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*Research Article*

# Numerical Analysis to Study Thermal Performance of Single Pipe Heat Exchanger Using Combined Technique of Nanofluid and Baffles

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**Abstract:**
*To enhance the performance of the thermal system, nanomaterials added with the basic working fluid have gained great attention in recent years as one of the practical solutions. However, to further improve the overall efficiency, common techniques were used, for example, fins and baffles or twisted tape with a nanofluid. The current study involves numerical simulation using the (Ansys Fluent) program to optimize the heat transfer rate and turbulent flow characteristics in a two-dimensional circular tube of a heat exchanger. Common optimization techniques were used, first, the inclusion of baffles with a square configuration along the axis of the fluid flow, and second, the addition of different nanomaterials ($Al_2O_3$ and CuO) with the basic working fluid with variable volume fractions (0.2 -1.2%). The surface of the upper and lower tubes is exposed to a uniform constant heat flux of (80 kW/m$^2$). The effect of Reynolds numbers within the ranges (6000-30000) on the thermal characteristics of the heat exchanger tube has been studied numerically. The numerical results found that the heat transfer coefficient gradually increases with increasing Reynolds number ranges, hence the gradual increase in the Nusselt number. Moreover, compared to a smooth tube, the amount of Nusselt number increases using baffles and nanomaterial, where the ratio of the increase to the heat transfer rate when baffles are inserted is (80.82%), but when using nanomaterials ($Al_2O_3$ and CuO), respectively, is (83.64 and 82.501). The volume fraction ratios of the nanomaterials improved by the improvement compared to the first material (0, 0.2, 0.7 and 1.2%) appeared (80.82, 83.64, 84.124 and 84.63%) respectively. Finally, the friction factor is affected by the velocity of the fluid, which gradually decreases as the Reynolds number ranges increase.*

**Keywords:** *Heat Exchanger, Thermal Performance, Nanofluids, Baffles, CFD, Simulation*

## 1. Introduction

Hoarding the size of equipment has become necessary to facilitate its carrying with little space, so in the past two decades, the size of electronic equipment has been observed to decrease sharply, which was negatively reflected by the increase in heating problems. Using these methods, heat transfer can be increased, including increasing the surface area, in addition to the use of ribs, tapes, pumps, baffles, vortex generators, etc. [1-5].

Using these methods, heat transfer can be increased, including increasing the surface area, in addition to the use of ribs, tapes, pumps, baffles, vortex generators, etc. [1-5]. Saad Raad Al-Haidari and Ahmed Ramadhan Al-Obaidi [6]

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numerically studied the improvement of heat transfer and flow patterns of a two-dimensional pipe by incorporating different Dimple configurations on the outer wall to generate turbulence and improve the thermal performance of the circular pipe. The numerical analysis was carried out using a simulation tool supported by experimental investigation. Three design factors have been studied numerically on their impact on thermal-hydraulic performance, including the number of dimples and the number of groups of dimples in addition to the diameter of the pipe of the dimples. The results of the study showed the effect of changing the number of boils by increasing the Reynolds numbers, the number of Nusselt increases, and the pressure decreases gradually, while the coefficient of thermal performance decreases, in general, the addition of boils, the rate of heat transfer by forced convection improves compared to the empty tube. In various large-scale engineering industrial fields such as petroleum refining, chemical processes, electric power generation, etc., shell-and-tube heat exchangers are applied [7-9]. Thus, improving heat exchange's thermal performance has a direct impact on cost, material, and energy savings. Therefore, enhancing the heat exchanger beyond what is typically done can greatly increase the thermal efficiency in these applications as well as the design and operation costs [10]. The transfer of heat from the hot liquid to the cold liquid by the double pipes of the heat exchangers is therefore considered one of the simple devices. As a result of the small diameter of the heat exchangers mainly with high pressure and heat applications are adapted. Compared to other types, the space it occupies is relatively large, but it is considered inexpensive [11]. K. Wansasueb et al. [12] use the finite volume method in the ANSYS Fluent program to improve thermal performance and reduce pressure loss by inserting baffles with the letter (U) inside a channel with a square cross-section as a heat exchanger application. Air was used as a working fluid at a Reynolds number value (4000) with a turbulent flow. The effect of changing the diameters and height of baffles was studied numerically. The results showed that the use of U-shaped baffles improved the hydraulic performance of the heat exchanger compared to its presence. Teerapat Chompookham et al. [13] presented a numerical study by applying different patterns of fluid flow in a circular tube inserted inside baffles in the form of (V) at an angle of (30). The baffles numbers (2, 3 and 4) and pitch ratios (1, 1.5 and 2) were investigated numerically at the ranges of Reynolds numbers (3000-20000). For four sections these results were proposed for numerical simulation. It was evident that more than one V-baffle may aid in creating an impinging jet, which would break the boundary layer, increase fluid mixing, and improve heat transfer over a plain tube alone. Selma Akçay [14] numerically checked the effect of nanofluidic insertion ($Al_2O_3$ + water) and the baffles within a zigzag horizontal channel with laminar flow at the range of Reynolds (200-1600) with volume fractions (0.01-0.03). Using a finite volume approach and then resolving all the flow equations, including the conservation of mass, momentum, and energy. The lower and upper walls of the channel are marked with a constant temperature along the flow of the fluid to calculate the friction factor and the Nusselt number. To monitor the parameters affecting flow and heat transfer in the winding channel, temperature, and velocity lines are obtained. Numerical results indicated a slight increase in the friction factor but heat transmission improves by increasing the size of nanoparticles and Reynolds numbers. Dipankar De et al. [15] provided numerical analysis using Ansys Fluent to improve heat transfer rate by designing heat exchanger type shall and tube using CATIA design tools. The physical model contains tubes of copper material number (7). Baffles have been listed in two different spiral and straight forms for comparison. The study examines how, while the flow rate is constant, the pressure drop and total heat transfer coefficient change as a result of varying helix angles. The design of the continuous helical baffles forces the flow pattern on the shell side of the heat exchanger with these baffles to be both helical and rotating. This leads to a considerable increase in the heat transfer coefficient per unit pressure drop in the heat exchanger. Simultaneously, a thermal fluid with a porous medium inserted with nanofluid is introduced to cool a separate heat source. Many researchers have used combined techniques to enhance heat transfer and improve the characteristics of single-phase, two- or three-dimensional turbulent flow in various pipes and channels and for different ranges of Reynolds numbers. Velocity, pressure, and temperature distribution are some of the important parameters to study [16-20]. Yuan Ma et al. [21] presented a numerical analysis to enhance the heat transfer by forced convection and improve the flow characteristics of the hybrid nanofluid (MWCNT+$Fe_3O_4$/ Water) in a type channel (backward-facing steps). Here, FORTRAN's code based on the lattice Boltzmann technique is employed. The effect of several parameters including Reynolds numbers within ranges (25-100), volumetric fractions within (0-0.003), location of baffles (3-7), and length of baffles (0-1.5) have been studied numerically. The results of numerical simulations showed an increase in the heat transfer rate by increasing the volume fractions and Reynolds numbers. Various nanomaterials are added with the basic working fluid (often water) to obtain thermal performance and efficiency in many engineering industrial applications such as CuO [22, 23], $Al_2O_3$ [24, 25], MgO [26], Cu [27], $TiO_2$ [28], MWCNT-$Fe_3O_4$ [29-31], MWCNT [32]. Sarmad A. Ali [33] presented a short review study on the inclusion of a wire coil to increase forced convection heat transfer in pipes or ducts used in industrial applications such as heat exchangers, automotive coolers, and thermal systems, as well as improving the flow characteristics of two types turbulent and laminar. The effect of several parameters is studied numerically or experimentally, including Reynolds numbers, Nusselt numbers, friction factor, volumetric fractions, pressure drop, as well as the distribution of velocity, pressure, and temperatures.

The current numerical work involves the enhancement of forced convection heat transfer and flow characteristics in a horizontal two-dimensional tube at ranges of a Reynolds number (6000-30000) single-phase steady state turbulent. The effect of inserting square-shaped baffles inside the tube with different nanofluids ($Al_2O_3$ and CuO) with volume fractions range of (0 – 1.2 %) added with the basic fluid (Water) has been used as a composite technique to further improve heat transfer, thereby raising efficiency and thermal performance. Several parameters were studied by numerical simulation (using commercial CFD code) against the Reynolds number, including the change of the Nusselt number, the friction factor, and the pressure drop. The current research differs from previous studies by using a different baffles configuration (square) inside the tube to demonstrate the effect on the hydrothermal performance.

## 2. Definition of Physical Problem and Numerical Modeling

Figure (1) highlights the current study methodology represented by the general flowchart of numerical simulation using the Ansys Fluent program. To model the physical model, the data is first collected, then entered, then the model is built, the boundary conditions and the mesh are implemented, then the transition to the stage of solving the equations governing the flow, then the numerical convergence of the solution, finally showing the results and interpreting them.

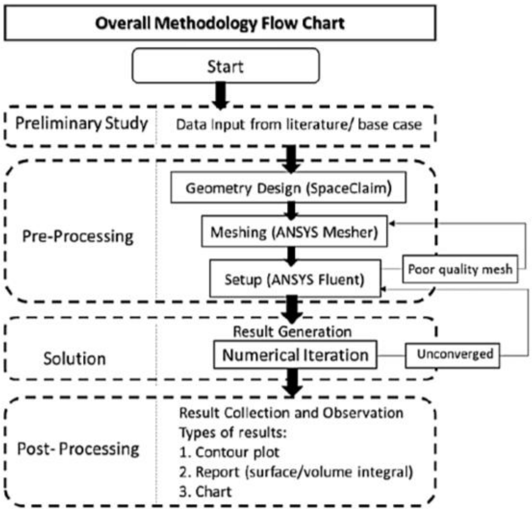


**Fig. 1**. General flowchart of the current work methodology.

### *2.1 Geometry of Numerical Model*

The physical model used in the numerical simulation of the current study consists of a two-dimensional horizontal tube with a length of ( 500mm) and a diameter of (50mm) inserted four square-shaped baffles inside the tube with equal height and width (25mm) and a distance between one and the other (60mm) as shown in Figure (2). Nanofluids ($Al_2O_3$ and CuO) added with water enter the tube from the left side (inlet) to flow through the tube to the outlet, taking into account the effect of the listed baffles. In Table (1) other details about the design criteria and the numerical engineering structure are listed.

**Table 1:** Design criteria with a geometric structure related to square pipe-inserted baffles.

| Description | Symbol | Dimension |
|---|---|---|
| Diameter outer of the pipe | D | 50mm |
| Height of baffle | H | 25mm |
| Total length of pipe | L | 500mm |
| Total number of baffles | n | 4 |
| Space of baffle | S | 60mm |
| Base of Baffle | W | 25mm |

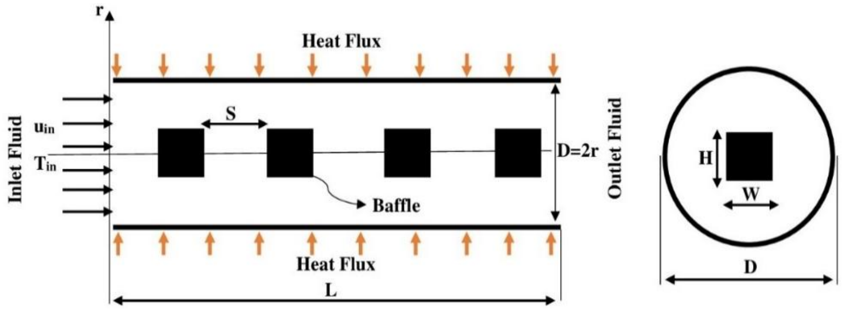


**Fig. 2**. Schematic diagram of single pipe heat exchanger with inserting square baffles.

*2.2 Fluid Governing Equations*

To analyze the physical model, many governing equations were adopted in the simulation program, for example, the equations of conservation of mass, momentum, and energy, in addition to the homogeneous mixture model, as follows [34-36]:

Equation of continuity (mass):

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

Equation of momentum:

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

where,

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

Equation of heat energy:

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

where,

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

and

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

The Re-Normalization Group (RNG) k-ε turbulence model was used in this simulation because it is a popular model in computational fluid dynamics because of its cost-effectiveness, simplicity, and robustness, which make it suitable for use in complex systems and certain flow conditions. To provide an effective balance between computational cost and accuracy, the appropriate (k-ε) model is used with high Reynolds numbers for fluid flows, so it is an important option in all thermal engineering systems. The transfer of kinetic energy of turbulent flow inside the tube is presented as follows [35]:

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

The equation for the dissipation of kinetic turbulent energy transfer is listed according to the following:

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

Using the Prandtl–Kolomogorov connection, the eddy viscosity derivative is as follows:

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

Pk, or the kinetic energy output for turbulence, may be calculated as follows:

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

In the RNG k-ε, the Rε,m might be computed as follows:

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

where,

$$\eta=\frac{SK}{\varepsilon} \quad (12)$$

The following equation can be used to calculate the coefficient ($C_3$):

$$C_3=\tanh\left|\frac{v}{u}\right| \quad (13)$$

*2.3 Nanofluids Thermal-physical properties*

At a temperature of (300K), all thermophysical properties of the basic fluid and nanomaterials were calculated using mathematical equations including density, viscosity, specific heat plus thermal conductivity and listed in Table (2) as follows [37-39]:

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

$$Cp_{nf}=Cp_{np}\varphi+(1-\varphi)Cp_{bf} \quad (15)$$

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

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

Here ρ, Ø, λ, μ and $C_p$ are the density ($k/m^3$), volume fraction (dimensionless), thermal conductivity (W/m. K), dynamics viscosity ($N.s/m^2$), and heat capacity at constant pressure (J/kg. K) respectively. bf, pf and nf indicate the base of fluid, the particle of fluid, and the nano of fluid respectively.

*2.4 Model Boundary Condition*

During the simplification of the numerical simulation of the program with the development of the physical model, the following considerations were taken into account as boundary conditions:

- The basic and nanofluid flow has been assumed turbulent, single-phase, steady-state, Newtonian, incompressible, and two-dimensional.
- Entry fluid temperature at (300K).

- Towards the flow axis, the pipe wall above and below is exposed to a constant, uniform heat flux.
- Temperature affects the thermophysical properties of nanomaterials.
- Exit point in the pipe the pressure is set to zero.
- All walls are non-slip.
- Neglect of heat transfer by radiation.
- The nanomaterials were traveling at the same velocity as the base fluid after being completely dissolved by it.
- The turbulence (K-ε) model was used due to the importance of separating the flow and The Eddy flows generated around the baffles inserted inside the pipe.

**Table 2**: All thermophysical properties of the basic fluid and Nanomaterials at a temperature of (300K).

| **Operational fluid** | **Ø (%)** | **ρ ($kg.m^{-3}$)** | **Cp ($J.kg^{-1}. K^{-1}$)** | **μ (Pa. s)** | **λ ($W.m^{-1}. K^{-1}$)** |
|---|---|---|---|---|---|
| Water | -------- | 998 | 4180 | 0.001 | 0.6 |
| $Al_2O_3$ | -------- | 3980 | 765 | -------- | 40 |
| CuO | -------- | 6400 | 535.6 | -------- | 76.5 |
| $Al_2O_3$ +Water | 0.2 | 1003.964 | 4173.17 | 0.0015 | 0.603 |
| | 0.7 | 1018.874 | 4156.09 | 0.00101 | 0.6121 |
| | 1.2 | 1033.784 | 4139.02 | 0.00103 | 0.6208 |
| | 0.2 | 1008.804 | 4172.7 | 0.0015 | 0.603 |
| CuO+Water | 0.7 | 1035.814 | 4154.48 | 0.00101 | 0.612 |
| | 1.2 | 1062.84 | 4136.26 | 0.00103 | 0.6213 |

*2.5 Analysis of Grid Independence*

Figure (3) shows the selection of the appropriate grid type (Triangles) to be generated in the empty tube and the tube supported by square baffles, where the edges of the inlet and outlet of the tube were divided by a number (100), and the upper and lower part is divided by a number (to obtain the maximum number of elements and nodes. Smoothing the pipe gives high accuracy in the simulation results as well as reaching numerical convergence concerning the governing equations of the flow. To improve accuracy for near-wall treatment, the test section's walls have been revised. Furthermore, the improved wall treatment is further refined by adjusting the y+ (nondimensional wall distance) value to be less than unity.

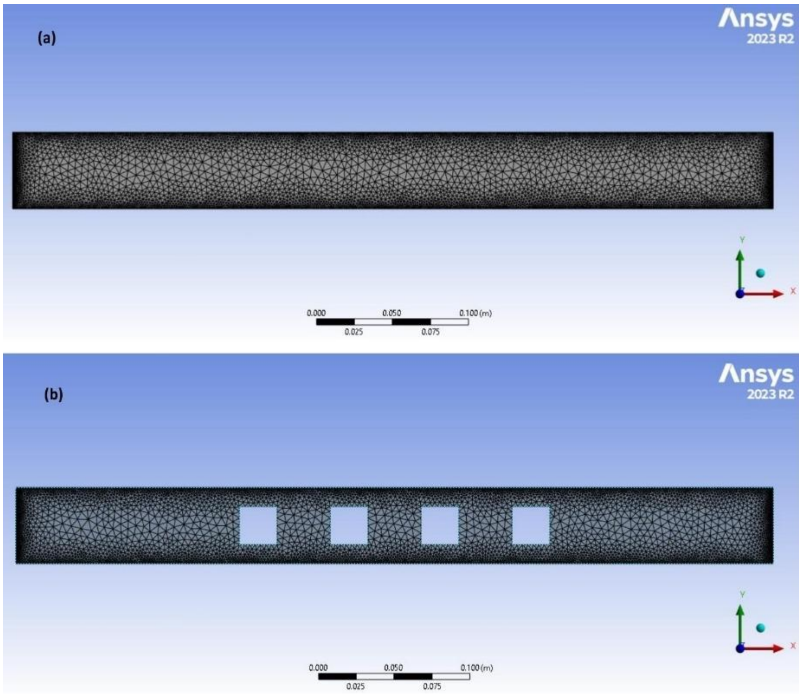


**Fig. 3**. Mesh generation of the computational model (a) plain pipe and (b) square baffles pipe.

The governing equations all have residuals of $1e^{-6}$. On a device with an Intel Core i7 processor, 2.60 GHz clock speed, and 8.0 GB of RAM, Ansys-based computations were carried out. With a maximum computation time of one hour and around 1000 iterations, convergence was achieved. Between 12,000 and 31,000 components were used in the grid-independent testing. Figure (4) shows the temperature change of the fluid at the exit zone and the change of the forced load heat transfer coefficient with the number of elements. The digital output of the simulation can be observed to stabilize and does not change significantly after the value (32500).

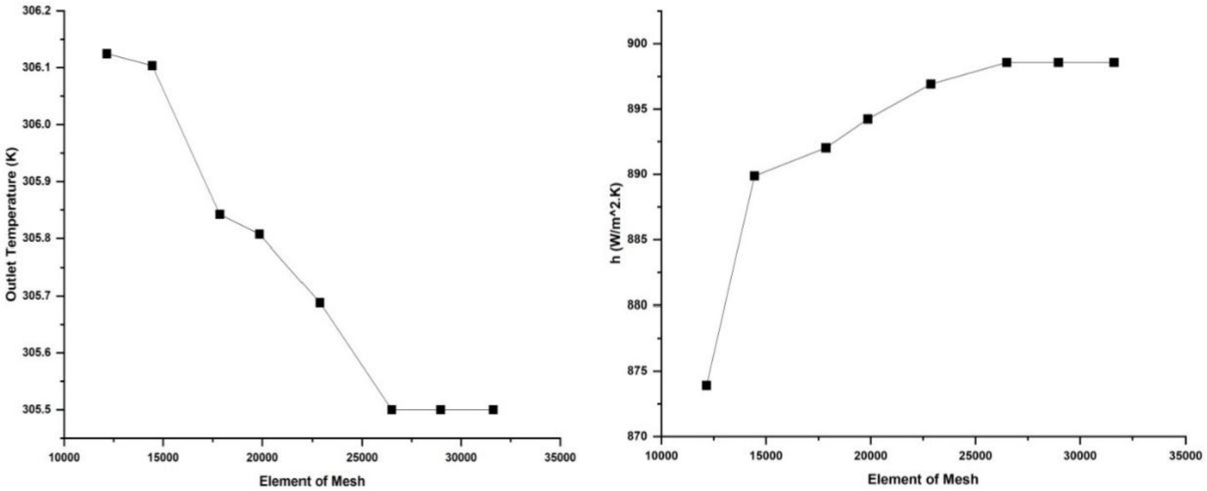


**Fig. 4**. Test independence of outlet fluid temperature and heat transfer coefficient with various ranges of elements mesh.

## 3. Results and Discussions

This section deals with the analysis and discussion of the numerical results of the current study, including the heat transfer rate represented by the Nusselt number and Reynolds numbers, the friction factor, the coefficient of heat transfer by forced load and pressure drop, as well as discussing the effect of changing the volumetric fractions of nanomaterials inserted inside the tube.

### *3.1 Heat Transfer Rate*

Figures (5 and 6) show the change of the Nusselt number against the Reynolds number ranges (6000-30000) in two parts, first, the effect of inserting square-shaped baffles inside the tube was taken into account, as well as the use of composite optimization techniques where nanomaterials ($Al_2O_3$, CuO) were added with the basic working fluid to become a turbulent flowing nanofluid for comparison with the empty tube. As for the second part, the effect of changing the ratios of the volume fractions of the nanomaterial was studied, which gave the best improvement in the heat transfer rate compared to the second material used (CuO). The use of square baffles gave an improvement compared to an ordinary tube, while the best improvement of heat transfer occurred at composite technologies (baffles with nanofluid) where all thermophysical properties were improved. The ratio of the increased heat transfer rate compared to a smooth tube when using baffles and nanofluids ($Al_2O_3$ and CuO) was given (80.82, 83.648 and 82.501 %), respectively. Moreover, the change in the ratios of the volumetric fractions of the nanomaterial ($Al_2O_3$) significantly affects the increase in the Nusselt number against the Reynolds numbers, where with the increase in volumetric fractions and Reynolds numbers, the Nusselt number gradually increases, as well as the increase in the rate of heat transfer (80.82, 83.64, 84.124 and 84.63 %) at the ratio of volumetric fractions (0, 0.2, 0.7 and 1.2%), respectively.

### *3.2 Heat Transfer Coefficient*

Figure (7) shows the change in the coefficient of heat transfer by forced convection against the ranges of the Reynolds numbers. It can be noted that by increasing the Reynolds numbers, the heat transfer coefficient also gradually increases to compare with the empty tube to highlight the effect of the baffles included in the flow stream and the nanofluid, the heat transfer coefficient can be improved gradually by increasing, moreover, the second nanomaterial compared to the first did not give a significant change, but in general, mixing the nanomaterial with water has improved the thermophysical properties.

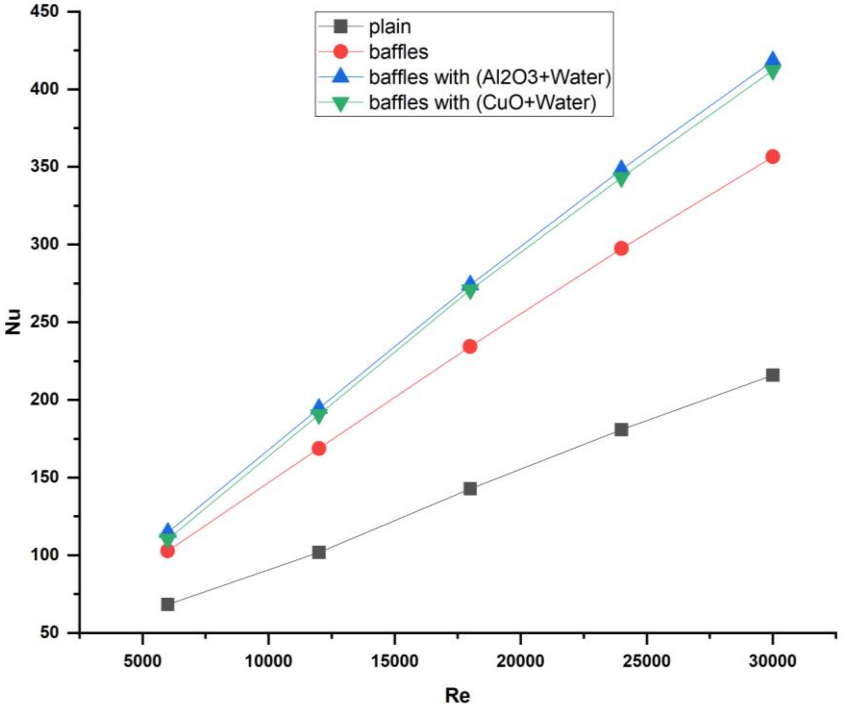


**Fig. 5**. Variation of Nusselt number with Reynolds number ranges in empty/baffles-filled tubes and nanofluids.

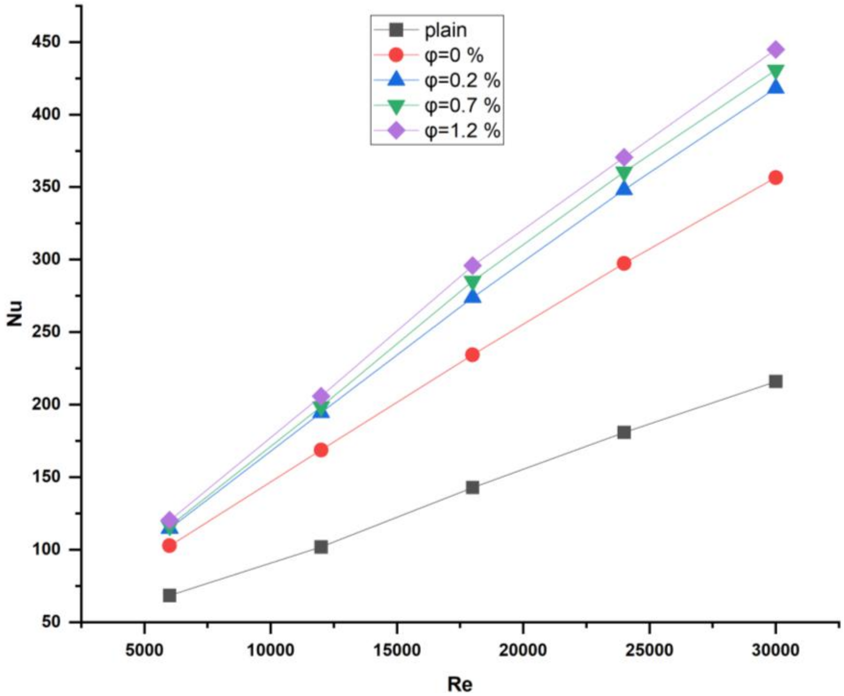


**Fig. 6**. Variation of Nusselt number against Reynolds number ranges of plain and nanomaterial ($Al_2O_3$) filled pipe with baffles at different volume fraction sizes.

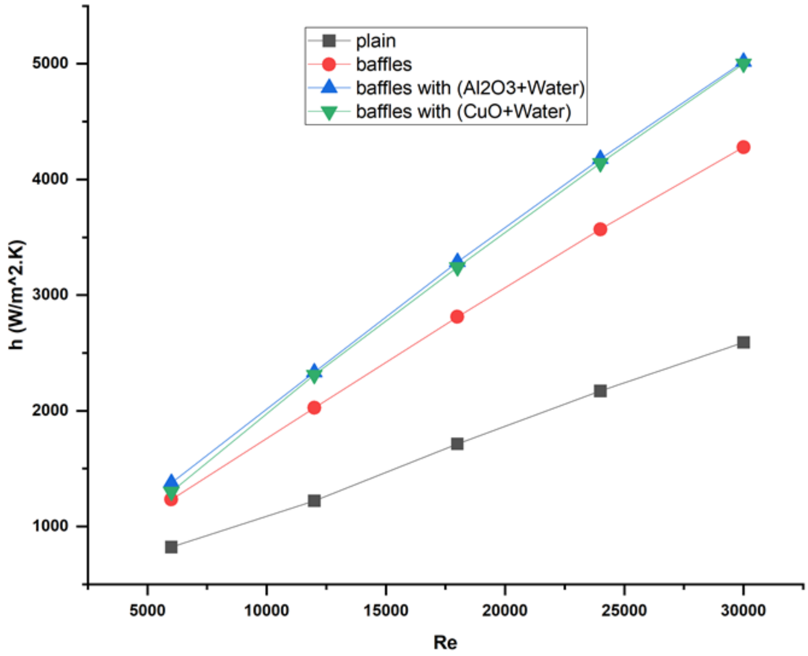


**Fig. 7**. Variation of heat transfer coefficient with Reynolds number ranges in empty/baffles-filled tubes and nanofluids.

*3.3. Pressure Drop and Friction Factor*

The pressure drop represents the difference between the fluid pressure at the entry point and the pressure at the exit point. It can be seen in Figure (8) representing the change in pressure drop against Reynolds numbers, where with an empty tube the amount of pressure drop is almost constant, while with the inclusion of baffles the pressure in the exit zone began to increase, where the difference gradually increased, moreover, the amount of pressure drop reached its maximum values when using common means to enhance heat transfer.

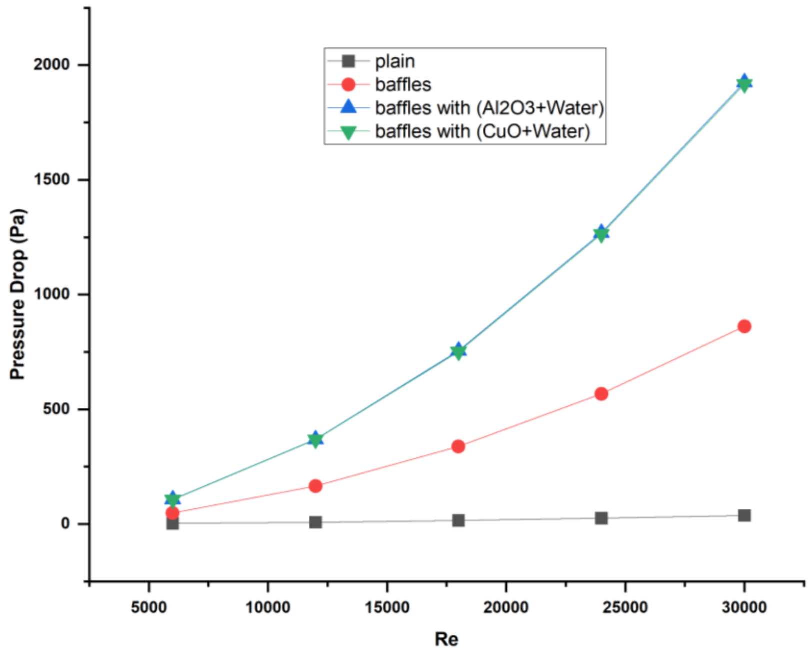


**Fig. 8**. Variation of pressure drop with Reynolds number ranges in empty/baffles-filled tubes and nanofluids.

The friction factor plays an important and effective role in the study of heat transfer and the flow of various liquids in thermal systems [40 and 41]. Figure (9) indicates the change of the friction factor with the Reynolds number, where it can be observed by increasing the fluid speed, i.e., by changing the Reynolds number, the friction factor gradually decreases due to the inverse ratio between the velocity and the friction factor, in addition, the friction factor increases when using an obstacle to the flow of fluid inside the Tube, so it is considered a negative case for improving heat transfer. The convergence of the values of the friction factor can also be observed when using the first and second nanomaterial with the listed baffles for all of them with a difference compared to an ordinary empty tube.

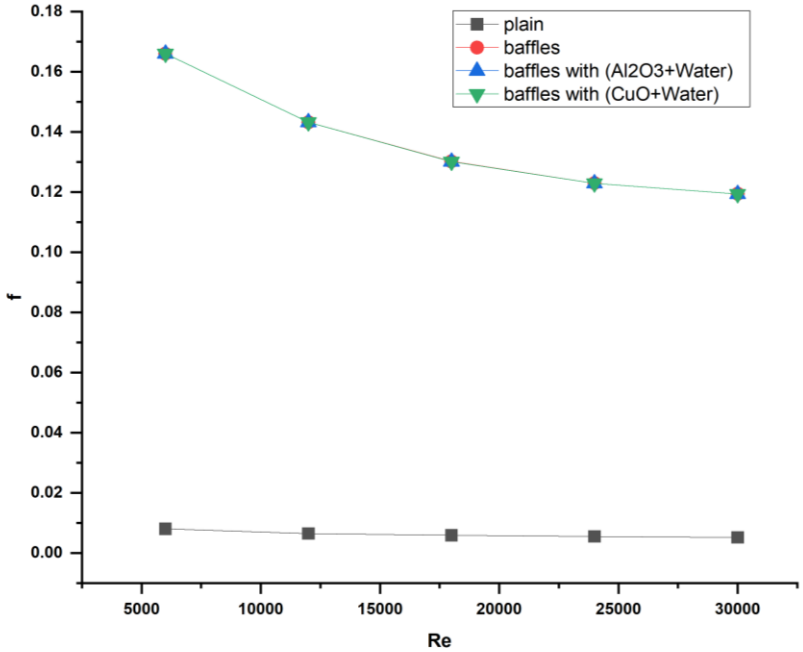


**Fig. 9**. Variation of friction factor with Reynolds number ranges in empty/baffles-filled tubes and nanofluids.

## 4. Conclusions

The current work involved a numerical study using commercial CFD code (Ansys Fluent) to improve the characteristics of turbulent flow within the ranges of Reynolds numbers (6000-12000) and forced convection heat transfer in a circular tube of a heat exchanger. The effect of adding nanomaterials ($Al_2O_3$ and CuO) with basic fluid (water), the inclusion of square baffles, and the change in the values of volumetric fractions were analyzed and discussed in the results section, therefore it was concluded the following points:

- The coefficient of heat transfer by forced convection gradually increases with increasing ranges of numbers. It can also be noted by inserting baffles inside the circular tube, an increase in the heat transfer coefficient compared to the empty tube, moreover, using composite techniques (baffles with nanofluid), an increase occurred even more with a marked improvement in the thermophysical properties of the working fluid.
- The heat transfer rate (Nusselt number) increases gradually by increasing the ranges of different Reynolds numbers also compared to the empty tube, an increase in the amount of Nusselt number can be observed when using baffles inside the circular tube, moreover, the heat transfer rate increased significantly when integrating another technology (nanofluid) with baffles.
- The rate of heat transfer is affected by the volumetric fractions of the nanofluid, where by increasing the proportions of volumetric fractions the number of Nusselt gradually increases compared to the normal empty tube.
- The pressure drop gradually increases with increasing Reynolds number, also the pressure drop values of the empty tube were observed almost constant, while with the inclusion of baffles or the use of complex means of improvement, the values were significantly increased.

- The techniques used to heat transfer heating have one of the disadvantages, where the friction factor increases compared to the additive-free tube, in addition, the friction factor gradually decreases with increasing Reynolds number ranges.

**List of Nomenclature and Abbreviations**

| | | |
|---|---|---|
| $Al_2O_3$ | Aluminum oxide | …….. |
| Ansys | Analysis System | …….. |
| CFD | Computational Fluid Dynamics | …….. |
| Cp | Specific heat at constant pressure | J/kg. K |
| CuO | Copper oxide | …….. |
| D | Pipe diameter | mm |
| f | Friction factor | …….. |
| H | Baffle height | mm |
| h | Heat transfer coefficient for forced convection | $W/m^2$. K |
| k | Turbulence kinetic energy | $m^2/s^2$ |
| L | Pipe length | mm |
| n | Number of Baffles | …….. |
| Nu | Nusselt Number | …….. |
| Re | Reynolds Number | …….. |
| S | Space baffle in the pipe | mm |
| T | Working fluid temperature | K |
| W | Baffle width | mm |
| Ø | The volume fraction of nanomaterial | …….. |
| ε | Rate of dissipation of kinetic energy | $m^2/s^3$ |
| λ | Thermal conductivity of the working fluid | W/m. K |
| ρ | Density working fluid | kg/ $m^3$ |

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