

Research Article

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Application of Nano-Fluids to Heat Transfer Enhancement in Double-Walled Reactor

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Abstract

Efficiently cooling of a reactor for an exothermic reaction can lead the efficiency to be increased, while reduces the size of the rector. In the present research, aqueous Nano-fluid of AI_2O_3 and CuO are used as heat transfer media flowing inside the reactor jacket to improve the heat transfer performance of a reacting system. Experiments have been performed to investigate the role of Nano-fluid in cooling of an exothermic reaction. The experimental facility provides conditions to control the generated heat during the reaction. Convective heat transfer coefficient and pressure drop of alumina/water and CuO/water Nano-fluids were experimentally measured. Nano-fluids were using two-step method at mass concentrations of 0.1-0.4%. The reactor is a stainless steel-made annular type, which is cooled by Nano-fluid flowing inside the annular section. For longer stability of Nano-fluid and Reynolds number, the heat transfer coefficient increased. For CuO Nano-fluid, rate of enhancement for the convective heat transfer coefficient was 13% at 0.3% in comparison with the base fluid. While for aluminum Oxide at wt. %=0.4, the enhancement rate was 11.7%. Utilizing the Nano-fluid instead of traditional coolants, (e.g., water) resulted in a small penalty for the pressure drop. Higher level of pressure drop was registered for alumina Nano-fluid at wt%=0.4, which was 12% more than that of reported for the distilled water?

Keywords: Convective heat transfer; Pressure drop; Double-walled reactor; Surfactant

Introduction

Cooling performance of a system plays an important role in many sectors such as refineries, power plants, petrochemical, nuclear reactors and process equipment. Therefore, in most of the industrial systems, heat should be transferred as an input energy to the system or should be dissipated from the system. For designing a reactor, thermal performance is a key parameter in terms of both operational and safety criteria. The major chemical reactions are exothermic or endothermic, thus during the reaction, the contents of the reactor may be heated or cooled. Overheating in the reactor can lead to the reactor failure or its control equipment. Most importantly, this can enhance the risk of explosion and leakage. In addition, if the reaction is endothermic, it can be cooled by the progress of the reaction, which leads the reactor to reduce the rate of the reaction even up to the freezing point. Accordingly, Temperature range inside the reactor should be kept in safety region. One of the most common methods to control the reactor temperature is to use a cooling/heating jacket or heat-exchanging coils. In jackets, a layer with higher or lower temperature is wrapped around the reactor to transfer the heat to the reactor indirectly. For such systems, poor thermal conductivity of conventional fluids such as oil, water and ethylene glycol is one of the major challenges of heat transfer fluids. One of the methods to overcome this challenge is to enhance the thermal conductivity and thermal features of coolants using engineered thermal fluids with higher thermal conductivity. For better understanding, following example is explained. Thermal conductivity of water is regarded as reasonable value, which equals to 0.6 W/m. K at temperature of 298 K. However, it is much lower than the thermal conductivity of common metal oxides such as copper, which is usually 700 times greater than water and 3000 times higher than oil. Therefore, a promising passive way to improve the transfer performance of traditional coolant is to use the Nano-fluids.

Nano-fluids are promising materials, which are comprised of the solid particles with nominal size of 0-100 nm dispersing into the traditional coolant. Nano-fluids have some minor issues such as sedimentation, fluid blockage, and erosive behavior in comparison with major challenges belonging to microfluidic working media. However, Nano-fluids are still in lab, although there are slender chances that such coolants can address most of the issues caused by conventional fluids due to the poor thermal conductivity. Following, there are some benefits of Nano-fluid outweighing its drawbacks:

- Higher thermal conductivity in comparison with those of predicted by macroscopic models
- Better stability in comparison with micro-fluids
- less damage caused due to the increase in pressure drop and erosion of pipes

Nano-fluids are extensively used in order to improve the heat transfer performance of heat exchanging media. Some of these efforts have been represented in the following section.

Literature Review

Zarifi et al. [1] used Al_2O_3 /water and TiO_2 /water in different volume fractions of nanoparticles as cooling fluid in VVER-1000 reactor. Their results showed that with increasing the volume fraction of nanoparticles, the temperature of output cooling fluid increases. Faulkner et al. [2] investigated the fully developed convective heat

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transfer with Nano-fluids of aqueous carbon nanotube. They observed the significant increase of heat transfer coefficient with increasing the Reynolds number. They also pointed out that in all cases, Nano-fluid was better than base fluid, but Nano-fluids with less volume concentration (1.1%) had better thermal performance rather than Nano-fluids with higher concentration (4.4% and 2.2%). Such findings can be referred to the increase of the interaction between nanoparticles. For increasing the production rate of gasoline in the process of Fischer-Tropsch (FT) synthesis, since the improvement of heat transfer can lead to increase the speed of exothermic reaction, Jayhooni et al. proposed to use the Nano-fluids. Studying the effect of Nano-fluid as coolant in the shell and reaction in the pipe of a tube exchanger showed that increasing the concentration of Nano-fluids could lead to the better heat transfer and higher gasoline production. Xuan and Li [3] performed an experimental study with copper Nano-fluids in a pipe with constant heat flux. They concluded that Nusselt number increased by 12% in the concentration volume of 1%. Chun et al. [4] investigated the heat transfer of Nano-fluids (prepared from oils and solvents and aluminum oxide nanoparticles) at laminar flow condition in a heat exchanger. They found that Nano-fluids containing nanoparticles equivalent to 0.5% by volume have thermal conductivity 10% more than the base fluid. Nazifi et al. [5] investigated the effects of Al₂O₂-water Nanofluid on thermos-hydraulic parameters to prepare the ground for the application of Nano-fluids in research reactors. Their results showed that use of aqueous Nano-fluids with volume fraction 1%, can enhance the heat transfer coefficient about 4% and pressure drop about 3%approximately. In this paper, application of Nano-fluids in a doublewalled reactor is investigated by studying the effects of concentration and flow rate of two copper oxide and aluminum oxide Nano-fluids on the thermal performance and cooling capacity of Nano-fluids. In addition, special emphasis is taken to the pressure drop as a challenging drawback of Nano-fluids.

Experimental Setup

Test rig

Figure 1 schematically demonstrates the experimental setup used in this research. This facility can measure the values of temperature, pressure and flow of fluid in a closed loop to determine the characteristics of heat transfer and pressure drop of Nano-fluid. Fluid enters to the loop from the reservoir, while its conditions (temperature and pressure and flow rate) is measured through the trajectory line of the fluid and then returns back to the reservoir while its temperature and pressure set again to the initial values. The section of fluid flow consists of a storage tank and centrifugal pump (model PKm60) with two valves for precisely regulating the flows, which of them is located on the path of main flow and another one is located on the return path as well. To measure the volumetric flow rate, a turbine flow meter (Model VISION 2000) connecting to a MP5W indicator is used. The Nanofluid enters to the reactor, heated up and then enters again into the heat exchanger. In heat exchanger, Nano-fluid is cooled by a cooling media flowing inside the heat exchanger. The main aim of using Nanofluid is to cool the center of the reactor. A detailed schematic diagram of the experimental facility is shown in Figure 2 Different type K thermocouples (connected to indicator Autonics TC4Y) are mounted at different parts of the tank, entrance and outlet of reservoir and the reactor in order to measure the average temperature value at any time during experiments. In order to measure the pressure in the input and output of reactor, two calibrated pressure transmitters (PSCH0.5 SENSYS, VCIA) are implemented as well.

Preparation of nano-fluid

Properties and behaviors of Nano-fluids depend to the type of the base fluid and nanoparticles, size and shape of particulate matter and the quality of particle dispersion within the base fluid. In the present work, CuO nanoparticles with mean size of 40 nm and Al₂O₃ with size of 20 nm are purchased from Research Nanomaterial's, USA. These particles are added to the base fluid to produce Nano-fluid suspensions. Transmission electron microscopy, (TEM) images of nanoparticles was also provided in order to ensure about the size, morphology and represented in Figures 3 and 4. Noticeably, to change the surface properties of suspended particles crack the agglomeration and cluster structures, the ultrasonic vibrator with a surfactant is used to create a stable Nano-fluid. For this purpose, first Sodium dodecyl sulfate, (SDS) is added into the water at concentration of 0.1%, and then it is stirred uniformly. Nano-fluids then are prepared at mass concentrations of 0.1, 0.2, 0.3 and 0.4. For the next step, an ultrasonic is used (20 kHz/400 W), therefore, stable and Nano-fluids are prepared.

Data reduction

In order to investigate the influence of flow rate and Nano-fluid concentration on the heat transfer and Nusselt number, it is necessary to estimate the thermos-physical properties of Nano-fluids accurately. Following equations are used for calculating the thermal properties of Nano-fluids:

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_p \tag{1}$$



Figure 1: Image of experimental setup.







Figure 4: (a) TEM image of ${\rm Al_2O_3}$ nanoparticles, (b) TEM image of CuO nanoparticles.

$$\left(\rho C_p\right)_{nf} = (1-\phi)\left(\rho C_p\right)_f + \phi\left(\rho C_p\right)_p \tag{2}$$

Corcione [6] has performed studies on dynamic viscosity of Nano-fluids. By using the experimental data available in the literature, he proposed a correlation for dynamic viscosity of Nano-fluids as represented in Equation (3).

$$\frac{\mu_{\rm eff}}{\mu_{\rm f}} = \frac{1}{1 - 34.87 \left(\frac{\rm d_p}{\rm d_f}\right)^{-0.3} \mathscr{O}^{1.03}}$$
(3)

 d_f is the average diameter of base fluid molecules, which can be obtained from Equation (4):

$$d_{f} = 0.1 \left(\frac{6M}{N \pi \rho_{f_0}} \right)^{\frac{1}{3}}$$
(4)

In this equation, M is the molecular weight of base fluid; N is the Avogadro's number and ρ_{f0} is the density of base fluid at the temperature (T₀=293K). For calculating the thermal conductivity of Nano-fluids, following equation was proposed by Corcione [6-11]:

$$\frac{k_{nf}}{k_f} = 1 + 4.4Re^{0.4}Pr^{0.66} \left(\frac{T}{T_{fr}}\right)^{10} \left(\frac{k_p}{k_f}\right)^{0.05} \varphi^{0.66}$$
(5)

Where P_r is the Prandtl number, T is the temperature of Nanofluid, T_{fr} is the freezing temperature of base fluid, k_p is the conductive heat transfer coefficient of Nano-particles and Re is the Reynolds number of nanoparticles, which is defined as equation. (6):

$$Re = \frac{2\rho_f k_b T}{\pi \mu_f^2 d_n} \tag{6}$$

Where, k_{μ} is the Boltzmann constant.

It is worth saying that all properties were calculated at the Nanofluid bulk temperature. The average temperature of Nano-fluid can be obtained from the inlet/outlet thermocouple's reading values. The thermocouples that are installed at the interior wall of reactor can also provide the average internal temperature of reactor. The amount of produced heat in the reactor is calculated by means of Joule's effect, which is the product of voltage and current (see equation. (7)):

$$Q = VI$$
 (7)

Considering the average temperature of tank, Nano-fluid and the resistor as well (thickness of 2.77 mm), the relation between quantities of heat transfer from the center of the reactor and resistance of chamber and can be obtained using equation. (8):

$$Q = \left\{ \overline{T}_r - \overline{T}_{nf} \right\} / \left\{ \frac{Ln\left(\frac{r_o}{r_i}\right)}{2\pi k_B L} + \frac{1}{h_o A_o} \right\}$$
(8)

By combining equations of (7) and (8), the heat transfer coefficient can be calculated from the following correlation:

$$h_{o} = \frac{1}{A_{o}} \left[1 / \left\{ \frac{\overline{T}_{r} - \overline{T}_{nf}}{\gamma V I} - \frac{Ln\left(\frac{r_{o}}{r_{i}}\right)}{2\pi k L} \right\} \right]$$
(9)

As fluid flows from the annular space between two cylinders, the hydraulic diameter is calculated from the following correlation:

$$D_e = 4 \times \frac{\text{Free cross} - \text{sectional area for current passing}}{\text{Wet environment by flow}} = \frac{4\pi \left(D_3^2 - D_2^2\right)}{4\pi \left(D_3 + D_2\right)} = D_3 - D_2 (10)$$

Noticeably, D_e cannot be used to calculate the heat transfer coefficient; because the environment of shell is not considered as heat transfer area (wet area) and should be omitted from the calculations. So following equation is used for estimating the hydraulic diameter:

$$D_e = \frac{4\pi \left(D_3^2 - D_2^2\right)}{4\pi D_2} = \frac{D_3^2 - D_2^2}{D_2}$$
(11)

Where D_3 is the inner diameter of wall, D_2 is the external diameter of reactor tank. The amount of Nusslet number is calculated by the hydraulic diameter obtained from equation 11 and by using the following equation.

$$Nu = \frac{h_o D_e}{k} \tag{12}$$

In the present study, different parameters are measured using inlab instruments with different accuracies. The measurement errors of these parameters may influence on the general accuracy of the experimental results. Specifications of the used devices are presented in Tables 1 and 2.

| Physical properties | Diameter of particles (nm) | surface area (m²/g) | Density (kg⁄m³) | Thermal conductivity (W/mK) | Heat |
|--------------------------------|----------------------------------|------------------------|--------------------|-----------------------------------|-------|
| CuO | 40 | 20 | 6400 | 69 | 535.6 |
| Al _a O _a | 20 | 138 | 3890 | 46 | 880 |

Table 1: Thermo-physical properties of Nano-fluids.

| Instrument | Measure | Model | Range | Accuracy |
|--------------------------|----------------|------------------------|--------------|--------------|
| Turbine Flow meter | Flow rate | Vision 2000 | 0.5-35 l/min | ± 0.15 l/min |
| thermocouples | Temperature | Omega K-type | -73 to 260°C | ± 0.2°C |
| Digital Panel Meter | Current | Ziegler Delta power | 0 to 6 A | ± 0.001 A |
| Pressure transmitters | Local pressure | PSCH0.05BCIA | 0 to 50 kpa | ± 0.01 kpa |

Table 2: The model, range, and accuracy of the measuring instruments.

It is necessary to find the influence of the main parameters on the uncertainty of heat transfer coefficient. The Mc- Klintock equation is the implemented to evaluate the uncertainty of the system as equation 13 [12].

$$E_{M} = \mp \left[\left(\frac{\partial M}{\partial X_{1}} E_{1} \right)^{2} + \left(\frac{\partial M}{\partial X_{2}} E_{2} \right)^{2} + \dots + \left(\frac{\partial M}{\partial X_{n}} E_{n} \right)^{2} \right]^{1/2}$$
(13)

Where X_i is the parameter, M is the calculated from Desired parameter and E_i is measurement error and E_M shows the maximum obtained error in estimating a quantity. Therefore, experimental error of the convective heat transfer coefficient according to Equation 9 and 17 can be obtained as follows:

$$E_{h} = \mp \left[\left(\frac{\partial h}{\partial \Delta T} E_{\Lambda T} \right)^{2} + \left(\frac{\partial h}{\partial r_{o}} E_{r_{o}} \right)^{2} + \left(\frac{\partial h}{\partial r_{i}} E_{r_{i}} \right)^{2} + \left(\frac{\partial h}{\partial V} E_{V} \right)^{2} + \left(\frac{\partial h}{\partial I} E_{I} \right)^{2} \right]^{1/2}$$
(14)

The measurement error of each parameter can be calculated by dividing the maximum error on the measured value. The mean uncertainties of the measured parameters are presented in Table 3 based on the uncertainty equations and Table 2. As can be seen, deviation for heat transfer coefficient is reasonable. Therefore, data represented in this work are reliable.

Results and Discussion

Validation of experimental data

Initial experiments were performed using distilled water to determine the accuracy and reliability of results. In fact, distilled water is regarded as a reference for comparing the results of Nano-fluids.

The equation, which is used for the chamber of a tank to calculate the Nusselt number, is in the form of Equation. (15) [10]:

Nu = 1.02 Re^{0.45} Pr^{0.33}
$$\left(\frac{D_e}{H}\right)^{0.4} \left(\frac{D_1}{D_2}\right)^{0.8} Gr^{0.05}$$
 (15)

Where H is the height of thermal jacket, D_1 is the inner diameter of reactor tank and Gr is the Grashof number, which is calculated by equation (16).

$$Gr = \frac{D_e^3 \rho_f^2 g\beta \left| T_r - T_f \right|}{\mu_f^2} \tag{16}$$

The experimental results were compared to those of theoretically obtained and represented in Figure 5 for the discharge period of reactor operation. Experimental Nusselt number showed that the obtained results are within the deviation of 1.38-8%, which is a reasonable value.

Heat transfer of nano-fluid

Heat transfer coefficient depends on the thermo-physical properties of the fluid and geometrical characteristics of the system. These quantities include fluid thermal features such as thermal conductivity, specific heat, density and viscosity and system characteristics such as diameter, length and flow speed as well. As can be seen in Figures 5 and 6, by increasing Reynolds number, the heat transfer coefficient increases and clearly, at a given Reynolds number, the heat transfer coefficient of Nano-fluid is relatively higher than water. Because adding the nanoparticles into base fluid changes the flow hydrodynamic properties subsequently, this can increase the thermal conductivity and increases the Brownian motion of particles inside the trajectory line and the heat exchanging media. Such behavior may lead to the local

| Parameter | Uncertainty (%) | | |
|--------------------------------------|-----------------|--|--|
| Convective heat transfer coefficient | 3.62 | | |
| Reynolds number | 4.61 | | |
| Prandtl number | 1.43 | | |
| Nusselt number | 3.34 | | |

Table 3: The main parameters and their uncertainties.









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turbulent behavior and a slight increase in convective heat transfer coefficient. For the fluid flow with higher discharge rate, the effect of distribution of nanoparticles in the fluid is improved and this may disrupt the formed thermal boundary layer towards the reduction of thickness, which consequently leads to a higher temperature gradient near the wall. All can lead to the increase in heat transfer coefficient and Nusselt number.

For the copper oxide, as can be seen in Figures 7 and 8, the heat transfer coefficient at mass concentration of 0.4 is higher than base fluid; however, it is lower when comparing to mass concentration of 0.3. In fact, the maximum increase of the heat transfer coefficient can be seen for 0.3%. Note that, although with increasing the nanoparticles concentration, thermal conductivity of Nano-fluid can be increased, other parameters may act in a way to reduce the thermal performance of system. Increase in the concentration of nanoparticles results in the enhancement of viscosity and density of Nano-fluid. This can have significant influence on the enhancement of thickness of thermal boundary layer. The Thermophoresis phenomenon is also responsible for the enhancement of heat transfer since it facilitates the heat transfer process by moving nanoparticles from the hot walls towards the cold side. Due to the higher density of copper oxide nanoparticles comparing to aluminum oxide, this phenomenon is less effective for the Nano-fluids of copper oxide-water. Buoyancy force is a function of the specific gravity lead to produce small secondary vortices near the walls, which can be negative parameter for reducing the effective flow rate through the adjacent wall and subsequently leads the heat transfer coefficient to be decreased.

With increasing concentration, the clustering phenomenon occurs and particles may form agglomeration inside the system. Such agglomeration can increase the possibility of sedimentation and decreases the thermal conductivity. It means that there is an optimal value for the concentration of nanoparticles. Since the copper oxide nanoparticles induce larger clustering phenomenon and vast agglomeration rather than aluminum oxide, rate of increase in thermal conductivity coefficient is higher, but its optimum concentration set to the lower concentration value. Figure 9 shows the changes of Nusselt number according to Reynolds number at different mass concentration for copper oxide Nano-fluids.

In Figure 10, the heat transfer coefficient of two Nano-fluids is compared at different weight concentrations. At low concentrations,





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Figure 8: Convective heat transfer coefficient of Cupric Oxide nano-fluid versus Reynolds number at different mass concentrations.









due to the higher thermal conductivity of copper oxide, the higher heat transfer coefficient is registered, while based on the above-mentioned point, there is an optimal concentration of copper oxide (0.3% by weight), therefore after this point. The heat transfer coefficient of copper oxide decreases such that the heat transfer coefficient of two Nano-fluids are overlapped at wt. %=0.4.

The effect of nanoparticles on pressure drop

When nanoparticles are added to the base fluid, dynamic viscosity of Nano-fluids increases. Since the pressure drop strongly depends on the viscosity, the higher values for pressure drop are reported. As can be seen in Figures 11 and 12, with increasing the mass concentration of Nano-particles, the viscosity and subsequently, the pressure drop value considerably increases such that at mass concentration of 0.4%, the highest value for pressure drop can be seen. The amount of penalty for the pressure drop (enhancement in pressure drop value) for aluminum oxide Nano-fluid is 12%.

In Figure 13, the changes of pressure drop are shown in terms of mass concentration in volumetric discharge rate of 4 lit/min. By increasing the mass concentration, the Nano-fluid viscosity increases and post-drop pressure represents the increasing upward trend. Because the viscosity of Nano-fluid has a reverse relation with the size of nanoparticles, as a result higher viscosity for aluminum oxide Nano-fluid (particle size=20 nm) is registered, when comparing to the copper oxide (particle size=40 nm). This also leads the higher penalty for pressure drop when aluminum oxide is used in the system.

Thermal performance

For the sake of validation in thermal performance assessment of Nano-fluids, the factor of Π is defined as follows [11]:

$$\eta = \left(\frac{Nu_{nf}}{Nu_f}\right) \left(\frac{f_f}{f_{nf}}\right)^{\frac{1}{3}}$$
(16)

And, *f* is the Friction factor, which can be calculated using Equation (17) as follows:

$$f = \frac{\Delta P}{\frac{1}{2}\rho u^2 \left(\frac{L}{D_e}\right)}$$
(17)



with different mass concentrations versus Reynolds number.



Figure 12: Variation of pressure drop for water and alumina oxide Nano-fluid with different mass concentrations versus Reynolds number.



Variations of thermal performance factor of reactor for the water-CuO and water-Al₂O₂ Nano-fluids are depicted in Figure 14 (A-B). As can be seen, the thermal performance at studied range of Nano-fluid concentration and Reynolds number is higher than unity. In Figure 15, the Thermal performance of two nano-fluids of copper oxide and aluminum oxide are compared in different mass concentrations. The maximum Thermal performance factor related to copper oxide in 0.3% concentration at Re=444 was 1.102.

Conclusions

- The thermal performance of two different Nano-fluids in cooling of a reactor with exothermic reaction is experimentally investigated and following conclusions have been drawn:
- Based on results, two Nano-fluids of copper oxide and aluminum oxide showed higher thermal performance over the base fluid and increase of concentration and Reynolds number led to the increase in the heat transfer coefficient and pressure drop.
- By increasing the mass concentration of aluminum oxide Nanofluid, the heat transfer coefficient increases up to concentration

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Figure 15: The comparison between thermal performance factor of aluminum and copper Oxide Nano fluid versus Reynolds number in different mass concentrations.

of 0.4%. However, for copper oxide, heat transfer coefficient increased up to concentration of 0.3% and gradually decreased due to the anomalous increase in viscosity and density, which had a negative impact on thermal performance of Nano-fluids. Therefore, there is an optimal concentration for Nano-fluids.

- The maximum heat transfer coefficient for copper oxide was registered at concentration of 0.3% by weight, which reports the 13% enhancement in heat transfer coefficient. This value was 11.7% for alumina Nano-fluid and at concentration of 0.4% by weight.
- Adding the nanoparticles into the base fluid increased the pressure drop as maximum pressure drop was seen at 0.4% by weight for alumina Nano-fluid. The penalty for the pressure drop was 12% higher when comparing to the base fluid.
- A rough comparison between pressure drops of two Nanofluids was performed. Results demonstrated that in a given volumetric flow rate, the higher pressure drop of Nano-fluid for aluminum oxide was obtained, because particles of aluminum oxide (20 nm) was smaller than copper oxide (40 nm), which caused higher viscosity for aluminum oxide Nano-fluid and

subsequently, pressure drop was higher for the aluminum oxide Nano-fluids.

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Nomenclature

| A | Outer surface of the inner cylinder (m ²) | | |
|----------------|---|--|--|
| C _P | Heat capacity (W/mk) | | |
| d _h | Hydraulic diameter (m) | | |
| d _p | Nanoparticles Diameter (m) | | |
| f | Friction factor | | |
| h | convective heat transfer coefficient (W/m ² k) | | |
| 1 | Current strength (A) | | |
| К | Thermal conductivity (W/mk) | | |
| LPM | liter per minute | | |
| Nu | Nusselt number | | |
| Р | Pressure (kgm ⁻¹ S ⁻²) | | |
| Pr | Prandtl number | | |
| Re | Reynolds number | | |
| r _o | Outer diameter of the central cylindrical (m) | | |
| Т | Temperature(k) | | |
| u | Velocity(m/s) | | |
| V | Voltage (v) | | |
| Greek symbols | | | |
| μ | Dynamic viscosity(kgm ⁻¹ s ⁻¹) | | |
| ρ | Density (kgm ⁻³) | | |
| φ | nanoparticles volume fraction | | |
| γ | Heat dissipation factor | | |
| η | thermal performance factor | | |
| Subscripts | | | |
| f | Base fluid | | |
| i | Inner | | |
| nf | Nano-fluid | | |
| 0 | outer | | |
| p | Particles | | |

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