A CFD Study on fly ash nanofluid heat transfer behavior in a circular tube
Praveen Kanti¹, K.V.Sharma²*, C.G.Ramachandra³, M Gurumurthy⁴
¹Department of Mechanical Engineering, Jyothy institute of technology, Bangalore,
Karnataka, India
²Center for Energy Studies, Department of Mechanical Engineering, JNTUH College
of Engineering, Kukatpally, Hyderabad, Telangana, India
³Department of Mechanical Engineering, Presidency University, Bangalore,
Karnataka, India
⁴Department of Mechanical Engineering, Jyothy institute of technology, Bangalore,
Karnataka, India
* Author correspondence E-mail: praveenkanti87@gmail.com

ABSTRACT

STAR CCM+ software is used to investigate the forced convection heat transfer of fly
ash/Water nanofluids flowing through a horizontal circular tube in the turbulent flow
regime under the constant heat flux of 707 W/m². The volume concentrations of
nanofluid are 0.3, 0.5, 1.0, and 1.5 vol. %, used in this analysis. The results revealed
that both the Reynolds number and concentration intensify the Nusselt number of fly
ash nanofluids. The highest heat transfer coefficient augmentation is about ~60%
observed at 1.5% concentration in comparison to the water.

1.0 Introduction

The most important technological issues affecting many sectors, such as power plants,
manufacturing processes, transportation, and electronics, are heating and cooling.
Classical heat transfer rate enhancement approaches, such as usage of fins, heat surface
vibration, fluid injection or suction, and the utilization of electrical or magnetic fields,
practically fulfill the requirements of heat flux increments [1–2]. Common heat transfer
fluids such as water, ethylene glycol, and glycerine appear to also have low conductivity
contrast to metals and metal oxides. Hence, fluids containing suspended solid particles
would have greater heat transfer capabilities relative to traditional heat transfer fluids [3-4].

Practical implications of fluids with a millimeter or micrometer-sized suspension particles display several issues, such as particle instability, oxidation, and flow path congestion, and produce additional pressure drop [5–8]. Modern developments in the processing of nanosized metal or non-metallic particles have permitted the development of a new category of fluid called nanofluid coined by Choi in 1995 [8]. Fotukian and Nasr [9] studied much diluted (< 0.24% volume) water-based copper oxide nanofluid turbulent convective heat transfer efficiency. In their analysis, it was described that the improvement in nanofluid concentration had a marginal impact on heat transfer amplification.

The convective heat transfer for water-dependent Al₂O₃ and CuO nanofluids was investigated by Heris et al. [10] through a circular coil in the laminar flow and noticed that alumina nanofluids displayed significant amplification in contrast to copper oxide nanofluids.

Variyenli. [11] examined the heat transfer behavior plate heat exchanger using fly ash nanofluid experimentally and numerically by changing fluid mass flow rate and temperature. ANSYS FLUENT is used to model heat transfer characteristics. The findings revealed that the nanofluid increased the overall heat transfer coefficient of about 6-20% compared to water.

In the present work, an efficient single-phase model was adapted to determine the heat transfer coefficient of fly ash nanofluid of volume concentrations 0.3 to 1.5% flows through a copper tube with a constant heat flux of 707 W/m² at various mass flow rates.

2.0 Methodology
2.1 Model details
The single-phase approach, which was predominantly used for nanofluids, is being introduced in this research [20]. Each of the governing equations was used for simulation, and various experiments were performed on the same basis. The turbulent viscous realizable k-ε, two-layer, all Y+ treatment was used for this research.

The 1kW capacity nichrome heater is mounted on the copper tube surface to provide constant heat flux. Three 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 heat losses. The copper tube inlet and outlet are extended to 5 times of tube inner diameter to get the fully developed flow

2.2 Theoretical analysis

The fly ash nanofluid simulation results were used to calculate the heat transfer coefficient and Nusselt number using Eqs. (1) and (2) respectively.

$$h = \frac{Q}{A_s(T_s - T_b)}$$  \hspace{1cm} (1)

Where, \( T_b = \frac{T_i + T_o}{2} \), and, \( T_s = \frac{T_1 + T_2 + T_3}{3} \)

Nusselt number of fly ash nanofluid was given by,

$$Nu_{nf} = \frac{h_{nf}D}{k_{nf}}$$  \hspace{1cm} (2)

The Reynolds number and Prandtl number of the fly ash nanofluid are estimated using Eqs. (3) and (4), respectively. The properties measured at bulk temperature \( T_b \).

$$Re_{nf} = \frac{\rho_{nf} V D}{\mu_{nf}}$$  \hspace{1cm} (3)

$$Pr_{nf} = \frac{h_{nf} C_{p nf}}{k_{nf}}$$  \hspace{1cm} (4)

The Dittus–Boelter [12] equation is applicable for the range of \( Re > 10^4 \) and \( 0.6 < Pr < 200 \)

$$Nu = 0.023 Re^{0.8} Pr^{0.4}$$  \hspace{1cm} (5)

Below are the correlations to determine the Nusselt number of nanofluids.

Pak and Cho [16] for TiO\(_2\) nanoparticles

$$Nu = 0.021Re^{0.8} Pr^{0.5}$$  \hspace{1cm} (6)

\( 10^4 < Re < 10^5 \)

Duangthongsuk and Wongwises [13] for TiO\(_2\) nanoparticles

$$Nu = 0.07Re^{0.707} Pr^{0.385} \varphi^{0.074}$$  \hspace{1cm} (7)

\( 3000 < Re < 18000, 0 < \varphi < 2\% \)

2.3 Thermophysical properties

Thermal conductivity and viscosity of fly ash nanofluid for all concentrations are determined using the KD2 Pro analyzer and LVDV-II Pro Brookfield Programmable
digital viscometer with the accuracy of ±5% and ±1%, respectively. Table 1 lists the thermophysical properties of fly ash nanoparticles. The test conditions of the present work are described in Table 2. The experimental values of fly ash nanofluid thermal conductivity contrasted to Patel et al. [14] and Maiga et al.[15] corresponding to viscosity.

Pak and Cho [16] relation used to determine the density of nanofluid is given by
\[
\rho_{nf} = (1 - \varphi)\rho_{bf} + \varphi\rho_{nf}
\]  
(8)

Xuan and Roetzel [17] relation used to determine the fly ash nanofluid specific heat is given by
\[
c_{p \, nf} = \frac{(1-\varphi)(\rho \, c_{p})_{bf} + \varphi(\rho \, c_{p})_{np}}{(1-\varphi)(\rho)_{bf} + \varphi(\rho)_{np}}
\]  
(9)

Maiga et al.[15] as a function of concentration is
\[
\frac{\mu_{nf}}{\mu_{bf}} = (1 + 7.3\varphi + 123\varphi^2)
\]  
(10)

Patel et al. [14]
\[
\frac{k_{nf}}{k_{w}} = \left(1 + 0.135\left(\frac{k_{p}}{k_{f}}\right)^{0.273}\left(\frac{\tau}{20}\right)^{0.547}\left(\frac{100}{d_{p}}\right)^{0.234}\varphi^{0.467}\right)
\]  
(11)

Table 1 Thermophysical properties of fly ash nanoparticle and 1 vol.% nanofluid

| Sl. No | Property                        | Fly ash nanoparticle | 1 vol.% nanofluid |
|--------|--------------------------------|----------------------|-------------------|
| 1.     | Density, kg/m³                  | 1920                 | 1005              |
| 2.     | Specific heat, J/kg K           | 514                  | 4108.29           |
| 3.     | Viscosity, kg/m s               | -                    | 0.00089           |
| 4.     | Thermal conductivity, W/m K     | 1.7                  | 0.715             |

Table 2 Testing conditions

| Sl.No  | Constraints                                      | Standards/Range     |
|--------|--------------------------------------------------|---------------------|
| 1.     | Tube material                                    | Copper              |
| 2.     | The inner and outer diameter of the tube         | 0.01 m and 0.013m   |
| 3.     | Heating material                                 | Nichrome wire       |
| 4.     | Length of the tube                               | 2 m                 |
| 5.     | Mass flow rates                                  | 2, 3, 4, 5, and 6 LPM|
| 6.     | Reynolds number range                            | 4500-16000          |
2.4 Boundary conditions

The volume concentrations of fly ash nanofluids from 0.3 to 1.5% are used as the input condition. In this analysis, water is also used to compare the results of nanofluids using a CFD approach. It was assumed that Reynolds number was increased as input data from 4500 to 16000 at each iteration run. Table 3 illustrates the boundary conditions of the present study.

| Sl.No | Constraints                                    | Standards/Range |
|-------|-----------------------------------------------|-----------------|
| 1.    | The inlet temperature of nanofluid            | 30°C            |
| 2.    | Uniform heating of the copper tube            | 45 W            |
| 3.    | Constant heat flux                            | 707 W/m²        |

2.5 CFD model

STAR-CCM+ 13.06.012 software creates the geometry, meshes the modeling, and also solves the turbulent heat transfer equations. The number of elements in the meshed model is 1445625. Figs. 1(a) and 1(b) illustrate the CAD model and meshed model.

3. Results and discussions

3.1 Thermophysical properties

The thermal conductivity and viscosity of fly ash nanofluids at volume concentration (0.3–1.5%) and base fluid were measured at 30°C temperature. The thermal
conductivity and viscosity of fly ash nanofluids with particle loading are significantly enhanced. The highest deviation between the thermal conductivity data from the experiment and the values obtained by Patel et al. [14] is -4.0%. Likewise, measured dynamic viscosity data has the maximum variance with the values estimated by Maiga [15] correlation is 2.89%. Such variations are due to the presence of a surfactant and even smaller spherical particle form due to the influence of the ball milling effect [21, 22, 23, 24].

3.2 Heat transfer coefficient (HTC)

Figs. 2 and 3 display the influence of Reynolds number on heat transfer coefficient and Nusselt number. It is found that from both the figures, the intensification of heat transfer and Nusselt number with the concentration of fly ash nanofluids and Reynolds number. This is due to the increment in the nanoparticles' number in the base fluid which enhances the Prandtl number and nanofluid thermal conductivity in contrast to the water. Also, Brownian movement and dispersion stability also responsible [18-19]. The largest augmentation in the HTC and Nusselt number is about 60% and 36% in the context of Reynolds number tested with a concentration of 1.5%. Figs. 4(a) and 4(b) illustrate the velocity plots for 2 and 6 LPM for the concentration of 1.5%. It is observed that fluid velocity is maximum at the center of the tube.
Fig. 3. Reynolds number against fly ash nanofluid Nusselt number

Fig. 4(a). Velocity plot for the concentration of 1.5% at 2 LPM

Fig. 4(a). Velocity plot for the concentration of 1.5% at 6 LPM

The Nusselt number for water determined using Eq. (2) compared with the Dittus–Boelter [12] equation in order to assess the reliability of numerical data is illustrated in
Fig. 5. A decent agreement between the computational data of the water Nusselt number and the data determined with Eq. (5) under various Reynolds numbers.

The Nusselt number of fly ash nanofluid determined using computational values is compared with the values estimated from various correlations. Fig. 6 depicts the comparison between the Nusselt number of fly ash nanofluid and that of estimated from Pak and Cho [16], and Duangthongsuk and Wongwises [13] correlation for 0.5% concentration. The fly ash contains TiO$_2$ has its chemical composition, hence comparison made with these two correlations. The largest deviation in Nusselt number of fly ash nanofluid and that of determined using Pak and Cho [16], and Duangthongsuk and Wongwises [13] correlation was 17.9% and 55%, respectively.
Figure 6. Comparison of Nusselt number of fly ash nanofluids with Eq. (6) and (7). Hussein et al. [20] performed the convective heat transfer characteristics of SiO₂ nanofluid for various concentrations numerically. The fly ash contains nearly 60% of silica along with other metal oxides in different mass ratios. Hence, the comparison is made with silica nanofluid. The Nusselt number of fly ash nanofluid contrasted to data of Hussein et al. [20] for 1.0% volume concentration is plotted in Fig. 7. It is witnessed that fly ash nanofluid shows a higher Nusselt number contrast to that of silica nanofluid at the same concentration and Reynolds number.

![Plot of Nusselt number vs Reynolds number](image)

Fig. 7. Comparison of Nusselt number of fly ash nanofluid with Hussein et al. [20]

4. Conclusions
Throughout this work, the numerical simulation approach was adopted to analyze the fly ash nanofluid heat transfer characteristics under constant heat flux for various flow conditions. 

1. The maximum deviation between the experimental viscosity and thermal conductivity values and that obtained from Eq. (10) and Eq. (11) is 2.9% and -4.0%, respectively.
2. The largest augmentation in the HTC was about 60% observed at a 1.5% concentration of fly ash nanofluid contrasted to water.
3. The maximum amplification in the Nusselt number was 36% obtained for a concentration of 1.5% of fly ash nanofluid contrasted to water.
4. Finally, the Reynolds number effect on nanofluid heat transfer is more powerful than the effect on volume concentration of fly ash nanofluids.
References

1. A. S. Ahuja, Augmentation of Heat Transport in Laminar Flow of Polystyrene Suspension, I. Experimental and Results, J. Appl. Phys., vol. 46, pp. 3408–3418, 1975.

2. B. M. Da Silva Miranda and N. K. Anand, Convective Heat Transfer in Channel with Porous Baffles, Numer. Heat Transfer A, vol. 46, pp. 425–452, 2004.

3. A. E. Bergles, Recent Development in Convective Heat Transfer Augmentation, Appl. Mech. Rev., vol. 26, pp. 675–684, 1973.

4. H. Masuda, A. Ebata, K. Teramat, and N. Hishinuma, Alteration of Thermal Conductivity and Viscosity of Liquid by Dispersing Ultra-fine Particles (Dispersion of Al₂O₃, SiO₂ and TiO₂ Ultra-fine particles), Netsu Bussei (Japan), vol. 4, pp. 227–233, 1993.

5. P. Kebliski, S. R. Phillpot, S. U. S. Choi, and J. A. Eastman, Mechanism of Heat Flow in Suspension of Nano-Sized Particle (Nanofluids), Int. J. Heat Mass Transfer, vol. 45, pp. 855–863, 2002.

6. H. Xie, J. Wang, T. Xi, and Y. Liu, Thermal Conductivity of Suspensions Containing SiC particles, Int. J. Thermophys., vol. 23, pp. 571–580, 2002.

7. B. X. Wang, L. P. Zhou, and X. F. Peng, A Fractal Model for Predicting the Effective Thermal Conductivity of Fluid with Suspension of Nanoparticles, Int. J. Heat Mass Transfer, vol. 46, pp. 2665–2672, 2003.

8. S. U. S. Choi, Enhancing Thermal Conductivity of Fluid with Nanoparticles, in D. A. Siginer and H. P. Wang (eds.), Developments and Applications of Non-Newtonian flows, FED-vol., vol. 66, p. 99, American Society of Mechanical Engineers, New York, 1995.

9. S. M. Fotukian and M. Nasr Esfahany, Experimental Study of Turbulent Convective Heat Transfer and Pressure Drop of Dilute Cu-Water Nanofluid Inside a Circular Tube, Int. Comm. Heat Mass Transfer, vol. 37, pp. 214–219, 2010.

10. S. Z. Heris, M. N. Esfahany, and S. G. Etemad, Experimental Investigation of Convective Heat Transfer of Al₂O₃-Water Nanofluid in Circular Tube, Int. J. Heat Fluid Flow, vol. 28, pp. 203–210, 2007.
11. H. İ. Variyenli, “Experimental and numerical investigation of heat transfer enhancement in a plate heat exchanger using a fly ash nanofluid,” Heat Transfer Research., vol. 50, no. 15, pp. 1477–1494, 2019.

12. F. W. Dittus, L. M. K. Boelter, “Heat Transfer in Automobile Radiators of the Tubular Type,” University of California Publications on Engineering., vol. 2, pp. 443–461, 1930.

13. Duangthongsuk W, & Wongwises S. An experimental study on the heat transfer performance and pressure drop of TiO$_2$–water nanofluids flowing under a turbulent flow regime. International Journal of Heat and Mass Transfer. 2010;53:334–344.

14. H. Patel, T. Sundararajan, S. K. Das, “An experimental investigation into the thermal conductivity enhancement in oxide and metallic nanofluids,” J. Nanopart. Res., vol.12, pp. 1015–31, 2010.

15. S. E. B. Maiga, S. J. Palm, C. T. Nguyen, G. Roy, N. Galanis, “Heat transfer enhancement by using nanofluids in forced convection Flows,” Int J Heat Fluid Flow., vol. 26, pp. 530–46, 2005.

16. B. C. Pak, Y. L. Cho, “Hydrodynamic and heat transfer study of Dispersed fluids with submicron metallic oxide particles,” Exp. Heat Transf., vol. 11, pp.151–170, 1998.

17. Y. Xuan and W. Roetzel, “Conceptions for heat transfer correlation of nanofluids,” International Journal of Heat and Mass Transfer., vol. 43, no. 19, pp. 3701–3707, 2000.

18. M. K. Moraveji, M. Hejazian, “CFD Examination of Convective Heat Transfer and Pressure Drop in a Horizontal Helically Coiled Tube with CuO/Oil Base Nanofluid,” Numerical Heat Transfer, Part A: Applications, vol. 66, no. 3, pp. 315–329, 2014.

19. M. Hejazian, M. K. Moraveji, “A Comparative Analysis of Single and Two-Phase Models of Turbulent Convective Heat Transfer in a Tube for TiO$_2$ Nanofluid with CFD,” Numerical Heat Transfer, Part A: Applications. vol. 63, no. 10, pp. 795–806, 2013.
20. A. M. Hussein, K. V. Sharma, R. A. Bakar, K. Kadigama, “The Effect of Nanofluid Volume Concentration on Heat Transfer and Friction Factor inside a Horizontal Tube,” *Journal of Nanomaterials.*, pp. 1–12, 2013. doi:10.1155/2013/859563

21. Praveen Kanti, Viswanatha Sharma Korada, C.G. Ramachandra, P.H.V. Sesha Talpa Sai. “Experimental study on density and thermal conductivity properties of Indian coal fly ash water-based nanofluid”, International Journal of Ambient Energy, 2020

22. Kanti P, Sharma KV, Ramachandra CG, Bhramara P. Stability and thermophysical properties of fly ash nanofluid for heat transfer applications. Heat Transfer. pp. 1–18, 2020. https://doi.org/10.1002/htj.21849.

23. Kanti P, Sharma KV, Ramachandra CG, Azmi WH. Experimental determination of Thermophysical Properties of Indonesian Fly Ash Nanofluid for Heat Transfer Applications. Particulate science technology. pp. 1–16, 2020. https://doi.org/10.1002/htj.21836

24. Kanti P, Sharma KV, Ramachandra CG, Minea AA. Effect of ball milling on the thermal conductivity and viscosity of Indian coal fly ash nanofluid. Heat Transfer. 2020;1–16. https://doi.org/10.1002/htj.21836

**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/m² K
- $K_p$: Thermal conductivity of nanoparticle, W/m K
- $L$: Length of the tube, m
- LPM: Litre per minute
- $m$: mass, kg
- $Nu$: Nusselt number
Re : Reynolds number
$T_b$ : bulk temperature °C
$T_i$ : fluid temperature at inlet, °C
$T_o$ : fluid temperature at outlet, °C
$T_s$ : Average surface temperature, °C
$V$ : velocity of the fluid, m/s

**Greek symbols**

$\rho$ : Density, kg/m$^3$
$\varphi$ : Volume concentration
$\mu$ : Viscosity, kg/m.s

**Subscript**

bf : base fluid
nf : nanofluid
np : nanoparticle
p : particle