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Numerical study on fly ash–Cu hybrid nanofluid heat transfer characteristics

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ABSTRACT

The current numerical study is aimed to examine the forced convection heat transfer of fly ash-Copper (80:20% by volume) water-based hybrid nanofluids flowing in a horizontal circular copper tube under a constant heat flux of 7962W/m² using STAR CCM+ software. The volume concentrations of 0.5% and 1% are considered for the analysis within the Reynolds number range of 6900-26500. The findings show that the heat transfer coefficient and the Nusselt number of hybrid nanofluid at a concentration of 1 vol.% are increased by about 66.0% and 36.67% compared to that of water.

Introduction

Hybrid nanofluids, in which two separate nanoparticles are dispersed in a base fluid, combine the advantages of increasing the thermal conductivity of both constituents and aim to maintain viscosity at low numbers [1-3]. Numerically and experimentally numerous studies have studied different kinds of nanofluids in laminar and turbulent flow conditions. The first research work on convective heat transfer of nanofluids in a circular tube was reported by Pak and Cho [4]. Hussein et al. [5] examined the influence of the cross-sectional area on heat and flow characteristics. They observed that in contrast with the circular tube and elliptical tube, the flat tube has a substantial enhancement in heat transfer and pressure drop.



Madhesh et al. [6] examined the augmentation in heat transfer and rheological characteristics of Cu-TiO₂ hybrid nanofluids flows in the tubular heat exchanger for the volume concentration of 0.1% to 1.0%. The findings showed that the hybrid nanofluid heat transfer coefficient improved by 59.3% for 0.7% of the hybrid nanocomposite volume concentration.

Sundar et al. [7] investigated the heat transfer characteristics of Fe₃O₄ / MWCNT hybrid nanofluids under turbulent conditions in a flat tube. Results showed a 32% augmentation in heat transfer with a penalty of 1.2 times increment in pumping power for volume concentration of 0.3% below 20,000 Reynolds contrast to water.

Moghadesi et al. [8] examine the influence of Al₂O₃ nanofluid and Al₂O₃-Cu hybrid nanofluid flowing through a horizontal circular tube under laminar forced convective heat transfer using CFD software. In contrast to alumina nanofluid and water, the average Nusselt number improvement for hybrid nanofluids at 0.1 vol. % was 4.73% and 13.46%, respectively.

The current research aims to study the heat transfer coefficient and Nusselt number of water-based fly ash–Copper (80:20% by volume) hybrid nanofluids for turbulent flow using the CFD method. The hybrid nanofluids volume concentrations of 0.5 and 1.0% flow in a circular copper tube having an inner and outer diameter 16mm and 19mm with a constant heat flux of 7962 W/m².

2.0 Nanofluid Preparation

The first step in the hybrid nanofluid preparation is the water suspension and stabilization of nanoparticles. Kumar and Arasu [9] used Eq. (1) to calculate the volume concentration of hybrid nanofluid.

$$\varphi(\%) = \frac{\left(\frac{m_{np1}}{\rho_{np1}}\right) + \left(\frac{m_{np2}}{\rho_{np2}}\right)}{\left(\frac{m_{np1}}{\rho_{np1}}\right) + \left(\frac{m_{np2}}{\rho_{np2}}\right) + \left(\frac{m_{bf}}{\rho_{bf}}\right)} \quad (1)$$

Using a two-step method, fly ash and copper nanoparticles in the ratio of 80:20% by volume are weighed with a digital electronic balance to prepare the hybrid nanofluid in 0.5 and 1.0 vol. % using water. This mixture is subjected to magnetic stirring for 30 min. The stability of the mixture is obtained by adding Triton X-100 surfactant 0.25% by weight of nanoparticles. After preparing the suspension, an ultrasonic probe is run for 180 min to break any agglomeration. The average size of hybrid consisting of fly

ash and Cu particles is also evaluated with Zeta sizer found to be 15 nm. The maximum and minimum zeta potential values of 36.6 mV and 34.1 mV are observed at 0.5% and 1.0% volume concentration respectively.

2.1 Thermophysical properties

LVDV-II Pro Brookfield digital viscometer and KD2 Pro analyzer were used to determine the dynamic viscosity and thermal conductivity of hybrid nanofluids respectively. Tables 1 and 2 displays the thermophysical properties of nanoparticles and test conditions.

Takabi and Salehi [10] developed a correlation given by Eq. (2). The experimental values of density for the hybrid nanofluid are compared with the values estimated with Eq. (2).

$$\rho_{hnf} = \varphi_{fnp} \rho_{fnp} + \varphi_{Cu} \rho_{Cu} + (1 - \varphi_{hnf}) \rho_{bf} \quad (2)$$

Where $\varphi_{hnf} = \varphi_{fnp} + \varphi_{Cu}$

The fly ash–Cu hybrid nanofluid specific heat have been estimated using the mixture relation proposed by Takabi and Salehi [10] given in Eq. (3)

$$(c_p)_{hnf} = \frac{(\rho\varphi c_p)_{fnp} + (\rho\varphi c_p)_{Cu} + (1 - \varphi_{hnf})(\rho\varphi c_p)_{bf}}{\rho_{hnf}} \quad (3)$$

Where $\varphi_{hnf} = \varphi_{fnp} + \varphi_{Cu}$

The measured viscosity values of hybrid nanofluid are then compared with relations proposed by Wang et al. [11] shown in Eq.(4).

The Eq. (4) proposed by Wang et al. [11] is given by

$$\frac{\mu_{nf}}{\mu_{bf}} = (1 + 7.3\varphi_{hnf} + 123\varphi_{hnf}^2) \quad (4)$$

The experimental thermal conductivity values of hybrid nanofluid are compared with the Maxwell model [12]. Eq. (5) is the Maxwell model [12] used to estimate the thermal conductivity of mono nanofluids. In the present study to assess the thermal conductivity of hybrid nanofluid, Eq. (6) resulted from the Maxwell equation, used to determine the thermal conductivity of fly ash- Cu (80:20% by volume) hybrid nanofluid.

$$\frac{k_{nf}}{k_w} = \frac{k_p + 2k_w - 2\varphi_p(k_w - k_p)}{k_p + 2k_w + \varphi_p(k_w - k_p)} \quad (5)$$

For hybrid nanofluid,

$$\frac{k_{hnf}}{k_{bf}} = \frac{(\varphi_{FA}k_{FA} + \varphi_{Cu}k_{Cu}) + 2k_{bf} + 2(\varphi_{FA}k_{FA} + \varphi_{Cu}k_{Cu}) - 2\varphi k_{bf}}{(\varphi_{FA}k_{FA} + \varphi_{Cu}k_{Cu}) + 2k_{bf} - (\varphi_{FA}k_{FA} + \varphi_{Cu}k_{Cu}) + \varphi k_{bf}} \quad (6)$$

Table 1 Thermophysical properties of fly ash nanoparticle

Sl. No	Property	Fly ash nanoparticle	Copper nanoparticle
1.	Density, kg /m ³	1920	8933
2.	Specific heat, J / kg- K	514	385
3.	Thermal conductivity, W/m-K	1.7	400

Table 2 Test conditions

Sl.No	Constraints	Standards/Range
1	Heating material and Tube material	Nichrome wire and copper
2.	Mass flow rates	5, 8, 11, 14, and 16 LPM
3.	Insulating material	Asbestos rope
4.	Thermocouples on the tube surface	5
5.	Thermocouples used to measure fluid inlet and outlet temperatures	2, (T _i and T _o)

2.2 Governing equations and CFD model

In this work, the single-phase method, incompressible fluid, the turbulent viscous realizable k-ε, two-layer, all Y+ treatment was used. The one kW capacity Nichrome heater is mounted on the tube surface to provide uniform heat flux. Five K- type thermocouples are positioned on the tube surface at equidistance from the pipe inlet to measure the surface temperature and the other two thermocouples are used to measure fluid inlet and outlet temperatures. The heater is wrapped with Asbestos insulation to minimize the heat losses to the surroundings. The tube inlet and outlet are extended to five times of tube inner diameter to get the fully developed flow

2.3 Theoretical analysis

The simulation results of nanofluid were used to calculate the heat transfer coefficient and Nusselt number using Eqs. (7) and (8) respectively

$$h_{hnf} = \frac{Q}{A_s(T_s - T_b)} \quad (7)$$

$$\text{Where, } T_b = \frac{T_1 + T_0}{2}, T_s = \frac{T_1 + T_2 + T_3 + T_4 + T_5}{5}$$

Nusselt number of water and hybrid nanofluid is given by,

$$Nu_{hnf} = \frac{h_{hnf} D}{k_{hnf}} \quad (8)$$

The Reynolds number and Prandtl number of water and hybrid nanofluid are estimated using Eqs. (9) and (10), respectively. The thermal properties have taken at the bulk temperature T_b .

$$Re_{hnf} = \frac{\rho_{hnf} V D}{\mu_{hnf}} \quad (9)$$

$$Pr_{hnf} = \frac{\mu_{hnf} C_{p_{hnf}}}{k_{hnf}} \quad (10)$$

The Dittus–Boelter [13] equation is applicable for $Re > 10^4$ and $0.6 < Pr < 200$ is given by

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad (11)$$

The Nusselt number correlations for nanofluids are listed below.

Pak and Cho [4]

$$Nu = 0.021 Re^{0.8} Pr^{0.5} \quad (12)$$

Duangthongsuk and Wongwises [14]

$$Nu = 0.07 Re^{0.707} Pr^{0.385} \varphi^{0.074} \quad (13)$$

Maiga et al. [15]

$$Nu = 0.085 Re^{0.71} Pr^{0.35} \quad (14)$$

2.4 Boundary conditions

The fly ash - Copper hybrid nanofluid 0.5 and 1.0 vol. % and the inlet temperature of the fluid in all the cases is 30°C used as input conditions. Water is also used to validate and compare the hybrid nanofluid results. The boundary conditions of the analysis presented in Table 3. STAR-13.06.012 (r8 Double Precision) software meshes the modeling of the test segment. Meshed model of test segment shown in Fig.1. The STAR CCM+ program is to solve turbulent heat transfer equations using a finite volume method (FVM).

Table 3 Boundary conditions

Sl.No	Constraints	Value
1.	The inlet temperature of nanofluid	30°C
2.	Uniform heating of the copper tube	600 W
3.	Heat flux	7962W/m ²
4.	Tube length and inner diameter	1.5m and 16mm

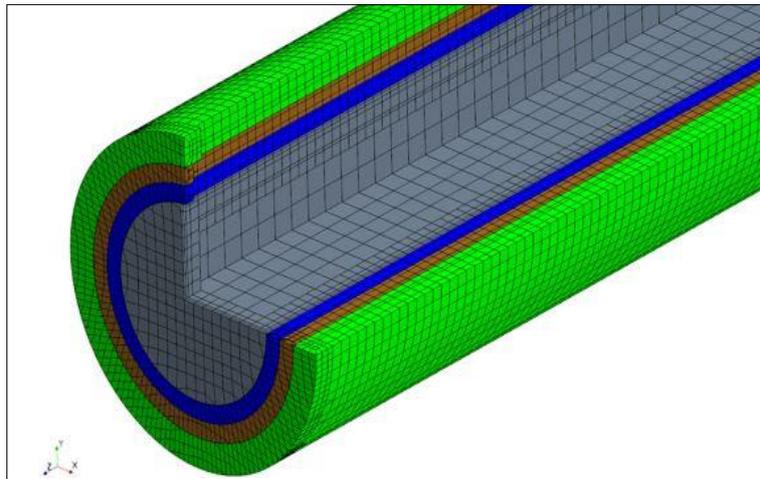


Fig. 1 Meshed model of the test section

3. Results and Discussions

3.1 Thermophysical properties

Thermal conductivity and viscosity of fly ash–Cu hybrid nanofluid measured with KD2 Prometer and LVDV-II Pro Brookfield Programmable digital viscometer respectively. The Maxwell model [12] underestimates the fly ash-copper hybrid nanofluid thermal conductivity. Similarly, the Wang model [11] also underestimates the experimental viscosity values of fly ash– copper hybrid nanofluid. The thermal conductivity and dynamic viscosity values of studied hybrid nanofluid at 30°C for different concentrations are presented in Table 4.

Table 4. Thermal conductivity and dynamic viscosity values of fly ash –Cu hybrid nanofluid at 30°C

Concentration	Thermal conductivity (W/m K)	Dynamic viscosity (mPa-s)
0.5 vol.%	0.7	0.975
1.0 vol.%	0.752	0.99

3.2 Heat transfer characteristics

The influence of Reynolds number on the heat transfer coefficient of fly ash-Cu hybrid nanofluid is plotted in Fig. 2. The heat transfer coefficient of hybrid nanofluid is found to intensify with the concentration of particles and Reynolds number. It is because of fly ash-Cu hybrid nanofluid has good thermal conductivity [7-8]. The presence of copper particles even in small amount enhance the hybrid nanofluid thermal conductivity.

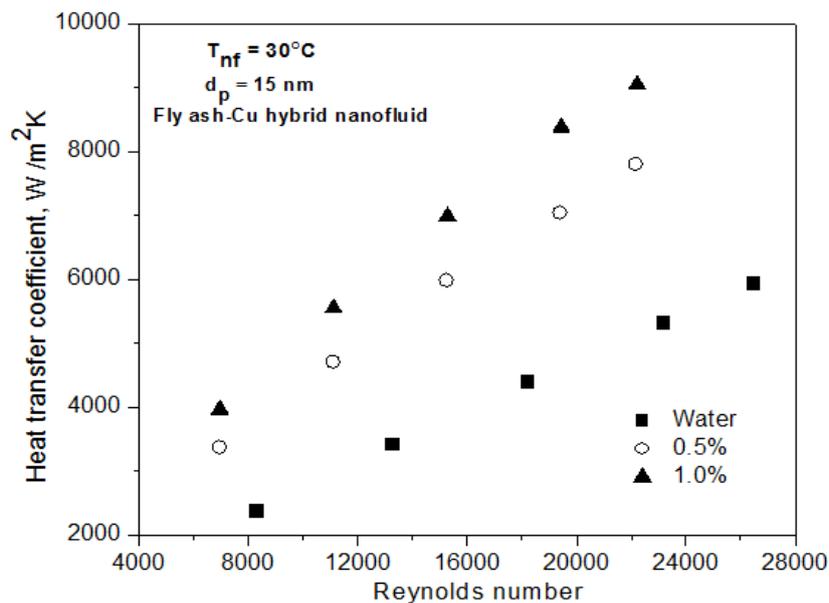


Fig. 2. Reynolds number on the heat transfer coefficient of hybrid nanofluid

To validate the results of a present study, The Nusselt numbers of water determined with Eq. (8) are shown in contrast with that of determined with the Dittus–Boelter [13] equation in Fig. 3. A fair agreement between the Nusselt number of water and that of estimated with Dittus –Boelter [13], i.e., Eq. (11) confirms the reliability of the data.

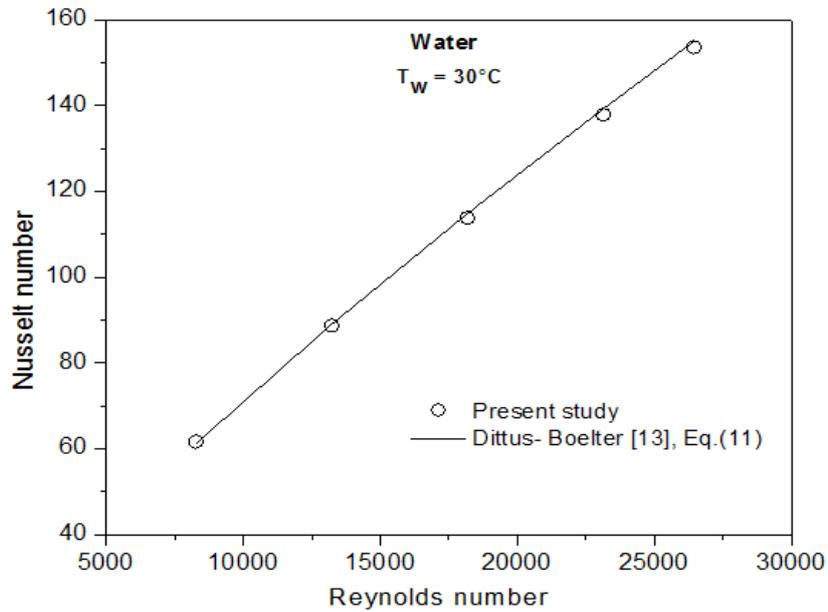


Fig. 3. Nusselt number of water estimated from Eq. (8) in contrast with correlations. The Nusselt number of hybrid nanofluids was determined using Eq. (8), and it is illustrated in Fig. 4. The Nusselt number of nanofluid enhances with particle concentration and Reynolds number. Since the thermal conductivity of fly ash –Cu hybrid nanofluid is more in contrast to water. The micro convection, the surface area of nanoparticles contributes to the thermal conductivity of hybrid nanofluid’s improvement [5-8].

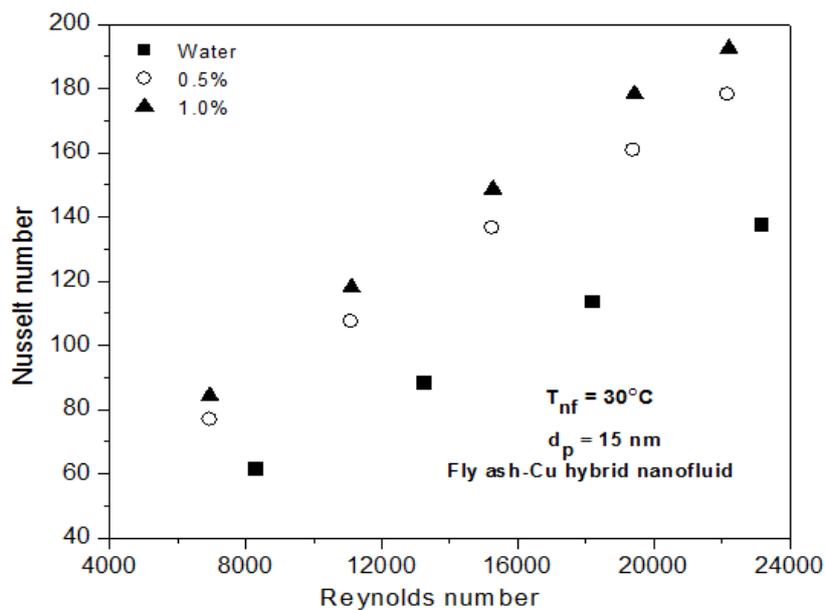


Fig. 4 Nusselt number of hybrid nanofluid variation with Reynolds number

The Nusselt number of fly ash –Cu hybrid nanofluids are compared with Pak and Cho [4], Duangthongsuk and Wongwises [14], and Maiga et al. [15] correlations available for the Nusselt number estimation of nanofluids is depicted in Fig. 5. Eqs. (12), (13), and (14) underestimate the Nusselt number of hybrid nanofluid. These variances due to the improved thermal properties of fly ash-Cu hybrid nanofluid [17].

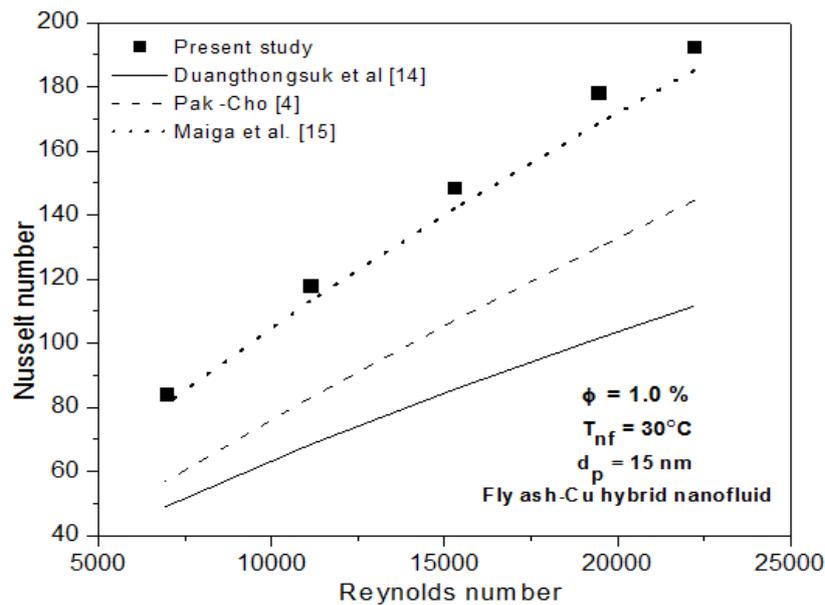


Fig. 5 Nusselt number of hybrid nanofluids comparison with that of correlations.

The fly ash –Copper hybrid nanofluid Nusselt number is compared with that of Cu-TiO₂ hybrid nanofluids used by the Madhesh et al. [6] at a 1.0 vol. % portrayed in Fig. 6. It is found that the Nusselt number of hybrid nanofluid enhanced with both particle loading and the Reynolds number in both the works. The deviation between the Nusselt numbers of both the hybrid nanofluids at lower Reynolds number is insignificant.

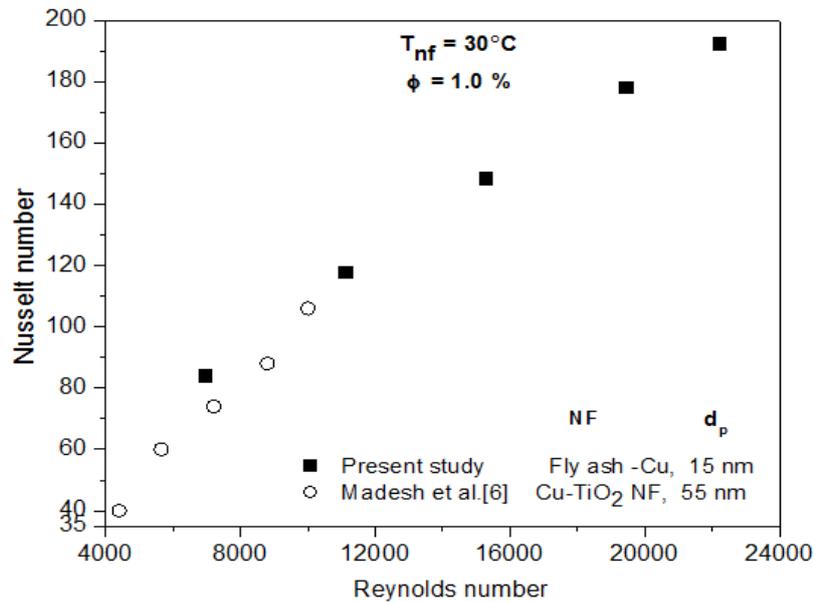


Fig. 6 Comparison of the Nusselt number of hybrid nanofluids with Madhesh et al. [6].

4. Conclusions

The following conclusions are taken from the work under consideration.

1. The correlations available in the literature failed to estimate the thermal conductivity and viscosity values of fly ash –Cu (80:20% by volume) hybrid nanofluid.
2. The addition of nanoparticles to the base fluid enhances the convective heat transfer. The maximum amplification in the heat transfer coefficient of 66.0% was observed at a concentration of 1.0 % of hybrid nanofluid compare to water.
3. The correlations available in the literature for estimation of Nusselt number of nanofluids were not suitable to estimate that of hybrid nanofluid.
4. Finally, fly ash-Cu hybrid nanofluid has exhibits better heat transfer characteristics compared to the base fluid, and also it is cost-effective.

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List of symbols

- A_s : surface area of the tube, m²
 C_p : specific heat, J /kg K
 D : diameter of a tube, m
 d_p : Diameter of nanoparticle, nm
 h : heat transfer coefficient, W/m K
 K_p : Thermal conductivity of nanoparticle, W/m K
 L : Length of the tube, m
 LPM : Litre per minute
 m : mass, kg
 NF : Nanofluid
 Nu : Nusselt number
 Pr : Prandtl number
 Re : Reynolds number
 T_b : bulk temperature °C

T_i : fluid temperature at inlet, °C

T_o : fluid temperature at outlet, °C

V : velocity of the fluid, m/s

Greek symbols

ρ : Density , kg/m³

φ : Volume concentration

μ : Viscosity, mPa.s

Subscript

bf : base fluid

Cu : Copper

FA : Fly ash

hnf : hybrid nanofluid

np : nanoparticle

w :Water