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Thermal Analysis on Heat Transfer Enhancement and Fluid Flow for Al_2O_3 Water-Ethylene Glycol Nanofluid in Single PEMFC Mini Channel

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Abstract**—**Thermal enhancement of a single mini channel in Proton Exchange Membrane Fuel Cell (PEMFC) cooling plate is numerically investigated. In this study, low concentration of Al_2O_3 in Water - Ethylene Glycol mixtures is used as coolant in single channel of carbon graphite plate to mimic the mini channels in PEMFC cooling plate. A steady and incompressible flow with constant heat flux is assumed in the channel of 1mm x 5mm x 100mm. Nano particle of Al_2O_3 used ranges from 0.1, 0.3 and 0.5 vol % concentration and then dispersed in 60:40 (water: Ethylene Glycol) mixture. The effect of different flow rates to fluid flow and heat transfer enhancement in Re number range of 20 to 140 was observed. The result showed that heat transfer coefficient was improved by 18.11%, 9.86% and 5.37% for 0.5, 0.3 and 0.1 vol. % Al_2O_3 in 60:40 (water: EG) as compared to base fluid of 60:40 (water: EG). It is also showed that the higher vol. % concentration of Al_2O_3 performed better in term of thermal enhancement but at the expense of higher pumping power required due to increase in pressure drop experienced. Maximum additional pumping power of 0.0012W was required for 0.5 vol % Al_2O_3 in 60:40 (water: EG) at Re number 140.

Keywords**—**Heat transfer, mini channel, nanofluid, PEMFC.

I. INTRODUCTION

FLUID flow and convective heat transfer study in mini channel has received significant attention from researchers due to miniaturization of components design nowadays. Adoptions of mini channel cover from high power densities of electronic devices, fuel cell power sources such as proton exchange membrane fuel cell (PEMFC) and also concentrated solar panels [1]. This miniaturization initiative in cooling channel has increased the heat flux per unit area but with a demerit of higher-pressure drop.

Liquid cooling is then enhanced by the dispersion of nano-sized particles with diameter of 1 to 100 nm into the base liquids which results in higher heat transfer coefficient compared to conventional liquids and it is termed as nanofluids [2]. Nanofluid was initially introduced by Choi of Argonne National Laboratory, USA [3] to further enhance the thermal properties of conventional heat transfer fluid. These uniformly dispersed nanoparticles in base fluids have attracted extensive researchers due to their highly enhanced thermal conductivity property. This enhancement is due to the thermal conductivity of nanoparticles, which can be either metal or metal oxides with many orders of magnitude higher than the liquid.

Nanofluid in mini channel has been experimentally investigated by researchers mostly for electronic heat sink application [4], [5]. TiO_2 in de-ionized water nanofluid has been studied by [5] in term of heat transfer characteristic by varying three different channel heights. Sohel et al. [4] on the other hand studied effect of different flow rates to thermal performance of Al_2O_3 in water at volume fractions range of 0.1 to 0.25%. Both studies reported an enhancement of 42.3% and 11% of max convective heat transfer respectively as compared to base fluids

Numerical studies of nanofluid in mini channel have been reviewed by [6] and also [7]. Ijam and Saidur [8] reported thermal conductivity, heat flux and pumping power of 0.8 to 4% volume fraction range of SiC and TiO_2 water nanofluid. This study has then extended by [6] by addition of friction factor effect. Xie et al. [7], on the other hand, studied different geometry effects namely channel dimensions, depth and inlet velocity to the heat transfer performance and pressure. Computational analysis of nanofluid performance in a simplified geometry such as a single channel domain is usually undertaken as a first step in designing a suitable applied environment with complex geometries for specific nanofluid based on its predicted thermofluids behavior.

Mini channel in an electrically active heat transfer environment such as cooling plate of PEMFC is desirable due to compactness of the stack size required. Mini channel also help to improve heat transfer rates which leads to a lower maximum cell temperature [9], [10]. Nanofluid in fuel cell mini channel is relatively new due to the limited availability of open literature on the electrical conductivity of nanofluid. Sarojini et al. [11] have measured electrical conductivity of Al_2O_3, CuO and Cu in distilled water and EG while [12] studied the effect of volume concentration on electrical conductivity of Al_2O_3 nanofluid

Electrical conductivity of nanofluid in PEMFC was investigated by [13] which has eventually established a thermo-electrical conductivity (TEC) ratio for Al_2O_3 nanofluid in water: EG mixture for PEMFC . The study shows that Ethylene glycol (EG) concentration of more than 40% in water: EG, mixture is feasible for PEMFC application when

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considering both thermal and electrical conductivity requirements. This study numerically investigates few potentials alternative nanofluids coolants for PEMFC which are 0.1, 0.3 and 0.5 % vol. concentration of Al_2O_3 in 60:40 (water: EG) in term of heat transfer and fluid flow characteristic. A constant heat flux is subjected to the carbon graphite channel and performance in Re number 20 to 140 was observed. The nanofluid mixture is selected due to TEC ratio compliance for Al_2O_3 in PEMFC application.

II. METHODOLOGY

A. Nanofluid Preparation

Nanoparticles used are Al_2O_3 with 99.8 % purity and 13 nm in size, which is procured from Sigma-Aldrich. The based fluid is the mixture of distilled water and ethylene glycol AR grade with 99.9% purity. Base fluids were prepared by mixing both distilled water and ethylene glycol to form 500 ml of base fluid. The nanofluids are prepared by two steps method without using any surfactant. Measured quantity of Al_2O_3 nanoparticles is added to a pre-determined volume of a base solution. The concentration of the nanofluid in volume percent ϕ can be estimated with (1). The mass of particles required to obtain a desired volume concentration can be estimated from (1), using the nanoparticle density in Table I.

$$\phi = \left(\frac{m_p}{\rho_p}\right) \bigg/ \left(\frac{m_p}{\rho_p} + \frac{m_{bf}}{\rho_{bf}}\right) \times 100 \qquad (1)$$

Nanoparticles are initially dispersed in base fluid. Then, the mixture is subjected to an ultrasonic homogenization for the duration of one to two hours to ensure a good dispersion of nanofluids. The sample of Al_2O_3 nanofluids were prepared for volume concentrations of 0.1 and 0.5 % in 60:40 (water: EG). It is observed through visual means for dispersion stability. No sedimentations were found within few hours after preparation. The samples appeared to be stable for more than a month.

B. Nanofluid Thermophysical Properties Measurement

TABLE I
PROPERTIES OF NANOPARTICLES AND BASE FLUID USED IN THE EXPERIMENT

Nano Particle / Base Fluid	**Thermal conductivity κ, W/m.K**	**Specific Heat Cp, J/kg.K**	**Viscosity μ, mPa.s**	**Density ρ, kg/m³**	**Ref**
Al_2O_3	36	765	-	4000	[14], [15]
Water	0.615	4180	0.854	999	[16], [17]
Water : EG 60:40	0.4096	3491.8	2.45	1057	

Thermal conductivity and viscosity are determined experimentally at a temperature of 30°C using KD2 Pro thermal property analyzer of Decagon Devices, Inc., USA and LVDV-III Brookfield rheometer as shown in Figs. 1 and 2.

The KD2 Pro uses the transient line heat source to measure the thermal properties of solids and liquids. The apparatus meets the standards of both ASTM D5334 and IEEE 442-1981.

Fig. 1 Thermal conductivity measurement using KD2 Pro Thermal Analyzer

Fig. 2 Viscosity measurement using LVDV-III Brookfield rheometer

The density of nanofluid is calculated using Pak and Cho [18] using (2):

$$\rho_{nf} = (1-\phi)\rho_{nf} + \phi\rho_p \qquad (2)$$

Specific heat calculated based on Xuan and Roetzel [19] using (3):

$$C_{nf} = \frac{(1-\phi)(\rho C)_f + \phi(\rho C)_p}{(1-\phi)\rho_f + \phi\rho_p} \qquad (3)$$

where, ∅ refers to particle volume fraction and subscripts f, p and nf refer to fluid, particle and nanofluid respectively.

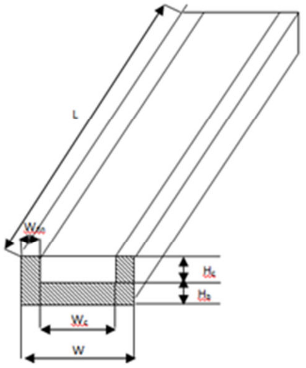
Experimental data on thermal conductivity and viscosity were then validated against Sundar et al model [20] in (4) and (5) respectively.

$$k_{nf} = k_{bf}(A + B\phi) \qquad (4)$$

$$\frac{\mu_{nf}}{\mu_{bf}} = Ae^{B\phi} \qquad (5)$$

where, A = 1.0806 and B = 10.164 for 60:40 (W:EG) nanofluid for thermal conductivity and A = 0.9299 and B = 67.43 for 60:40 (W:EG) nanofluid viscosity.

C. Mini Channel Geometry



Parameter	*Dimension (mm)*
W_{fin}	1
W_c	5
W	7
L	100
H_c	1
H_b	1.5

Fig. 3 Schematic view and dimensions of mini channel

A 3D computational fluid dynamic (CFD) was developed based on a single channel dimensions as in Fig. 3. The material for the mini channel is carbon graphite to mimic the conventional material used in cooling plate of PEMFC.

D. Mathematical Modeling and Numerical Method

In order to simplify the analysis, flow of incompressible, laminar and steady state has been considered. The fluid used was treated as a single-phase flow with both fluid and nano particles are in thermal equilibrium with zero relative velocity. It is also assumed that all mini channels are identical in heat transfer and fluid flow characteristic thus; only one channel is simulated for computation.

The conservation equations of continuity, momentum, energy and boundary conditions respectively are given [6]:

Continuity equation:

$$\nabla.(\rho_{nf}.V_m) = 0 \tag{6}$$

Momentum equation:

$$\nabla.(\rho_{nf}.V_m.V_M) = \nabla.(k_{nf}.\nabla T) \tag{7}$$

Energy equation for coolant:

$$\nabla.(\rho_{nf}.C.V_m.T) = \nabla.(k_{nf}.\nabla T) \tag{8}$$

The heat conduction through the solid wall:

$$0 = \nabla.(k_s.\nabla T_s) \tag{9}$$

No slip boundary at the wall:

$$\vec{V} = 0(@\,walls) \tag{10}$$

Boundary conditions at channel inlet were assumed as:

$$\vec{V} = V_m(@\,inlet) \tag{11}$$

$$P = atmospheric\ pressure(@\,outlet) \tag{12}$$

Heat is conducted through the solid and dissipated away via forced convection of cooling liquid that passes through the mini channel. Bottom surface is uniformly heated with constant heat flux.

$$-k_{nf}.\nabla T = q^{"}(@\,Bottom\ of\ \text{mini}\,channel) \tag{13}$$

$$-k_{nf}.\nabla T = 0(@\,Top\ of\ \text{mini}\,channel) \tag{14}$$

1. Heat Transfer Analysis

The hydraulic diameter is defined as the ratio of cross sectional area over the wetted parameter and it is calculated using (15):

$$D_h = \frac{4W_cH_c}{2(W_c + H_c)} \tag{15}$$

Heat transfer coefficient is then calculated using general equation (16):

$$h = \frac{Nuk_{nf}}{D_h} \tag{16}$$

2. Pumping Power Analysis

Pressure drop is determined through Darcy Friction factor [21] for fully developed laminar flow and expressed as:

$$\Delta p = f\,\frac{\rho u_m{}^2 L}{2D_h} \tag{17}$$

Pumping power is estimated using (17):

$$W_p = \dot{Q} \times \Delta P \tag{18}$$

III. RESULT AND DISCUSSION

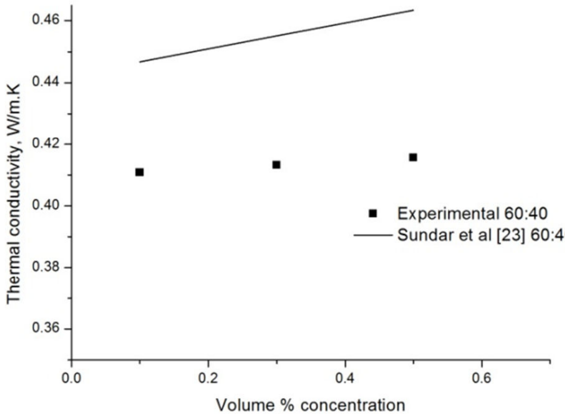


Fig. 4 Thermal conductivity of Al_2O_3 in 60:40 (water: EG) mixture

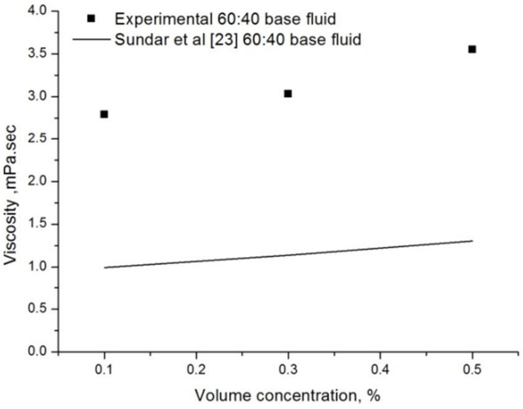


Fig. 5 Viscosity of Al_2O_3 in 60:40 (water: EG) mixture

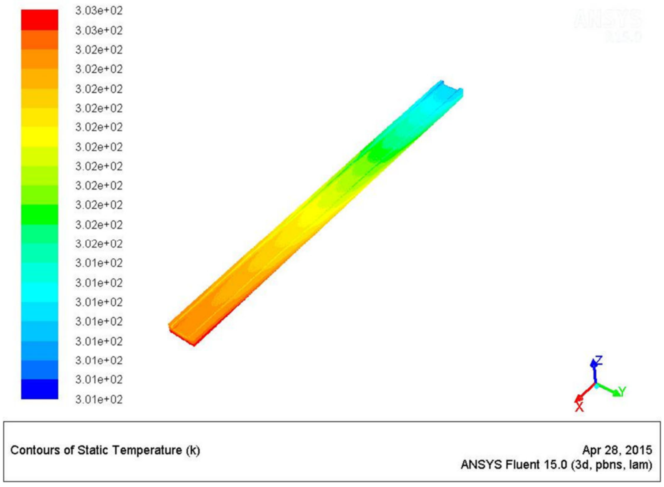


Fig. 6 Channel temperature contour of 0.5% vol concentration Al_2O_3 in 60:40 (water: EG) mixture at Re 140

Figs. 4 and 5 represent experimental data on thermal conductivity and viscosity properties for Al_2O_3 in 60:40 (water: EG) mixture respectively. The experimental data is validated against model of [20] for Al_2O_3 in water: EG mixture for both thermal conductivity and viscosity. It is shown that the mathematical model is over predicted the experimental data for thermal conductivity property. The experimental data ranges from 3 to 6% lower compared to the predicted model. However, the viscosity model under predicted the experimental data with difference of more less 60% than that of the model However, the trend of both thermal conductivity and viscosity increases as the volume % concentration increased still complied. The addition of nanoparticles has enhanced the thermal conductivity and Brownian motion of nanofluids, which will eventually improve the thermal performance of the nanofluids.

Numerical simulation was done in different mass flow rates to represent the corresponding Re number of 20 to 120. Fig. 6 shows the channel temperature contour of 0.5 vol % Al_2O_3 in 60:40 (water: EG) at Re 140.

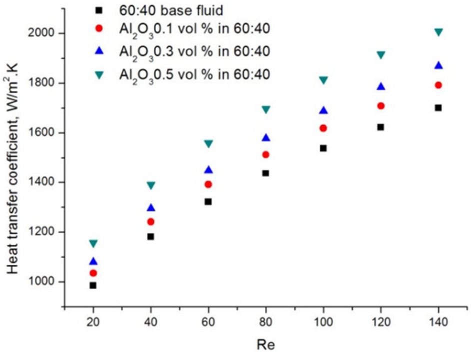


Fig. 7 Heat transfer coefficient for Al_2O_3 in 60:40 (water: EG) mixture

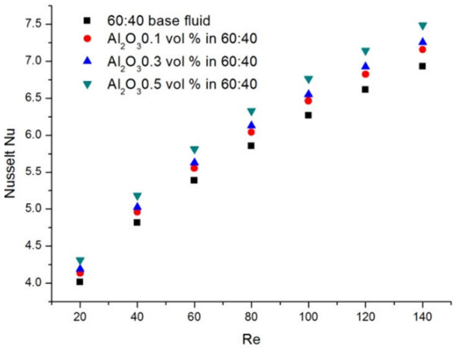


Fig. 8 Nusselt number for Al_2O_3 in 60:40 (water: EG) mixture

Fig. 7 represents the heat transfer coefficient of Al_2O_3 in 60:40 (water: EG) mixture as the Reynold number varied. It is shown that the heat transfer coefficients are enhanced as both volume % concentration and Re number increased as compared to base fluid. Max heat transfer coefficient observed to be increased by 18.11%, 9.86% and 5.37% for 0.5, 0.3 and 0.1 vol. % Al_2O_3 in 60:40 (water: EG) mixture at Re 140.

Nusselt number variation across Re number for Al_2O_3 in 60:40 (water: EG) mixture is shown in Fig. 8. Nusselt number increased as both vol. % concentration and Re number increased. Max increase of 8% is observed for 0.5 vol % Al_2O_3 in 60:40 (water: EG) mixture at Re 140.

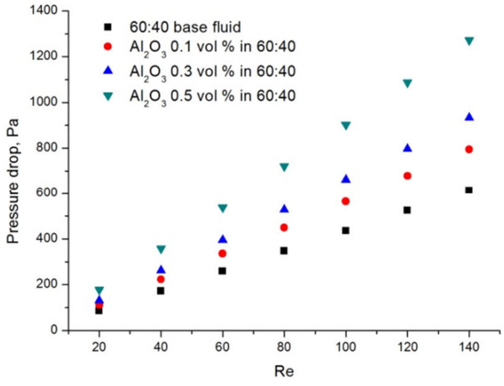


Fig. 9 Pressure drop experienced between inlet and outlet fluid as an effect from adoption of Al_2O_3 in 60:40 (water: EG) mixture

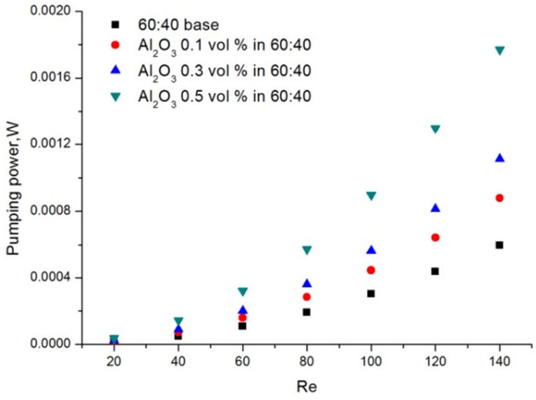


Fig. 10 Pumping power effect from adoption of Al_2O_3 in 60:40 (water: EG) mixture

Fig. 9 shows the drawback of having nanofluid in the fluid flow as it can increase the pressure loss in the channel in the range of 30, 50 and 107% for 0.1, 0.3 and 0.5 vol. % concentration at Re 140 consecutively. It is observed that the higher the volume % concentration, the higher the loss is. The pressure loss also increases as the velocity of fluid increases. This noticeable increase is expected in mini channel as compared to conventional channel since the coolant is forced to flow through a narrow channel [4].

In order to overcome such significant pressure drop, extra pumping power is needed in the system as depicted in Fig. 10. The pumping power is proportional to the experienced pressure loss. Maximum additional of 0.0012 W was required as compared to base fluid to pump 0.5 vol. % Al_2O_3 concentration at Re 140. This small figure seems to be acceptable considering such gain in heat transfer aspect. However, when translated to percentage the increase is almost 200% as compared to base fluid, which is quite huge.

Further study needed to balance out between these two properties of both heat transfer enhancement and additional pumping power required in order to have such beneficial adoption of Al_2O_3 in 60:40 (water: EG) in mini channel.

IV. CONCLUSION

The heat transfer and pressure drop characteristic for laminar flow of 0.1, 0.3 and 0.5 % vol. concentration of Al_2O_3 in 60:40 (water: EG) in single carbon graphite mini channel has been analyzed. Heat transfer coefficient increased by 18.11%, 9.86% and 5.37% for 0.5, 0.3 and 0.1 vol. % Al_2O_3 in 60:40 (water: EG) consecutively at Re 140. However, the penalty was at the pressure drop increment of 30, 50 and 107% for 0.1, 0.3 and 0.5 vol. % concentration at Re 140. This increment in pressure drop across inlet and outlet fluid is resulted an additional of almost 200% increase in pumping power needed to overcome such losses. Further study needed to confirm on the feasibility of Al_2O_3 in 60:40 (water: EG) adoption in mini channel in carbon graphite PEMFC considering both enhancement in heat transfer and fluid flow.

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