Use of Organic and Copper-Based Nanoparticles on the Turbulator Installment in a Shell Tube Heat Exchanger: A CFD-Based Simulation Approach by Using Nanofluids

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Heat exchangers with unique specifications are administered in the food industry, which has expanded its sphere of influence even to the automotive industry due to this feature. It has been used for convenient maintenance and much easier cleaning. In this study, two different nanomaterials, such as Cu-based nanoparticles and an organic nanoparticle of Chlorodifluoromethane (R22), were used as nanofluids to enhance the efficiency of heat transfer in a turbulator. It is simulated by computational fluid dynamics software (Ansys-Fluent) to evaluate the Nusselt number versus Reynolds number for different variables. These variables are diameter ratio, torsion pitch ratio, and two different nanofluids through the shell tube heat exchanger. It is evident that for higher diameter ratios, the Nusselt number has been increased significantly in higher Reynolds numbers as the heat transfer has been increased in turbulators. For organic fluids (R22), the Nusselt number has been increased significantly in higher Reynolds numbers as the heat transfer has been increased in turbulators due to the proximity of heat transfer charges. At higher torsion pitch ratios, the Nusselt number has been increased significantly in the higher Reynolds number as the heat transfer has been increased in turbulators, especially in higher velocities and pipe turbulence torsions.

1. Introduction

The heat exchanger is used to transfer heat efficiently between two fluids (gas or liquid) to another [1–3]. The most common heat exchangers are car radiators and radiators [4–6]. Heat exchangers are used in various industries such as air conditioning [7–11], automobile, oil and gas, and many other industries [6, 12, 13]. Heating equipment in process systems such as refineries is generally divided into two general categories of furnaces and heat exchangers [14–19]. The difference between a furnace and a heat exchanger is in the heating source [20–23], which means that the heating source is liquid and gas [24–29]. While in a heat exchanger, the heating source is a hot fluid. In the furnace, according to the type of heating source, the heat transfer mechanism in the form of convection and radiation
is combined [30–33], while the heat transfer mechanism in
the heat exchanger is only convection [34–36]. In general,
heat transfer calculations from high-temperature plates lead
to the simultaneous creation of different effects of heat trans-
fer mechanisms on the characteristics of heat exchangers and
other heat transfer equipment [37–39].

On the other hand, forced displacement in the heated
layers of nanofluid around a rotating area is still a fundamental
issue that needs further study [40–45]. Access to smaller, ligh-
ter, and more efficient devices for better heat transfer has
always been desirable in industrial equipment such as elec-
tronic components and heat exchangers [46–48]. Since nano-
fluids have a higher thermal conductivity than normal fluids,
they have always been of interest in recent years [49–53]. Ho
et al. conducted a limited-volume numerical study to investi-
gate the free heat transfer of water/aluminum oxide in a cylin-
drical chamber with insulated inner walls and hot and cold
outer walls. Based on their findings, the choice of different
models for viscosity predicts different values for the Nusselt
number [54, 55]. Xu et al. and Dalkilic and Wongwises inves-
tigated the combined displacement of water/aluminum oxide
nanofluids in a right-angled triangular chamber [56, 57].
According to their reports, with an increasing amount of
nanoparticles, heat transfer occurs [58].

Jahanshahi et al. conducted an experimental and numeri-
cal study with a finite-volume numerical method to investigate the free
heat transfer of water/silicon oxide in square chambers with
hot and cold vertical walls and horizontal insulated walls.
According to their findings, the average unsalted number in all Riley
numbers increases with the increasing volume fraction of nanoparticles [59]. Aminossadati and Ghasemi
numerically investigated the natural displacement of water/copper oxide nanofluids in Grashof numbers and different
volume fractions in a square chamber with local heating. According to their results, with increasing Riley number and volume fraction of nanoparticles, the average Nusselt
number increases [60]. Basak et al. numerically examined fluid flow and heat transfer in natural displacement in hot-
bottomed triangular chambers and cold lateral walls in a porous medium. The average Nusselt number increases [61].

In the present study, two different nanomaterials, such as
Cu-based nanoparticles and an organic nanoparticle of
Chloro-difluoromethane (R_{22}), were used as nanofluids to
improve the heat transfer efficiency of a turbulator. It is sim-
ulated by computational fluid dynamics software (Ansys-
Fluent) to evaluate the Nusselt number versus Reynolds
number for different variables. These variables are diameter
ratio, torsion pitch ratio, and two different nanofluids through the shell tube heat exchanger. One of the reasons for
this choice is the current applications of this geometry in
thermal insulation processes, cooling of various rotating
machine components, and energy management in general.

2. Materials and Methods

2.1. Materials

2.1.1. Cu-Based Nanoparticle. A copper-based nanoparticle
is a type of copper-based particle between 1 and 100 nm.

Like many other nanoparticle forms, Cu-based nanoparticles
could be formed by natural processes or through chemical
synthesis.

2.1.2. R_{22}. Chloro-difluoromethane is a complex type of
hydrochlorofluorocarbon (HCFC). This colorless gas is
commonly known as R_{22}, which is used for refrigeration or
propellant properties.

2.2. Mesh Convergence. To achieve a correct numerical solu-
tion in simulating single-phase fluid flows when accurate
flow information is not available, it is necessary to use clas-
sical smooth flow equations within the Reynolds number
range to ensure smooth flow. The equations of mass, momentum, and energy survival governing the displacement
flow problem in cylindrical properties can be summarized as
follows:

\[
\begin{align*}
\frac{1}{r^2} \frac{\partial}{\partial r} \left[ (\rho_{nf} V_{nf}) \frac{\partial r}{\partial r} \right] + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left[ \rho_{nf} V_{nf} \theta \right] - \frac{\partial}{\partial z} \left[ \rho_{nf} V_{nf} z \right] - \Gamma_3,
\end{align*}
\]

where \(r_1\) to \(r_3\) is explicitly defined in Table 1 for various
situations.

It is clear that to solve the set of Equation (1), it is neces-
sary to introduce the fluid and thermal properties of nano-
fluids. These properties include conductivity, viscosity, density, coefficient of thermal expansion, and specific heat
capacity. After reviewing a large number of theoretical and
quasiexperimental models presented by researchers to model
the thermal conductivity and effective viscosity of water-
copper oxide nanofluids and compare their results with each
other, it was decided to use the models presented by Cor-
sion. These models are semiexperimental, and their results
are very consistent with the experimental results of others.
The corrosion model for the thermal conductivity is

\[
k_{nf} = 1 + 4.4 \text{Re}^{0.4} \phi^{0.66} \left( \frac{T}{T_{fr}} \right)^{10} \left( \frac{k_f}{k_g} \right)^{0.03},
\]

where \(\text{Pr}\) is the Prandtl number for the base fluid and \(\text{Re}\) is
the Reynolds number for the brown motion of the nanoparticle
and is obtained from the following equation:

\[
\text{Re}_b = \frac{2 \rho_f k_b T}{\eta \mu_f d_p}.
\]

As given in the momentum survival equations, the density
changes in the Boeing force term follow the Bozinsky
approximation. The effective density of the nanofluid, the
Bozinsky term coefficient, and the denominator of the ther-
mal diffusion coefficient are also calculated using the mixing
law:

\[
\rho_{nf} = (1 - \phi) \rho_f + \phi \rho_{np},
\]

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Table 1: Calculation of various parameters.

| Governing equations | $\Gamma_1$ | $\Gamma_2$ | $\Gamma_3$ |
|---------------------|------------|------------|------------|
| Continuity          | 1          | 0          | 0          |
| Momentum            | $V_r$      | $\mu_{nf}$ | 0          |
| Momentum, $\theta$  | $V_{\theta}$ | $\mu_{nf}$ | 0          |
| Momentum, $z$       | $V_z$      | $\mu_{nf}$ | 0          |
| Energy              | $C_{p_{nf}} T$ | $k_{nf}$   | 0          |

\[
\left(\rho c_p\right)_{nf} = (1 - \varphi)\left(\rho c_p\right)_f + \varphi\left(\rho c_p\right)_{np}, \quad (5) \\
(\rho \beta)_{nf} = (1 - \varphi)(\rho \beta)_f + \varphi(\rho \beta)_{np}. \quad (6)
\]

The base fluid is specific heat density and capacity, in contrast to the conductivity, viscosity, and thermal expansion coefficient, which are considered during the numerical solution of the temperature variable, which is determined for the water-based fluid as the following correlation relations:

\[
C_{p_{nf}} = 2 \times 10^{-6} T^4 - 3 \times 10^{-3} T^3 + 1.6T^2 - 357.7T + 342.82,
\]

where $R^2 = 0.9995$ and $\rho_f = -0.0034T^2 + 1.7538T + 775.93$.

Although the above equations take more time to converge or so-called converge problem, it provides more accurate modeling results.

2.3. Computational Fluid Dynamics (CFD) Solver. The non-linear equation system is solved using the CFD solver in Ansys-Fluent software. This solver discretizes the equations by the volume control method but solves them in a coupled manner using the finite element method. The playback sentences are carefully double-discretized, and the Ray and Chou algorithm is used to couple the speed and pressure. Nonuniform networks network the computational domain with the organization. The criterion for $y^+ < 10$ is used for the boundary layer elements in all geometries that the size of the elements adjacent to the walls and the entrance grows with a ratio of 1.08. The minimum number of elements for the aspect ratio is 75 times 595428, and the maximum number of elements for the aspect ratio is 15 times 2530800. The output of the problem is calculated in the form of dimensionless Nusselt numbers and coefficient of friction in the inner and outer walls to express the amount of heat transfer from the walls and dynamic flow analysis using:

\[
Nu = \frac{h D_h}{k_{nf}}, \quad (8) \\
Nu_{\theta} = \frac{h D_h}{k_{nf}}, \quad (9)
\]

\[
C_{f_i} = \frac{r_{w_i}}{0.5 \rho_{nf} V_{in}^2}, \quad (10) \\
C_{f_i} = \frac{r_{w_i}}{0.5 \rho_{nf} V_{in}^2}. \quad (11)
\]

3. Results

3.1. Validation. To determine the correct values of the variables and the accurate boundary layer modeling, the network independence test from numerical solution was performed using velocity and temperature profiles for different aspect ratios of the desired geometry. This test was performed for water fluid without considering nanoparticles. All networks have a boundary layer with the condition $y^+ < 10$, and the number of elements increases in both axial and radial directions. The criterion for selecting a network is to reach a single answer to increase the number of elements in all directions and the boundary layer. The results were validated by previous literature to continue the evaluations from simulations. It is depicted in Figure 1. As it is evident, the error percentage is negligible, and our simulations can be trusted.

3.2. Nusselt Number. As shown in Figure 2, the effect of various diameter ratios (0.2, 0.15, 0.05, and 0) has been evaluated on the Nusselt number (Nu) in different Reynolds numbers. The Nusselt number has been increased for higher diameter ratios, especially in higher Reynolds numbers, as the heat transfer has been increased in turbulators.

As shown in Figure 3, the effect of various torsion pitch ratios (0.45, 0.30, 0.15, and 0) has been evaluated on the Nusselt number (Nu) in different Reynolds numbers. The Nusselt number has been increased for higher torsion pitch ratios, especially in higher Reynolds numbers, as the heat transfer has been increased in turbulators, especially in higher velocities and pipe turbulence torsions.

As shown in Figure 4, the effect of various $R_{22}$ and Cu-based nanoparticles has been evaluated on the Nusselt number (Nu) in different Reynolds numbers. It is evident that for organic fluids ($R_{22}$), the Nusselt number has been increased, especially in higher Reynolds numbers, as the heat transfer has been increased in turbulators due to the proximity of heat transfer charges.
4. Discussion and Conclusions

Despite the limitations of validating the problem, the correctness of the code can be ensured by solving classical governing equations for similar geometries, regardless of the rotation of the inner cylinder, and comparing the results of the present numerical solution with the work of others. Figure 1 shows a comparison between the present work results and the study of Safikhani et al. (2016), and there is an excellent correlation between these results for the two heat flux ratios of 0.5 and 2. The maximum numerical error for the Reynolds number is 9.2%. The amount of numerical error of the coefficient of friction between both numerical solutions in the inner and outer walls is negligible, which shows a good agreement between the results of these solutions.

Heat transfer media are usually composed of fluids such as water and oil with a lower thermal conductivity than these nanoparticles. For example, the thermal conductivity of copper is 700 times the thermal conductivity of water and 300 times the thermal conductivity of engine oil, or the thermal conductivity of copper oxide is about 60 times the thermal conductivity of water. Therefore, fluids containing fine particles of metal compounds, metal oxides, carbon nanotubes, graphene, or hybrids are expected to exhibit better thermal properties than pure fluids. The larger surface area of the nanoparticles increases the intensity of heat transfer from the fluid to the particles where the fluid is warmer than the nanoparticles and transfers heat from the particles to the fluid where the fluid is cold. To transfer heat by displacement, the particles must be easily displaced by the fluid. Due to technological problems, studies in this field have focused more on suspensions that include particulate matter suspended in millimeters and with a maximum of micrometers. Particles on this scale cause acute problems in the heat transfer equipment so that these particles quickly settle in the system and become clogged as they pass through the ducts, causing a significant pressure drop. In addition to the collision of these particles with each other and with the system’s wall and equipment causing abrasion, it is theoretically determined that the smaller the particles, the higher their heat transfer level.

Figure 1: Validation between our simulations and Safikhani et al. [62].

Figure 2: Effect of various diameter ratios on Nusselt number (Nu) in different Reynolds numbers.

Figure 3: Effect of various torsion pitch ratios on Nusselt number (Nu) in different Reynolds numbers.

Figure 4: Effect of R22 and Cu-based nanoparticles on Nusselt number (Nu) in different Reynolds numbers.

4. Discussion and Conclusions
Power plants are considered one of the most important industrial centers of the country and have a particular sensitivity. This importance includes the various parts used in it, such as turbines, boilers, and converters. The transfer of thermal energy from one fluid to another in the industry is done by a heat exchanger device. There are two fluids with different temperatures in heat exchangers, which provide the conditions for heat exchange between the two fluids, usually exchangers. Thermals are used to cool a hot fluid, heat a fluid to a lower temperature, or both. The heat exchanger transfers energy between two fluids through an interface. Since nanoparticles affect the fluid’s thermal properties, nanofluids in heat exchangers can be very efficient and helpful. Viscosity is the resistance to the relative motion of a fluid. This parameter plays a crucial role in momentum transmission between fluid layers, and its effect becomes more pronounced when there is movement between fluid layers. In liquids, viscosity is caused by the presence of van der Waals forces between molecules.

It should be noted that this simulation has been done with Ansys-Fluent software, and after designing the initial design using the study of existing articles and researches. Simulation is an educational technique that provides all or part of a clinical experience in a safe environment and helps a person learn without fear of personal weakness or fear of self-harm through interactive activities. The use of simulation in the industry is widely evolving worldwide. Its prevalence is influenced by technological advances, changes in ethical issues raised in learning industrial skills, the congestion of industrial environments for training, and the lack of manpower. Experts work in companies to help with the training process. Simulation has several benefits, including increasing personal safety, enhancing interactive and inclusive learning, helping to improve learners’ problem-solving and critical thinking skills, and achieving self-regulated learning. However, despite all the mentioned advantages, it is noteworthy that due to the financial costs of providing simulation equipment and the need for proper cost management, especially in educational centers in the present era, the results of using similar types should be done through numerous researches. Instruments should be examined on learners’ learning, and according to the effectiveness of different types of simulators, each of them was prepared and prepared for educating learners.

The main findings of this study are as follows:

(i) The Nusselt number has been increased for higher diameter ratios, especially in higher Reynolds numbers, as the heat transfer has been increased in turbulators

(ii) For organic fluids (Re₉), the Nusselt number has been increased, especially in higher Reynolds numbers, as the heat transfer has been increased in turbulators due to the proximity of heat transfer charges

(iii) At higher torsion pitch ratios, the Nusselt number has been increased, especially in higher Reynolds numbers, as the heat transfer has been increased in turbulators, especially in higher velocities and pipe turbulence torsions

**Abbreviations**

- Re: Reynolds number
- Pr: Prandtl number
- α: Twist angle (degree)
- Nu: Nusselt number
- μ: Viscosity (kg·m⁻¹·s⁻¹)
- f: Friction coefficient
- D: Pipe diameter (m)
- d: Wire diameter (m)
- ρ: Density (kg/m³)
- h: Displacement heat transfer coefficient (W/K)

**Data Availability**

There is no available data for this paper.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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