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REGULAR ARTICLE

Cooling Performance of Ternary Nanofluids under Magnetic Field Influence

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This study conducts a detailed CFD analysis of the thermo-hydraulic performance of a Mini Channel Heat Sink (MCHS) cooled using a ternary hybrid nanofluid comprising Fe_3O_4, Al_2O_3, and ZnO nanoparticles dispersed in water. The thermophysical properties of the nanofluid are derived from experimentally developed correlations. The effects of volume fraction and Reynolds number on heat transfer and pressure drop were investigated. Furthermore magnetic field effect on the Ternary nanofluid is also discussed. Results indicate that the ternary nanofluid significantly enhances heat dissipation but increases viscosity and pressure drop due to nanoparticle dispersion, particularly at higher Reynolds numbers. The application of a magnetic field further improves heat transfer with minimal additional pressure drop. The study found that at a Reynolds number of 1900, the Nusselt number increased by 15 %, 25 %, 36 %, and 46 % for volume fractions of 0.5 %, 0.75 %, 1 %, and 1.25 %, respectively, compared to water. Similarly, the pressure drop was higher by 22 %, 44 %, 112 %, and 218 % for the same volume fractions. These findings highlight the potential of ternary hybrid nanofluids in optimizing thermal performance in MCHSs.

Keywords: Ternary nanofluids, Nusselt number, Pressure drop, Cooling, Magnetic field.

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1. INTRODUCTION

Advances in microscale electronics have led to ultrahigh heat fluxes, making efficient cooling crucial for proper device functionality. Conventional coolants like water, ethylene glycol, and oils have low thermal conductivity, limiting their heat transfer capabilities. To address this, researchers have developed nanofluids by dispersing nanoparticles into conventional coolants, significantly enhancing their thermal conductivity and heat transfer performance. MCHS are compact heat exchangers designed to efficiently handle ultrahigh heat fluxes in small spaces [1-2]. Monodisperse nanofluids have certain limitations, leading to the development of binary nanofluids, which offer improved stability and higher thermal conductivity. Recently, researchers have advanced to ternary nanofluids, which outperform binary nanofluids in these aspects [3]. Studies also highlight the potential for heat transfer enhancement using magnetic fields [4-6]. Uysal et al. [7] studied a diamond/Fe_3O_4 hybrid nanofluid in a minichannel heat sink, finding a 29.96 % heat transfer improvement at Re = 1000. The hybrid nanofluid outperformed mono nanofluids but caused a higher pressure drop. Souby et al. [8] investigated a MCHS using a ternary nanofluid. Their findings concluded that hybrid nanofluids offer greater potential as heat transfer fluids compared to conventional ones like water. Specifically, the CuO/MgO/TiO_2-water ternary hybrid (TNF) nanofluid demonstrated superior heat transfer efficiency compared to the MgO/TiO_2-water binary hybrid nanofluid. Bhattacharjee et al. [9] worked with minichannel cooling in Solar PV panels. They reported that heat transfer enhancement was significantly influenced by magnetic field intensity and placement. The study on Fe_3O_4–TiO_2 nanofluid showed a 230 % increase in the Nusselt number and a 133 % rise in the friction factor under a 2000 G magnetic field with magnets placed at specific intervals. These findings highlight the importance of magnetic field optimization. Another study revealed that, Fe_3O_4-TiO_2/water nanofluids in a MCHS showed improved heat transfer but increased the friction factor by 25.87 % without a magnetic field (MF) and 67.64 % with a 1000 G magnetic field at Re = 1873.33 [10].

This literature review highlights the widespread use of MCHS for effective heat removal from electronic devices and the enhanced heat transfer achieved with ternary nanofluids. Additionally, applying a magnetic field significantly boosts heat transfer. However, the impact of a transverse magnetic field on three-dimensional laminar flow and heat transfer in an MCHS using a ternary nanofluid remains underexplored. This study aims to fill this gap, considering the potential influence of magnetic fields generated by electrical components or materials. The research utilizes a Fe_3O_4/Al_2O_3/ZnO-water TNF with volume fractions from 0.5 % to 1.25 % and Reynolds numbers ranging from 500 to 1900.

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2. COMPUTATIONAL MODEL

2.1 Geometry

The geometry of the heat sink is adopted from the work of Sundar et al. [10] The heat sink was constructed using a squared aluminum block with dimensions of 50 mm × 50 mm × 10 mm. It is segmented into four circular channels, each with an interior diameter of 4 mm. A uniform magnetic field was employed perpendicular to the heat sink, while a consistent heat flux of 64,000 W/m^2 was imposed on its bottom surface. The heat sink is subjected to 500 and 1000G magnetic field. Moreover, the computational domain can be reduced to a single microchannel because of the micro channel's symmetry [8].

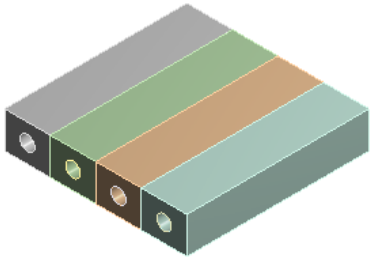

Fig. 1 – Schematic diagram of heat sink

2.2 Governing Equation

The study makes several key assumptions about the operating conditions of the heat sink: it is under steady-state conditions, single phase fluid and the outer walls are adiabatic. The analysis focuses on three-dimensional, incompressible, laminar flow. The governing equations are as follows [11-12].

$$\nabla \circ \vec{v} = 0 \quad (1)$$

$$(\vec{v} \circ \nabla)\vec{v} = \frac{1}{\rho}\nabla p + \nu\nabla^2\vec{v} + \frac{1}{\rho}(j \times B) \quad (2)$$

$$(\vec{v} \circ \nabla)T = \alpha\Delta T \quad (3)$$

The continuity, momentum, and energy equations are outlined, with J and B defined as the current density and magnetic flux, respectively. To solve the above mentioned equation finite volume method is used along with SIMPLE algorithm. The convergence criteria for all the field equations have been set at ~ 10^{-6}. Velocity is fixed by the Reynolds Number. Pressure Outlet Boundary condition is used.

3. TERNARY NANOFLUID THERMOPHYSICAL PROPERTIES

Adun et al. [13-14] synthesis this $Fe_3O_4/Al_2O_3/ZnO$-water ternary nanofluid. In this study, the amount of nanoparticles remains consistent throughout. Density and electrical conductivity [15] are calculated using equations (7) and (8), while viscosity, thermal conductivity, and specific heat capacity are determined based on the correlations proposed by Adun et al.[13-14]

$$k_{TNF} = \begin{pmatrix} 0.568607 + 0.151120 * \varphi + 0.00192917 * T \\ -0.10 * M_R \end{pmatrix} * k_{bf} \quad (4)$$

$$\mu_{TNF} = \begin{pmatrix} 0.0405274 + 0.00305333 * \varphi - 0.000144667 * T \\ -0.108406 * M_R \end{pmatrix} * \mu_{bf} \quad (5)$$

$$C_{TNF} = \left(a_1 + a_2 * T + a_2 * \varphi + a_3 * M_R\right) * C_{pbf} \quad (6)$$

In Eq (5) M_R is the ratio of the Fe_3O_4 in the TNF, φ is the volume concentration, and the T is the temperature and a_1 .... a_{10} are regression constants.

$$\rho_{nf} = (1-\varphi_1)\rho_f + \varphi_1\rho_{s1}$$
$$\rho_{hnf} = (1-\varphi_2)[(1-\varphi_1)\rho_f + \varphi_1\rho_{s1}] + \varphi_2\rho_{s2}$$
$$\rho_{tnf} = (1-\varphi_3)\left\{(1-\varphi_2)[(1-\varphi_1)\rho_f + \varphi_1\rho_{s1}] + \varphi_2\rho_{s2}\right\} + \varphi_3\rho_{s3} \quad (7)$$

$$\frac{\sigma_{nf}}{\sigma_f} = \frac{(1+2\varphi_1)\sigma_{s1} + (1-2\varphi_1)\sigma_f}{(1-\varphi_1)\sigma_{s1} + (1+\varphi_1)\sigma_f}$$
$$\frac{\sigma_{hnf}}{\sigma_{nf}} = \frac{(1+2\varphi_2)\sigma_{s2} + (1-2\varphi_2)\sigma_{nf}}{(1-\varphi_2)\sigma_{s2} + (1+\varphi_2)\sigma_{nf}} \quad (8)$$
$$\frac{\sigma_{tnf}}{\sigma_{hnf}} = \frac{(1+2\varphi_3)\sigma_{s3} + (1-2\varphi_3)\sigma_{hnf}}{(1-\varphi_3)\sigma_{s3} + (1+\varphi_3)\sigma_{hnf}}$$

4. DATA PROCESSING

Nusselt number is measured by Eq (9)

$$Nu = \frac{hD}{k} \quad (9)$$

Where h is heat transfer coefficient D is hydraulic diameter and k is thermal conductivity. Heat transfer coefficient can be calculated as

$$h = \frac{\dot{Q}}{A(T_s - T_b)} \quad (10)$$

Q is heat transfer rate of the fluid, and T_s and T_b is base temperature of heat sink and bulk mean temperature.

5. RESULTS AND DISCUSSION

5.1 Heat Transfer

To ensure the accuracy of the numerical code, its results were validated against Sundar et al. [10] using the same geometry and boundary conditions with water and binary nanofluids as heat transfer media. The comparison showed maximum deviations of 3.6 % for the Nusselt number and 4 % for friction factor, confirming the model's validity. The model was also validated against Narrein et al. [11] with water under a magnetic field, showing maximum deviations of 4-5 % in the Nusselt number and pressure difference, further proving the model's accuracy.

Figure 2 to 4 illustrates the Nusselt number for water and ternary nanofluids flowing inside a heat sink across various volume fractions and Reynolds numbers. The results reveal that the Nusselt number increases linearly with rising Reynolds numbers [10]. The superior thermophysical properties of the ternary nanofluid compared to distilled water primarily account for its enhanced convective performance. Increasing the nanoparticle volume fraction in the base fluid improves k

and promotes Brownian motion, which significantly contributes to the nanofluid's superior thermal performance over water. Furthermore, a higher *Re* enhances the convective heat transfer capacity of the coolant, effectively lowering the T_b. Specifically, the Nusselt number of the ternary nanofluid is 15 %, 25 %, 36 %, and 46 % higher for volume fractions of 0.5 %, 0.75 %, 1 %, and 1.25 %, respectively, compared to water at a Reynolds number of 1900. For Al_2O_3/water maximum heat transfer enhancement is 27.6 % at 2.5 vol % [16]. While, for Fe_3O_4/TiO_2 – water nanofluid, it is 38.16 % at 2 % vol %. [10]. Figure 3 and 4 illustrates the Nusselt number (Nu) for a 1.0 % and 1.25 % volume nanofluid under the influence of magnetic fields. The Nu increases as the intensity of the MF. For a 1.0 % volume nanofluid with magnetic field strengths of 500 G and 1000 G, the Nusselt number (Nu) increased by 7.9 % and 12.7 %, respectively, compared to the 1.0 % nanofluid without a MF at a Reynolds number (Re) of 600. For Re Number 1900 this value is increased by 11.3 % and 18.5 %. The enhancement in heat transfer is attributed to the interaction between charged particles and the magnetic field, which induces localized turbulence and leads to an improved heat transfer coefficient.

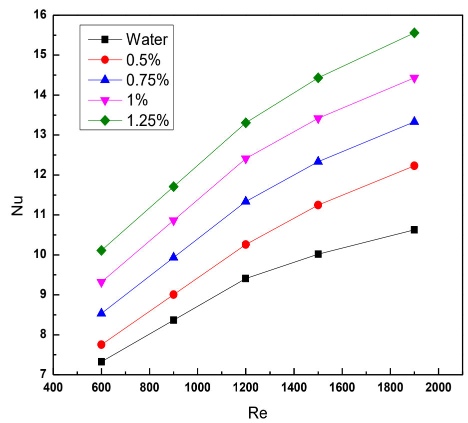

Fig. 2 – Nusselt number of ternary nanofluids at different Reynolds number

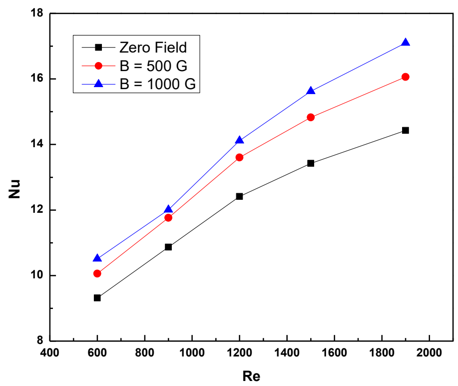

Fig. 3 – Nusselt number analysis of ternary nanofluids under the influence of a magnetic field at a 1 % volume fraction with varying Reynolds numbers

Similarly, for a 1.25 % volume nanofluid under magnetic fields of 500 G and 1000 G, the Nu rose by 8.01 % and 13.03 % respectively, compared to the 1.25 % nanofluid without a MF at a Re of 600. For Re Number 1900 this value is 16 % and 22.73 %.

5.2 Pressure Drop

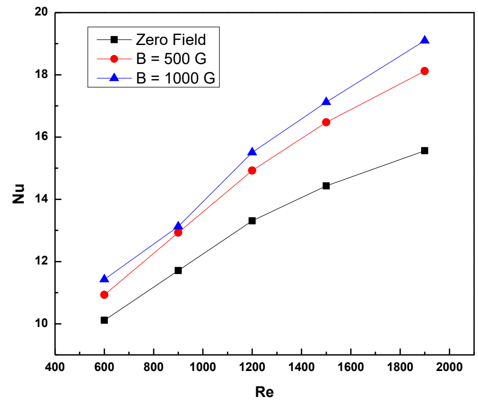

Fig. 4 – Nusselt number analysis of ternary nanofluids under the influence of a magnetic field at a 1.25 % volume fraction with varying Reynolds numbers

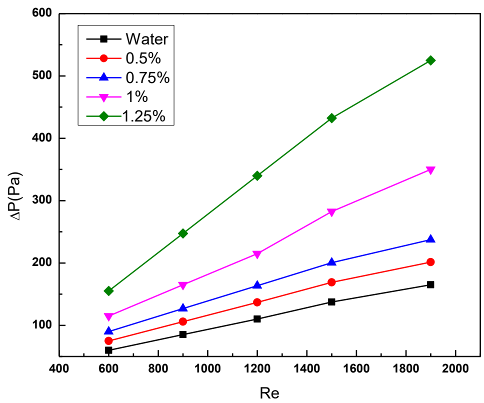

Fig. 5 – Pressure difference of ternary nanofluids at different Reynolds number

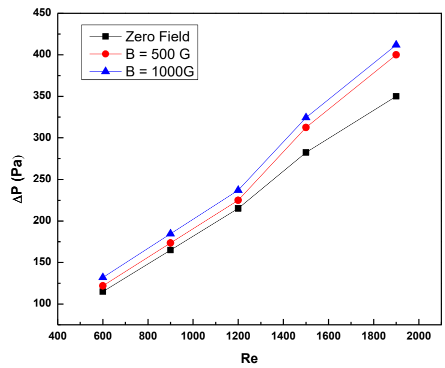

Fig. 6 – Pressure difference of ternary nanofluids under the influence of magnetic field at 1 % vol fraction with varying Reynolds number

As the volume percentage of the TNF increases, the pressure drop also increases. Similarly, as the Reynolds number rises, the pressure drop grows exponentially.

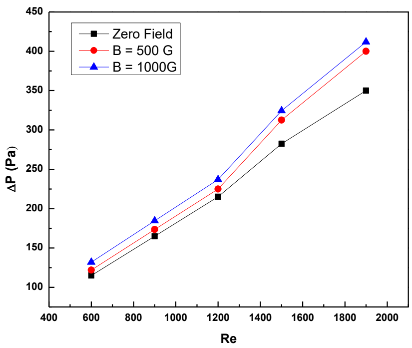

Fig. 7 – Pressure difference of ternary nanofluids under the influence of magnetic field at 1.25 % vol fraction with varying Reynolds number

This behavior has been observed and reported by several researchers for various types of nanofluids. [8, 17]. An increase in pressure drop indicates that more pumping power is required to maintain the flow. At a Reynolds number of 600, the pressure drop increases by 25 %, 50 %, 91.67 %, and 158 % for volume fractions of 0.5 %, 0.75 %, 1 %, and 1.25 %, respectively, compared to the base fluid (water). Likewise, at a Reynolds number of 1900, the pressure drop increases by 22 %, 44 %, 112 %, and 218 % for the same respective volume fractions compared to the base fluid. When a MF is applied, the pressure drop increases for a 1 % volume fraction of the ternary nanofluid. At a Reynolds number of 1900, the pressure drop rises by 14.3 % and 17.71 % as the magnetic field strength increases from 500 G to 1000 G. For a 1.25 % volume fraction at the same Reynolds number, the pressure drop increases by 15.4 % and 18 % with the magnetic field increasing from 500 G to 1000 G. This is due to the applied magnetic field interacts with charged or magnetic particles nanofluid, generating Lorentz forces. These forces resist fluid motion, increasing flow resistance and leading to a higher pressure drop.

From Fig. 5, it is evident that at a 1.25 % volume fraction, there is a significant rise in pressure, resulting in a substantial increase in pumping power. Moreover, beyond a Reynolds number (Re) of 1200, a pronounced pressure surge is observed. Excessive volume loading leads to a drastic rise in pumping power. Below Re ~ 1200, Applying a magnetic field improves heat transfer while causing only a minor increase in pressure drop, making it an effective method to enhance heat transfer performance without substantially increasing pressure losses.

6. CONCLUSION

This study conducted a detailed CFD analysis to evaluate the thermos-hydraulic performance of MCHSs cooled with $Fe_3O_4/Al_2O_3/ZnO$-water ternary hybrid nanofluid. The analysis examined the effects of volume fraction and Reynolds number (Re) on the Nusselt number and pressure drop. The key findings are as follows:

(a) Ternary nanofluids offer significant advantages in dissipating heat from electronic devices.

(b) The dispersion of nanoparticles increases the fluid's viscosity, leading to a rise in pressure difference within the system and consequently higher pumping losses.

(c) At higher Reynolds numbers, the pressure drop increases considerably; therefore, it is recommended to operate the system at lower Reynolds numbers.

(d) Applying a magnetic field enhances heat transfer with only a minimal increase in pressure drop, making it a beneficial approach.

(d) This paper examines the interaction between a magnetic field and a ternary nanofluid, focusing on the resulting improvements in heat transfer performance. This approach is particularly beneficial for temperature control in electronic devices making passive use of external field-actuated thermal transport. In addition, similar field-fluid applications could be explored in areas such as nanoparticle induced site-specific hyperthermia in biomedical applications, medical imaging and in fields of nano-optiocs.

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Охолоджувальна здатність потрійних нанорідин під впливом магнітного поля

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У цьому дослідженні проводиться детальний CFD-аналіз термогідравлічних характеристик мініканального радіатора (MCHS), охолоджуваного за допомогою потрійної гібридної нанорідини, що містить наночастинки Fe_3O_4, Al_2O_3 та ZnO, дисперговані у воді. Теплофізичні властивості нанорідини отримані з експериментально розроблених кореляцій. Було досліджено вплив об'ємної частки та числа Рейнольдса на теплопередачу та перепад тиску. Крім того, обговорюється вплив магнітного поля на потрійну нанорідину. Результати показують, що потрійна нанорідина значно покращує тепловіддачу, але збільшує в'язкість та перепад тиску через дисперсію наночастинок, особливо при вищих числах Рейнольдса. Застосування магнітного поля додатково покращує теплопередачу з мінімальним додатковим перепадом тиску. Дослідження показало, що при числі Рейнольдса 1900 число Нуссельта збільшилося на 15%, 25%, 36% та 46% для об'ємних часток 0,5%, 0,75%, 1% та 1,25% відповідно порівняно з водою. Аналогічно, падіння тиску було вищим на 22%, 44%, 112% та 218% для тих самих об'ємних часток. Ці результати підкреслюють потенціал потрійних гібридних нанорідин в оптимізації теплових характеристик у MCHS.

Ключові слова: Потрійні нанорідини, Число Нуссельта, Перепад тиску, Охолодження, Магнітне поле.