of heat load and input current to the thermoelectric cooler. The thermal resistance at the high heat load of 100 W is 0.664 K/W at the optimal electric current of 6–7 A. A theoretical model of thermal analogy network was also developed to predict the thermal performance of the thermoelectric air-cooling module. Huang et al. [18] experimentally investigated influences of heat load and input current on the cooling performance of thermoelectric water cooling system for electronic cooling applications. The thermal resistance of 0.62 K/W was observed at the high heat load of 100 W with the optimal electric current of 7 A. A novel analytical model of thermal analogy network was developed to predict the thermal capability of the thermoelectric device. Zhang et al. [19] developed analytical expressions based on TEC module parameters to analyze TEC thermal performance for high power electronic packages. The analytical results were validated with experimental measurements. Al_2O_3–water, TiO_2–water nanofluids were used in the analysis. The highest heat flux enhancement of 16.53% by using TiO_2–water nanofluid was achieved. Nnanna et al. [20] experimentally investigated the performance of thermoelectric module with nanofluid heat exchanger. The nanofluid used is Al_2O_3–water with volume fraction between 0% and 2%. It was found that the temperature difference between the hot and cold side was almost zero for nanofluid and greater than zero for water for the chip powers of 28.3, 49.6 and 78.5 W. The average thermal contact resistance was 0.18 and 0.12 °C/W respectively observed for deionized water and nanofluid. The COP was between 1.96 and 0.68 for optimum range of current, 1.2 and 4.1 A. Faraji et al. [21] designed and constructed a 430 ml capacity thermoelectric water chiller and measured the coefficient of performance and cooling down period for the constructed system. The results were compared with analytical solutions for different input voltages and currents applied to the system. Naphon and Wiriyasart [22] studied the performance of a liquid cooling system using small scale heat sinks in the presence and absence of thermoelectric modules for CPU cooling applications. The de-ionized water was used as the coolant. It was reported that the effect of channel width, coolant flow rate, heat