

Computational analysis of turbulent flow characteristics in nanofluids containing 1-D and 2-D carbon nanomaterials: grid optimization and performance evaluation

Hai Tao, Mohammed Suleman Aldlemy, Raad Z. Homod, Mustafa K. A. Mohammed, Abdul Rahman Mallah, Omer A. Alawi, Shafik S. Shafik, Hussein Togun, Blanka Klimova, Hassan Alzahrani & Zaher Mundher Yaseen

To cite this article: Hai Tao, Mohammed Suleman Aldlemy, Raad Z. Homod, Mustafa K. A. Mohammed, Abdul Rahman Mallah, Omer A. Alawi, Shafik S. Shafik, Hussein Togun, Blanka Klimova, Hassan Alzahrani & Zaher Mundher Yaseen (2024) Computational analysis of turbulent flow characteristics in nanofluids containing 1-D and 2-D carbon nanomaterials: grid optimization and performance evaluation, *Engineering Applications of Computational Fluid Mechanics*, 18:1, 2396058, DOI: [10.1080/19942060.2024.2396058](https://doi.org/10.1080/19942060.2024.2396058)

To link to this article: <https://doi.org/10.1080/19942060.2024.2396058>



© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



[View supplementary material](#)



Published online: 11 Sep 2024.



[Submit your article to this journal](#)



Article views: 1269



[View related articles](#)



[View Crossmark data](#)



Citing articles: 2 [View citing articles](#)

Computational analysis of turbulent flow characteristics in nanofluids containing 1-D and 2-D carbon nanomaterials: grid optimization and performance evaluation

Hai Tao^{a,b,c}, Mohammed Suleman Aldlemy^{d,e}, Raad Z. Homod^f, Mustafa K. A. Mohammed^g, Abdul Rahman Mallah^{h,i}, Omer A. Alawi^j, Shafik S. Shafik^k, Hussein Togun^l, Blanka Klimova^m, Hassan Alzahraniⁿ and Zaher Mundher Yaseen^o

^aSchool of Computer and Information, Qiannan Normal University for Nationalities, Duyun, Guizhou, People's Republic of China; ^bArtificial Intelligence Research Center (AIRC), Ajman University, Ajman, UAE; ^cSchool of Information and Artificial Intelligence, Nanchang Institute of science & Technology, Nanchang, People's Republic of China; ^dDepartment of Mechanical Engineering, Collage of Mechanical Engineering Technology, Benghazi, Libya; ^eLibyan Center for Solar Energy Research and Studies, Benghazi Branch, Libya; ^fDepartment of Oil and Gas Engineering, Basrah University for Oil and Gas, Basra, Iraq; ^gCollege of Remote Sensing and Geophysics, Al-Karkh University of Science, Baghdad, Iraq; ^hDepartment of Engineering, Reykjavik University, Menntavegur 1, Reykjavik, Iceland; ⁱCompuAI PTY LTD, Melbourne, VIC, Australia; ^jDepartment of Thermofluids, School of Mechanical Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia; ^kExperimental Nuclear Radiation Research Group, Scientific Research Center, Al-Ayen University, Thi-Qar, Iraq; ^lDepartment of Mechanical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq; ^mUniversity of Hradec Kralove, Hradec Kralove, Czech Republic; ⁿDepartment of Geology and Geophysics, College of Science, King Saud University, Riyadh, Saudi Arabia; ^oCivil and Environmental Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

ABSTRACT

1D and 2D carbon nanomaterials such as multi-walled carbon nanotubes (MWCNTs) and graphene nanoplatelets (GNPs) were investigated numerically. The thermophysical properties of water and nanofluids using MWCNTs in different outer diameters (ODs) and GNPs in different surface areas (SSA) were measured at an inlet temperature of 303.15 K and 0.1 wt.%. The 3D geometry was solved under a fully developed turbulent flow of $6000 \leq Re \leq 16,000$ using the model of $k-\omega$ SST via (ANSYS FLUENT 2022R2) software. Four numerical networks, Polyhedra, Polyhexacore, Hexacore, and Tetrahedral, were optimized. Moreover, seven parameters were discussed, namely wall surface temperature (T_w), heat transfer coefficient (h_{tc}), average Nusselt number (Nu_{avg}), friction factor (f), pressure drop (ΔP), and total thermal performance index (PI_{th}). Polyhexacore was the main grid over Polyhedra, Hexacore, and Tetrahedral with the average error (Dittus-Boelter: 2.754%, Gnielinski: 2.343%, Blasius: 1.441%, and Petukhov: 0.640%). Heat transfer increased by 18.38% with GNPs-300, 22.05% with GNPs-500, 23.25% with GNPs-750, 13.63% with CNT < 8 nm, and 11.42% with CNT 20–30 nm, relative to H₂O at $Re = 16,000$. Pressure drop increased by about 42.01% with GNPs-300, 45.16% with GNPs-500, 44.84% with GNPs-750, 36.72% with CNT < 8 nm, and 34.39% with CNT 20–30 nm.

ARTICLE HISTORY

Received 11 May 2024
Accepted 19 August 2024

KEYWORDS

Carbon-based nanomaterials; turbulent flow; shear stress transport; multi-walled carbon nanotubes; graphene nanoplatelets

Nomenclature

Abbreviations

Al ₂ O ₃	Aluminium oxide
ANFIS	Adaptive neuro-fuzzy inference system
CFD	Computational fluid dynamics
C-GNPs	Clove-Graphene Nanoplatelets
COOH	Carboxylic acid
DLS	Dynamic light scattering

DSC	Differential scanning calorimetry
DTHE	Double-tube-type heat exchanger
EG	Ethylene glycol
EO	Engine oil
EVs	Electric vehicles
FPG	Functionalized propylene glycol
FTIR	Fourier-transform infrared spectroscopy
FTM	Functionalized amine terminated
FVM	Finite volume method

CONTACT Zaher Mundher Yaseen  z.yaseen@kfupm.edu.sa  Civil and Environmental Engineering Department, King Fahd University of Petroleum and Minerals, 31261, Dhahran, Saudi Arabia

 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/19942060.2024.2396058>.

© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

GA	Gallic acid
GDWC	Gradually decreasing wall corrugation
GIT	Grid independence test
GIWC	Gradually increasing wall corrugation
GNPs	Graphene Nanoplatelets
H ₂ O	Distilled water
LPM	Litre per minute
MLPNN	Multi-layer perceptron neural network
MWCNTs	Multi-Walled Carbon Nanotubes
ODs	Outer diameters
PDEs	Partial differential equations
PEC	Performance evaluation criteria
PWC	Periodic wall corrugation
RBFNN	Radial basis function neural network
rGO	Reduced graphene oxide
RMSE	Root Mean Square Error
SDBS	Sodium dodecylbenzenesulfonate
SiO ₂	Silicon dioxide
SSAs	Specific surface areas
SST	Shear stress transport
TEM	Transmission Electron Microscopy
UWC	Uniform wall corrugation
XRD	X-Ray Diffraction

Parameters

$\dot{V}$	Volume flow rate (m ³ /s)
$\dot{W}$	Hydraulic pumping power (W)
CHF	Constant heat flux (W/m ²)
D_h	Hydraulic diameter (m)
f	friction factor
h_{tc}	Heat transfer coefficient
L	Total length (m)
Nu_{avg}	Average Nusselt number
PI_{th}	Thermal performance index
Re	Reynolds number
T_b	Bulk temperature (K)
T_{in}	Inlet fluid temperature (K)
T_{out}	Outlet fluid temperature (K)
T_w	wall surface temperature (K)
ΔP	Pressure drop (P)
C_p	Specific heat capacity (J/kg.K)
k	Thermal conductivity (W/m.K)
ν	Inlet velocity (m/s)
μ	Dynamic viscosity (mPa.s)
ρ	Density (kg/m ³)
ϵ	Energy dissipation rate (m ² /s ³)

Subscripts

<i>bf</i>	Base fluid
<i>nf</i>	Nanofluid

1. Introduction

1.1. Background and purpose of the study

Convective heat transfer is the primary method for heat dissipation applications such as heat exchangers, heat pipes, solar collectors, and electronic devices. Since, standard heat transfer liquids such as distilled water (H₂O), engine oil (EO), and ethylene glycol (EG) will show insufficient heat transport due to their low thermal conductivity, as outlined by numerous researchers (Mahian et al., 2021). In this regard, producing novel heat transfer liquids with higher thermal efficiency is crucial in various engineering and industrial applications (Ghorabae et al., 2021). In the past decade, nanofluids development has been a major trend in heat transport in academic and industry applications. Nanofluids can be produced by incorporating nanomaterials (organic, inorganic, or metallic) into base fluids such as water. Some nanomaterials have excellent thermal conductivity values of more than 3000 or 5000 W/m-K, than the poor thermal conductivity of standard base fluids will increase; accordingly, therefore, the heat transport rates will enhance (Abdelrazek et al., 2021; Bahiraei et al., 2021; Sadri, Hosseini, et al., 2018; Vallejo et al., 2021).

1.2. Literature review on nanofluids-based heated pipes

In recent years, academic literature has focused on carbon-based nanostructures such as multi-walled carbon nanotubes (MWCNTs) and graphene nanoplatelets (GNPs) due to their high thermal conductivity and low density (Balaji et al., 2021). MWCNTs in one-dimensional (1D) and GNPs in two-dimensional (2D) carbon-based nanomaterials have outstanding thermal, mechanical, and optical properties due to their unique dimensions and the ability of carbon atoms to produce different shapes (Joseph & Sajith, 2019). MWCNTs have two dimensions in the nanoscale, but one dimension is out of the range; adding them into base fluids significantly enhances heat transport relative to other nanomaterials, for example, metal or metal oxide nanofluids (Sardarabadi et al., 2019). MWCNT nanofluids have been utilized in various experiments or simulations for cooling electronic devices (Li et al., 2020; Singh & Sarkar, 2021) or for more applications like energy storage systems. Furthermore, MWCNTs have shown thermoelectric properties that convert heat into electricity. Additionally, graphene nanoplatelets (GNPs) are 2D nanomaterials because one dimension in the nanoscale and two dimensions are out of the range; therefore, they are produced in flat, layer or sheet shapes. In comparison to metallic nanomaterials such as copper and aluminium,

GNPs have a higher thermal conductivity in the range of 3000 to 5000 W/m-K, thus it is preferable in thermal management applications. Furthermore, GNP nanofluids are advantageous in more applications such as polymer composites, energy storage systems, thermoelectric devices, heat transport, and electronics devices. Additionally, GNPs can be used in advanced applications related to thermal management for electric vehicles (EVs) and aerospace applications (Bai et al., 2020; Fares et al., 2020; Kılınç et al., 2020).

In the past, nanofluids were created by adding materials in the nanoscale into classic base fluids in long-term suspension. In this context, MWCNT and GNP nanofluids are advantageous for thermal management applications due to their promising properties. To avoid using hazardous materials or chemicals in production nanofluids, certain research has focused on using green and eco-friendly synthesis methods such as plant extracts rather than acid treatments (Akram et al., 2022; Hosseini et al., 2018; Sadri et al., 2017; Sadri, Mallah, et al., 2018). One study discussed the GNP/H₂O nanofluids in different wt.% concentrations, which was made by using Gallic acid (GA) and employed inside a heat pipe subjected to a constant heat flux (CHF) of 12,752 W/m² as a heating source (Sadri et al., 2017). They concluded that the convective heat transport coefficient (h_{tc}) and average Nusselt number (Nu_{avg}) increased to 38.58% and 18.75%, respectively, under the turbulent condition of $Re = 15,927$. On the other hand, the friction factor (f) values increased by about 1.46% for 0.025wt.%, 3.35% for 0.075wt.%, and 3.9% for 0.1wt.%, respectively, relative to H₂O. Moreover, GNP nanomaterials were treated by clove buds (aromatic herbs). The new developed nanofluids C-GNPs at 0.1wt.% enhanced the heat transport parameters such as 37.54% (for h_{tc}) and 18.69% (for Nu_{avg}), under the turbulent condition of $Re = 15,927$ (Sadri, Hosseini, et al., 2018). Meanwhile, they reported a 3.79% increase in the friction factor (f), under the same turbulent and wt.% conditions. Similarly, the surface of MWCNT nanomaterials was modified by clove extracts to produce nanofluids, which can be tested numerically in a concentric pipe (Hosseini et al., 2018). The heat transport enhanced by about 9% for 0.075wt.%, 8% for 0.125wt.%, and 10% for 0.175 wt.%, respectively, relative to H₂O. On the other hand, the (f) increased by 1.96% for 0.075wt.%, 3.64% for 0.125 wt.%, and 4.06% for 0.175 wt.%, respectively, relative to H₂O. A facile, green fabrication using gallic acids was employed to prepare GA-MWCNT nanofluids and tested in a closed horizontal flow passage (Akram et al., 2022). In their conduct experiment, the heat transport and friction factor (f) were increased by the percentages of 33.049% and 3.62% using 0.1wt.% nanofluid under the turbulent condition

of $Re = 15,927$ and $CHF = 12,752$ W/m². Researchers in 2021 discussed the heat transfer characteristics of Functionalized GNP/MWCNT-H₂O hybrid nanofluids (Balaji et al., 2021). They confirmed that, the thermal conductivity and the heat transport enhanced by $\sim 25\%$ and $\sim 85\%$ for thermal conductivity and heat transport properties, respectively @ 0.2 vol.%. However, the pressure drop (ΔP) decreased by the percentage of 32%. In another experimental work, GNPs with $SSA = 120\text{--}150$ m²/g and MWCNTs with $OD = 20\text{--}30$ nm were utilized in the nanofluids production as heat transfer liquids in a concentric pipe (Dayou et al., 2022). The authors confirmed that, the heat transport of GNP nanofluids enhanced by 16.8% for 1.5 LPM, 24.2% for 2 LPM, and 26.1% for 2.5 LPM, respectively. Furthermore, the heat transport of MWCNT nanofluids was enhanced by 8.8% for 1.5 LPM, 13.8% for 2 LPM, and 14.4% for 2.5 LPM, respectively.

Recent research has focused on the thermal properties of carbon-based nanostructures like Multi-walled Carbon Nanotubes (MWCNTs) and Graphene Nanoplatelets (GNPs), emphasizing their high conductivity and potential for thermal management applications. However, significant research gaps remain, including the need for direct comparisons between MWCNT and GNP nanofluids under standardized conditions, exploration of the long-term stability of eco-friendly synthesis methods, and assessments of scalability and cost-effectiveness for industrial applications. Standardized testing protocols are also lacking, which impacts the reproducibility of findings across studies and limits broader adoption in practical settings.

1.3. Research objectives and novelty

This study delves into the intricate thermal characteristics of carbon-based nanomaterials, focusing on both one-dimensional (1D) and two-dimensional (2D) structures such as Multi-Walled Carbon Nanotubes (MWCNTs) and Graphene Nanoplatelets (GNPs). Through extensive simulation encompassing varying specific surface areas (SSAs) of GNPs (300, 500, and 750 m²/g) and outer diameters (ODs) of MWCNTs (< 8 nm and 20–30 nm), the research investigates how the dimensions and shapes of these nanostructures influence heat transport mechanisms. A rigorous grid independence test (GIT) optimized the computational grid across four distinct networks—Polyhedra, Polyhexacore, Hexacore, and Tetrahedral—balancing accuracy and computational efficiency. Employing ANSYS software with the Shear Stress Transport (k-SST) model in a three-dimensional (3D) physical model, simulations explored the thermal behaviours of water (H₂O) as a base fluid and various

GNP/H₂O and MWCNT/H₂O nanofluids. Key parameters examined included wall surface temperature, convective heat transfer coefficient (h_{tc}), average Nusselt number (Nu_{avg}), friction factor (f), pressure drop (ΔP), and overall thermal performance index (PI_{th}). This research adds significantly to the field of thermal engineering and nanotechnology by clarifying the benefits and constraints of using nanomaterials of various dimensions and shapes to enhance heat transport applications through environmentally friendly synthesis methods for nanofluids.

2. Simulation methodologies

2.1. Physical model and solution methods

In the simulation cases, the 3-D geometry solved in this study was a circular heated pipe with a hydraulic diameter (D_h) of 20 mm and a total length (L) of 900 mm, as shown in Figure 1. In this context, the combination of a 20 mm hydraulic diameter and a 900 mm total length is selected to balance practical constraints with the need for accurate simulation of fully developed flow, ensuring that entrance effects are adequately accounted for in the study. The thermophysical properties of base fluid (H₂O), three GNPs/H₂O nanofluids and two MWCNTs/H₂O nanofluids were measured through various tools at a temperature of 303.15 K. The turbulent convective heat transfer mechanisms were solved via ANSYS FLUENT version 2022R2 software under the flow condition of $6000 \leq Re \leq 16,000$. Meanwhile, the heating source was characterized by constant heat flux (CHF) applied at the external walls of the circular pipe and having a constant value of 58,866 W/m². The computational grids were optimized through the approach of grid independence test (GIT) by testing four different networks Polyhedra, Polyhexacore, Hexacore, and Tetrahedral. The criteria for grid selections were based on two main factors: accuracy with empirical correlations and computational time. In this study, no complex boundary conditions were applied since the velocity equation was solved at the pipe entrance and the pressure equation was used at the pipe exit, with a No-slip condition (a viscous liquid attains zero velocity at the solid boundary). The ANSYS software successfully solved the partial differential equations (PDEs) that describe the motion of fluids, such as Navier-Stokes equations. Furthermore, the finite volume method (FVM) was employed to convert the PDEs into algebraic equations through a numerical space discretized to many grid cells (computational grids). In this study, the algorithm of 2nd-order Upwind SIMPLE was employed to solve the pressure-velocity coupling schemes. Additionally, the under-relaxation (implicit relaxation) of equations was utilized, and the default convergence criterion of 10^{-3} for

all equations except the energy, for which the criterion is 10^{-6} .

2.2. Mathematical expressions

The problem was addressed using ANSYS software for the following reasons: making experimental work unnecessary. (i) Cost-effectiveness: Heat transport simulations can be conducted on a computational machine, reducing the need for costly equipment, tools, chemicals, or materials. (ii) Safety: Heat transport simulations can solve unsafe or harmful situations without causing harm to researchers or the environment. (iii) Self-control: The simulation software has complete control over the flow conditions and variables, allowing more accurate results. (iv) Repeatability: Heat transport simulations can be conducted multiple times under the same turbulent conditions, which allows for more reliable and accurate results. (v) Speed: Heat transport simulations can be conducted significantly faster than lab work, allowing more data to be collected in a shorter period.

Nanofluids are nanoscale materials suspended in a classic base fluid to produce innovative working fluids with higher thermal transport properties. The nanomaterials are well-dispersed in the hosting fluids and demonstrate long-term stability, they can be treated as a single-phase flow in the simulation software. The assumption of a single-phase approach has been investigated for various nanofluid applications, including thermal and electronic devices (Bahiraei et al., 2019; Onyiriuka et al., 2018).

The complete assumptions taken in the current study can be found here: (i) 1D (MWCNTs) and 2D (GNPs) nanomaterials are uniformly dispersed in H₂O and did not reveal settlement or aggregation formation. (ii) MWCNTs and GNPs nanofluids are Newtonian fluids. (iii) MWCNTs and GNPs nanofluids flow under conditions of turbulence, which is steady-state and incompressible. In this regard, the governing equations for mass, momentum, and energy conservation, which are solved in ANSYS software, can be written as per Equations (1-3) (Sadri, Mallah, et al., 2018):

Conservation of Mass

$$\nabla \cdot (\rho \vec{V}) = 0 \quad (1)$$

Conservation of Momentum

$$\nabla \cdot (\rho \vec{V} \vec{V}) = -\nabla P + \nabla \cdot ((u + u_t)(\nabla \vec{V} + \nabla \vec{V}^T)) + \rho \vec{g} \quad (2)$$

Conservation of Energy

$$\nabla \cdot (\rho C_p \vec{V}) = \nabla \cdot (k_{eff} \nabla T) + \rho \epsilon \quad (3)$$

where, $\vec{V}$ is the vector of the mean velocity, K_{eff} is the effective thermal conductivity for MWCNTs/H₂O and

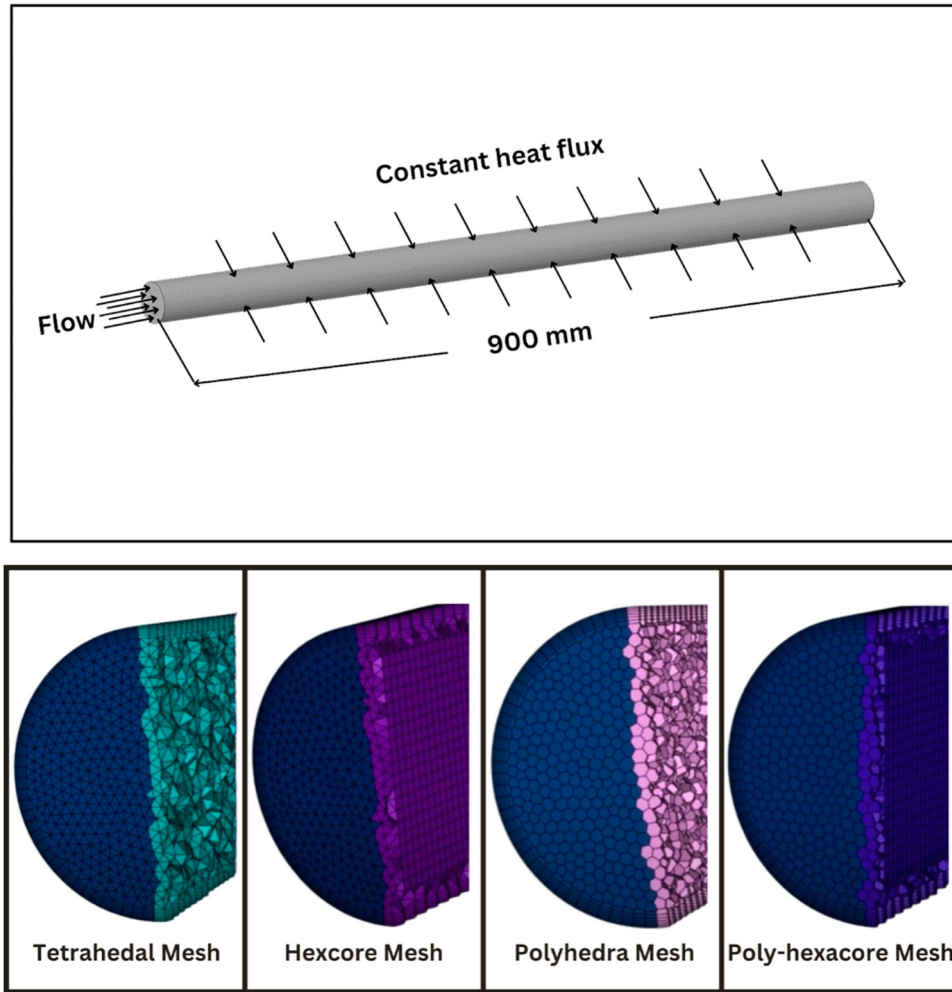


Figure 1. Schematic diagram of the circular pipe and four computational grids.

GNPs/H₂O nanofluids, and ϵ represents the energy dissipation rate (m^2/s^3). Moreover, (ρ) , (C_p) , (k) , and (μ) are the density (kg/m^3), specific heat capacity ($\text{J}/\text{kg}\cdot\text{K}$), thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$), and dynamic viscosity ($\text{mPa}\cdot\text{s}$) of MWCNTs/H₂O and GNPs/H₂O nanofluids. The thermophysical properties were measured at the same constant inlet fluid temperature, $T_{\text{in}} = 303.15 \text{ K}$. The thermophysical properties used in the current simulations were obtained from previous experimental work to ensure accuracy and reliability (Sarsam et al., 2016; Sarsam et al., 2017; Sarsam et al., 2020; Sarsam et al., 2022). Properties like thermal conductivity, specific heat, viscosity, and density were carefully selected and documented, ensuring the simulations closely replicate real-world conditions.

In this study, the shear stress transport (k - ω SST) model was utilized to solve the turbulent kinetic energy (k) and the specific dissipation rate (ω). The (k - ω SST) model is highly effective as it combines the strengths of the (k - ω) model for managing the inner regions of the boundary layer (viscous sub-layer) with the (k - ϵ) model,

which reduces sensitivity to inlet free-stream turbulence properties. Introduced in 1994, this model is renowned for its strong efficiency in addressing common issues such as adverse pressure gradients and separating flows (Bashtani et al., 2021; Menter, 1994). Additionally, this model was calibrated based on experiments to verify its technical closure coefficients and auxiliary relations. The following governing equations (4-12) can describe the (k - ω SST) model in detail:

Kinematic Eddy Viscosity

$$\nu_T = \frac{a_1 k}{\max(a_1 \omega, SF_2)} \quad (4)$$

Turbulence Kinetic Energy

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left((\nu + \sigma_k \nu_T) \frac{\partial k}{\partial x_j} \right) \quad (5)$$

Specific Dissipation Rate

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j} \left((v + \sigma_{\omega} v_T) \frac{\partial \omega}{\partial x_j} \right) + 2(1 - F_1) \sigma_{\omega}^2 \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (6)$$

Closure Coefficients and Auxiliary Relations

$$F_2 = \tanh \left(\max \left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right)^2 \right) \quad (7)$$

$$P_k = \min \left(\tau_{ij} \frac{\partial U_i}{\partial x_j}, 10\beta^* k \omega \right) \quad (8)$$

$$F_1 = \tanh \left(\left(\min \left(\max \left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right), \frac{4\sigma_{\omega}^2 k}{CD_{k\omega} y^2} \right) \right)^4 \right) \quad (9)$$

$$CD_{k\omega} = \max \left(2\rho \sigma_{\omega}^2 \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}, 10^{-10} \right) \quad (10)$$

$$\phi = \phi_1 F_1 + \phi_2 (1 - F_1) \quad (11)$$

$$\alpha_1 = \frac{5}{9}, \alpha_2 = 0.44$$

$$\beta_1 = \frac{3}{40}, \beta_2 = 0.0828 \quad (12)$$

$$\beta^* = \frac{9}{100}$$

$$\sigma_{k_1} = 0.85, \sigma_{k_2} = 1$$

$$\sigma_{\omega_1} = 0.5, \sigma_{\omega_2} = 0.856$$

where, S represents the strain rate magnitude, and y refers to the distance to the next surface. Meanwhile, there is a set of constants, such as $\alpha_1, \alpha_2, \beta_1, \beta_2,$

$\beta^*, \sigma_{k_1}, \sigma_{k_2}, \sigma_{\omega_1}$ and σ_{ω_2} . Meanwhile, F_1 and F_2 are the blending functions of the (k- ω SST) model.

In this study, various parameters or calculations related to heat transport utilizing nanofluids were considered. The following equations describe the turbulent flow of 1D (MWCNTs) and 2D (GNPs) nanofluids within the 3D geometry of a circular pipe, as solved using ANSYS software (Abdelrazek et al., 2020; Tao et al., 2022a):

Reynolds number

$$Re = \frac{\rho v D_h}{\mu} \quad (13)$$

Prandtl number

$$Pr = \frac{\mu C_p}{k} \quad (14)$$

Heat transfer coefficient (W/m².K)

$$h_{tc} = \frac{q''}{A_s \times (T_w - T_b)} \quad (15)$$

Average Nusselt number

$$Nu_{avg} = \frac{h_{tc} D_h}{k} \quad (16)$$

Friction factor

$$f = \frac{2 \times \Delta P \times D_h}{\rho \times v^2 \times L} \quad (17)$$

Pressure drop (Pa)

$$\Delta P = P_{in} - P_{out} \quad (18)$$

Dittus - Boelter Equation

$$Nu_{avg} = 0.023 \times Re^{0.8} \times Pr^{0.4} \quad (19)$$

Petukhov Equations

$$Nu_{avg} = \frac{\left(\frac{f}{8}\right) Re Pr}{1.07 + 12.7 \left(\frac{f}{8}\right)^{1/2} (Pr^{2/3} - 1)} \quad (20)$$

$$f = (0.78 \ln Re - 1.64)^{-2}$$

Gnielinski Equation

$$Nu_{avg} = \frac{\left(\frac{f}{8}\right) (Re - 1000) Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{1/2} (Pr^{2/3} - 1)} \quad (21)$$

Blasius Equation

$$f = \frac{0.3164}{Re^{0.25}} \quad (22)$$

Thermal performance index

$$PI_{th} = \frac{h_{tcnf}}{h_{tcbf}} \bigg/ \frac{\dot{W}_{nf}}{\dot{W}_{bf}} \text{ where;}$$

$$\frac{\dot{W}_{nf}}{\dot{W}_{bf}} = \left(\frac{\mu_{nf}}{\mu_{bf}} \right)^{0.25} \times \left(\frac{\rho_{nf}}{\rho_{bf}} \right)^2 \quad (23)$$

$$\dot{W} = \dot{V} \Delta P$$

The main parameters mentioned in the above equations can be interpreted as, (ρ) is the density of the base fluid and nanofluids (kg/m³), (v) is the inlet velocity of the base fluid and nanofluids (m/s), (D_h) is the hydraulic diameter of the 3D circular pipe (m), and (μ) is the dynamic viscosity of the base fluid and nanofluids (mPa.s). Also, (C_p) is the specific heat capacity of the base fluid and nanofluids (J/kg.K), and (k) is the thermal conductivity of H₂O and nanofluids (W/m.K). (q'') is the constant heat flux applied at the surface wall as a heating source (W/m²). Besides, (T_w) is the surface wall temperature (K), and (T_b) is the average bulk temperature (K),

Table 1. Thermophysical properties of 2D GNPs nanofluids (different SSAs) and 1D MWCNTs nanofluids (different ODs) (Sarsam et al., 2016, 2017, 2020, 2022).

	Thermo-physical properties	DW	0.025%	0.05%	0.075%	0.1%
GNP-300	Density (kg/m ³)	995.180	1010.32	1025.058	1040.232	1055.863
	Specific heat capacity (J/kg.K)	4070.2	4067.02	4064.52	4062.68	4061.76
	Thermal conductivity (W/m.K)	0.619	0.634995	0.646809	0.671154	0.693902
	Viscosity (mPa.s)	0.777330	0.874286	0.908571	0.96	1.05143
	Pr	5.11	5.60	5.71	5.81	6.15
GNP-500	Thermo-physical properties	DW	0.025%	0.05%	0.075%	0.1%
	Density (kg/m ³)	995.180	1010.783	1026.011	1041.705	1057.886
	Specific heat capacity (J/kg.K)	4070.2	4068.72	4066.33	4064.34	4063.14
	Thermal conductivity (W/m.K)	0.619	0.671077	0.695213	0.710315	0.737805
	Viscosity (mPa.s)	0.777330	0.898547	0.95022	0.990392	1.08226
GNP-750	Thermo-physical properties	DW	0.025%	0.05%	0.075%	0.1%
	Density (kg/m ³)	995.180	1014.139	1032.95	1052.473	1072.747
	Specific heat capacity (J/kg.K)	4070.2	4068.9	4067.18	4064.8	4062.56
	Thermal conductivity (W/m.K)	0.619	0.689118	0.717553	0.733566	0.757317
	Viscosity (mPa.s)	0.777330	0.927094	0.980296	1.03941	1.0867
CNT < 8 nm	Thermo-physical properties	DW	0.025%	0.05%	0.075%	0.1%
	Density (kg/m ³)	995.180	995.411	995.551	995.812	995.972
	Specific heat capacity (J/kg.K)	4070.2	4064.66	4061.87	4060.47	4056.11
	Thermal conductivity (W/m.K)	0.619	0.627246	0.639565	0.658406	0.666377
	Viscosity (mPa.s)	0.777330	0.875122	0.90439	0.954146	0.977561
CNT 20-30 nm	Thermo-physical properties	DW	0.025%	0.05%	0.075%	0.1%
	Density (kg/m ³)	995.180	995.552	995.67	995.768	995.867
	Specific heat capacity (J/kg.K)	4070.2	4058.14	4051.63	4041.16	4033.72
	Thermal conductivity (W/m.K)	0.619	0.612319	0.626812	0.638986	0.648841
	Viscosity (mPa.s)	0.777330	0.880976	0.907317	0.933659	0.96
	Pr	5.11	5.84	5.86	5.90	5.97

which can be calculated as ($T_b = T_{out} - T_{in}/2$). In addition, ($\dot{W}$) is the hydraulic pumping power (W), ($\dot{V}$) is the volume flow rate (m³/s), and (ΔP) is the pressure drop (Pa). Finally, the two subscripts *bf* and *nf* refer to H₂O and nanofluids, respectively.

2.3. Thermophysical properties

At the beginning of the process, the thermophysical properties of 1D and 2D nanofluids should be evaluated relative to H₂O to determine its advancements in heat transport. As mentioned in the previous section, the thermophysical property values of 2D GNP-based nanofluids with three different SSAs and 1D MWCNT-based nanofluids with two different ODs were gathered from various previous experiments (Sarsam et al., 2016, 2017, 2020, 2022). Their results measured the thermophysical properties at various temperatures, whereas the current study considered a temperature of $T_{in} = 303.15$ K. The thermophysical properties were collected using well-known testing tools: the Mettler Toledo density meter (DM40) for density, the TA Instruments (DSC-Q2000) for specific heat capacity, the KD2 Pro analyzer (Decagon Devices, Inc., USA) for thermal conductivity, and the Anton Paar rotational rheometer (model Physica MCR 301, Anton Paar GmbH) for dynamic viscosity.

According to Table 1, the general trend of thermal conductivity and dynamic viscosity increased by adding more GNPs and CNT mass fractions into the base fluid. Moreover, adding more GNPs and CNT mass fractions into the base fluid was a minor issue for the density of the GNP and MWCNT nanofluids. Additionally, the specific heat capacity values decreased by adding more GNPs and CNT mass fractions into H₂O. In detail, the GNP-300 nanofluid at 0.1 wt.% showed the following percentages: 6.1% (for density (ρ)), -0.21% (for specific heat (C_p)), 12% (for thermal conductivity (k)), and 35.3% (for viscosity (μ)), respectively. In addition, the GNP-500 nanofluid at the same 0.1 wt.% showed the following percentages: 6.3% (for density (ρ)), -0.17% (for specific heat (C_p)), 19.1% (for thermal conductivity (k)), and 39.2% (for viscosity (μ)), respectively. Besides, the GNP-750 nanofluid at 0.1 wt.% showed the following percentages: 7.8% (for density (ρ)), -0.19% (for specific heat (C_p)), 22.3% (for thermal conductivity (k)), and 39.8% (for viscosity (μ)), respectively. On the other hand, the CNT < 8 nm nanofluid at 0.1 wt.% showed the following percentages: 0.1% (for density (ρ)), -0.35% (for specific heat (C_p)), 7.6% (for thermal conductivity (k)), and 25.8% (for viscosity (μ)), respectively. Also, the CNT 20–30 nm nanofluid at the same wt.% showed the following increments: 0.1% (for density (ρ)), -0.9% (for

Table 2. Summary of qualitative results for different networks.

Mesh types	Surface Diagnostics			Volume Diagnostics			Time
	Total Number of Faces	Maximum Skewness	Maximum Ratio	Total Number of Cells	Minimum Orthogonal Quality	Maximum Aspect Ratio	
Polyhedra	66,333	0.1086	12.31	607,981	0.4821	16.29	0.55 mins
Polyhexacore	66,333	0.1086	12.31	662,810	0.3372	16.29	0.62 mins
Hexacore	131,654	0.4008	12.51	1,544,734	0.2001	17.1	0.52 mins
Tetrahedral	131,654	0.4008	12.51	1,882,736	0.1595	17.1	0.65 mins

specific heat (C_p)), 4.8% (for thermal conductivity (k)), and 23.5% (for viscosity (μ)), respectively.

3. Validation/mesh dependence approaches

According to the computational fluid dynamics (CFD) definitions, a polyhedron network is a 3D geometric shape with flat faces and straight edges. A Polyhexacore is a unique type of polyhedron characterized by its six complex faces. A hexacore is another 3D network that has a six-faced shape, which divides a larger geometry into more minor elements. Meanwhile, the tetrahedral network comprises small shapes in 3D and four-faced tetrahedrons. These four networks were tested and validated with previous experimental work to obtain the most accurate and less computational time for the subsequent simulation cases. Table 2 shows the performance of these networks was evaluated using three essential criteria such as surface and volume diagnostics and the required time. For surface and volume diagnostics, there are another three sub-criteria such as (total number of faces, maximum skewness, and maximum aspect ratio) and (total number of cells, minimum orthogonal quality, and maximum aspect ratio).

To evaluate the performance of the four selected networks using H_2O , the results of these computational grids were validated against well-known empirical correlations. The Dittus-Boelter and Gnielinski correlations were used to examine heat transport properties, while the Blasius and Petukhov correlations were utilized to assess both heat transport and pressure drop properties, as illustrated in Figure 2. Moreover, Figure 3 presents the statistical analysis, including the maximum error, the average error, and the standard deviation of using four networks, compared to the empirical correlations, such as heat transport and pressure drop properties. Furthermore, a grid independence test (GIT) was conducted to ensure that the ANSYS results were not affected by the size of the networks utilized in the modelling. According to Figure 3, the maximum error values when using the Polyhedra and Polyhexacore networks were consistently lower than the maximum error values obtained when using the Hexacore and Tetrahedral networks. In specific, the average error between Polyhedra and

Polyhexacore was as follows; (2.903% and 2.754% for the Dittus-Boelter equation), (1.517% and 2.343% for the Gnielinski equation), (1.816% and 1.441% for the Blasius equation) and (0.866% and 0.640% for the Petukhov equation). Since the Polyhexacore network significantly outperformed Polyhedra, Polyhexacore is chosen for the following simulation scenarios. The selection of network type and size generally depends on the physical geometry, the numerical methods used to solve it, and the available computational resources, including the specifications of the computational machine.

In conclusion, the Polyhexacore network outperformed the Polyhedra, Hexacore, and Tetrahedral networks in simulations. As per Figure 4, it demonstrated high accuracy in predicting heat transfer and pressure drop of functionalized graphene nanoplatelet-based water nanofluids compared to prior studies (Abdelrazek et al., 2020; Arzani et al., 2015). Heat transfer errors were 8.65% for DW, 5.75% for GNP-COOH, and 3.33% for GNP-SDBS, while pressure drop errors were 5.86% for DW and 5.54% for both GNP-COOH and GNP-SDBS. These findings highlight the Polyhexacore network's superior predictive capabilities for nanofluid behaviour.

4. Results and discussion

4.1. Fully developed flow

The enhancement of heat transport properties through the addition of carbon-based nanomaterials to base fluids can be attributed to several key mechanisms. Firstly, the mixture of nanomaterials and H_2O increases the effective surface area available for heat transfer, with the nanomaterials acting as localized hot spots along the pipe wall. Secondly, the dimensions (1D and 2D), size (nanoscale or microscale), and shape (tubes or sheets) of the carbon-based nanomaterials significantly influence the enhancement of heat transport. Thirdly, the superior thermal conductivity of carbon-based nanomaterials, augmented by their random Brownian motion, is a crucial factor in the heat transport mechanism. Lastly, the reduction in boundary layer thickness decreases thermal resistance, thereby facilitating an improved rate of heat transfer (Demirkır & Ertürk, 2021; Vallejo et al., 2022). In addition, the thermal entry length for a fully developed

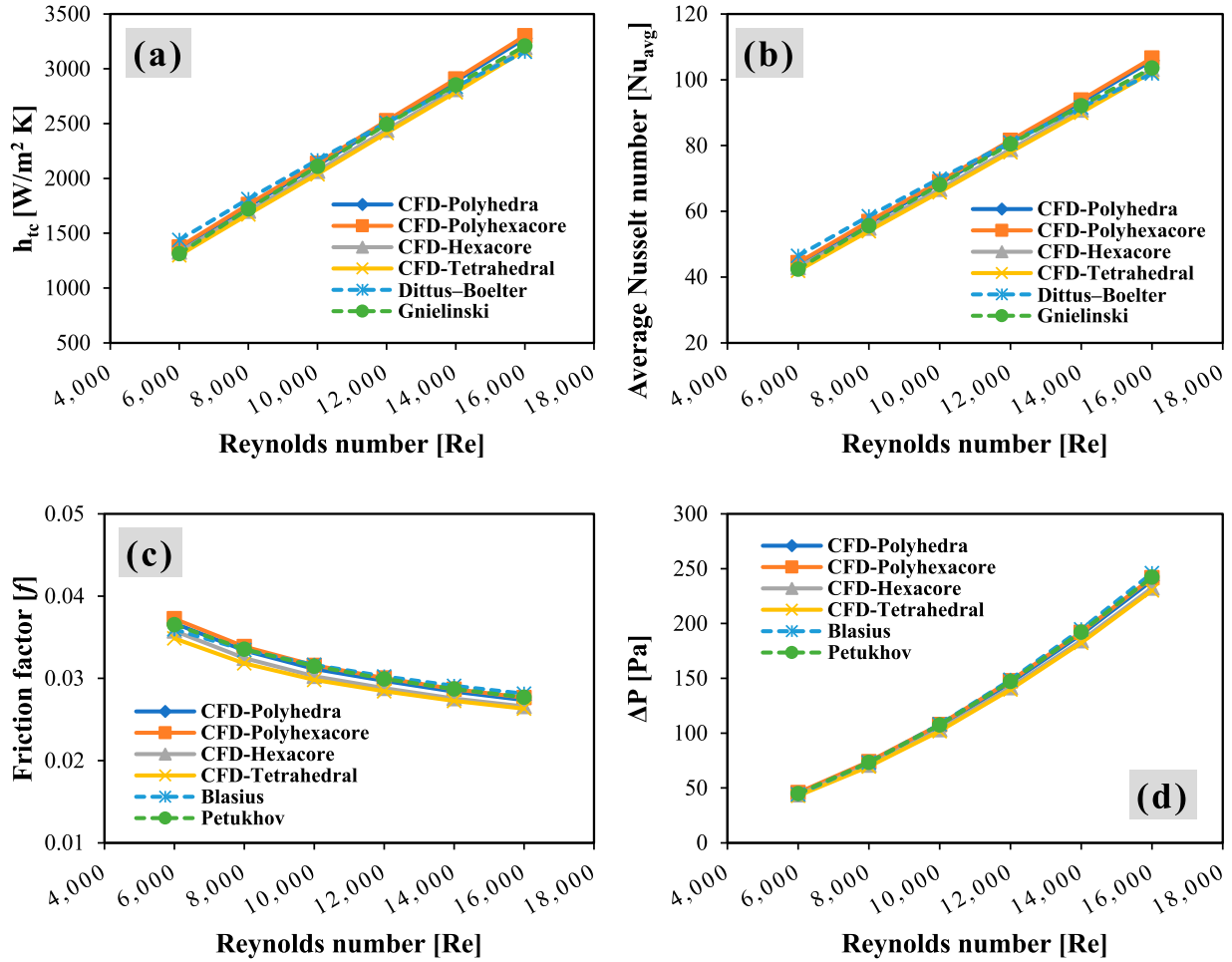


Figure 2. Heat transport and hydrodynamic properties of H₂O vs. Reynolds numbers using four networks and empirical correlations: (a) Heat transport coefficient (h_{tc}), (b) Average Nusselt number (Nu_{avg}), (c) Friction factor (f), (d) Pressure drop (ΔP).

turbulent nanofluids flow is in the following condition of $x/D_h > 10$ (Balaji et al., 2021).

Figure 5(a-f) demonstrates the velocity profiles at different cross-sectional locations such as inlet, $x/D = 9$, $x/D = 18$, $x/D = 27$, $x/D = 36$, and outlet of (H₂O and 1D-2D carbon-based nanofluids @ 0.1wt.%) under the turbulent flow of $Re = 16,000$. The Fully developed turbulent flow occurs when the velocity and pressure in the circular pipes are constant in time (steady state) under high Reynolds numbers and large pipes. As a result, the velocity profile is parabolic, with the highest values of fluid velocity near the centre of the circular pipe and the lowest velocities near the pipe walls (Ahmed et al., 2022).

4.2. Heat transfer enhancement

Figure 6 shows the variations in wall surface temperatures (T_w) using H₂O, 2D-GNPs with three different SSAs, and 1D-MWCNTs with two different ODs versus the Reynolds numbers. As the H₂O and 1D-2D carbon-based nanofluids flow at higher Re, the T_w

value decreases, which is a common factor in convective turbulent heat transport under CHF conditions. In this regard, the maximum T_w of H₂O and nanofluids at $Re = 6000$ were as follows: 347.85 K for H₂O, 339.86 K for GNPs-300, 338.16 K for GNPs-500, 337.59 K for GNPs-750, 341.94 K for CNT < 8 nm, and 342.94 K for CNT 20–30 nm, respectively. The meaning of that, the T_w decreased by a percentage of 2.35% for GNPs-300, 2.86% for GNPs-500, 3.04% for GNPs-750, 1.73% CNT < 8 nm, and 1.43% for CNT 20–30 nm, respectively, relative to H₂O. These percentages decrement in T_w can be attributed to the increased thermal conductivity of 1D and 2D carbon-based nanomaterials; liquids with higher thermal conductivity will be able to enhance heat transport (Balaga et al., 2023; Narankhishig et al., 2021).

In Figure 7, the heat transport properties (h_{tc} and Nu_{avg}) using 1D-MWCNT/H₂O nanofluids with two different ODs and 2D-GNPs/H₂O nanofluids with three different SSAs are discussed versus Reynolds numbers. The h_{tc} increases as the turbulent flow increases

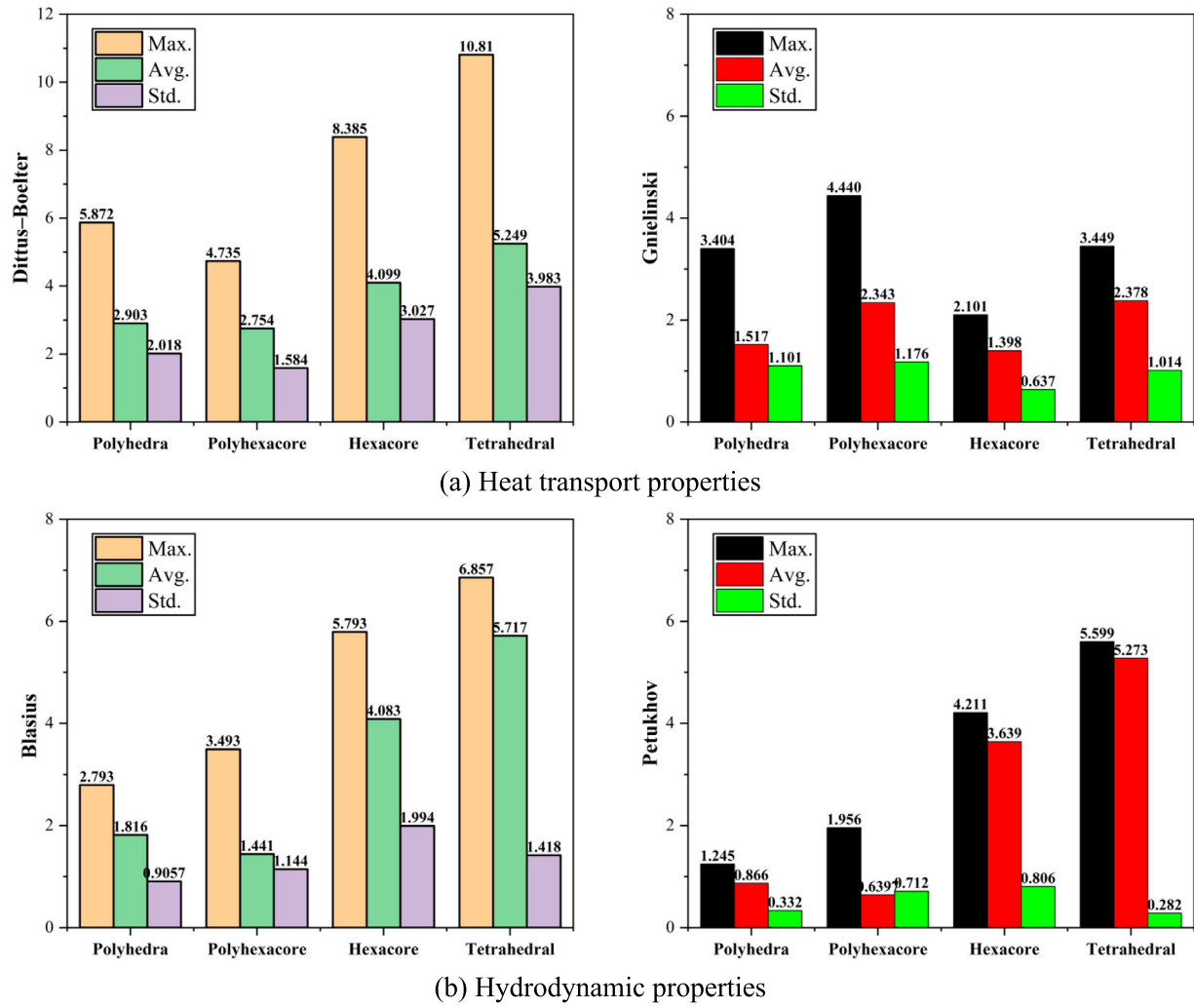


Figure 3. Maximum, average, and standard errors using different networks. (a) Heat transport properties; (b) Hydrodynamic properties

for H₂O and nanofluids. In specific, the h_{tc} increased by 18.38% using GNPs-300 nanofluid, 22.05% using GNPs-500 nanofluid, 23.25% using GNPs-750 nanofluid, 13.63% using CNT < 8 nm nanofluid, and 11.42% using CNT 20–30 nm nanofluid, respectively, relative to H₂O at $Re = 16,000$. Enhancing convective heat transport using 1D-MWCNTs and 2D-GNPs nanofluids can be attributed to several key factors: (i) Exceptional thermal conductivity of 1D-MWCNTs and 2D-GNPs enables efficient dissipation of heat from thermal and electronic devices. (ii) High surface area-to-volume ratio of 1D-MWCNTs and 2D-GNPs enhances their ability to transfer heat effectively. (iii) Nanoscale and microscale dimensions of 1D-MWCNTs and 2D-GNPs facilitate good dispersion and long-term stability in the nanofluid. (iv) Low density of 1D-MWCNTs and 2D-GNPs minimizes settling and aggregation issues, particularly against gravitational forces.

In addition, advection and diffusion are the two main mechanisms in the heat transport concept from one place to another by moving a working fluid. Advection is the heat transfer through the direction of the working fluid, while diffusion is the heat transfer through the movement of the nanoscale and microscale particles in the base fluid. In addition, factors such as kinematic viscosity (ν), thermal diffusion (α), and Prandtl number (Pr) are the critical points in regulating heat transport efficiency in nanofluids. As shown in Figure 7(b), the nanofluids with higher Pr values show the highest value of Nu_{avg} and vice versa. The previous reasons explain why the average Nusselt number (Nu_{avg}) of 2D-GNP-300 nanofluid is higher than that of the other nanofluids. In detail, the Pr shows the following values such as 5.11 for H₂O, 6.15 for GNPs-300 nanofluid, 5.96 for GNPs-500 nanofluid, 5.83 for GNPs-750 nanofluid, 5.95 for CNT < 8 nm nanofluid, and 5.97

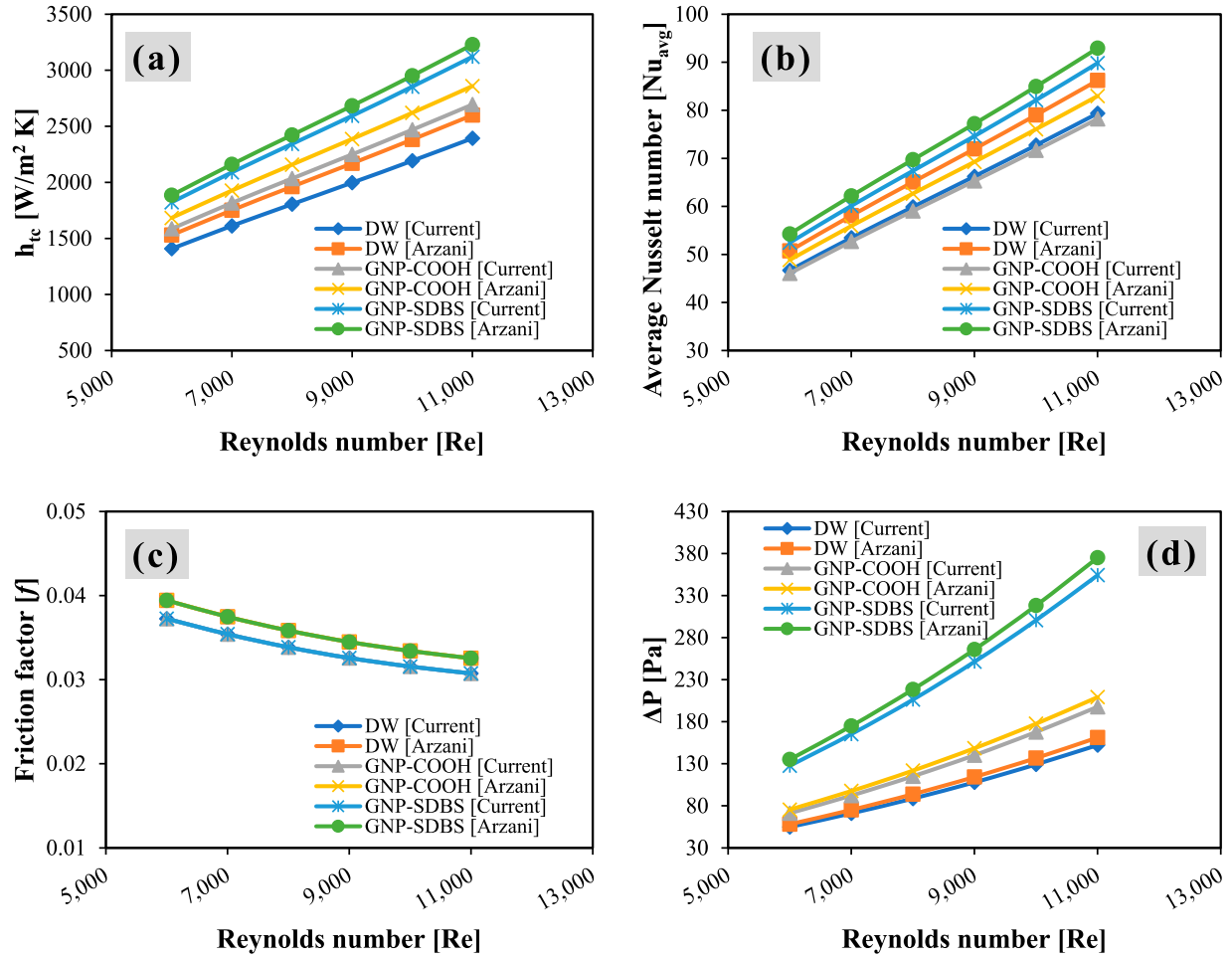


Figure 4. Comparison between the current Polyhexacore network and previous work (Arzani et al., 2015).

for CNT 20–30 nm nanofluid, respectively @ 0.1wt.%. The results of Nu_{avg} are significantly related to Pr value (Eqs. (19–21)). Moreover, the Nu_{avg} shows the following percentages of enhancement such as 8.56% using GNPs-300 nanofluid, 7.15% using GNPs-500 nanofluid, 6.16% using GNPs-750 nanofluid, 7.08% for MWCNT < 8 nm nanofluid, and 7.21% for MWCNT 20–30 nm nanofluid, respectively, compared to H_2O @ $Re = 16,000$.

4.3. Friction factor and pressure drop

The friction factor (f) and pressure drop (ΔP) of 1D-MWCNT/ H_2O nanofluids with two different ODs and 2D-GNPs/ H_2O nanofluids with three different SSAs are shown in Figure 8. Figure 8(a) shows the variation of (f) vs. Reynolds numbers using H_2O , GNPs and MWCNTs nanofluids. The CFD results confirmed that, the friction factor (f) using nanofluids is highly related to the Reynolds number, as detailed in Eq. (22), indicating that nanofluids flow can be considered as a homogeneous mixture in a single-phase model

with steady thermophysical properties (Alawi et al., 2021). Furthermore, as shown in Figure 8(b), the pressure drop (ΔP) shows the following decrement percentages at $Re = 16,000$ as 42.01% using GNPs-300 nanofluid, 45.16% using GNPs-500 nanofluid, 44.84% using GNPs-750 nanofluid, 36.72% using CNT < 8 nm nanofluid, and 34.39% using CNT 20–30 nm nanofluid, respectively, relative to H_2O . Basically, the higher kinematic viscosity of nanofluids leads to a higher pressure drop in a circular pipe. Nanofluids are liquids with solid particles in the nanoscale, and the viscosity of these nanoparticles is the reason for increasing the nanofluid's viscosity due to higher flow resistance. Additionally, the density of the nanofluids could be another reason for dropping the pressure between the inlet and the outlet of a circular pipe. In this regard, the kinematic viscosity (ν) values are as follows: 9.95802E-07 for GNPs-300 nanofluid, 1.02304E-06 for GNPs-500 nanofluid, 1.01301E-06 for GNPs-750 nanofluid, 9.81515E-07 for CNT < 8 nm nanofluid and 9.63984E-07 for CNT 20–30 nanofluid, respectively.

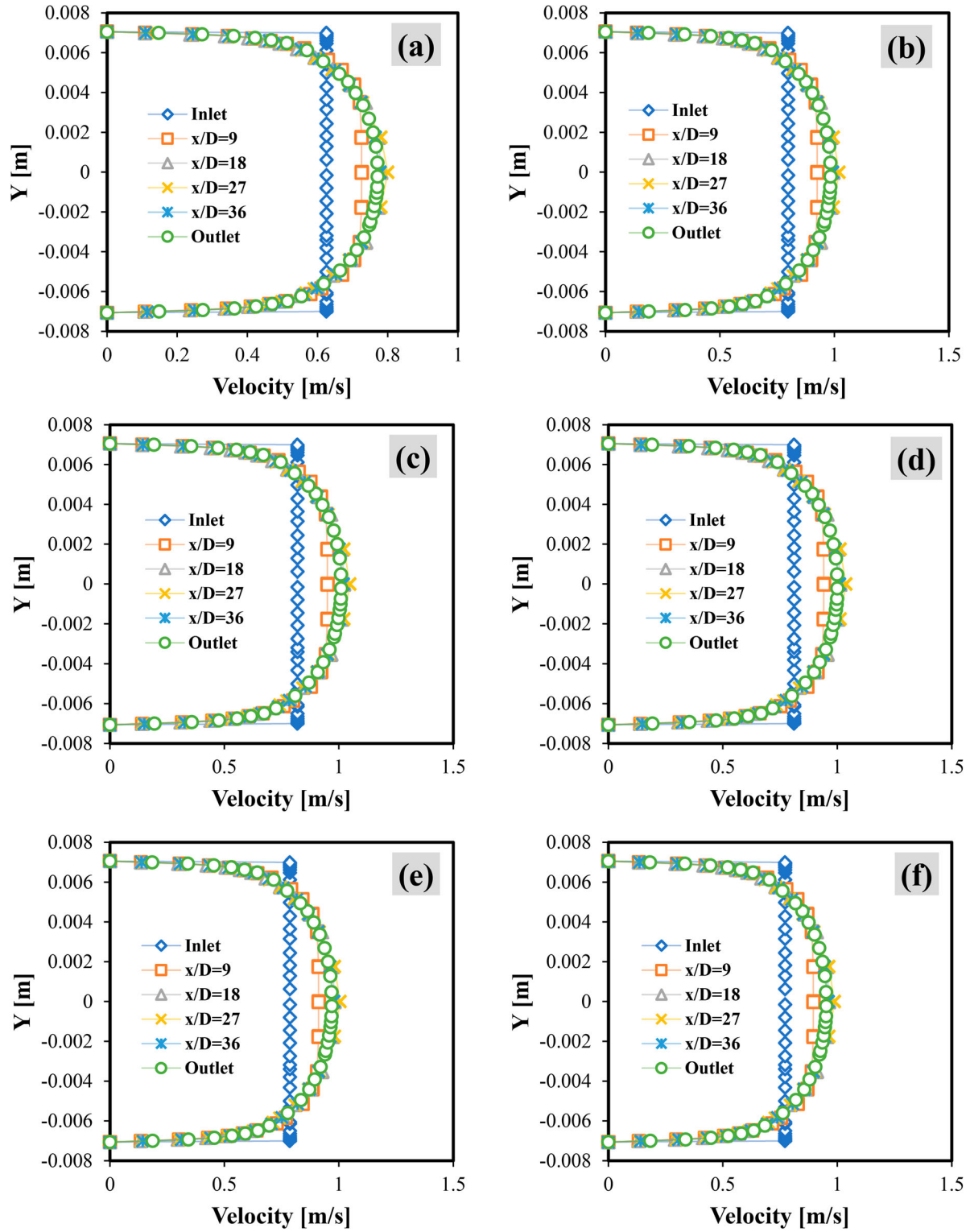


Figure 5. Velocity profiles utilizing different fluids at $Re = 16,000$ and $0.1\text{wt.}\%$; (a) DW, (b) GNPs-300, (c) GNPs-500, (d) GNPs-750, (e) MWCNTs < 8 nm, (f) MWCNTs 20–30 nm.

4.4. Thermal performance index

The prior sections have discussed the heat transport and hydrodynamic properties of a fully developed turbulent flow using 1D-MWCNT/ H_2O nanofluids with

two different ODs and 2D-GNPs/ H_2O nanofluids with three different SSAs. This section will evaluate the overall thermal performance to determine the best nanofluid to be used for thermal and electronic applications.

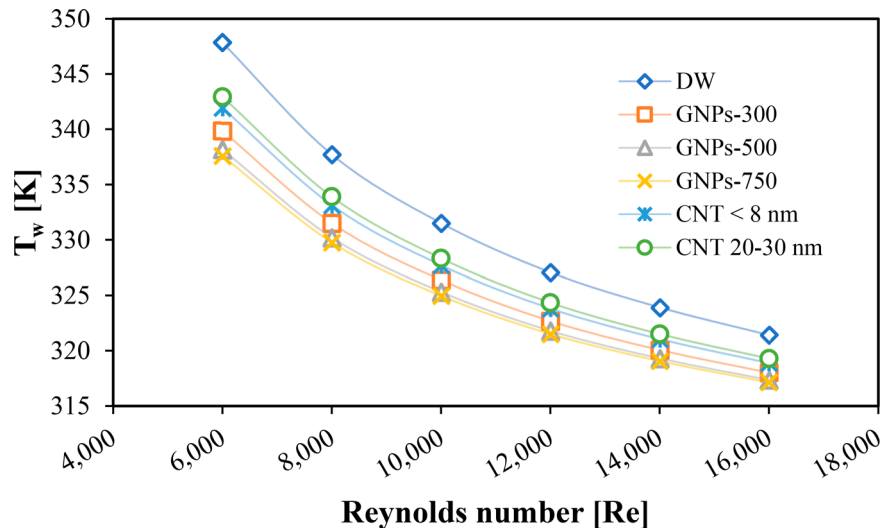


Figure 6. Wall surface temperature of H₂O and 1D-2D carbon-based nanofluids versus Reynolds numbers.

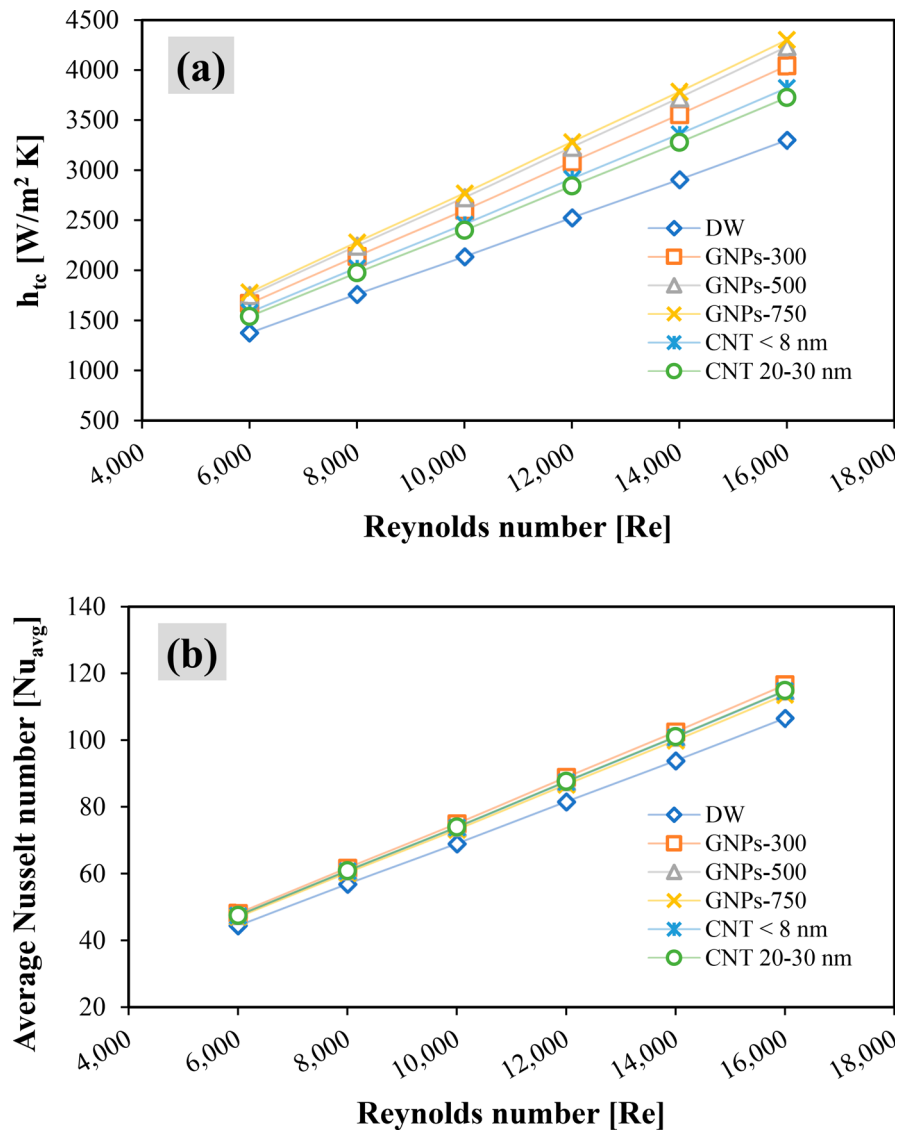


Figure 7. The heat transport enhancement using H₂O and GNP-MWCNTs nanofluids vs. Reynolds numbers; (a) Heat transport coefficient, (b) Average Nusselt number.

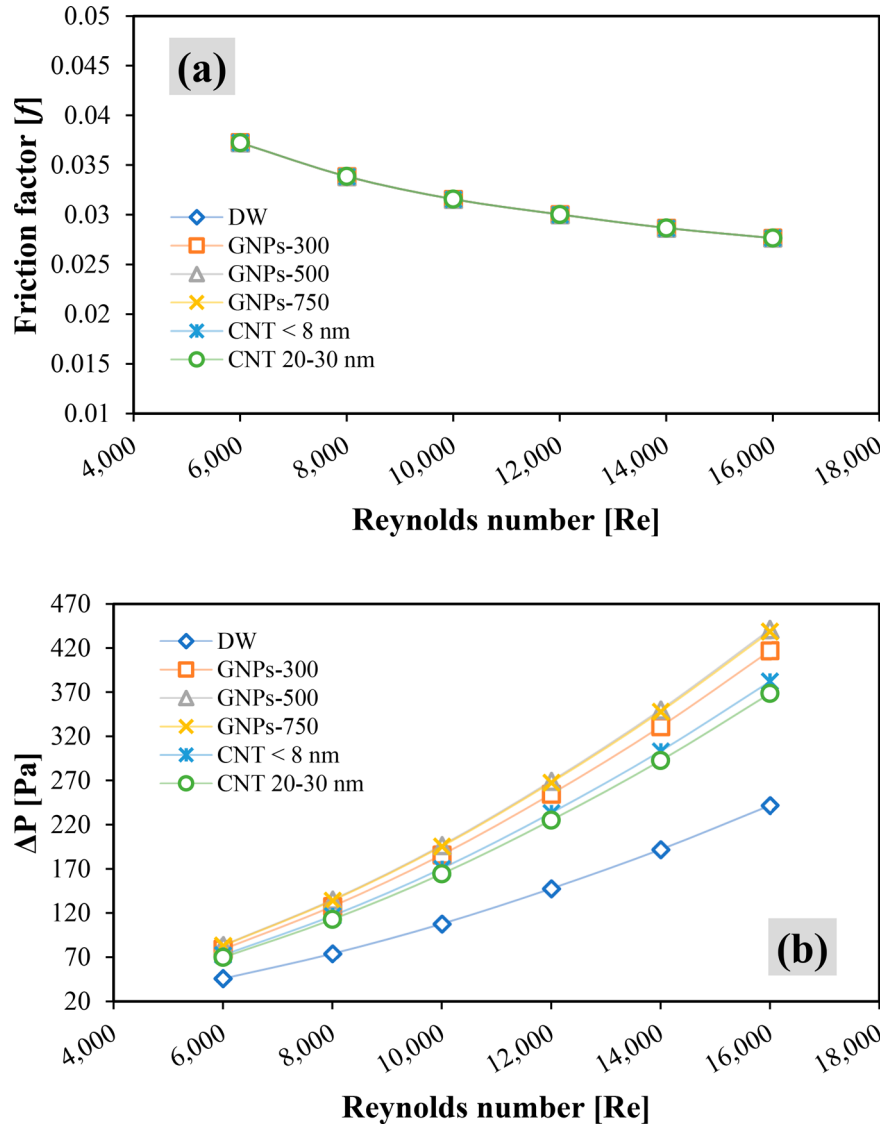


Figure 8. Hydrodynamic Properties of H₂O and 1D-2D carbon-based nanofluids vs. Reynolds numbers; (a) Friction factor, (b) Pressure drop.

The overall thermal performance index (PI_{th}) values for the different nanofluids versus Re is illustrated in Figure 9. Interestingly, all the (PI_{th}) values using 1D and 2D nanofluids are > 1 , which indicates that, the 1D (MWCNTs) and 2D (GNPs) nanofluids outperform the (H₂O) and can be suggested as applicable alternative working fluids for heating and cooling uses. The average value of PI_{th} can be listed as follows: (GNPs-750) with $PI_{th} = 1.388 >$ (GNPs-500) with $PI_{th} = 1.329 >$ (GNPs-300) with $PI_{th} = 1.273 >$ (CNTs < 8 nm) with $PI_{th} = 1.091 >$ (CNTs 20–30 nm) with $PI_{th} = 1.068$, respectively. These values indicate that the heat transfer performance (positive parameter) is higher overall than the pumping power (negative parameter) in turbulent flow regimes. Furthermore, 2D-GNP nanofluids showed better PI_{th} than

1D-MWCNTs nanofluids because 2D-GNP nanoparticles have a higher thermal conductivity and a smaller size than 1D-MWCNTs nanoparticles. Additionally, 2D-GNPs have a higher aspect ratio (length-to-diameter ratio) than 1D-MWCNTs nanoparticles, participating in their superior thermal performance.

4.5. Temperature, turbulence kinetic energy and velocity profiles

Appendix A shows the profiles of temperature, turbulent kinetic energy, and velocity using H₂O, 2D-GNPs with three different SSAs, and 1D-MWCNTs with two different ODs. The profiles of temperature, turbulent kinetic energy, and velocity were taken under the conditions of 1wt.%, Re = 16,000, and $z = 400$ mm.

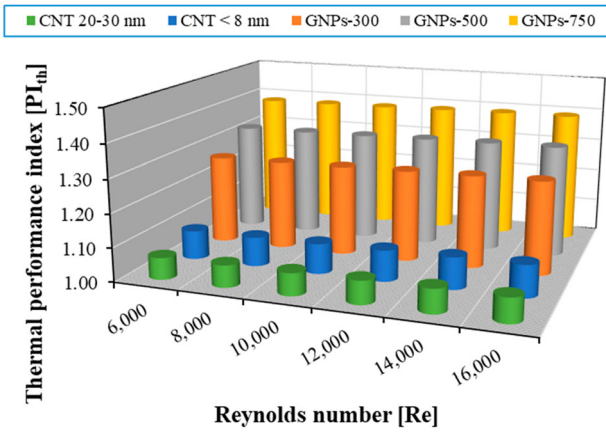


Figure 9. Thermal performance index of 2D-GNPs with three different SSAs and 1D-CNTs with two different ODs.

Turbulent kinetic energy (TKE) profiles were presented since they measure the turbulent motion and mixing within a fluid turbulent flow. The nanofluid flow in a circular pipe and the suspension of carbon-based nanoparticles can increase the TKE due to the increased collision and interaction of the particles with the H₂O molecules. This phenomenon can lead to increased mixing and turbulent motion, resulting in the carbon-based nanofluid's heat transport coefficient and PI_{th} . Fluid dynamics is the equivalent kinetic energy per unit mass for a turbulent flow. This indicates that velocity variations in the turbulent flow in a circular pipe are increasing. Furthermore, velocity profiles indicate that it is maximum in the centre of the circular pipe and decreases gradually until zero at the pipe walls. The velocity value changes as the working fluids change from H₂O to 2D-GNPs with three different SSAs and 1D-MWCNTs with two different ODs. According to Appendix A, the temperature contours in the circular pipe decrease in the mainstream area and increase in the boundary area. A thin flow layer with a high-temperature gradient is formed near the pipe wall when the working fluid flows through the boundary layers at different temperatures. The relatively reduced thermal resistance increases heat transport when the temperature boundary layer is thinner.

4.6. Comparison with previous experimental work

Table 3 summarizes experimental and numerical studies on nanofluids-based heated pipes from 2022 to 2024, focusing on heat exchanger performance enhancement using carbon-based nanofluids. In 2024, An experimental study tested rGO-based H₂O, ethanol, and DMF in a concentric tube heat exchanger, finding that H₂O-based graphene increased conductivity by 48.15% at $\phi = 0.5\%$. Still, high rGO concentrations and low flow rates reduced

thermal efficiency (Aich et al., 2024). Another experimental study integrated inserts and graphene-H₂O nanofluids, showing excellent thermal performance but lacking generalization (Dagdelen & Ozceyhan, 2024). A CFD study on eco-friendly graphene nanofluids with various inner rod shapes found that the pentagonal rod shape enhanced heat transfer by 13.9%, though long-term validity was not evaluated (AbdRabbuh et al., 2024). Lastly, a CFD study on Al₂O₃/GO nanofluids in annular flow found that the diamond-shaped inner rod had a higher performance index than the circular rod within a limited Re range (3,000-8,500) (Abdelrazek et al., 2024).

In 2023, An experimental study on GNPs/H₂O in a shell-and-tube heat exchanger found a maximum h_{tc} enhancement of 910 W/m²K with 0.06 wt.% GNP, but increased ΔP with higher concentrations and flow rates (Zolfalizadeh et al., 2023). A CFD study on finned annular conduits with CGNP/H₂O nanofluid enhanced h_{tc} by 49.88% with minimal ΔP increase (Wang et al., 2023). An experimental and AI model study on a counter-current double pipe heat exchanger with GO nanofluid found the RBFNN model predicted h_{tc} more accurately than the MLPNN, with the nanofluid increasing f by 72% and ΔP by 111% (Zakeri & Emami, 2023). An experimental study on various nanofluids in stainless steel tubes of different diameters found the highest h_{tc} enhancement in a 2-mm-diameter tube with FPG-H₂O at 0.1 wt.% (Solangi et al., 2023). An experimental and CFD study on GNPs/H₂O in a double-tube heat exchanger found 0.025 wt.% GNP exhibited 28% higher temperature gain, while 0.05 wt.% GNP showed slightly better thermal effectiveness (Lima et al., 2023). A CFD analysis of a flat tube with semi-circular fins using graphene-based nanofluids found that 0.4% concentration showed 36.84% effectiveness at 4 LPM (Konni et al., 2023). An experimental and ANFIS study on MWCNTs nanofluids in a tube-in-tube heat exchanger found enhancements in Nu , h_{tc} , efficiency, and NTU at 0.3 vol.% and Re of 10005 (Sundar et al., 2023). Lastly, a CFD study on non-uniform wall corrugations with GNPs/MWCNT-H₂O found PWC showed the highest heat transfer enhancement but increased the pumping power ratio (Islam et al., 2023).

In 2022, An experimental study on a concentric pipe heat exchanger with GNPs and MWCNTs nanofluids found GNPs increased heat transfer by up to 26.1%, while MWCNTs increased it by up to 14.4% (Dayou et al., 2022). Another study found that GNP nanofluids enhanced heat transfer by 200%, while MWCNT showed no significant enhancement in a channel with micro-cylinders (Meng et al., 2022). Finally, a study on GNPs-SDBS@H₂O and GNPs-COOH@H₂O in a circular tube with turbulators found GNPs-SDBS@H₂O

Table 3. Previous experimental and numerical studies on carbon nanofluids-based heated pipes.

Study	Insights	Methods Used	Results	Limitations
Aich et al. (2024)	Solvent selection was vital for rGO suspension stability, with H ₂ O showing the best for thermal transport.	XRD, DSC, and FTIR were used for characterization. Meanwhile, a magnetic stirrer and ultrasonic vibrator were used for preparing different rGO in different solvents.	(i) H ₂ O, ethanol, and DMF suspensions were stable. (ii) H ₂ O-based rGO increased conductivity by 48.15% at $\phi = 0.5\%$. (iii) optimal thermal efficiency at $\phi = 0.35\%$ and 3 LPM.	Thermal efficiency was reduced @ high rGO concentrations and low flow rates.
Dagdelen and Ozceyhan (2024)	Integrating inserts and graphene-H ₂ O nanofluids significantly enhanced heat exchanger efficiency.	Twisted tape and helically wire coil inserts were tested with graphene-H ₂ O nanofluids @ various ratios and Re.	Excellent thermal performance was achieved with 1% graphene-H ₂ O, separation ratio 0.05, twisted tape ratio 2.1, and coil ratio 0.8.	There was a lack of generalization as the findings were specific to tested configurations.
AbdRabbuh et al. (2024)	Eco-friendly graphene nanofluids enhanced thermal performance in annular passages.	Synthesized graphene nanofluids @ different concentrations were then tested in various inner rod shapes using CFD.	(i) 0.1 wt.% nanofluids showed (18.25% for thermal conductivity) and (8.23% for viscosity). (ii) pentagonal rod shape had the highest heat transfer enhancement (13.9%).	(i) Results were based on specific geometries and concentrations; (ii) long-term effects beyond 39 days were not evaluated.
Abdelrazek et al. (2024)	Intrinsic and extrinsic parameters of annular flow were examined using Al ₂ O ₃ /GO nanofluids.	Circular and diamond-shaped annular were solved via a 3D CFD using Al ₂ O ₃ /GO with 0.1, 0.3, 0.5 vol.%, and 0.75vol.%	(i) Diamond-shaped inner rod had a higher shape performance index than the circular. (ii) the inner heating had a higher h_{tc} than that of the outer heating for all nanofluids.	Theoretical nanofluid properties calculations and a limited Re range (3000–8500).
Zolfalizadeh et al. (2023)	Thermal efficiency and convective heat transfer coefficients of a newly designed shell-and-tube heat exchanger using GNP/H ₂ O.	(i) Designed and built a new shell-and-tube heat exchanger; (ii) analyzed GNP properties via XRD and TEM; (iii) nanofluid stability using zeta potential, DLS, and camera images.	(i) Maximum h_{tc} enhancement of 910 (W/m ² K) with 0.06 wt.%; (ii) 8.88% improvement in heat exchanger efficiency; (iii) 15.65% increase in heat transfer rate @ maximum wt.%. (i) 8-hole configuration had the highest PEC; (ii) CGNP nanofluid enhanced h_{tc} by 49.88% with minimal ΔP increase.	Increased ΔP with higher wt.% and flow rates could increase pump power consumption; experimental validation was limited to specific GNP wt.% and conditions.
Wang et al. (2023)	Finned annular conduits with varying hole configurations on thermo-hydraulic performance using CGNP/H ₂ O nanofluid.	Flow characteristics and heat transfer with five curve fins using ANSYS, Re from 611 to 10,389.	(i) 8-hole configuration had the highest PEC; (ii) CGNP nanofluid enhanced h_{tc} by 49.88% with minimal ΔP increase.	(i) Limited to laminar and transitional flow regimes; (ii) Lack of generalization based on specific Re and fin configurations.
Zakeri and Emami (2023)	Thermohydraulics of a counter-current flow double pipe heat exchanger using GO nanofluid, emphasizing the impact of nanoparticle concentration and flow rate on heat transfer.	Experiments @ varying T_{in} , nanofluid concentrations (0.01–0.1%), and cold fluid flow rates (14.4–23.4 ml/s); measured h_{tc} , f , and ΔP ; developed RBFNN and MLPNN models for h_{tc} prediction.	(i) higher flow rate and higher nanoparticle concentration enhanced h_{tc} ; (ii) T_{in} had minimal effect on h_{tc} relative to concentration and flow rate; (iii) nanofluid exhibited higher f with 72%, and ΔP with 111%; (iv) RBFNN model showed higher accuracy in h_{tc} prediction than MLPNN.	(i) Limited to specific experimental conditions and nanofluid concentrations; (ii) neural network models' accuracy dependent on training data and model complexity; (iii) steady-state conditions and ideal fluid behaviour assumptions.

Solangi et al. (2023)	Studied heat transfer enhancement of FPG, FTM, Al ₂ O ₃ , and SiO ₂ nanofluids in stainless steel circular tubes of different diameters under CHF conditions.	(i) Applied FPG-H ₂ O and FTM-H ₂ O nanofluids; (ii) measured thermo-physical properties; (iii) measured h_{tc} , Nu_{avg} , f across different tube diameters (2, 4, 15 mm).	(i) the 2-mm-diameter tube showed the highest h_{tc} up to 116.4% in FPG- H ₂ O @ 0.1wt.% relative to H ₂ O; (ii) In 4-mm- and 15-mm-diameter tubes, the highest h_{tc} was detected to 100.6% and 91.7%. (iii) Al ₂ O ₃ and SiO ₂ showed improvements of up to 32.2% and 34.6% respectively.	(i) Restricted to certain tube diameters and CHF conditions; (ii) assumed optimal fluid behaviour and steady-state conditions; (iii) practical applicability may vary with various operational parameters and configurations.
Lima et al. (2023)	Comparing experimental results with CFD simulations of heat transfer performance using GNPs/H ₂ O nanofluids in a (DTHE).	(i) Experiments with GNP/H ₂ O in counterflow DTHE; (ii) varied GNPs wt.% (0.0125%, 0.025%, 0.050%), operating temperatures (50°C, 60°C), and Re (2000–6000); (iii) empirical correlations and CFD modelling for validation.	(i) 0.025 wt.% GNP nanofluid exhibited 28% higher temperature gain and slightly better Nu; (ii) 0.05 wt.% GNPs showed slightly better thermal effectiveness; (iii) maximum and minimum relative error of 9% and a minimum of 1% between Exp. and CFD.	(i) Limited to specific nanofluid wt.%, temperatures, and Re; (ii) ideal fluid behaviour and steady-state conditions assumptions; (iii) experimental setup limitations may bound generalizability to other heat exchanger configurations.
Konni et al. (2023)	Explored thermal conductivity enhancement and effectiveness of graphene-based nanofluids in a CFD analysis of a flat tube with semi-circular fins under laminar flow conditions.	(i) CFD simulations with graphene-based nanofluids @ concentrations of 0.01%, 0.1%, 0.2%, and 0.4%; (ii) varied (4, 6, 8, and 10 LPM) and h_{tc} (50, 100, 150, and 200 W/m ² K); (iii) considered nanofluids as incompressible.	(i) higher nanofluid concentration enhanced thermal conductivity by 200% relative to H ₂ O; (ii) nanofluid at 0.4% concentration exhibited 36.84% effectiveness at 4 LPM, relative to 28.22% for H ₂ O; (iii) significant temperature drop observed with flow rate increase and higher h_{tc} .	(i) analysis conducted on a single tube because of meshing challenges in ANSYS; (ii) assumptions of laminar flow and incompressible nanofluid behaviour may limit applicability; (iii) results specific to flat tube geometry and may not generalize to other configurations or operational conditions.
Sundar et al. (2023)	Experimental heat transfer characteristics of MWCNTs nanofluids in a tube-in-tube heat exchanger, focusing on Re and vol.%..	(i) Experiments varying Re (3500–12000) and nanofluid vol.% (0%–0.3%); (ii) predicted parameters (h_{tc} , Nu, efficiency, number of transfer units) using ANFIS with Re and particle vol.% as inputs.	(i) Observed enhancements of 31.3% in Nu, 44.17% in h_{tc} , 2.51% in efficiency, and 2.76% in number of transfer units at 0.3 vol.% and Re of 10005 relative to H ₂ O; (ii) ANFIS achieved ($R^2 = 0.9978$ for h_{tc} , 0.9998 for Nu) and low RMSE.	(i) Limited to specific Re and nanofluid vol.%; (ii) ideal fluid behaviour and steady-state conditions; (iii) ANFIS predictions depending on preferred input parameters and neural network structure.
Islam et al. (2023)	Non-uniform wall corrugations (GIWC, GDWC, PWC) using (GNPs/MWCN-H ₂ O) demonstrated potential for enhanced heat transfer efficiency but with increased pumping power requirements.	(i) CFD numerical simulations; (ii) investigated heat transfer efficacy and pumping power for different wall corrugations and Re; (iii) validated model against published experimental data on corrugated conduits.	(i) PWC showed highest heat transfer enhancement (up to 21.16% compared to UWC); (ii) GNPs/MWCN-H ₂ O @ 0.2 vol.% showed a 23.75% increase in Nu_{avg} relative to H ₂ O; (iii) increased pumping power ratio for non-uniform corrugations compared to UWC.	(i) Relies on numerical simulations and lacks full experimental validation of non-uniform wall corrugations; (ii) ideal fluid behaviour and steady-state conditions; (iii) specific to laminar flow regimes and may not generalize to turbulent flows or different geometries.
Dayou et al. (2022)	GNP nanofluid significantly outperformed MWCNT nanofluid in heat transfer. GNP was effective even at lower concentrations and flow rates.	(1) Preparation: nanofluids with 0.01 to 0.35 vol.%. (2) Setup: concentric pipe heat exchanger. (3) Flow Rates: 1.5 to 2.5 LPM.	(i) GNP nanofluids: h_{tc} increased by 16.8%, 24.2%, and 26.1% @ 1.5, 2.0 and 2.5 LPM. (ii) MWCNT-nanofluid: h_{tc} increased by 8.8%, 13.8%, and 14.4% @ 1.5, 2.0 and 2.5 LPM.	(1) Stability: Long-term stability not included. (2) Applications: Specific setup results may vary. (3) Cost: Economic analysis lacking.

(continued)

Table 2. Continued

Study	Insights	Methods Used	Results	Limitations
Meng et al. (2022)	(i) GNP nanofluids showed significant heat transfer enhancement, almost twice that of H ₂ O and much better than MWCNT nanofluids. (ii) GNPs' unique structure improved friction and heat transfer, making them superior for thermal applications.	(1) Conductivity Measurement: 3ω method. (2) Viscosity Measurement: Rheometer. (3) Flow Characteristics: ΔP , f , and Nu_{avg} . (4) Soret Effect: Influence on spatial distribution and heat transport.	(1) Viscosity: More affected by temperature and concentration than conductivity. (2) Friction Coefficient: Decreased with increasing Re. (3) Nu_{avg} : Increased with Re. (4) h_{tc} : GNP nanofluids enhanced heat transfer by 200%, MWCNT showed no significant enhancement.	(1) Temperature Sensitivity: Viscosity changed significantly with temperature. (2) Negative Effects: Increased heating power negatively impacts heat transfer due to the Soret effect. (3) Specific Setup: Results may vary with different experimental setups.
Tao et al. (2022b)	(i) GNPs-SDBS@DW nanofluids outperformed GNPs-COOH@DW in thermohydraulic performance, especially @ higher wt.%. (ii) Twisted tape inserts with 45° and 90° helix angles improved heat transfer.	(i) Numerical simulation using SST k- ω turbulence model. Tested nanofluids in a circular tube with twisted tape inserts at 0.025, 0.05, and 0.1 wt.%. (ii) Evaluated six parameters: T_{out} , h_{tc} , Nu_{avg} , f , ΔP , and PEC.	(i) GNPs-SDBS@DW: Performance increased with concentration: 1.17 (0.025 wt.%), 1.19 (0.05 wt.%), 1.26 (0.1 wt.%). (ii) GNPs-COOH@DW: Lower performance: 1.02 (0.025 wt.%), 1.05 (0.05 wt.%), 1.02 (0.1 wt.%). (iii) Helix Angles: Both 45° and 90° angles enhanced performance.	(i) Specific Conditions: Results specific to Re (7000 to 17,000) and 308 K. (ii) Model Reliance: Dependent on SST k- ω model accuracy. (iii) Scalability: Large-scale application not addressed.
Current	(i) Thermophysical properties and flow characteristics of H ₂ O-based nanofluids containing MWCNTs and GNPs. (ii) Polyhexacore grid was identified as the most effective for accurate and efficient simulations under turbulent flow conditions.	Software: ANSYS FLUENT 2022R2. Model: Extended k- ω SST (Shear Stress Transport). Nanomaterials: MWCNTs with ODs of < 8 nm and 20–30 nm. GNPs with SSAs of 300, 500, and 750 m ² /g. Nanofluid @ 0.1 wt.%. Grids: Polyhedra, Polyhexacore, Hexacore, Tetrahedral. Parameters Evaluated: T_w , h_{tc} , Nu_{avg} , f , ΔP , Pl_{th} . Re Range: 6000 to 16,000. Temperature: 303.15 K	(1) i) Polyhexacore grid outperformed other grids in accuracy and computational efficiency. (2) ii) h_{tc} increased by 18.38% using GNPs-300, 22.05% using GNPs-500, 23.25% using GNPs-750, 13.63% using CNT < 8 nm, and 11.42% for CNT 20–30 nm, respectively, relative H ₂ O at Re = 16,000.	Scope of Nanomaterials: Only specific ODs and SSAs were tested. Simulation Conditions: Limited to Re of 6000 to 16,000. Temperature Range: Only evaluated at 303.15 K.

showed higher enhancement than GNPs-COOH@H₂O (Tao et al., 2022b).

The investigation of GNPs nanofluids in different specific surface areas (SSA) such as (300, 500, and 750 m²/g) and MWCNTs nanofluids in different outer diameters (ODs) such as (< 8 nm and 20–30 nm) has not been previously investigated in the literature. The thermophysical properties were collected from experimental studies, and then the CFD approach was developed to solve the 3D physical model. In general, the 2D-GNP nanofluids showed higher heat transfer properties than 1D-MWCNTs.

5. Conclusions, limitations and future directions

The current study examined the properties of heat transport, friction factor (f), and pressure drop (ΔP) using H₂O, 2D-GNPs nanofluids with three different SSAs, and 1D-MWCNTs nanofluids with two different ODs through ANSYS simulations. 1D-MWCNTs and 2D-GNPs nanomaterials were suspended in H₂O and tested inside a circular pipe under the heating and flow conditions of $T_{in} = 303.15$ K, 0.1 wt.%, $6000 \leq Re \leq 16,000$ and $CHF = 58,866$ W/m². The thermal performance of MWCNT-GNP carbon-based nanofluids was examined through six different parameters. The simulation study leads to the following conclusions:

- (i) The average errors of Polyhedra, Polyhexacore, Hexacore, and Tetrahedral networks compared to various equations were as follows: Polyhedra: 2.903% (Dittus-Boelter), 1.517% (Gnielinski), 1.816% (Blasius), 0.866% (Petukhov). Polyhexacore: 2.754% (Dittus-Boelter), 2.343% (Gnielinski), 1.441% (Blasius), 0.640% (Petukhov). Hexacore: 4.099% (Dittus-Boelter), 1.398% (Gnielinski), 4.083% (Blasius), 3.639% (Petukhov). Tetrahedral: 5.249% (Dittus-Boelter), 2.378% (Gnielinski), 5.717% (Blasius), 5.273% (Petukhov).
- (ii) The velocity profiles at different x -locations, such as inlet, $x/D = 9$, $x/D = 18$, $x/D = 27$, $x/D = 36$, and outlet, showed fully developed turbulent conditions.
- (iii) T_w decreased by the following percentage of 2.35% for GNPs-300, 2.86% for GNPs-500, 3.04% for GNPs-750, 1.73% for CNT < 8 nm, and 1.43% for CNT 20–30 nm, respectively compared to H₂O at $Re = 6000$.
- (iv) The h_{tc} increased by the following percentage of 18.38% using GNPs-300, 22.05% using GNPs-500, 23.25% using GNPs-750, 13.63% using CNT < 8 nm, and 11.42% for CNT 20–30 nm, respectively relative H₂O at $Re = 16,000$.
- (v) The Nu_{avg} enhanced by the following percentage of 8.56% using GNPs-300, 7.15% using GNPs-500, 6.16% using GNPs-750, 7.08% using CNT < 8 nm, and 7.21% using CNT 20–30 nm, respectively relative to H₂O at $Re = 16,000$.
- (vi) ΔP increased by about the following percentages: 42.01% using GNPs-300, 45.16% using GNPs-500, 44.84% using GNPs-750, 36.72% using CNT < 8 nm, and 34.39% using CNT 20–30 nm, respectively, compared to H₂O at $Re = 16,000$.
- (vii) PI_{th} showed the following average values as 1.388 using GNPs-750 > 1.329 using GNPs-500 > 1.273 using GNPs-300 > 1.091 using CNTs < 8 nm > 1.068 using CNTs 20–30 nm, respectively.

The study's limitations include its focus on a single concentration (0.1 wt.%) and inlet temperature (303.15 K), which may not capture the full range of nanofluid behaviours. Additionally, only specific sizes and surface areas of MWCNTs and GNPs were examined, and the $k-\omega$ SST model's assumptions might not fully reflect real-world complexities. Future research should explore varying concentrations and temperatures, investigate other nanomaterials or combinations, and validate findings through experimental studies. Long-term stability assessments and economic analyses will also be crucial for practical applications and optimization of nanofluid use in thermal management.

Appendix_A_CLEAN.docx

Acknowledgements

The authors would like to express their gratitude and appreciation for the respected reviewers and handling editors for their constructive comments to improve the manuscript. This research was supported by Researchers Supporting Project number (RSP2024R425), King Saud University, Riyadh, Saudi Arabia. Hai Tao would like to thanks the Open Fund of Key Laboratory of Advanced Manufacturing Technology, Ministry of Education, (GZUAMT2022KF[07]). Zaher Mundher Yaseen would like to thank the Civil and Environmental Engineering Department, King Fahd University of Petroleum & Minerals, Saudi Arabia.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

All data used in the current research are presented in the article.

ORCID

Zaher Mundher Yaseen  <http://orcid.org/0000-0003-3647-7137>

References

- Abdelrazek, A. H., Alawi, O. A., Kazi, S. N., & Yusoff, N. (2021). Thermal performance evaluation for alumina coated MWCNTs composite nanofluid in annular passage of various eccentricities. *Powder Technology*, 391, 114–132. <https://doi.org/10.1016/j.powtec.2021.06.005>
- Abdelrazek, A. H., Alawi, O. A., Mat Ali, M. S., Zaki, S. A., Ahmed, K. I., & Kazi, S. (2024). Thermal performance assessment of alumina/graphene oxide hybrid nanofluid in annular passage of multiple configurations. *Journal of Thermal Analysis and Calorimetry*, 1–17.
- Abdelrazek, A. H., Kazi, S., Alawi, O. A., Yusoff, N., Oon, C. S., & Ali, H. M. (2020). Heat transfer and pressure drop investigation through pipe with different shapes using different types of nanofluids. *Journal of Thermal analysis and Calorimetry*, 139(3), 1637–1653. <https://doi.org/10.1007/s10973-019-08562-5>
- AbdRabbuh, O. A., Kazi, S., Zubir, M. N. B. M., Chowdhury, Z., & Abdelrazek, A. H. (2024). Heat transfer inside annular passages: A comparison of non-circular and fully circular passages using eco-friendly graphene nanofluid. *Case Studies in Thermal Engineering*, 104659, 1–25.
- Ahmed, W., Alawi, O. A., Abdelrazek, A. H., Yaseen, Z. M., Falah, M. W., & Hussein, O. A. (2022). Numerical and experimental evaluation of thermal enhancement using zinc nano-suspensions in a square flow passage. *Journal of Thermal analysis and Calorimetry*, 139(3), 1–20.
- Aich, W., Khlissa, F., Alshammari, B. M., & Kolsi, L. (2024). Experimental study of graphene-based nanofluid dispersions stability for efficient heat transmission within a concentric tube heat exchanger. *Case Studies in Thermal Engineering*, 59, 104523. <https://doi.org/10.1016/j.csite.2024.104523>
- Akram, N., Hosseini, M., Sadri, R., Kazi, S., Kasaeian, A., Yarmand, H., Hooman, K., & Ahmad, R. (2022). A facile, green fabrication of aqueous nanofluids containing hydrophilic functionalized carbon nanotubes toward improving heat transfer in a closed horizontal flow passage. *Powder Technology*, 404, 117451. <https://doi.org/10.1016/j.powtec.2022.117451>
- Alawi, O. A., Abdelrazek, A. H., Aldlemy, M. S., Ahmed, W., Hussein, O. A., Ghafel, S. T., Khedher, K. M., Scholz, M., & Yaseen, Z. M. (2021). Heat transfer and hydrodynamic properties using different metal-oxide nanostructures in horizontal concentric annular tube: An optimization study. *Nanomaterials*, 11(8), 1979. <https://doi.org/10.3390/nano11081979>
- Arzani, H. K., Amiri, A., Kazi, S., Chew, B., & Badarudin, A. (2015). Experimental and numerical investigation of thermophysical properties, heat transfer and pressure drop of covalent and noncovalent functionalized graphene nanoplatelet-based water nanofluids in an annular heat exchanger. *International Communications in Heat and Mass Transfer*, 68, 267–275. <https://doi.org/10.1016/j.icheatmasstransfer.2015.09.007>
- Bahiraei, M., Mazaheri, N., Aliee, F., & Safaei, M. R. (2019). Thermo-hydraulic performance of a biological nanofluid containing graphene nanoplatelets within a tube enhanced with rotating twisted tape. *Powder Technology*, 355, 278–288. <https://doi.org/10.1016/j.powtec.2019.07.053>
- Bahiraei, M., Naseri, M., & Monavari, A. (2021). A second law analysis on flow of a nanofluid in a shell-and-tube heat exchanger equipped with new unilateral ladder type helical baffles. *Powder Technology*, 394, 234–249. <https://doi.org/10.1016/j.powtec.2021.08.040>
- Bai, M.-J., Liu, J.-L., He, J., Li, W.-J., Wei, J.-J., Chen, L.-X., Miao, J.-Y., & Li, C.-M. (2020). Heat transfer and mechanical friction reduction properties of graphene oxide nanofluids. *Diamond and Related Materials*, 108, 107982. <https://doi.org/10.1016/j.diamond.2020.107982>
- Balaga, R., Koonan, R., & Tunuguntla, S. (2023). Heat transfer enhancement of the f-MWCNT-Fe₂O₃/Water hybrid nanofluid with the combined effect of wire coil with twisted tape and perforated twisted tape. *International Journal of Thermal Sciences*, 184, 108023. <https://doi.org/10.1016/j.ijthermalsci.2022.108023>
- Balaji, T., Rajendiran, S., Selvam, C., & Lal, D. M. (2021). Enhanced heat transfer characteristics of water based hybrid nanofluids with graphene nanoplatelets and multi walled carbon nanotubes. *Powder Technology*, 394, 1141–1157. <https://doi.org/10.1016/j.powtec.2021.09.014>
- Bashtani, I., Esfahani, J. A., & Kim, K. C. (2021). Effects of water-aluminum oxide nanofluid on double pipe heat exchanger with gear disc turbulators: A numerical investigation. *Journal of the Taiwan Institute of Chemical Engineers*, 124, 63–74. <https://doi.org/10.1016/j.jtice.2021.05.001>
- Dagdelen, O. H., & Ozceyhan, V. (2024). Experimental investigation of the effects of graphene nano particle added water fluid on heat transfer in a smooth tube with double inserts. *International Journal of Thermal Sciences*, 203, 109125. <https://doi.org/10.1016/j.ijthermalsci.2024.109125>
- Dayou, S., Ting, T. W., & Vigolo, B. (2022). Comparison of heat transfer performance of water-based graphene nanoplatelet- and multi-walled carbon nanotube-nanofluids in a concentric tube heat exchanger. *Diamond and Related Materials*, 125, 108976. <https://doi.org/10.1016/j.diamond.2022.108976>
- Demirkır, Ç., & Ertürk, H. (2021). Convective heat transfer and pressure drop characteristics of graphene-water nanofluids in transitional flow. *International Communications in Heat and Mass Transfer*, 121, 105092. <https://doi.org/10.1016/j.icheatmasstransfer.2020.105092>
- Fares, M., Mohammad, A.-M., & Mohammed, A.-S. (2020). Heat transfer analysis of a shell and tube heat exchanger operated with graphene nanofluids. *Case Studies in Thermal Engineering*, 18, 100584. <https://doi.org/10.1016/j.csite.2020.100584>
- Ghorabae, H., Emami, M. R. S., Moosakazemi, F., Karimi, N., Cheraghian, G., & Afrand, M. (2021). The use of nanofluids in thermosyphon heat pipe: a comprehensive review. *Powder Technology*, 394, 250–269. <https://doi.org/10.1016/j.powtec.2021.08.045>
- Hosseini, M., Abdelrazek, A. H., Sadri, R., Mallah, A. R., Kazi, S. N., Chew, B. T., Rozali, S., & Yusoff, N. (2018). Numerical study of turbulent heat transfer of nanofluids containing eco-friendly treated carbon nanotubes through a concentric annular heat exchanger. *International Journal of Heat and Mass Transfer*, 127, 403–412. <https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.040>
- Islam, R. M. I., Hassan, N., Rasul, M., Gudimetla, P., Nabi, M. N., & Chowdhury, A. (2023). Effect of non-uniform wall corrugations on laminar convective heat transfer through rectangular corrugated tube by using graphene

- nanoplatelets/MWCN hybrid nanofluid. *International Journal of Thermal Sciences*, 187, 108166. <https://doi.org/10.1016/j.ijthermalsci.2023.108166>
- Joseph, M., & Sajith, V. (2019). Graphene enhanced paraffin nanocomposite based hybrid cooling system for thermal management of electronics. *Applied Thermal Engineering*, 163, 114342. <https://doi.org/10.1016/j.applthermaleng.2019.114342>
- Kılınç, F., Buyruk, E., & Karabulut, K. (2020). Experimental investigation of cooling performance with graphene based nano-fluids in a vehicle radiator. *Heat and Mass transfer*, 56(2), 521–530. <https://doi.org/10.1007/s00231-019-02722-x>
- Konni, R. R., Kumar, A., & Chand, P. (2023). CFD analysis of a flat tube with semi-circular fins using graphene nanofluid and to compare performance with square type of fins. *Heat Transfer*, 52(2), 1673–1688. <https://doi.org/10.1002/htj.22758>
- Li, Z., Khaled, U., Al-Rashed, A. A., Goodarzi, M., Sarafraz, M., & Meer, R. (2020). Heat transfer evaluation of a micro heat exchanger cooling with spherical carbon-acetone nanofluid. *International Journal of Heat and Mass Transfer*, 149, 119124. <https://doi.org/10.1016/j.ijheatmasstransfer.2019.119124>
- Lima, C. C., Ochoa, A. A., da Costa, J. A., de Menezes, F. D., Alves, J. V., Ferreira, J. M., Azevedo, C. C., Michima, P. S., & Leite, G. N. (2023). Experimental and computational fluid dynamic—CFD analysis simulation of heat transfer using graphene nanoplatelets GNP/water in the double tube heat exchanger. *Processes*, 11(9), 2735. <https://doi.org/10.3390/pr11092735>
- Mahian, O., Bellos, E., Markides, C. N., Taylor, R. A., Alagumalai, A., Yang, L., Qin, C., Lee, B. J., Ahmadi, G., & Safaei, M. R. (2021). Recent advances in using nanofluids in renewable energy systems and the environmental implications of their uptake. *Nano Energy*, 86, 106069. <https://doi.org/10.1016/j.nanoen.2021.106069>
- Meng, G., Chen, G., Tan, Z., & Wang, Z. (2022). Fluid flow and heat transfer of carbon nanotubes-or graphene nano platelets-based nanofluids in a channel with micro-cylinders: an experimental study. *Heat and Mass transfer*, 58(12), 2221–2234. <https://doi.org/10.1007/s00231-022-03236-9>
- Menter, F. R. (1994). Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal*, 32(8), 1598–1605. <https://doi.org/10.2514/3.12149>
- Narankhishig, Z., Ham, J., Lee, H., & Cho, H. (2021). Convective heat transfer characteristics of nanofluids including the magnetic effect on heat transfer enhancement—a review. *Applied Thermal Engineering*, 193, 116987. <https://doi.org/10.1016/j.applthermaleng.2021.116987>
- Onyiriuka, E., Obonor, A., Mahdavi, M., & Ewim, D. (2018). Evaluation of single-phase, discrete, mixture and combined model of discrete and mixture phases in predicting nanofluid heat transfer characteristics for laminar and turbulent flow regimes. *Advanced Powder Technology*, 29(11), 2644–2657. <https://doi.org/10.1016/j.apt.2018.07.013>
- Sadri, R., Hosseini, M., Kazi, S. N., Bagheri, S., Abdelrazek, A. H., Ahmadi, G., Zubir, N., Ahmad, R., & Abidin, N. I. Z. (2018). A facile, bio-based, novel approach for synthesis of covalently functionalized graphene nanoplatelet nano-coolants toward improved thermo-physical and heat transfer properties. *Journal of colloid and interface science*, 509, 140–152. <https://doi.org/10.1016/j.jcis.2017.07.052>
- Sadri, R., Hosseini, M., Kazi, S., Bagheri, S., Ahmed, S., Ahmadi, G., Zubir, N., Sayuti, M., & Dahari, M. (2017). Study of environmentally friendly and facile functionalization of graphene nanoplatelet and its application in convective heat transfer. *Energy Conversion and Management*, 150, 26–36. <https://doi.org/10.1016/j.enconman.2017.07.036>
- Sadri, R., Mallah, A. R., Hosseini, M., Ahmadi, G., Kazi, S. N., Dabbagh, A., Yeong, C. H., Ahmad, R., & Yaakup, N. A. (2018). CFD modeling of turbulent convection heat transfer of nanofluids containing green functionalized graphene nanoplatelets flowing in a horizontal tube: comparison with experimental data. *Journal of Molecular Liquids*, 269, 152–159. <https://doi.org/10.1016/j.molliq.2018.06.011>
- Sardarabadi, H., Heris, S. Z., Ahmadvpour, A., & Passandideh-Fard, M. (2019). Experimental investigation of a novel type of two-phase closed thermosyphon filled with functionalized carbon nanotubes/water nanofluids for electronic cooling application. *Energy Conversion and Management*, 188, 321–332. <https://doi.org/10.1016/j.enconman.2019.03.070>
- Sarsam, W. S., Amiri, A., Shanbedi, M., Kazi, S., Badarudin, A., Yarmand, H., Bashirnezhad, K., & Zaharinie, T. (2017). Synthesis, stability, and thermophysical properties of aqueous colloidal dispersions of multi-walled carbon nanotubes treated with beta-alanine. *International Communications in Heat and Mass Transfer*, 89, 7–17. <https://doi.org/10.1016/j.icheatmasstransfer.2017.09.006>
- Sarsam, W. S., Amiri, A., Zubir, M. N. M., Yarmand, H., Kazi, S., & Badarudin, A. (2016). Stability and thermophysical properties of water-based nanofluids containing triethanolamine-treated graphene nanoplatelets with different specific surface areas. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 500, 17–31. <https://doi.org/10.1016/j.colsurfa.2016.04.016>
- Sarsam, W. S., Kazi, S. N., & Badarudin, A. (2020). Thermal performance of a flat-plate solar collector using aqueous colloidal dispersions of graphene nanoplatelets with different specific surface areas. *Applied Thermal Engineering*, 172, 115142. <https://doi.org/10.1016/j.applthermaleng.2020.115142>
- Sarsam, W. S., Kazi, S., & Badarudin, A. (2022). Thermal performance of a flat-plate solar collector using aqueous colloidal dispersions of multi-walled carbon nanotubes with different outside diameters. *Experimental Heat Transfer*, 35(3), 258–281. <https://doi.org/10.1080/08916152.2020.1847215>
- Singh, S. K., & Sarkar, J. (2021). Thermohydraulic behavior of concentric tube heat exchanger inserted with conical wire coil using mono/hybrid nanofluids. *International Communications in Heat and Mass Transfer*, 122, 105134. <https://doi.org/10.1016/j.icheatmasstransfer.2021.105134>
- Solangi, K., Larik, T., Memon, I., Abro, A., & Kazi, S. (2023). Effect of different tube sizes on heat transfer characteristics of functionalized GNP and metal oxide nanofluids in conduit flow heat exchanger. *Journal of Thermal analysis and Calorimetry*, 148(24), 13775–13790. <https://doi.org/10.1007/s10973-023-12595-2>
- Sundar, L. S., Deepanraj, B., & Mewada, H. K. (2023). ANFIS based effectiveness and number of transfer units predictions of MWCNT/water nanofluids flow in a double pipe U-bend heat exchanger. *Case Studies in Thermal Engineering*, 43, 102645. <https://doi.org/10.1016/j.csite.2022.102645>

- Tao, H., Alawi, O. A., Hussein, O. A., Ahmed, W., Abdelrazek, A. H., Homod, R. Z., Eltaweel, M., Falah, M. W., Al-Ansari, N., & Yaseen, Z. M. (2022a). Thermohydraulic analysis of covalent and noncovalent functionalized graphene nanoplatelets in circular tube fitted with turbulators. *Scientific Reports*, 12(1), 1–24. <https://doi.org/10.1038/s41598-021-99269-x>
- Tao, H., Alawi, O. A., Hussein, O. A., Ahmed, W., Abdelrazek, A. H., Homod, R. Z., Eltaweel, M., Falah, M. W., Al-Ansari, N., & Yaseen, Z. M. (2022b). Thermohydraulic analysis of covalent and noncovalent functionalized graphene nanoplatelets in circular tube fitted with turbulators. *Scientific Reports*, 12(1), 17710. <https://doi.org/10.1038/s41598-022-22315-9>
- Vallejo, J. P., Prado, J. I., & Lugo, L. (2021). Hybrid or mono nanofluids for convective heat transfer applications. A critical review of experimental research. *Applied Thermal Engineering*, 117926.
- Vallejo, J. P., Żyła, G., Ansia, L., Fal, J., Traciak, J., & Lugo, L. (2022). Thermophysical, rheological and electrical properties of mono and hybrid $\text{TiB}_2/\text{B}_4\text{C}$ nanofluids based on a propylene glycol: water mixture. *Powder Technology*, 395, 391–399. <https://doi.org/10.1016/j.powtec.2021.09.074>
- Wang, Y., Oon, C. S., Foo, J.-J., Tran, M.-V., Nair, S. R., & Low, F. W. (2023). Numerical investigation of thermo-hydraulic performance utilizing clove-treated graphene nanoplatelets nanofluid in an annular passage with perforated curve fins. *Results in Engineering*, 17, 100848. <https://doi.org/10.1016/j.rineng.2022.100848>
- Zakeri, F., & Emami, M. R. S. (2023). Experimental and numerical investigation of heat transfer and flow of water-based graphene oxide nanofluid in a double pipe heat exchanger using different artificial neural network models. *International Communications in Heat and Mass Transfer*, 148, 107002. <https://doi.org/10.1016/j.icheatmasstransfer.2023.107002>
- Zolfalizadeh, M., Zeinali Heris, S., Pourpasha, H., Mohammadpourfard, M., & Meyer, J. P. (2023). Experimental investigation of the effect of graphene/water nanofluid on the heat transfer of a shell-and-tube heat exchanger. *International Journal of Energy Research*, 2023(1), 3477673.