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Experimental Investigation of Nanofluid-Based Heat Transfer Enhancement in a Triangular Microchannel Heat Exchanger

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Abstract:- Microchannel heat exchangers (MCHEs) play a critical role in miniature-scale thermal management systems, particularly in cooling applications such as microelectronics, refrigeration, biomedical devices, and electric vehicle battery systems, where efficient heat removal is essential. This study experimentally investigates the influence of channel geometry and nanofluid concentration on the thermal and hydraulic performance of MCHEs featuring triangular microchannels. Three types of nanofluids, CuO, Al_2O_3, and carbon nanotubes (CNT), were examined at concentrations of 0.01%, 0.03%, and 0.05% under laminar flow conditions (Re = 100–500). The results revealed that increasing nanoparticle concentration significantly enhanced heat transfer for all nanofluids. At 0.05% concentration and Re = 500, the triangular microchannel achieved Nusselt number enhancements of 24.55% for CuO, 28.65% for Al_2O_3, and 43.06% for CNT, accompanied by pressure drop increases of 22.03% (CuO), 27.46% (Al_2O_3), and 249.49% (CNT), respectively. Overall, CNT-based nanofluids in triangular microchannels exhibited the highest thermal performance, demonstrating the strong synergistic effect of geometry and nanoparticle type on MCHE efficiency.

Keywords: Microchannel heat exchanger, Nanofluids, Heat Transfer, Pressure drop.

1. Introduction

Heat exchangers have emerged as a critical technology for efficient thermal management, particularly amid growing demand for cleaner, more sustainable energy solutions. In this study, the authors investigate how modifying channel geometries from circular to trapezoidal or rectangular shapes can significantly enhance heat transfer performance [1]. They presented the heat transfer characteristics of an MCHE with fan-shaped cavities (FSCs). The results indicate that the MCHE with FSCs achieves higher heat transfer than the MCHE without FSCs and requires lower pumping power [2]. The impact of trapezoid-shaped re-entrant cavities on a plate microchannel heat exchanger was numerically analyzed. Results showed that heat transfer initially increased and then decreased with rising mass flow rate in both the ITRC and conventional rectangular MHXs. However, the MHX with ITRCs demonstrated superior performance, especially at higher mass flow rates [3]. Experiments were conducted in trapezoidal microchannels to investigate flow and heat transfer characteristics. A numerical model was developed for geometries with angles of 30° and 60°, and ratios ranging from 0.1 to 10, under both developing and fully developed flow conditions. Generalized correlations for the Poiseuille number, Nusselt number, and entry length were established, closely matching the 3D model results. These correlations can aid in the design of trapezoidal microchannels for thermal applications [4]. Flow characteristics of straight, standard serpentine, and wavy serpentine microchannels were studied using µPIV and thermal measurements.

Serpentine channels demonstrated superior efficiency, characterized by higher Nusselt numbers and lower pressure drops. Zigzag geometries enhanced boiling performance by lowering wall temperature, increasing CHF and HTC, and improving flow stability [5].

A 3D numerical study of counter-flow microchannel heat exchangers (CFMCHEs) analyzed the impact of channel size and shape—including circular, square, rectangular, isosceles triangular, and trapezoidal—on thermal and hydraulic performance. Circular channels performed best, followed by square channels. Increasing the number of channels improved heat transfer but also raised pressure drop and pumping power. The performance index decreased with increasing Reynolds number. Correlations were developed to predict the effectiveness and performance index from Re, Kr, and Vr [6]. A combined numerical and experimental study was conducted on MHEs with elliptical concave cavities of varying ellipticity (0.4-1.2) to assess their impact on heat transfer and pressure drop. Results showed that both parameters initially improved, then declined as ellipticity increased. The MHE with ellipticity 1.0 exhibited the lowest pressure drop and best thermal performance across the tested range. Temperature trends at outlets also varied nonlinearly with flow rate, confirming the influence of ellipticity on thermal behavior. The findings were validated through CFD simulations and experimental data [7].

A numerical study of straight, through-dimple, and circular-dimple-protrusion microchannels filled with CuO nanofluids demonstrated enhanced thermal performance. At a 0.2% CuO concentration, circular dimple-protrusion channels improved the Nusselt number by 10%, while dimple-protrusion designs achieved a 10.5% enhancement in heat transfer. The pressure drop increased with the Reynolds number due to flow disturbances [8]. A numerical CFD study examined the effects of surface roughness peak (SRP) configurations aligned, offset, and hybrid on airflow in microchannels. Heat transfer was less sensitive to SRP pitch, while increased roughness width improved performance. Aligned SRP outperformed offset SRP by 9% in overall performance. Roughness geometry significantly influences flow behavior and thermal enhancement [9]. The findings indicate that cavities with sidewalls effectively enhance heat transfer while reducing flow resistance, whereas those featuring a smaller expansion angle and streamlined edges further improve overall thermal performance [10]. The performance of microchannel heat exchangers (MCHEs) featuring three types of reentrant cavities—circular, trapezoidal, and rectangular—was systematically investigated. Results indicate that rectangular cavities produce higher pressure drops and larger Darcy friction coefficients. In contrast, MCHEs with circular cavities demonstrate the highest performance index and Nusselt number, confirming their superior thermal-hydraulic efficiency compared to other cavity geometries [11]. The results show that nanofluid cooling enhances the heat sink's thermal performance by 3–15% compared to water. The heat sink with multiple CCZ-HS configurations also outperforms the CZ-HS design, achieving a 2–6% increase in efficiency. While the pressure drop (Δp) increases with flow rate, it decreases slightly with higher nanoparticle concentrations and is largely unaffected by the cross-cut configuration of the flow channel [12].

Flow-boiling performance was compared between reentrant and conventional rectangular microchannels with equal hydraulic diameter. The study examined the influence of channel geometry on heat transfer and found that re-entrant microchannels significantly enhance two-phase heat transfer under subcooled conditions [13]. A numerical study examined the effects of channel and rib geometries and their placement at various water flow rates in a microprocessor heat sink. Reducing the base temperature from 44°C to 36.25°C and increased total heat transfer by 17.7% in dual circular channels [14]. A numerical study investigated the impact of rib shape on heat transfer in microchannels with triangular, rectangular, and trapezoidal ribs. At a nanoparticle concentration of 4% and Re of 50–100, triangular ribs exhibited superior thermal performance. Streamline variation was highest in rectangular ribs. Thermal performance improved by 4–7% compared to rectangular configurations [15]. A numerical study investigated the impact of rib shape on heat transfer in microchannels with triangular, rectangular, and trapezoidal ribs. Triangular ribs exhibited superior thermal performance at a nanoparticle concentration of 4% and a Reynolds number (Re) of 50–100. Streamline variation was highest in rectangular ribs. Thermal performance improved by 4–7% compared to rectangular configurations [16]. A numerical study using ICEM CFD analysed the effect of corrugated baffle inserts in a rectangular heat exchanger. Straight baffles exhibited stronger vortex formation and higher heat transfer, but also a greater pressure drop, especially at $\alpha = 0°$. Corrugated baffles improved the thermal performance factor from 1.27 to 1.53 as α increased. Optimal thermal efficiency was observed at $h/H = 0.5$ [17]. A numerical study using ANSYS CFX v18 investigated the effect of 90° V-shaped baffle orientations and arrangements in a channel heat exchanger with Ketrol solution. +V baffles in a staggered configuration provided the highest heat-transfer enhancement but also resulted in a higher pressure drop. The maximum thermal performance factor (TPF) of 1.52 was achieved with this setup [18]. A numerical study examined the effect of MWCNT/oil-based nanofluid and baffle orientation (upstream, downstream, vertical) at various attack angles (α) and Reynolds numbers.

The results showed a maximum TEF of 5.634 for vertical baffles at Re = 20,000. For inclined baffles, the highest TEF = 4.814 was observed, with Nu/Nu_0 and f/f_0 increasing with α and Re [19]. New-generation nanofluids, such as Al_2O_3 and CuO, exhibit higher heat-transfer coefficients than conventional fluids, enabling compact, lightweight radiator designs. Studies of flat-tube radiators have shown significant performance improvements and volume reductions. However, this comes at the cost of increased pumping power after downsizing [20]. The use of nanofluids has emerged as an effective method for enhancing the performance of concentrating solar collectors (CSCs). A comprehensive analysis of nanofluids as working fluids in various collector types reveals significant improvements in thermal efficiency. Specifically, nanofluids increase efficiency by up to 35% in evacuated-tube collectors (ETCs) with boosters, by approximately 13% in compound parabolic concentrators (CPCs), and by approximately 16% in solar dish systems. The improvement in linear Fresnel reflectors is relatively modest at about 1%. Furthermore, integrating nanofluids into photovoltaic-thermal (PVT) systems increased electrical output by nearly 8%, though the corresponding thermal efficiency gain was minimal [21]. Al_2O_3 and MgO nanoparticles were added at 0.12% and 0.4% concentrations to improve nanofluid stability [22]. A numerical study using the finite-volume method examined laminar heat transfer and the injection of an oil/MWCNT nanofluid jet. Parameters included Reynolds numbers from 10–50, slip coefficients of 0–0.08, and particle sizes up to 0.4%. Results revealed that higher, well-dispersed nanoparticle concentrations improved temperature distribution and Nusselt number. This indicates enhanced convective heat transfer performance [23]. Al_2O_3 and TiO_2 nanoparticles were tested in a mini-channel heat sink. At 0.5 vol%, Al_2O_3 improved heat transfer by 9.30%, while TiO_2 showed a 4.56% enhancement [24]. A review of metallic and non-metallic nanoparticles, such as TiO_2, Al_2O_3, Cu, and SiO_2, highlighted their impact on nanofluid thermophysical properties across systems, including heat exchangers and refrigeration systems. Even small additions of nanoparticles significantly enhanced thermal conductivity [25].

The literature review indicates that extensive research has been conducted on microchannel heat exchangers (MCHEs) using conventional base fluids across various geometries. Additionally, numerous simulation studies have examined the thermal and hydraulic performance of MCHEs using various base fluids. However, experimental investigations of single- or hybrid-nanofluids remain relatively limited. Notably, there is a clear research gap in the comparative experimental analysis of multiple nanofluids within a single microchannel configuration. To address this gap, the present study evaluates Al_2O_3, CuO, and CNT nanofluids in a triangular microchannel geometry at mass concentrations of 0.01%, 0.03%, and 0.05% under laminar flow conditions with Reynolds numbers ranging from 100 to 500. This work aims to provide a detailed comparison of heat transfer and pressure drop characteristics for different nanofluids within a unified geometric framework

2. Experimental procedure

2.1 Nanofluids

In the experiments, commercially sourced nanoparticles of Al_2O_3, CuO, and CNT, each with an average diameter of 30 nm, were used. Deionized water served as the base fluid, and the nanofluids were carefully prepared in a dedicated research laboratory. The specific concentrations used in the study are detailed in Table 1.

Table 1. Type of nanoparticles and concentrations

Nanoparticles (np)	Concentrations in % by weight fraction (ϕ)
Cupor oxide (CuO)	0.01, 0.03nd 0.05
Aluminium oxide (Al_2O_3)	
Carbon nanotubes (CNT)	
Basic fluid	Deionizedater

Nano-fluids can be prepared using one-step or two-step methods; this study employed the two-step method. Here, 0.5 gm of 30 nm nanoparticles was added to 5 L of distilled water in an open container [26]. The nanoparticles were measured using a high-precision instrument.

Three nanofluids, Al_2O_3, CuO, and CNT, were prepared at concentrations of 0.01%, 0.03%, and 0.05%, using distilled water as the base fluid, as shown in Figure 2. During the preparation of the CNT nanofluid, a surfactant was added to ensure uniform dispersion of nanoparticles within the base fluid. In the absence of a surfactant, CNT particles tend to agglomerate and float to the surface, resulting in poor stability and non-uniform distribution.
Among the tested nanofluids, Al_2O_3, CuO, and carbon nanotubes (CNT), CNT exhibits the highest thermal

conductivity, followed by CuO and then Al_2O_3. This hierarchy in thermal conductivity directly translates into their heat-transfer capabilities: CNT-based nanofluids demonstrated the most excellent heat-transfer enhancement, as the high thermal conductivity of CNTs promotes more efficient energy transport from the heated surface to the fluid. In contrast, Al_2O_3 and CuO, while still superior to water, show comparatively lower enhancement. Thus, the improved thermal performance observed in CNT nanofluids is primarily attributed to their intrinsically high thermal conductivity, which facilitates rapid heat dissipation and efficient cooling in microchannel applications.

2.2 Test Model

High-precision machining was used to fabricate copper-based Microchannel Heat Exchangers (MCHEs), resulting in a Triangular Microchannel Heat Exchanger (TMHX) model. Each had a surface area of 210 × 150 mm² with nine channels spaced 15 mm apart. Two 0.2 mm-deep ribs were placed at the inlet and outlet to ensure flow uniformity.

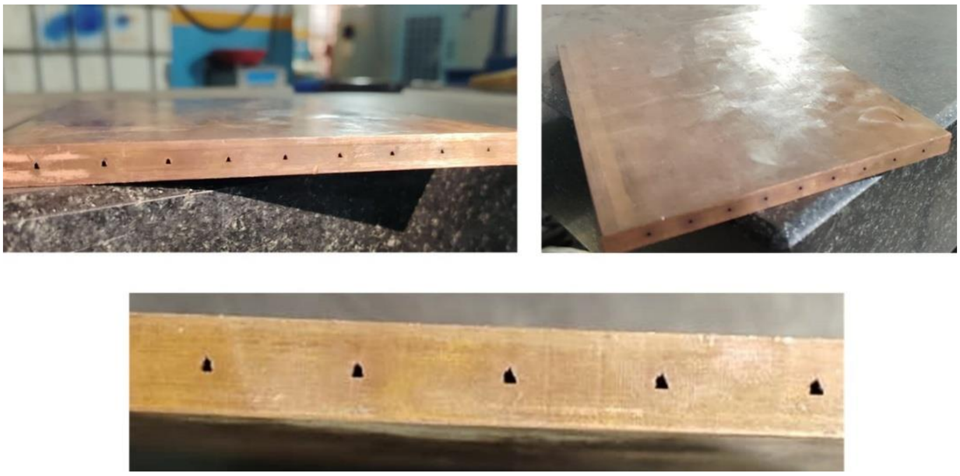


Fig.1.Dimensional details of the triangular microchannel heat exchanger test plate. -Fabricated Model

Fig. 1 depicts the intricate dimensions of the Microchannel Heat Exchanger (MCHE). The heat exchanger comprised nine circular channels, each 0.8 mm in diameter and 210 mm long, spaced at 15 mm intervals. To facilitate temperature measurement, two rows of 2 mm-diameter, three mm-deep thermocouple holes were drilled at the top of each channel, for a total of 18 thermocouples.

2.3 Experimental setup

The experimental setup for the MCHE is shown in Fig. 2. A closed-loop system was built, consisting of a 15 L water tank, a 24 VDC diaphragm pump (1.6 lpm), and a machined rectangular test section (240 × 170 × 25 mm³), housing a triangular MCHE (210 × 150 × 10 mm³). A 1000 W mica heater supplied heat beneath the MCHE, with dual-layer insulation (glass wool and 12 mm Hylam sheet) minimizing losses. A submersible pump ensured uniform nanofluid suspension, while a downstream cooling tower helped regulate the fluid temperature.

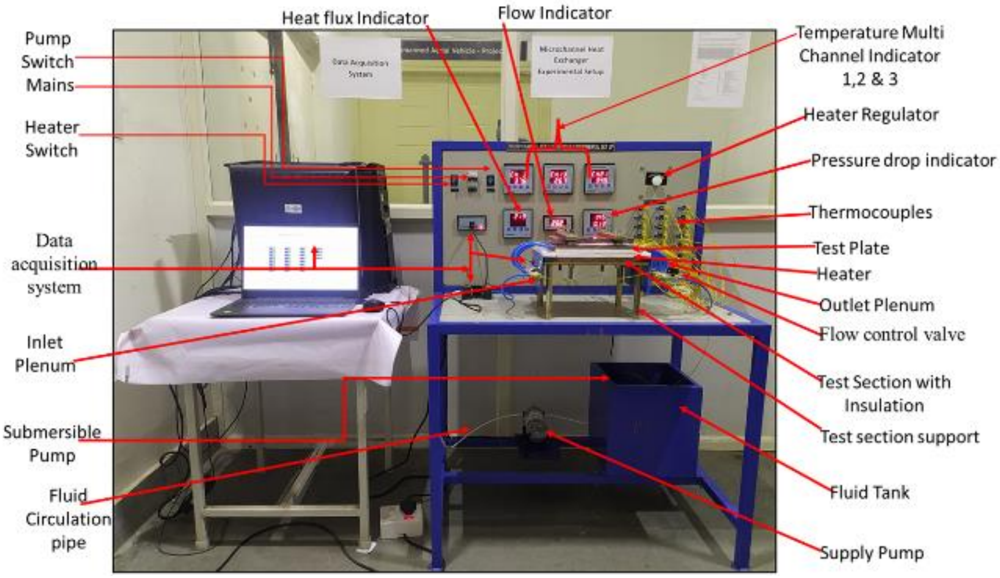


Fig.2. Microchannel heat exchanger experimental setup

Following micromachining, 3.2 mm-diameter holes were drilled in the inlet and outlet sides of the channel plate to accommodate inlet plenum connectors. Eighteen thermocouples were strategically installed within the MCHE channels in two rows to monitor temperature distribution [26]. Each row contained nine thermocouples, with one set positioned 70 mm from the inlet and the other 140 mm from it, as illustrated in Fig. 3.

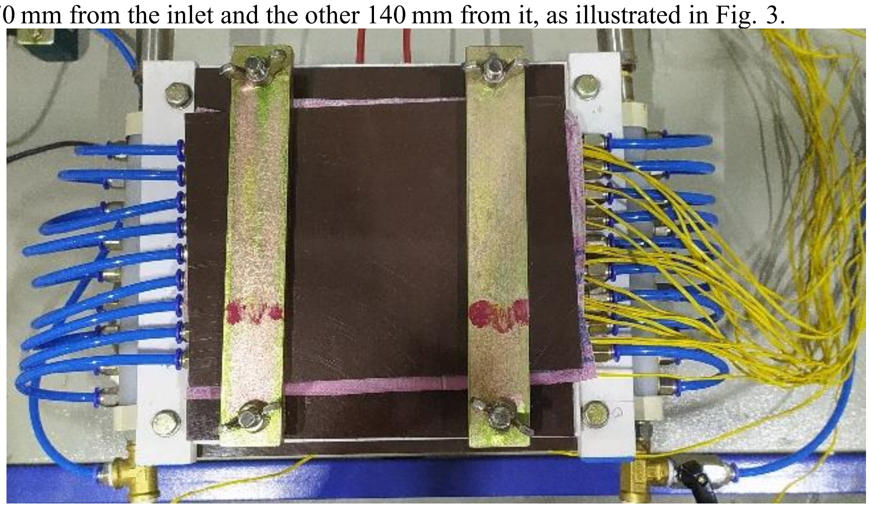


Fig. 3. Test plate with thermocouple locations and pressure transducer

2.3.1 Experimental instrumentation and measurement

Accurate instrumentation and measurement are essential in any experimental study to ensure reliable data and valid results. Fig. 4 shows the instrumental setup.

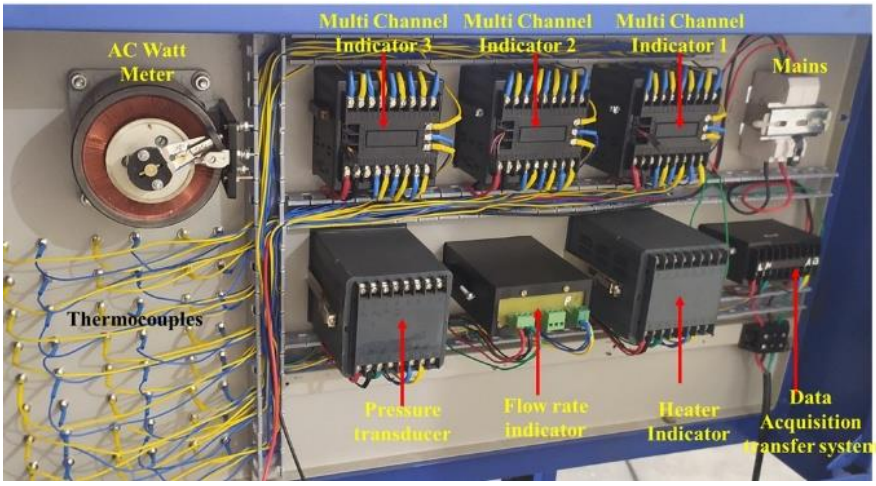


Fig. 4. Instrumentation Employed in Microchannel Heat Exchanger Testing

Key measurements were obtained using carefully positioned equipment to assess the microchannel heat exchanger (MCHE) hydraulic and thermal performance. To record the temperature distribution along the flow path, 18 thermocouples were inserted into the channels in two rows, nine at 70 mm and nine at 140 mm from the inlet. Determining the Reynolds number and flow regime required precise monitoring of the fluid flow rate, provided by a turbine-type flow indicator. Data for determining the friction factor was obtained from pressure sensors placed upstream and downstream of the MCHE, which recorded pressure drops throughout the test section. A thorough evaluation of heat transfer was enabled by using temperature and pressure data to calculate the Nusselt number and friction factor, based on channel geometry and fluid properties.

3. Results and discussion

The experimental findings show that across all tested nanofluids, heat transfer increases with nanoparticle concentration. CNT-based nanofluids exhibited the highest pressure drop and Nusselt number among the three. Due to enhanced wall contact and secondary-flow effects, the triangular microchannel geometry significantly improved thermal performance.

3.1 Effect of Al_2O_3, CuO, and CNT nanofluids on heat transfer

The Nusselt number, a key indicator of heat transfer in microchannel heat exchangers, was calculated from the heat-transfer coefficient, fluid thermal conductivity, and hydraulic diameter. Temperature profiles were recorded along the channels using K-type thermocouples.

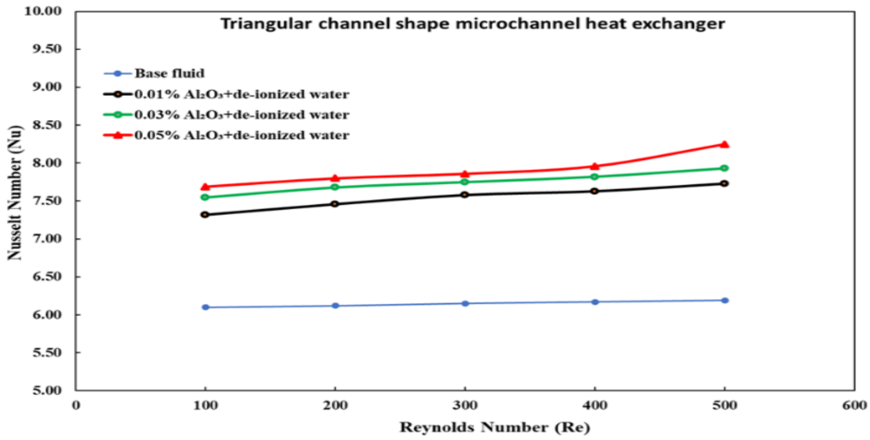


Fig. 5. Nusselt number with Reynolds number for the triangular MCHE for the Al_2O_3 nanofluid.

The variation of the Nusselt number with Reynolds number for three different nanofluids, Al_2O_3, CuO, and CNT, at nanoparticle concentrations of 0.01%, 0.03%, and 0.05% by weight, is presented in Fig. 5, 6, and 7. To achieve Reynolds numbers between 100 and 500, the fluid flow rate was adjusted in the experimental setup. The graphs also illustrate the influence of nanoparticle concentration in deionized water on convective heat transfer. Across all concentrations, a consistent increase in the Nusselt number with increasing Reynolds number was observed, with the highest values attained at 0.05% nanoparticle concentration and Re = 500. At this peak condition, the

Nusselt number improved by 28.65% for Al_2O_3, 24.55% for CuO, and 43.06% for CNT nanofluids compared to the base fluid, indicating CNT's superior thermal performance. This enhancement is attributed to the increased thermal conductivity and stability of CNT nanofluids.

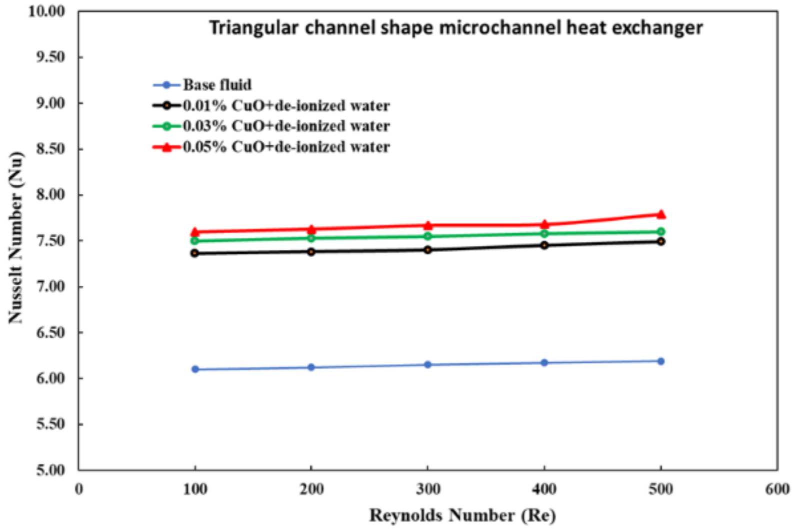


Fig. 6: Nusselt number with Reynolds number for the triangular MCHE for the CuO nanofluid.

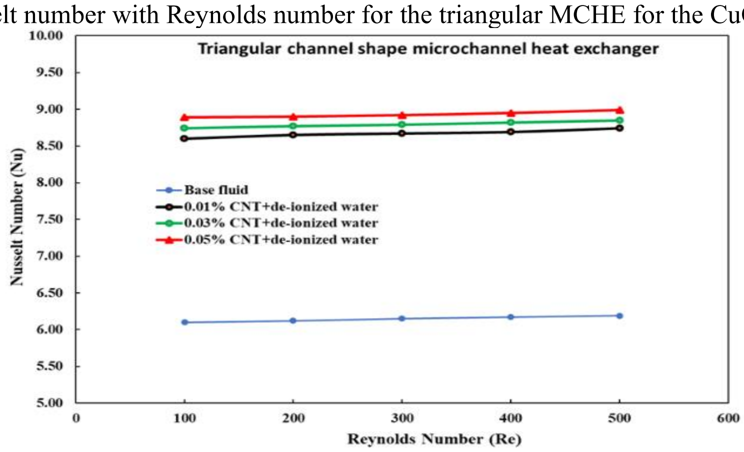
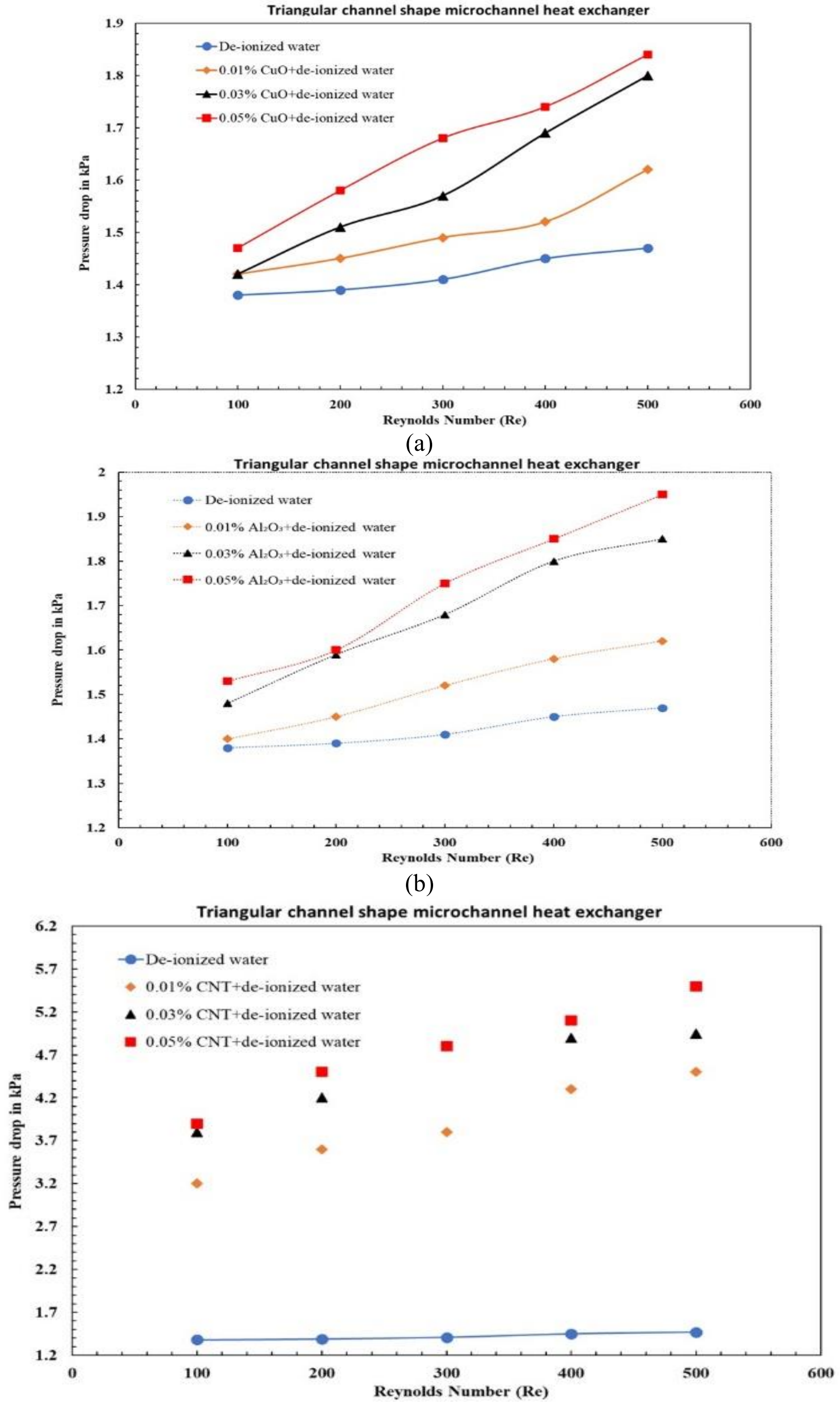


Fig. 7. Nusselt number with Reynolds number for the triangular MCHE for the CNT nanofluid.

The increase in Reynolds number intensifies momentum transport in the channel, resulting in a thinner thermal boundary layer and higher heat transfer coefficients. Regardless of Reynolds number or nanofluid concentration, the triangular microchannel geometry consistently exhibited superior heat-transfer performance. This is due to three key factors: an increased surface-area-to-volume ratio. Triangular channels offer a greater surface area per unit volume than circular or rectangular channels. This expanded wall-fluid interface enhances conductive and convective heat transfer. Enhanced Wall-to-Fluid Contact in Corners: Triangular corners create low-velocity zones with steep temperature gradients, enabling longer fluid residence time and more effective heat transfer near the walls. Induced Secondary Flow and Boundary Layer Disruption: The non-uniform, angled geometry of triangular channels promotes secondary flow patterns even in laminar regimes. These flow disturbances enhance mixing, disrupt thermal boundary layers, and significantly boost convective heat transfer. Overall, the results underscore the combined influence of nanofluid selection, concentration, and channel geometry in optimizing the thermal performance of microchannel heat exchangers.

3.2 Impact of nanofluids in triangular channel geometry on pressure drop (Δp)

The fluctuation in pressure drops along the length of triangular microchannel heat exchangers (MCHE) for the CuO, Al_2O_3, and CNT-based nanofluid at various Reynolds numbers is illustrated in Fig. 8 (a), (b), and (c). The results indicate an increase of 0.01%, 0.03%, and 0.05% by weight in nanofluids led to respective increases of 10.13%, 17.33%, and 22.03%; 11.16%, 23.35%, and 27.46%; and 184%, 232%, and 249.49%, respectively. On average, the pressure drop rose by 16.49% (CuO), 20.65% (Al2O3), and 221.83% (CNT) compared to the base fluid. The elevated pressure drop in triangular MCHEs can be attributed to several interrelated factors. Mainly, Sharp Geometrical Features: The acute angles and corners in triangular channels introduce regions of high viscous dissipation and increased local wall shear stress. These zones disrupt fully developed flow, causing additional resistance to motion. Secondary Flow and Flow Separation: Triangular geometries generate non-uniform velocity distributions and secondary flow structures, especially near corners. These disturbances thicken the boundary layer, disrupt laminar flow paths, and elevate flow resistance. Nanoparticle Effects: As nanoparticle concentration increases, the effective viscosity of the nanofluid rises due to stronger particle–fluid and particle–particle interactions. This leads to higher momentum diffusion, resulting in greater pressure losses along the channel. CNT-Specific Behavior: Carbon nanotubes, owing to their strong van der Waals forces, tend to form agglomerates or networks within the fluid. Even with surfactant stabilization, these clusters can increase flow obstruction, leading to significantly higher pressure drops than spherical nanoparticles such as CuO and Al_2O_3.



(c)

Fig.8. Variation of pressure drop with Reynolds number for the triangular MCHE (a) for Al_2O_3 Nanofluid (b) for CuO nanofluid (c) for CNT nanofluid

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3.3 Influence of triangular channel geometry on friction factor (FF)

The correlation between the friction factors of nanofluids at different concentrations and the Reynolds number is shown in Fig. 9, for the triangular microchannel heat exchanger. Across all nanofluids (Al_2O_3, CuO, and CNT), the friction factor decreased monotonically with increasing Re.

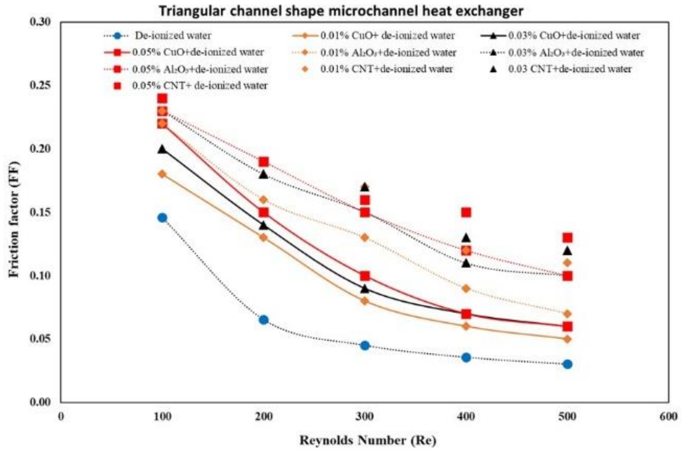

Fig.9. Friction factor (FF) with Reynolds number in MCHE for nanofluids

The experimental results showed that the friction factor decreased more sharply at lower Reynolds numbers, consistent with laminar flow, where viscous forces dominate. At these lower Re values, flow resistance is susceptible to changes in fluid properties, such as viscosity, which is influenced by nanoparticle addition. It was observed that the friction factor was minimized at low nanoparticle concentrations, particularly at 0.01 wt%, owing to minimal viscosity increase and reduced disturbance to the boundary layer. However, as the nanoparticle concentration increased to 0.03% and 0.05%, the friction factor correspondingly increased. This can be attributed to elevated effective viscosity, greater interparticle interactions, and increased momentum diffusion within the flow, all of which contribute to higher wall shear stress. Among the tested nanofluids in triangular microchannel configurations, the CuO-based nanofluid consistently exhibited a lower friction factor than Al_2O_3 and CNT-based nanofluids at equivalent Reynolds numbers and concentrations. This can be attributed to CuO relatively moderate thermal conductivity and viscosity. In contrast, CNT nanofluids exhibited the highest friction factor, especially at lower Reynolds numbers, which may be due to their elongated shape, tendency to form agglomerates, and higher intrinsic viscosity, all of which intensify flow resistance and boundary-layer disruption.

4. Conclusion

This experimental study presents the heat transfer and pressure drop characteristics of a triangular MCHE. It is investigated for three different types of nanofluids, i.e., CuO, Al_2O_3, and CNT, at concentrations of 0.01%, 0.03%, and 0.05%, at Reynolds numbers in the 100-500 range. The findings of this study are explained in detail below.

1. Heat transfer increased with higher concentrations of nanoparticles and mass flow rates across all three concentrations of nanofluid. A consistent increase in the Nusselt number with increasing Reynolds number was observed, with the highest values attained at 0.05% nanoparticle concentration and Re = 500. At this peak condition, the Nusselt number improved by 24.55% for CuO, 28.65% for Al2O3, and 43.06% for CNT nanofluids compared to the base fluid, indicating CNT's superior thermal performance.

2. The pressure drop in triangular MCHEs using CuO, Al_2O_3, and CNT nanofluids was studied across various Reynolds numbers and nanoparticle concentrations (0.01%, 0.03%, and 0.05% by weight). Results show that the pressure drop increases with Reynolds number (Re = 500) and nanoparticle loading (0.05%), reaching 22.03% (CuO), 27.46% (Al_2O_3), and 249.49% (CNT), thereby increasing pumping power requirements.

3. Experimental results showed the friction factor decreased sharply at low Reynolds numbers due to laminar flow dominated by viscosity. The friction factor was lowest at 0.01 wt% nanoparticle concentration, but increased at higher concentrations (0.03% and 0.05%) due to greater viscosity and boundary-layer disturbance.
4. CNT nanofluids exhibited the highest friction factor, especially at lower Reynolds numbers, which may be due to their elongated shape, tendency to form agglomerates, and higher intrinsic viscosity, all of which intensify flow resistance and boundary-layer disruption.

5. Overall, the results underscore the combined influence of nanofluid selection, concentration, and channel

geometry in optimizing the thermal performance of microchannel heat exchangers

Declaration of Competing Interest
The authors declare that they have no known financial interests or personal relationships that could have influenced the work reported in this paper

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