1. Introduction

Now a day's demand of energy is growing rapidly due to population growth\(^1\). For increasing efficiency cooling is one of the most important factor in any industrial sector. In nuclear power generation cooling play a main role for reducing the thermal hydraulics problems. Various conventional fluids have been used which have limited thermal conductivity like water, oil, gases and various refrigerant. From past few years researchers invent a new method for improving the heat transfer by mixing a metallic particles of nano size in base fluid. This method had disadvantages due to bad suspension stability and creating erosion in channels\(^2\) in 1995, at the Argonne National Laboratory of USA provide a nanofluids concept. In past decades lot of experimental and numerical research has been done for enhancing the heat transfer properties of nanofluids. Few experimental studies are\(^3\) performed the experiment for evaluating the consequences of particle size on heat transfer characteristics in laminar fluid flow. Experiment performed on two different particle sizes one is size of 45 nm and another one is 150 nm. Experimental investigation indicated that both nanofluids represent larger value of heat transfer coefficient than the base fluid. But lesser particle diameter showed higher value of heat transfer coefficient than that of bigger one.

Abstract

Nanofluid plays a very crucial role in nuclear power plant for improving heat transfer. It opens a new portal for improving heat transfer by reducing thermal hydraulics problems in nuclear reactor. The aim of this study to represent the numerically investigated result of CuO/Water based nanofluid heat transfer in light water nuclear reactor. In this investigation the 1/6th part of hexagonal geometry of nuclear fuel rod assembly has been taken for simulation. For focusing the effect of nanoparticle concentration and flow rate on heat transfer fluid flow in triangular channel two phase model is used. For improving the thermal properties of conventional fluid CuO/water nanofluid is used. A uniform heat flux is applied at the inner wall. Profiles of heat transfer coefficient and wall adjacent temperature are shown and these are the function of flow rate of nanofluid and concentration of nanoparticles. For getting better result accuracy, k-ω SST turbulence model and mesh quality of fuel rod bundle in triangular array are studied. Results are compared with analytical equations of heat transfer. The results show that prediction of nanofluid heat transfer is very well by using two phase model in place of using single phase model. Results indicates that heat transfer coefficient is increasing by adding the nanoparticles which is in low concentration and heat transfer coefficient is also increasing with increase in Reynold Number. It also indicates that wall adjacent temperature is decreasing by adding the nanoparticles and heat transfer coefficient is also decreasing with increase in diameter of nanoparticles.

Keywords: CFD, Copper Oxide Nanoparticles, Heat Transfer Coefficient, Nanofluid
in particle size heat transfer coefficient decreased. Fotukian et al. performed an experiment for finding out the pressure drop and enhancement of heat transfer in turbulent condition in a circular tube. It observed that 20% pressure drop in a circular tube due to increase in 25% heat transfer. It also observed that with increase in Reynold number heat transfer coefficient increased but wall adjacent temperature decreased. Fotukian et al.\textsuperscript{5} work represented that less amount of Al$_2$O$_3$ nanoparticles added to base fluid water heat transfer increased but varying particle concentration of Al$_2$O$_3$ did not represent a reasonable effect. Our present numerical investigation is based on dilute concentration of CuO nanoparticles. So the present aim of this investigation is to carry out the heat transfer characteristics by using CuO/Water based nanofluid in turbulent condition inside a 1/6th part of hexagonal fuel rod assembly.

Nomenclature

| Symbol | Definition |
|--------|------------|
| $p$    | Pressure (Pa) |
| $E$    | Energy (J/kg) |
| $V$    | Velocity (m/s) |
| $Pr$   | Prandtl Number |
| $P$    | Pitch (mm) |
| $h$    | Heat Flux (W/m$^2$) |
| $\alpha$ | Thermal diffusivity (m$^2$/s) |
| $d$    | Nanoparticle diameter (mm) |
| $\rho$ | Density (kg/m$^3$) |
| $\kappa$ | Boltzmann constant (J/K) |

2. Mathematical and Numerical Modelling

In this numerical investigation VVER-440 type reactors are considered. The assembly consist 61 fuel rods arranged in hexagonal configuration. The triangular configuration which is used for simulation consist 8 full rods and 4 half rods and a central rod arranged in a triangular configuration. The total height of fuel rod bundle is 1000 mm. The fuel rods pitch are 12.75mm and rod inner and outer diameter are 9.1 and 7.57mm respectively. Figure 1 shows full rod bundle assembly and for clear visual, triangular configuration of rod bundle is shown Trans parable. The coolant is flowing axially in subchannel which is formed in between the rods. Rods are made of uranium di-oxide and upper part of rod is made of cladding material Zircaloy.

2.1 Simulation and Boundary Condition

Sufficient boundary condition requires for performing the numerical investigation. In this numerical investigation, the nanofluid which is used as a coolant for flowing in the domain with velocity of 3.5m/s and temperature of 265 °C. The turbulence intensity was put constant 5% at the inlet. The hydraulic diameter of the fuel rod bundle is 6.45 mm. The pressure of nanofluid coolant is assumed at the inlet is 124 bar. Walls of triangular configuration is considered as no slip adiabatic and boundary condition for rod walls is considered as no slip with uniform heat flux 1047340 W/m$^2$ is set. The pressure is fixed as zero at the outlet of the fuel rod bundle. In present numerical investigation the $k$-$\omega$ SST turbulence model were used for discretizing the domain using finite volume technique. For good convergence and better accuracy in simulated results the top model is $k$-$\omega$ SST because it can predicted the flow in the wake of the sub channel very well. The governing equations which are using in this investigation are solved by using CFX. The scheme of central difference technique and QUICK scheme were applied for convective and diffusive parameters, respectively. Various meshes of different element size has been tested and it is shown in Figure 2. The convergence criterion was satisfied very well and it is given in Table 1.
3. Governing Equations

In this investigation single phase model is considered so governing equations of steady fluid flow and following assumptions have been taken below:

- The flow of flowing flow is incompressible in nature, Newtonian and turbulent.
- Fluid phase and nanoparticles phase are in thermal equilibrium.
- Non radiation effects are considered and viscous effect are negligible.

Under the above assumptions continuity, momentum and energy equations for the three dimensional models have been considered. For incompressible flow Navier Stokes equations can be written in the Cartesian coordinate which are given below:

\[ \nabla \cdot (\rho \nabla) = 0 \]  
(1)

\[ \nabla \cdot (\rho u) \nabla = -\nabla P + \mu \nabla^2 \nabla - \rho \nabla (u' u') \]  
(2)

\[ \nabla \cdot (\rho C_{p,eff} \nabla T) = \nabla \cdot (k_{eff} + k) \nabla T \]  
(3)

4. Data Analysis for Thermo Physical Properties

4.1 Properties of Nanofluid

To carry out the heat transfer parameters nanofluid properties such as density, specific heat, viscosity and thermal conductivity should be measured or calculated by theoretical models.

Density of Nanofluid:

The effective density of the nanofluid is given by Wang and Mujumdar\(^6\):

\[ \rho_{nf} = (1 - \varnothing)\rho_{bf} + (\varnothing)\rho_{np} \]  
(4)

Specific heat of Nanofluid:

The heat capacitance is defined as (Wang and Mujumdar)\(^7\):

\[ C_{p,ef} = \frac{(1 - \varnothing)\rho_{bf}C_{p,bf} + (\varnothing)\rho_{np}C_{p,np}}{(1 - \varnothing)\rho_{bf} + (\varnothing)\rho_{np}} \]  
(5)

Dynamic viscosity of nanofluid:

In this study Corcione\(^8\) empirical correlation proposed for nanofluids dynamic is used.

\[ \frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{1 - 34.87(d_{nf}/d_{bf})^{-0.3} \varnothing^{0.08}} \]  
(6)

where, \(d_{nf}\) is the equivalent diameter of base fluid molecule, given by:

\[ d_{nf} = 0.1 \left( \frac{6M}{N\rho_{bf0}} \right)^{1/3} \]  
(7)

In which \(N\) is the Avogadro number, \(M\) is the molecular weight of base fluid, and \(\rho_{bf0}\) is the mass density of base fluid calculated at temperature \(T= 293\) K.

Thermal conductivity of nanofluid:

Corcione correlation (Corcione, 2011) was used for determination of nanofluid effective thermal conductivity versus nanofluid temperature, particles mean diameter, volume fraction of nanofluid, particles Reynolds number and thermal conductivity of nanoparticles and base fluid as follows:

\[ \frac{k_{nf}}{k_{bf}} = 1 + 4.4 Re_{np}^{0.4} Pr_{bf}^{0.66} \left( \frac{T}{T_{f}} \right)^{10} \left( \frac{k_{np}}{k_{bf}} \right)^{0.03} \varnothing^{0.66} \]  
(8)

where, \(T_{f}\) is freezing point of base fluid (about 273.16 K). Reynolds is nanoparticle Reynolds number, defined as:
\[ \text{Re}_{nf} = \frac{2 \rho_{nf} K_x T}{\pi \mu_{nf} d_{nf}} \]  

(9)

Correlation is applicable for nanoparticles diameter between 10 nm and 150 nm, volume concentration between 0.2\% and 9\% and nanofluid temperature between 294 K and 324 K.

### 4.2 Heat Transfer Analysis

In this study it is assumed that heat generation is completely cosine:

\[ q''(y) = \frac{P}{4 r_{in} l} \cos \left(\frac{\pi y}{l}\right) \]  

(10)

In this equation P stand for total power of test section heater, \( r_{in} \) is inner tube radius and \( l = 1 \) m is length of heating area.

For calculating local heat transfer coefficient wall adjacent temperature and fluid temperature is needed. Wall adjacent temperature is achieved by simulation. For getting better result take average of left and right side wall temperature.

\[ T_w = \frac{T_{right} + T_{left}}{2} \]  

(11)

and bulk temperature is calculated by following expression (Incropera and DeWitt, 1996):  

\[ T_{bulk} = T_m \frac{q}{m C_p} \]  

(12)

Hence, local heat transfer coefficient is obtained by Incropera and DeWitt:

### Table 2. Thermo physical properties of CuO-water based nanofluid at various weight concentration

| Water   | 1\%  | 2\%  | 3\%  |
|---------|------|------|------|
| Density, \( \rho \) (kg/m\(^3\)) | 994  | 1047 | 1097 | 1147 |
| Specific heat \( C_p \) (J/kg-K) | 4178 | 3971 | 3782 | 3609 |
| Thermal conductivity \( k \) (W/m\(^2\cdot\)K) | 0.6230 | 0.630 | 0.648 | 0.666 |
| Viscosity, \( \mu \) (Pa\(-\)s)\times10\(^{-4}\) | 8.89  | 9.14 | 9.37 | 9.61 |

### 5. Validation

Results of numerical investigation is validated by analytical equation of heat transfer. The numerical modeling consist a vertical triangular channel which is used to simulate flow over nuclear fuel rods in a non-radiation environment as shown in Figure 1. Comparison of numerical result with the analytical result represent accurate and superior in nature. Wall adjacent temperature profiles can be seen in Figure 3 at Reynold number 10000 and 1\% volume concentration is validated by analytical result and it is calculated from the formula approximately overlying with coming result from ANSYS CFX.

\[ T_w(Z) = T_m + \left(\frac{q \times p}{m \times C_p}\right) Z \]  

(14)

### Figure 3. Comparison of numerical and analytical result of temperature profile.

### 6. Results and Discussion

The numerical investigated results of vertical triangular channel are calculated and presented in this section. Effect on heat transfer characteristics by using without nanofluid or with CuO/water based nanofluid, are reported in this section. Figures (4, 5 and 6) shows the contours of wall adjacent temperature of clad, heat transfer coefficient and velocity contours.

### Figure 4. Wall Adjacent Temperature at \( \phi = 1\% \).
6.1 Effect of Varying Reynold Number on Clad Wall and Heat Transfer Coefficient

Figure 7 shows the plots of clad temperature for nanofluid weight concentration of 1% at varying Reynold number. As shown in Figure 7 as the Reynolds number is increasing clad wall temperature decreases due to varying inlet velocity of nanofluid.

Figure 7. Wall adjacent temperature on varying Reynold number.

Figure 8 shows the plots of heat transfer coefficient for nanofluid weight concentration of 1% at varying Reynold number. As shown in Figure 8 as the Reynold number is increasing heat transfer coefficient increases due to varying inlet velocity of nanofluid.

Figure 8. Heat transfer coefficient on varying Reynold number.

6.2 Effect of Varying Particle Size on Heat Transfer Coefficient

Figure 9 shows plots of heat transfer coefficient at different nanoparticle size. As shown in Figure 9 as the particle size become smaller heat transfer coefficient is increasing.

Figure 9. Heat transfer coefficient for pure water and varying particle size.

6.3 Effect of Varying Volume Concentration of Nanoparticle on Heat Transfer Coefficient

Figure 10 shows the temperature plots of clad wall temperature at different nanofluid concentration. As shown in Figure 10 as the weight concentration of nanoparticle is increasing clad wall temperature decreases.

Figure 10. Wall adjacent temperature at different nanofluid concentration.
7. Conclusion

In this numerical investigation consequence of nanofluid properties on heat transfer characteristics has been identified. In order to simulate the annular hot channel Navier Stokes equations has been used. CFD code has been used for this analysis. In this study the nanoparticles effect was included by averaging the thermo physical properties used in the flow field equations. It was observed from the simulation that the CuO/water based nanofluid enhanced the heat transfer characteristic compared to the base fluid water. Simulation for clad temperature and heat transfer coefficient were performed and compared with a fluid of without nanoparticles. Various effects are obtained from this numerical investigations are:

- Heat transfer enhancement significantly increases after addition of CuO nanoparticles in base fluid compared to pure fluid.
- Heat transfer coefficient is enhancing with increase in particle concentration. For example: At various Reynold number with varying volume concentration from 1 to 3% the local heat transfer coefficient increases between 19% to 24%.
- Clad wall temperature of a fuel rod is decreasing with increase in nanoparticle concentration and Reynold number of cooling nanofluid due to high thermal conductivity of nanofluid.
- Heat transfer enhancement takes place due to smaller size of nanoparticles. Heat transfer coefficient increases when particle size becomes smaller. Particle size 10nm shows greater heat transfer value compare to particle size 20 and 30nm.

8. References

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