Misan Journal of Engineering Sciences ISSN-E: 2957-4250
Vol. 3, No.2, Dec 2024 ISSN: 2957-4242

Conjoint effect of nanofluids and baffles on a heat exchanger thermal performance: Numerical approach

Hayder Al-Lami[1]* , Dheyaa S.J. Al-Saedi[1], Ali A.H. AlMaidi[2], Qudama Al-Yasiri[1]
[1]*College of Engineering, University of Misan, Al Amarah city, Maysan, 62001, Iraq*
[2]*College of Agriculture, University of Misan, Al Amarah city, Misan, 62001, Iraq*
**Corresponding author E-mail*: hayderallami@uomisan.edu.iq

(Received 1Sep, Revised 22 Nov, Accepted 7 Dec)

Abstract: Nanofluids have gained attention in recent years as a practical solution for enhancing thermal system performance. However, conjoint enhancement methods, such as fins and baffles, have shown further improvement in overall efficiency of systems. This paper explores the advancements of heat characteristics of a circular heat exchanger pipe with conical geometry baffles employing three nanofluid types, namely oxide (Al_2O_3), metallic (Fe), and carbon (Gr) based water. The baffled pipe was examined for varying nanofluid concentrations, represented by the volume fraction of nanoparticles in water (0.5%, 1%, and 1.5%) and exposed to a constant surface heat flux in turbulent flow conditions. The impact of various Reynolds numbers (Re), ranging from 5000 to 25000, on the thermal characteristics of the baffled heat exchanger pipe is studied. The numerical findings showed that employing nanofluids as an alternative working fluid to water has improved thermal properties considerably. Moreover, nanoparticles have increased the Nu of nanofluids compared to the usage of water. Significant improvements in the heat transfer coefficient were observed for all three nanofluids at a Reynolds number (Re) of 25000 and a nanoparticle concentration of 1.5%, compared to water. The Al_2O_3 -water nanofluid showed the most notable enhancement, with a 4.5% increase in the heat transfer coefficient. This improvement is due to the superior thermal conductivity of Al_2O_3 nanoparticles and their ability to induce localized turbulence within the fluid. Meanwhile, the Fe-water nanofluid demonstrated a 3.1% enhancement due to its metallic properties promoting better thermal energy transfer than the base fluid. Lastly, the Gr-water nanofluid achieved a 1.4% increase, which, while lower than the other two, still indicates that carbon-based nanoparticles can provide a measurable boost in thermal performance under turbulent conditions.
.

Keywords: Heat transfer; Heat exchanger; Nanofluid; Fraction factor; Turbulent flow

NOMENCLATURE

Abbreviations

Eff	Efficiency
Nu	Nusselt number
Re	Reynolds number

Symbols

u, v	Fluid flow velocity in 2D directions (m/s)
C_p	Specific heat capacity (J/kg.K)
d	Baffle base (mm)
T	Temperature (K)
T_{in}	Inlet temperature (K)
bf	Base fluid
nf	nanofluid
np	nanoparticles
k	Thermal conductivity (W/m.K)
U_{in}	Inlet velocity (m/s)
m	Mass flow rate (kg/s)
h	Heat transfer coefficient (W/m^2.K)
D	Pipe diameter (m)

DOI: https://doi.org/10.61263/mjes.v3i2.105

L Pipe length (m)
q'' Heat flux
s Baffle space (m)
Greek Symbols
$\boldsymbol{\rho}$ Density (kg/m^3)
ε Dissipation rate of turbulent kinetic energy (m^2/s^3)
μ Dynamic viscosity (Pa.s)
Φ Volume fraction of nanoparticles (%)

1. Introduction

Extensive research has focused on enhancing thermal system performance by implementing advanced and varied heat removal techniques[1]. Various methods have been developed to improve heat transfer efficiency in thermal engineering applications, including nuclear chemical processes, heat exchangers, and automotive cooling systems [2]. These improvements have contributed to a reduction in system size and a decrease in installation and maintenance costs [3]. These techniques can be classified into two main categories: active methods and passive methods. Active methods entail the application of external influences to the fluid or machinery, including mechanical agitation or external forces. Conversely, passive methods employ enhancements such as turbulence supporters (including unique surface geometries [4], baffles [5], twisted taps [6], tangential inlet nozzles [7], spiral fins [8], and many others) or fluid additives, including nanofluids [9].

Nanofluids are one of the typical passive methods used successfully in recent years, utilized by disparate micrometre or even millimetre particles in the base fluid [10]. It has been involved in various sectors, including the medical field [11], food industry [12], construction [13], energy-related [14], transportation [15], thermal applications [16], and many others [17–19]. Nanofluids have been broadly investigated in thermal applications including traditional and renewable systems [20].

However, previous attempts have encountered challenges, such as rising pressure drop, particle sedimentation, and equipment attrition. According to the literature studies, nanoparticles can enhance the thermal conductivity of the base fluid, and positively improve the thermal performance of various industrial applications [21]. Following the outline of nanoparticle suspension and nanofluid preparation by many researchers, more efforts were introduced to commercialize and industrialise the usage of nanofluids with better stability and agglomeration issues [22,23]. Many research works have introduced flow channels and pressure drop as critical parameters in such systems [24].

As previously stated, using nanoparticles led to more improvement in thermal conductivity and heat capacity than common working fluids such as water, oil, and so on [25]. As a result, nanofluids are likeable heat transfer mediums for various applications compared with regular fluids. For instance, a new heat transfer study using nanofluid for heat tube systems, namely microchannel, PV/T panel, and heat exchanger, has piqued the interest of researchers [26]. Different nanofluid types were examined, demonstrating that the system's heat transfer could be improved once nanoparticles were added to the base fluid thanks to the Brownian motion of nanoparticles, thermophoresis effect, and anxiety of particle movement [27,28]. Amongst others, Ambreen and Kim [29] modelled a micro-channel filled with Al2O3 and TiO2 nanofluids under steady-state flow presuming that nanofluids are incompressible with Newtonian behaviour. The study results discovered that using nanofluids has decreased the thermal resistance of base fluid and temperature gradient due to increasing the concentration.

Furthermore, nanofluids with smaller diameter nanoparticles demonstrated lower thermal resistance. Abdollahi-Moghaddam et al. [30] explored the advantages of using CuO nanoparticles on a heated tube's thermal performance. Nanofluids were prepared and tested with concentrations of up to 0.7 vol.% at Reynolds number (Re) between 6200 and 14200. The study results indicated an increment of the heat transfer coefficient of heated pipe by 280% while using 0.7 vol.% has decreased the fluid volume by 37%, contributing to a 55% reduction in heat exchanger size. Alrashed et al. [31] performed a numerical examination of FMWCNT/H2O nanoparticles in a contracting backwards-facing channel. The outcomes demonstrated that the average friction coefficient did not significantly alter when nanomaterials were added to the working fluid. Table 1 summarizes further literature studies that present the remarkable

enhancement of nanofluids for different thermal systems.
Baffle optimization is an effective strategy for heat transfer rate improvement by increasing the fluid mixing, acting as an impediment to the flow particles, and making turbulence [36]. Besides, it is considered a viable and feasible means to modify the thermal performance and hydrodynamics of heat exchangers [37].

Table 1. Summary of literature studies on thermal systems-based nanofluids

Authors	Study type	Study system	Nanofluid	Main findings
Keklikcioğl et al. [32]	Numerical	Corrugated channel	Graphene Oxide-water	At Re of 133, the most significant enhancement ratio was 1.84 for 0.556 volume fraction and 5 mm corrugation height.
Rahimi Gheynani et al. [33]	Numerical	Microtube	CuO/CMC	Maximum Nu increment by 51%.
Bahiraei et al. [34]	Numerical	Microchannel with channels and ribs	Hybrid nanofluid	Improved convective heat transfer coefficient by up to 17%.
Chaurasia and Sarviya [35]	Numerical & Experimental	Helical screw-taped pipe with single and double strips	CuO/water	Improvement of Nu by 170% using single strip and by 182% with the double-strip helical screw tapes.

Therefore, many researchers have studied baffles to show their influence on the thermal properties of heat exchangers. For instance, Hayder et al. [36] studied numerically the heat transfer and turbulent flow characteristics of a 3D circular tube with conical baffle inserts. The study implemented with a Re ranging from 10000 to 50000 and a pitch ratio of 1 to 5. The study findings revealed that the pipe's heat transfer rate with baffles was more significant compared to a smooth pipe, demonstrating the effectiveness of baffles. More researchers have combined utilizing different nanofluids with numerous shapes of baffles to improve heat transfer characteristics. For instance, Heydari et al. [38] carried out numerical simulations with three-dimensional modelling to investigate the impact of incorporating various nanoparticles into base fluids inside a baffled shell-and-tube heat exchanger. Nanofluids including Al_2O_3, CuO, Fe_2O_3, Cu, Fe, SiO_2, and Au were evaluated using water and ethylene glycol as base fluids, taking into account different volume fractions and particle sizes. The findings indicated that the nanoparticles decreased the heat transfer coefficient, pressure drop, and heat transfer rate while raising the output shell temperature. Ethylene glycol exhibited superior efficacy as a base fluid in the heat exchanger compared to water. Mehrarad et al. [39] revealed that the friction factor of a brazed-plate heat exchanger has increased by 12.87 % compared with the water base fluid using MWCNT with 0.05 % concentration at 55 °C temperature and 23.4 l/min volume flow rate. Sundar [40] experimentally showed that using the nanodiamond-Fe_3O_4/water hybrid nanofluid with 0.2 % vol. concentration in a tube heat exchanger with twisted tape insert could achieve a maximum friction factor of about 61.93 % more than the water base fluid. Mashhour et al. [41] have carried out a numerical investigation on the thermal performance and flow characteristics of a shell and tube heat exchanger with varying baffle angles. They employed water and hybrid nanofluids at two distinct concentrations of GNP-Ag/water, 0.04% and 0.1%, within the Reynolds number (Re) range of 10,000 to 20,000. They discovered that the Nusselt number (Nu) associated with the baffle angle of 135° was exceedingly near to the recorded value at 180° at a low Re number. The Nu number increased by 35% in comparison to the reference case at Re = 20,000. Reddy et al. [42] numerically explore the influence of internal baffles and aqueous-silver nanofluids on heat transfer in a vertical annulus. The findings show that sphere- and blade-shaped nanoparticles enhanced heat transfer by around 30%, while an increase in baffle height augmented thermal performance by 40%.

In light of the preceding literature, using nanoparticles with baffled pipes effectively enhances systems' thermal performance and has become an active research topic. Nevertheless, the influence of conical baffle shapes on heat transfer and flow characteristics under the effect of nanoparticles has received little attention in the literature exploration. Such baffles were selected for this investigation due to their ability to create localised vortices, increase turbulence, and boost mixing within the flow, augmenting nanofluids' benefits. This work aims to study the impact on heat transfer performance of three different nanoparticle types (Al_2O_3, Fe, and Gr) based water on a conical-baffled pipe heat exchanger at various nanoparticle concentrations and Reynolds numbers. These nanofluids have been selected due to their excellent thermophysical characteristics as presented in the literature studies. For instance, Al_2O_3 has been selected due to its excellent thermal conductivity, stability, and cost-effectiveness. Besides, Fe exhibits strong thermal conductivity and magnetic characteristics, whereas Gr enhances heat transfer because of its remarkable thermal conductivity and distinctive structure. This study will be done numerically, as the numerical modelling helps to facilitate a comprehensive examination of heat transfer and flow characteristics in controlled environments, thereby minimizing the necessity for expensive and time-intensive experiments. Therefore, this research is believed to shed light on further investigating heat transfer enhancement using multiple methods, including fins and nanofluids.

2. Problem Description and Modelling

2.1 Physical model

Figure 1 presents a diagram of the physical model adopted in the current research work. The model consists of a pipe with a 1000 mm length and 15 mm diameter incorporated six conical baffles insides. The nanofluid enters the pipe from the inlet and flows through the pipe to the outlet considering the effect of the baffles. More information about the geometrical structure and design standards is listed in Table 2.

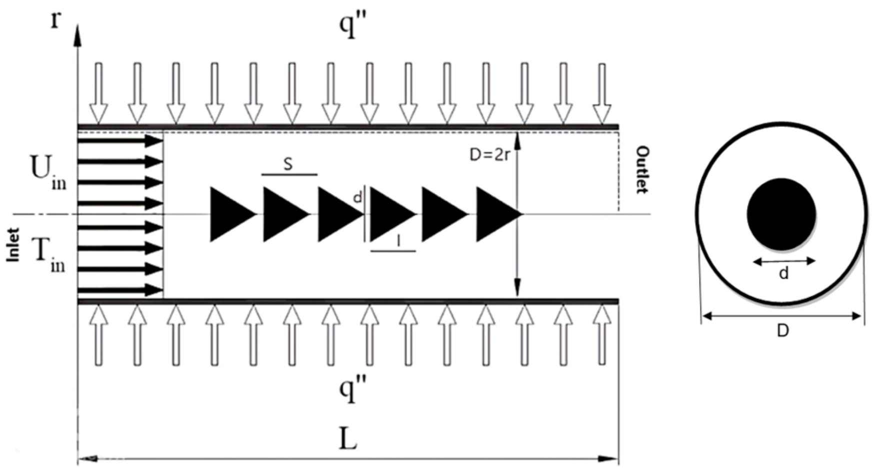

Fig. 1. Schematic presentation of the pipe heat exchanger with inside conical baffles.

Table 2. Table 2. Geometrical structure and design standards of the baffled pipe model

Geometry	Dimension
Pipe length (L)	1000 mm
Pipe inner diameter (D)	15 mm
Pipe outer diameter	15.2 mm
Baffle base (d)	8 mm
Baffle number (n)	6
Baffle space (s)	8 mm

2.2 Governing equations

Several governing equations were adopted in the simulation software to analyze the physical model such as the 3D homogeneous mixture model conservation equations, as follows [33]:

Continuity Equation:

$$\nabla.(\rho_m V_m) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial t}(V_m) + \nabla.(V_m V_m) = -\nabla P_m + \nabla.[\mu_m(\nabla V_m + \nabla V_m^T)] \tag{2}$$

where,

$$\mu_m = \sum_{Z=1}^{n} \varphi_Z \mu_Z \tag{3}$$

Energy Equation:

$$\frac{\partial}{\partial t} h_m + \nabla.(h_m V_m) + \nabla.(P V_m) = \nabla.\left(k_{eff} \nabla T\right) \tag{4}$$

where,

$$h_m = \sum_{Z=1}^{n} \varphi_Z h_Z \tag{5}$$

and,

$$k_{eff} = \sum_{Z=1}^{n} \varphi_Z (k_z + k_t) \tag{6}$$

The Re-Normalisation Group (RNG) k-ε turbulence model was adopted in this simulation modelling since this model is widely used in Computational Fluid Dynamics due to its robustness, simplicity, and cost-effectiveness, making it sufficient to be applied for specific flow conditions, particularly in complex systems. The strength of the k-epsilon model is appropriate for fluid flow with high Reynolds numbers where it offers an efficient balance between computational cost and accuracy, making it a popular choice for thermal engineering systems. The turbulent kinetic-energy transport is presented as:

$$\frac{\partial K}{\partial t} + u_m \frac{\partial K}{\partial x} + v_m \frac{\partial K}{\partial y} = \frac{\partial}{\partial x}\left(v_m + \frac{v_{t,m}}{\sigma_k}\right)\frac{\partial K}{\partial x} + \frac{\partial}{\partial y}\left(v_m + \frac{v_{t,m}}{\sigma_k}\right)\frac{\partial K}{\partial y} + P_{k,m} - \varepsilon \tag{7}$$

The dissipation of the turbulent kinetic energy transport equation is presented as follows:

$$\frac{\partial \varepsilon}{\partial t} + u_m \frac{\partial \varepsilon}{\partial x} + v_m \frac{\partial \varepsilon}{\partial y} = \frac{\partial}{\partial x}\left(v_m + \frac{v_{t,m}}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x} + \frac{\partial}{\partial y}\left(v_m + \frac{v_{t,m}}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y} + C_1 \frac{\varepsilon}{K} P_{k,m} + C_2 \frac{\varepsilon^2}{K} + C_3 \frac{\varepsilon}{K} G_{k,m} - R_{\varepsilon,m} \tag{8}$$

The eddy viscosity derivative is as follows from the Prandtl–Kolomogorov relationship:

$$v_{t,m} = C_\mu f_\mu \frac{K^2}{\varepsilon} \tag{9}$$

P_k is the kinetic energy production for turbulence, which could be determined as:

$$P_{k,m} = v_{t,m}\left[2\left(\frac{\partial u_m}{\partial x}\right)^2 + 2\left(\frac{\partial v_m}{\partial x}\right)^2 + \left(\frac{\partial u_m}{\partial y} + \frac{\partial v_m}{\partial y}\right)^2\right] \tag{10}$$

The Rε,m in the RNG k-ε could be calculated by:

$$R_{\varepsilon,m} = \frac{C_{\mu,m}\eta^3\left(1 - \frac{\eta}{\eta^0}\right)}{1 + \beta\eta^3}\ \frac{\varepsilon^2}{K} \tag{11}$$

where,

$$\eta = \frac{SK}{\varepsilon} \tag{12}$$

In which C_3 could be presented as:

$$C_3 = tanh\left|\frac{v}{u}\right| \tag{13}$$

2.3 Thermophysical Characteristics of Nanofluids

Nanofluid's thermal and physical characteristics, including density, specific heat, viscosity, and thermal conductivity, were calculated using Eqs. (14-17) enlisted in Table 3. All properties of nanofluids were calculated using the bulk temperatures between the outlet and inlet [43].

$$\rho_{nf} = \varphi\rho_{np} + (1-\varphi)\rho_{bf} \tag{14}$$

$$cp_{nf} = cp_{np}\varphi + (1-\varphi)cp_{bf} \tag{15}$$

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{np} + 2k_{bf} + 2\varphi(k_{np} - k_{bf})}{k_{np} + 2k_{bf} - \varphi(k_{np} - k_{bf})} \tag{16}$$

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\varphi)^{2.5}} \tag{17}$$

where ρ is the density, φ is the nanoparticle volume concentration, Cp is the specific heat, k is the thermal conductivity, and μ is the dynamic viscosity. $nf, pf,$ and bf refer respectively to the characteristics of nanofluid, particle, and base fluid.

Table 3. Thermophysical characteristics of examined fluids.

Working fluid	φ (%)	ρ (kg/m^3)	Cp (J/K·kg)	μ (Pa.s)	k (W/m^1.K^1)
	0.5	1012.460	4162.965	0.00101261	0.608648
Al_2O_3-water	1	1026.920	4145.930	0.00102544	0.617380
	1.5	1041.380	4128.895	0.00103851	0.626196
	0.5	1004.260	4162.650	0.00101261	0.609037
Fe-water	1	1010.520	4145.300	0.00102544	0.618165
	1.5	1016.780	4127.950	0.00103851	0.627386
	0.5	1032.460	4161.335	0.00101261	0.608845
Gr-water	1	1066.920	4142.670	0.00102544	0.617777
	1.5	1101.380	4124.005	0.00103851	0.626798
Water	----	998	4180	0.001	0.6

2.4 Boundary conditions

The following boundary conditions were taken into account while developing the model and to simplify the simulation:

- The fluid flow is assumed as three-dimensional, Newtonian, turbulent, steady-state, and incompressible,
- The temperature of Tin is maintained at 300 K at the inlet,
- The inlet velocity is set to a constant,
- The gravity force was negligible,
- The pipe's top and bottom walls experience a constant heat flux q,
- There is no slippage at the walls (i.e., u=v=w),
- The pressure is set to 0 at the pipe's outlet,
- Nanofluid properties are affected by temperature,
- The nanofluids' behaviour is suggested as Newtonian,
- The base fluid had entirely dissolved the nanomaterials, and they were moving at the same speed as the fluid.
- The RNG k-ε model is chosen due to its ability to manage flow separation and swirling flows, commonly observed in baffled heat exchangers.

2.5 Grid independent test

The grid independency check was implemented to guarantee that the model's findings are independent of mesh number, structure, and size (Fig. 2). For this purpose, six different mesh element numbers ranging from 19573 to 2075270 were deliberated at one Re value to check the validity of the grid independency.

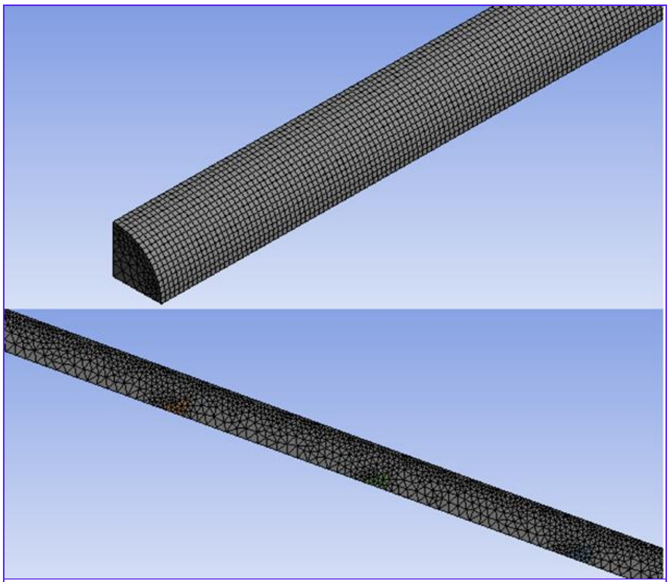

Fig. 2. Mesh for the computational domain of the model.

Figure. 3 depicts the grid independence test, demonstrating that the output of outlet temperature and convective heat transfer coefficient are independent after 603329 elements. The average skewness quality was recorded as 0.36, considered acceptable quality according to the Guide of Fluent [44]. Up to two decimal places, the inaccuracy is estimated at 0%.

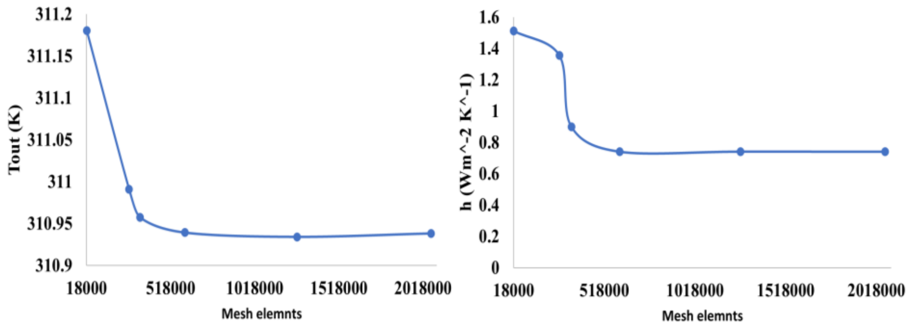

Fig. 3. Outlet temperature and convective heat transfer coefficient versus mesh element.

2.6 Validation of the numerical model

A validation for the model was carried out by comparing the current study's findings against the outputs of a previous study conducted for the same physical model. Fig. 4 shows a good agreement in comparing the Nu of the current model at various Re to the results reported by Hayder et al. [36], with a maximum deviation of about 4%.

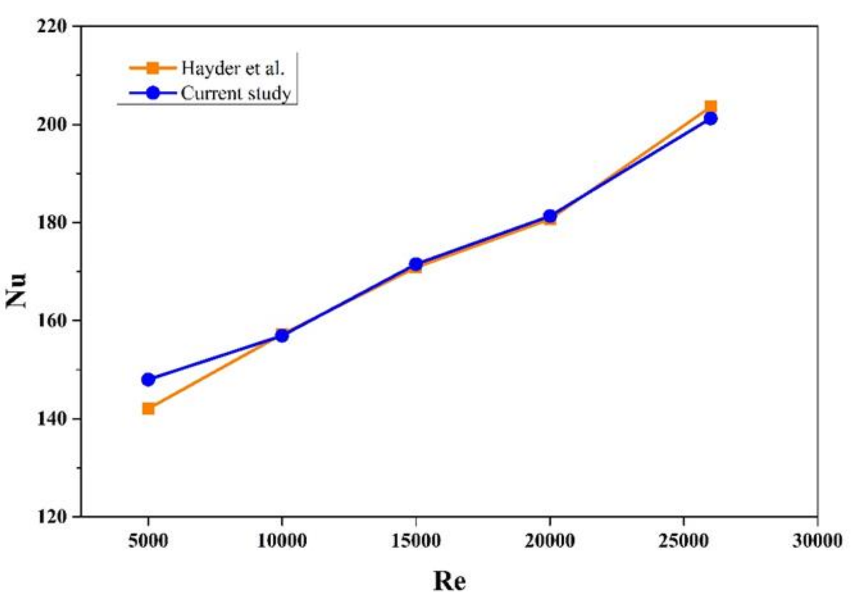

Fig. 4. Comparison of the current study's Nu and Hayder et al. [36].

The results were compared to comparable numerical investigations in the literature, despite the absence of experimental validation. The objective of future research is to incorporate experimental verification to substantiate the findings of this study.

3. Results and Discussion

The numerical modelling was verified over fifty runs by Ansys Fluent CFD software. In the first five runs, water was used as a base fluid without adding any nanoparticles, and the simulation was conducted with Re varying from 5000 to 25000. Afterwards, the simulations were done using three types of nanoparticles with concentrations varying between 0.5% and 1.5% vol. The effect of nanofluids on the circular pipe heat exchanger with baffles will be analyzed and discussed in the following subsections in light of the main heat transfer characteristics.

3.1 Nusselt number

The Nu is an essential indicator of heat transfer performance in non-dimensional form. Fig. 5 displays the Nu for all examined working fluids used in the study as a function of Re considering the conical baffles. The data reveal that both Re and nanoparticle concentration greatly impact Nu. Nu specifically rises with increased Re and larger nanoparticle concentrations across all nanofluid types, underscoring the superior convective heat transfer efficiency of nanofluids relative to water.

At a Reynolds number of 5000 and a nanoparticle concentration of 0.5%, the Al_2O_3, Fe, and Gr-based nanofluids demonstrated enhancements in heat transfer of 12.4%, 6.7%, and 4.2%, respectively, compared to water. Among the evaluated nanofluids, Al_2O_3 consistently exhibited the greatest boost owing to its greater thermal conductivity, reaching performance increases of 3.16% and 1.2% above Gr-water and Fe-water nanofluids, respectively. The use of conical baffles in this model enhanced the heat transfer rate by disturbing the thermal boundary layer and fostering turbulence, hence facilitating improved nanoparticle-fluid interactions.

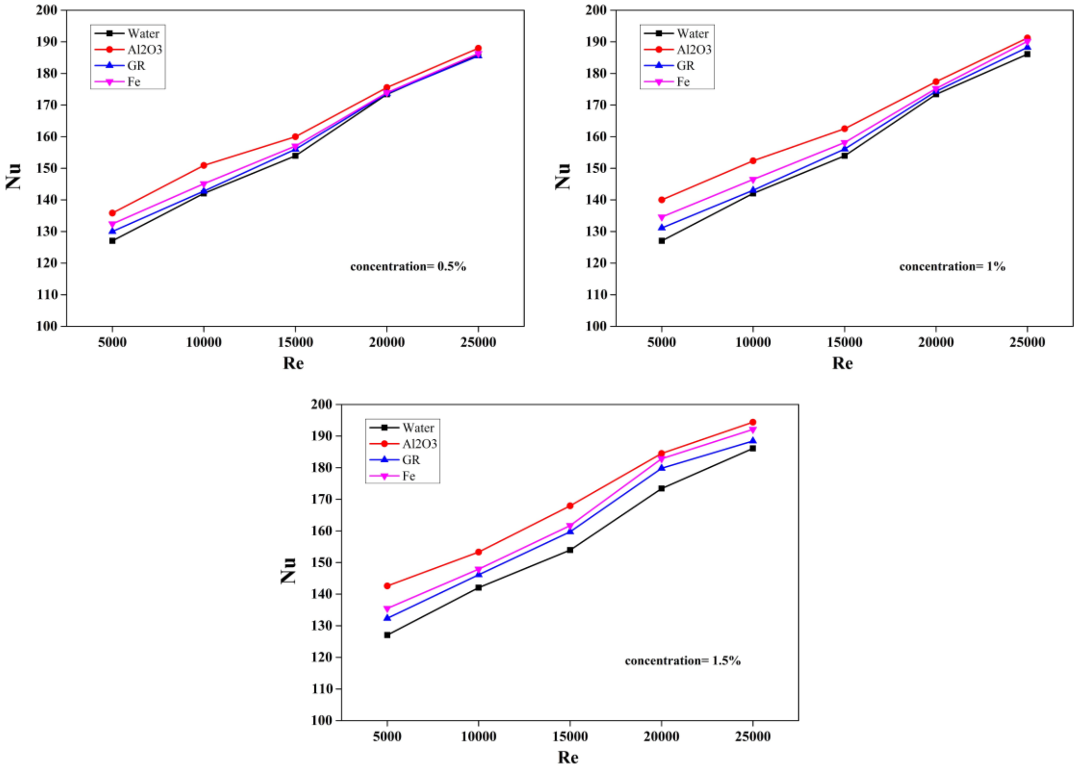

Fig. 5. Nu for all working fluids vs Re at varying NF concentrations.

Figure 6 illustrates the significant increase in Nu at reduced Re, principally due to micro-convection phenomena resulting from the Brownian motion and thermophoresis of nanoparticles. Nevertheless, when Re grows, the relative enhancement decreases. This decrease arises when fluid momentum prevails over particle-induced micro-convection, resulting in the convergence of the simulation outcomes at higher Re values.

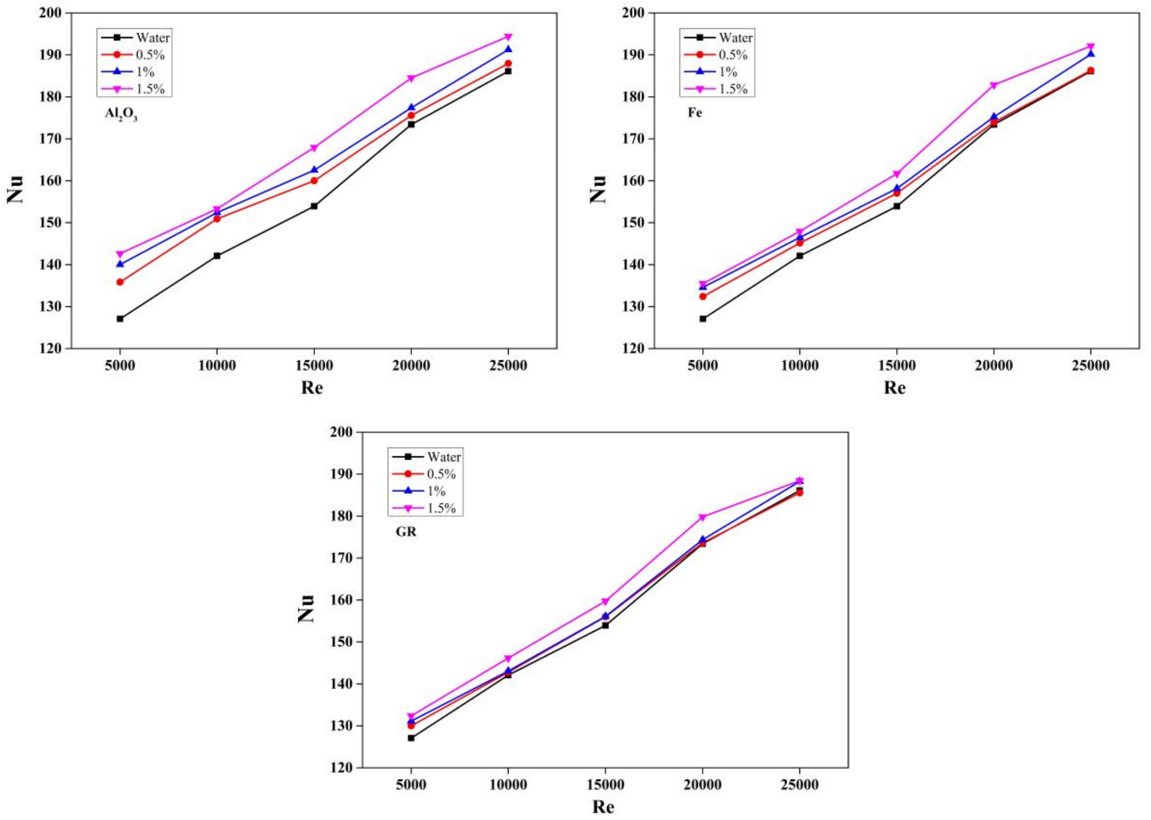

Fig. 6. Nu vs Re at all concentrations for Al2O3, Gr, and Fe-based fluids against water.

The Nu reported in this research is in good agreement with the findings of literature studies. For instance, Maghrabie et al. [45] reported that using Al2O3-water and SiO2-water nanofluids with 0.1 vol% concentration in a shell and helically-coiled tube heat exchanger has improved the Nu by 8.3% and 7.5%, respectively. Krishna et al. [46] indicated that the Nu attained from using Cu-Al2O3-water nanofluid with 2.5 vol% used in a microchannel heat sink could improve the Nu by about 13.2% than Cu-water and by 23.07% than the Al2O3-water nanofluids. Heidarshenas et al. [47] showed that in a cylindrical mini channel, using Al2O3-ionic liquid with 50 nm has augmented the Nu by about 26% compared with the water base fluid.

3.2 Convective heat transfer coefficient

As previously stated, the thermal performance of systems could improve using nanofluids compared to the usage of water. According to Fig. 7, employing nanofluids has a higher convective heat transfer coefficient (h) value than the water. The curve trend of h was clear between tested nanofluids at 0.5% nano concentration; then they get narrow at Re=20000 and above. In comparison to water at Re = 25000 and concentration 1.5%, the improvement in h for nanofluids base Al2O3, Fe, and Gr were 4.5%, 3.1%, and 1.4%, respectively. These results somehow agree with many studies reported in the literature illustrating that nanofluids increase the heat transfer capabilities of traditional heat transfer fluids by floating nanoparticles in these base liquids. For instance, Guo et al. [48] reported that employing Al2O3 in a Helically-coiled tube heat exchanger with 1.5 vol% concentration has enhanced the convective heat transfer coefficient higher than using the water as a base fluid by 1.14 times. Rasheed et al. [49] reported that heat transfer enhancement of a helical copper coil tube heat exchanger could be maximized by 3.646 %and 3.623% using Al2O3-water and ZnO-water with 2% volume concentration and Re = 1800. However, using hybrid nanofluids has reported better thermal characteristics enhancements for heat exchangers. For instance, Kumar and Sarkar [50] stated that the heat transfer coefficient of a rectangular heat exchanger has improved by 9%, 12%, and 15.6% about using Al2O3-MWCNT/DI Water hybrid nanofluid with 0.01% volume concentration at ratios of 9:1, 8:2, and 7:3, respectively.

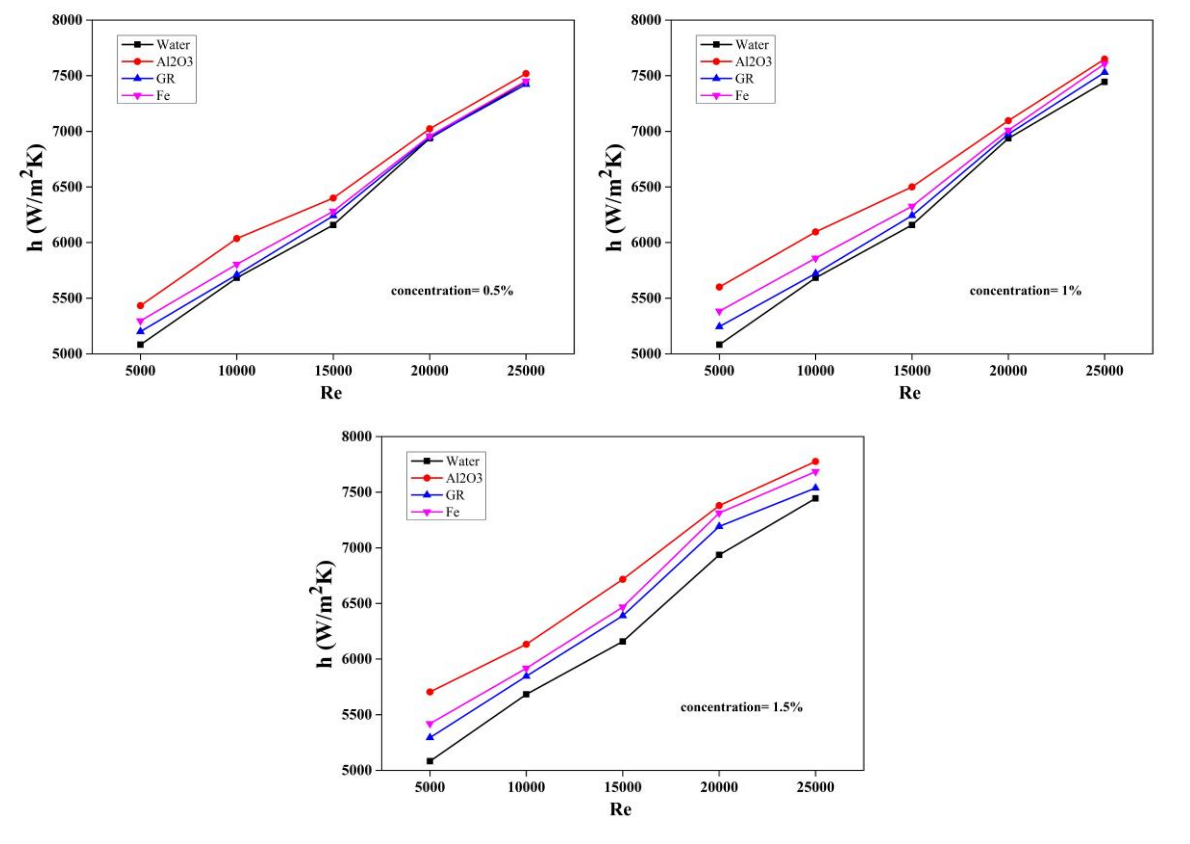

Fig. 7. Heat transfer fluid vs. Re for all working fluid concentrations.

3.3 Friction Factor

The friction factor (f) plays a significant role in studying the system heat transfer and fluid flow due to its relation to the pumping power required to push coolant through the connected channels [51]. Fig. 8 illustrates the friction factor for all working fluids concerning Re.

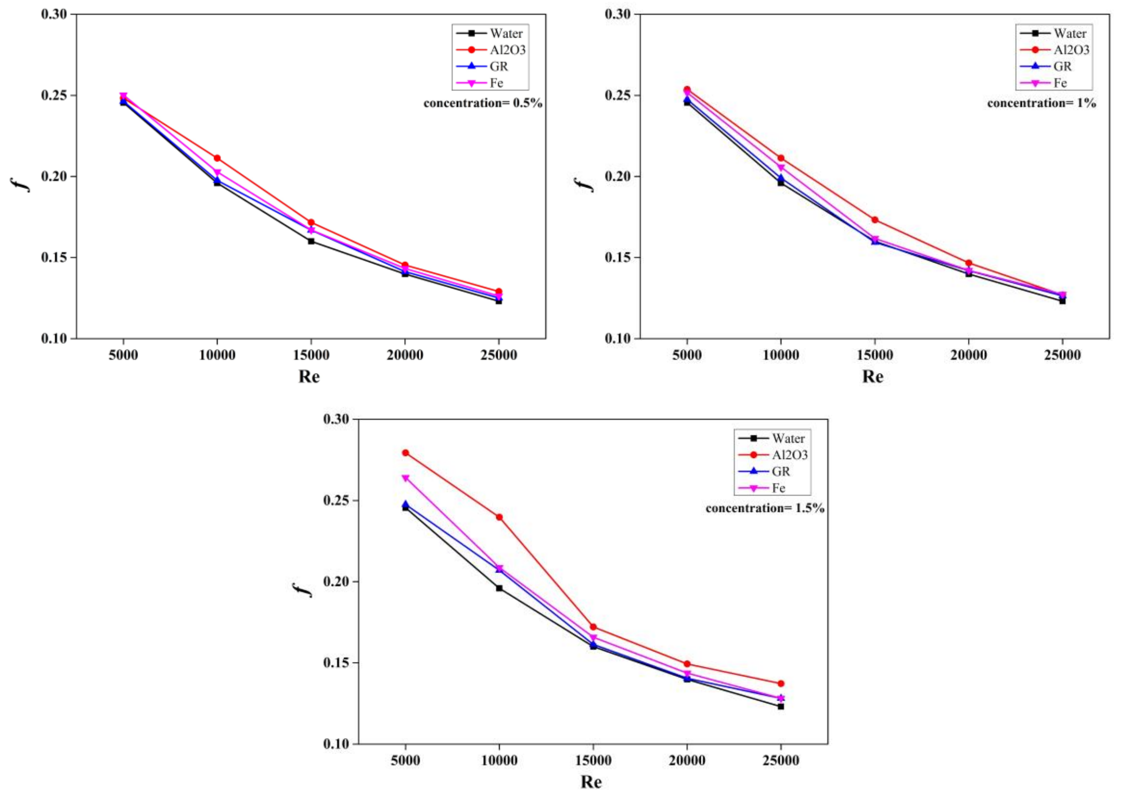

Fig. 8. f vs Re for examined nanofluid concentrations.

The findings illustrated in Fig. 8 show that increasing the Re has raised the friction factor under nanofluids and water. At Re = 15000 and φ= 1.5%, Al2O3-water nanofluid has greater friction factor values than other varieties of nanofluid and attained improvement by about 7.6%, followed by Fe-water, and Gr-water which achieved 3.6% and 0.8% respectively, more than the water base fluid. Additionally, the significance of vortex generation caused by baffles cannot be overlooked since it increases fluid friction and contributes to increased heat transfer. These results are much better than many reported in the literature.

The impetus for creating this model arises from integrating nanofluids' advantages with conical baffle configurations to enhance heat exchanger efficiency. Although nanofluids may enhance heat transfer, conventional heat exchanger designs often do not maximize their efficacy. Conical baffles were selected for this investigation due to their ability to create localized vortices, increase turbulence, and boost mixing within the flow, augmenting nanofluids' benefits. The model offers a distinct framework to assess the interaction of these advancements under different situations, providing insights for improving heat exchanger setups in industrial applications. This technique gives a more thorough understanding of thermal performance by addressing the constraints of previous models that typically disregard the synergy between flow geometry and nanofluids.

4. Conclusions

The main conclusions derived from the current research are as follows:

1. The Al_2O_3-water nanofluid exhibited greater heat transfer improvement than the other nanofluids and pure water.
2. The Nu and friction factor improvement using Al_2O_3-water nanofluid reached 12.4% and 7.6% respectively, whereas they reached 3.6% and 6.7% for Fe-water, respectively.
3. Gr-water showed lower enhancement than the other two nanofluids in which the Nu and friction factor were increased by only 4.2% and 0.8% compared with the water.
4. Based on the numerical findings, the Al_2O_3-based nanofluid displayed superior enhancement in the heat transfer coefficient, showing worthy effectiveness in heat transfer applications.

Author Contributions: The authors contributed to all parts of the current study.

Funding: This study received no external funding.

Conflicts of Interest: The authors declare no conflict of interest

References

[1] M.M. Sarafraz, Z. Tian, I. Tlili, S. Kazi, M. Goodarzi, Thermal evaluation of a heat pipe working with n-pentane-acetone and n-pentane-methanol binary mixtures, J Therm Anal Calorim 139 (2020) 2435–2445. https://doi.org/10.1007/s10973-019-08414-2.

[2] S.D. Shelare, K.R. Aglawe, P.N. Belkhode, A review on twisted tape inserts for enhancing the heat transfer, Mater Today Proc 54 (2022) 560–565.

[3] B.E. Jebasingh, A.V. Arasu, A detailed review on heat transfer rate, supercooling, thermal stability and reliability of nanoparticle dispersed organic phase change material for low-temperature applications, Mater Today Energy 16 (2020) 100408.

[4] P. Élesztos, L. Écsi, R. Jančo, J. Gabková, Thermal field of a solid particle for bi > 0 and fluid medium of a countercurrent heat exchanger, Periodica Polytechnica Mechanical Engineering 64 (2020) 15–19. https://doi.org/10.3311/PPme.13473.

[5] Y.N.Y.W.R.H.W.H.N.Z.Y.L.D.J. Pengjie Yu Shuangfei Zhao, K. Guo, Mass and heat transfer enhancement by a novel mixer with triangular-notched rectangular baffles for continuous flow chemical process, Numeri Heat Transf A Appl 85 (2024) 659–678. https://doi.org/10.1080/10407782.2023.2190938.

[6] P.K. Chaurasiya, J. Heeraman, S.K. Singh, T.N. Verma, G. Dwivedi, A.K. Shukla, Exploring the combined influence of primary and secondary vortex flows on heat transfer enhancement and friction factor in a dimpled configuration twisted tape with double pipe heat exchanger using SiO2 nano fluid, International Journal of Thermofluids 22 (2024) 100684. https://doi.org/https://doi.org/10.1016/j.ijft.2024.100684.

[7] K.V. Warghat, D. Sathish Kumar, S. Jayavel, CFD Analysis on Heat Transfer Enhancement in a Pipe

in Pipe Heat Exchanger with Tangential Injection, IOP Conf Ser Mater Sci Eng 1013 (2021) 012028. https://doi.org/10.1088/1757-899X/1013/1/012028.

[8] F. He, R. Bo, C. Hu, X. Meng, W. Gao, Employing spiral fins to improve the thermal performance of phase-change materials in shell-tube latent heat storage units, Renew Energy 203 (2023) 518–528. https://doi.org/https://doi.org/10.1016/j.renene.2022.12.091.

[9] R. Saini, B. Gupta, A. Prasad Shukla, B. Singh, P. Baredar, A. Bisen, CFD analysis of heat transfer enhancement in a concentric tube counter flow heat exchanger using nanofluids (SiO2/H2O, Al2O3/H2O, CNTs/H2O) and twisted tape turbulators, Mater Today Proc 76 (2023) 418–429. https://doi.org/https://doi.org/10.1016/j.matpr.2022.12.044.

[10] M. Habibishandiz, M.Z. Saghir, A critical review of heat transfer enhancement methods in the presence of porous media, nanofluids, and microorganisms, Thermal Science and Engineering Progress 30 (2022) 101267. https://doi.org/https://doi.org/10.1016/j.tsep.2022.101267.

[11] A. Haleem, M. Javaid, R.P. Singh, S. Rab, R. Suman, Applications of nanotechnology in medical field: a brief review, Global Health Journal 7 (2023) 70–77. https://doi.org/https://doi.org/10.1016/j.glohj.2023.02.008.

[12] A. Sharma, N. J, K. Gopalakrishnan, V. Bodana, A. Singh, P.K. Prabhakar, R. Suhag, R. Kumar, Chapter9 - Nanotechnology applications and implications in food industry, in: A. Sharma, P.S. Vijayakumar, Er.P.K. Prabhakar, R. Kumar (Eds.), Nanotechnology Applications for Food Safety and Quality Monitoring, Academic Press, 2023: pp. 171–182. https://doi.org/https://doi.org/10.1016/B978-0-323-85791-8.00016-1.

[13] M.S. Aljibory, Prof.Dr.B.J. Alsulayfani, Prof.Dr.M.N. Mahmood, Improvement of Concrete Mechanical Properties by Adding Nanomaterials, Misan Journal of Engineering Sciences 2 (2023) 57–70. https://doi.org/10.61263/mjes.v2i2.62.

[14] R.B. Onyancha, K.E. Ukhurebor, U.O. Aigbe, O.A. Osibote, H.S. Kusuma, H. Darmokoesoemo, J.K.R. Modigunta, A Methodical Review on Carbon-Based Nanomaterials in Energy-Related Applications, Adsorption Science \& Technology 2022 (2022) 4438286. https://doi.org/10.1155/2022/4438286.

[15] M. Daraee, S.S. Hassani, R. Saeedirad, Chapter 21 - Nanomaterials in the transportation industry, in: M.I. Malik, D. Hussain, M.R. Shah, D.-S. Guo (Eds.), Handbook of Nanomaterials, Volume 1, Elsevier, 2024: pp. 567–591. https://doi.org/https://doi.org/10.1016/B978-0-323-95511-9.00018-4.

[16] D.S. Soudani Azeddine, I. Rahmoune, Computational investigation on the energy efficiency of heat exchangers using Al2O3 nanofluids, Numeri Heat Transf A Appl (2024) 1–21. https://doi.org/10.1080/10407782.2024.2329313.

[17] Q. Al-Yasiri, M. Szabó, M. Arıcı, Single and Hybrid Nanofluids to Enhance Performance of Flat

Plate Solar Collectors : Application and Obstacles, Periodica Polytechnica Mechanical Engineering 65 (2021) 86–102. https://doi.org/https://doi.org/10.3311/PPme.17312.

[18] W. Ajeeb, S.M.S. Murshed, Nanofluids in compact heat exchangers for thermal applications: A State-of-the-art review, Thermal Science and Engineering Progress 30 (2022) 101276. https://doi.org/https://doi.org/10.1016/j.tsep.2022.101276.

[19] O. Gohar, M. Zubair Khan, I. Bibi, N. Bashir, U. Tariq, M. Bakhtiar, M. Ramzan Abdul Karim, F. Ali, M. Bilal Hanif, M. Motola, Nanomaterials for advanced energy applications: Recent advancements and future trends, Mater Des 241 (2024) 112930. https://doi.org/https://doi.org/10.1016/j.matdes.2024.112930.

[20] R.R. Souza, I.M. Gonçalves, R.O. Rodrigues, G. Minas, J.M. Miranda, A.L.N. Moreira, R. Lima, G. Coutinho, J.E. Pereira, A.S. Moita, Recent advances on the thermal properties and applications of nanofluids: From nanomedicine to renewable energies, Appl Therm Eng 201 (2022) 117725. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2021.117725.

[21] A.M. Alklaibi, K.V. V Chandra Mouli, L. Syam Sundar, Experimental investigation of heat transfer and effectiveness of employing water and ethylene glycol mixture based Fe3O4 nanofluid in a shell and helical coil heat exchanger, Thermal Science and Engineering Progress 40 (2023) 101739. https://doi.org/https://doi.org/10.1016/j.tsep.2023.101739.

[22] H. Babar, H.M. Ali, Towards hybrid nanofluids: preparation, thermophysical properties, applications, and challenges, J Mol Liq 281 (2019) 598–633. https://doi.org/10.1016/j.molliq.2019.02.102.

[23] H.A. Hasan, K.I. Ajeel, Preparation of Poly O-Toluidine/Titanium Dioxide by In situ Chemical Oxidation Polymerization and Application for Solar Cell, Journal of Misan Researches 16 (2020) 382–400. https://doi.org/https://doi.org/10.52834/jmr.v16i31.35.

[24] S. Masoud Hosseini, M.R. Safaei, P. Estellé, S. Hadi Jafarnia, Heat transfer of water-based carbon nanotube nanofluids in the shell and tube cooling heat exchangers of the gasoline product of the residue fluid catalytic cracking unit, J Therm Anal Calorim 140 (2020) 351–362. https://doi.org/10.1007/s10973-019-08813-5.

[25] I. Pop, T. Groșan, C. Revnic, A. V Roșca, Unsteady flow and heat transfer of nanofluids, hybrid nanofluids, micropolar fluids and porous media: A review, Thermal Science and Engineering Progress 46 (2023) 102248. https://doi.org/https://doi.org/10.1016/j.tsep.2023.102248.

[26] A.G. Olabi, K. Elsaid, E.T. Sayed, M.S. Mahmoud, T. Wilberforce, R.J. Hassiba, M.A. Abdelkareem, Application of nanofluids for enhanced waste heat recovery: A review, Nano Energy 84 (2021) 105871. https://doi.org/https://doi.org/10.1016/j.nanoen.2021.105871.

[27] M. Goodarzi, S. Javid, A. Sajadifar, M. Nojoomizadeh, S.H. Motaharipour, Q.-V. Bach, A.

Karimipour, Slip velocity and temperature jump of a non-Newtonian nanofluid, aqueous solution of carboxy-methyl cellulose/aluminum oxide nanoparticles, through a microtube, Int J Numer Methods Heat Fluid Flow 29 (2019) 1606–1628. https://doi.org/10.1108/HFF-05-2018-0192.

[28] S.A. Kadhim, A.H. Askar, A. Abed, M. Saleh, An enhancement of double pipe heat exchanger performance at a constant wall temperature using a nanofluid of iron oxide and refrigerant vapor, 10 (2024) 78–87. https://doi.org/10.18186/thermal.1429191.

[29] T. Ambreen, M.-H. Kim, Effects of variable particle sizes on hydrothermal characteristics of nanofluids in a microchannel, Int J Heat Mass Transf 120 (2018) 490–498. https://doi.org/https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.067.

[30] M. Abdollahi-Moghaddam, K. Motahari, A. Rezaei, Performance characteristics of low concentrations of CuO/water nanofluids flowing through horizontal tube for energy efficiency purposes; an experimental study and ANN modeling, J Mol Liq 271 (2018) 342–352. https://doi.org/https://doi.org/10.1016/j.molliq.2018.08.149.

[31] A.A.A.A. Alrashed, O.A. Akbari, A. Heydari, D. Toghraie, M. Zarringhalam, G.A.S. Shabani, A.R. Seifi, M. Goodarzi, The numerical modeling of water/FMWCNT nanofluid flow and heat transfer in a backward-facing contracting channel, Physica B Condens Matter 537 (2018) 176–183. https://doi.org/https://doi.org/10.1016/j.physb.2018.02.022.

[32] O. Keklikcioğlu, T. Dagdevir, V. Ozceyhan, Numerical Investigation on Heat Transfer Enhancement of Graphene Oxide-Water Nanofluids in a Corrugated Channel, International Journal of Natural and Engineering Sciences 10 (2016) 10–14.

[33] A. Rahimi Gheynani, O. Ali Akbari, M. Zarringhalam, G. Ahmadi Sheikh Shabani, A.A. Alnaqi, M. Goodarzi, D. Toghraie, Investigating the effect of nanoparticles diameter on turbulent flow and heat transfer properties of non-Newtonian carboxymethyl cellulose/CuO fluid in a microtube, Int J Numer Methods Heat Fluid Flow 29 (2019) 1699–1723. https://doi.org/10.1108/HFF-07-2018-0368.

[34] M. Bahiraei, M. Jamshidmofid, M. Goodarzi, Efficacy of a hybrid nanofluid in a new microchannel heat sink equipped with both secondary channels and ribs, J Mol Liq 273 (2019) 88–98. https://doi.org/https://doi.org/10.1016/j.molliq.2018.10.003.

[35] S.R. Chaurasia, R.M. Sarviya, Thermal performance analysis of CuO/water nanofluid flow in a pipe with single and double strip helical screw tape, Appl Therm Eng 166 (2020) 114631. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2019.114631.

[36] H. Al-Lami, M.S. Mohammed, R. Ali, A. Alshara, H.K.A. Zahra, Characteristics of Heat Transfer and Turbulent Flow in a Baffled Pipe with Different Arrangements, European Journal of Engineering and Technology Research 7 (2022) 113–119. https://doi.org/10.24018/ejeng.2022.7.6.2921.

[37] M.A. Alazwari, M.R. Safaei, Combination effect of baffle arrangement and hybrid nanofluid on

thermal performance of a shell and tube heat exchanger using 3-d homogeneous mixture model, Mathematics 9 (2021) 881. https://doi.org/10.3390/math9080881.

[38] A. Heydari, M. Shateri, S. Sanjari, Numerical analysis of a small size baffled shell-and-tube heat exchanger using different nano-fluids, Heat Transfer Engineering 39 (2018) 141–153.

[39] H. Mehrarad, M.R. Sarmasti Emami, K. Afsari, Thermal performance and flow analysis in a brazed plate heat exchanger using MWCNT@water/EG nanofluid, International Communications in Heat and Mass Transfer 146 (2023) 106867. https://doi.org/https://doi.org/10.1016/j.icheatmasstransfer.2023.106867.

[40] L. Syam Sundar, Heat transfer, friction factor and exergy efficiency analysis of nanodiamond-Fe3O4/water hybrid nanofluids in a tube with twisted tape inserts, Ain Shams Engineering Journal 14 (2023) 102068. https://doi.org/https://doi.org/10.1016/j.asej.2022.102068.

[41] M.A. Alazwari, M.R. Safaei, Combination effect of baffle arrangement and hybrid nanofluid on thermal performance of a shell and tube heat exchanger using 3-d homogeneous mixture model, Mathematics 9 (2021). https://doi.org/10.3390/math9080881.

[42] N.K. Reddy, A. Yoon, S. Mani, H.A.K. Swamy, Numerical investigation of nanofluid buoyant flow behavior and heat transfer characteristics in annular-shaped enclosure with internal baffle, Int J Numer Methods Heat Fluid Flow 34 (2024) 203–230.

[43] M. Ataei, F. Sadegh Moghanlou, S. Noorzadeh, M. Vajdi, M. Shahedi Asl, Heat transfer and flow characteristics of hybrid Al2O3/TiO2–water nanofluid in a minichannel heat sink, Heat and Mass Transfer 56 (2020) 2757–2767. https://doi.org/10.1007/s00231-020-02896-9.

[44] A. Fluent, FLUENT 6.3 Getting Started Guide, Engineering. New Hampshire, USA (2006) 1–37.

[45] H.M. Maghrabie, M. Attalla, A. A. A. Mohsen, Performance assessment of a shell and helically coiled tube heat exchanger with variable orientations utilizing different nanofluids, Appl Therm Eng 182 (2021) 116013. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2020.116013.

[46] V. Murali Krishna, M. Sandeep Kumar, R. Muthalagu, P. Senthil Kumar, R. Mounika, Numerical study of fluid flow and heat transfer for flow of Cu-Al2O3-water hybrid nanofluid in a microchannel heat sink, Mater Today Proc 49 (2022) 1298–1302. https://doi.org/https://doi.org/10.1016/j.matpr.2021.06.385.

[47] A. Heidarshenas, Z. Azizi, S.M. Peyghambarzadeh, S. Sayyahi, Experimental investigation of heat transfer enhancement using ionic liquid-Al2O3 hybrid nanofluid in a cylindrical microchannel heat sink, Appl Therm Eng 191 (2021) 116879. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2021.116879.

[48] W. Guo, G. Li, Y. Zheng, C. Dong, The effect of flow pulsation on Al2O3 nanofluids heat transfer behavior in a helical coil: A numerical analysis, Chemical Engineering Research and Design 156 (2020) 76–85. https://doi.org/https://doi.org/10.1016/j.cherd.2020.01.016.

[49] A.H. Rasheed, H.B. Alias, S.D. Salman, Experimental and numerical investigations of heat transfer enhancement in shell and helically microtube heat exchanger using nanofluids, International Journal of Thermal Sciences 159 (2021) 106547. https://doi.org/https://doi.org/10.1016/j.ijthermalsci.2020.106547.

[50] V. Kumar, J. Sarkar, Two-phase numerical simulation of hybrid nanofluid heat transfer in minichannel heat sink and experimental validation, International Communications in Heat and Mass Transfer 91 (2018) 239–247. https://doi.org/https://doi.org/10.1016/j.icheatmasstransfer.2017.12.019.

[51] F. Sadegh Moghanlou, S. Noorzadeh, M. Ataei, M. Vajdi, M. Shahedi Asl, E. Esmaeilzadeh, Experimental investigation of heat transfer and pressure drop in a minichannel heat sink using Al2O3 and TiO2–water nanofluids, Journal of the Brazilian Society of Mechanical Sciences and Engineering 42 (2020) 315. https://doi.org/10.1007/s40430-020-02403-5.