Theoretical Study of Forced Convective Heat Transfer in Hexagonal Configuration with 7 Rod Bundles Using Zirconia-water Nanofluid

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ABSTRACT

Many researches and developments are carrying out to improve the heat transfer properties of different fluids. In this project CFD calculations will be done for a seven vertical rod bundle with a hexagonal configuration to see and determine the improvement of heat transfer properties while using Nano fluid with different concentrations in compare of traditional fluids which in this project, water is used as the basic fluid and Zr\textsubscript{O\textsubscript{2}} is represented as Nanofluid. The numerical simulation is done using ANSYS FLUENT 14.5 assuming the fluids are single phase. The hexagonal arrangement of seven rods is designed and meshed by GAMBIT 2.3.16. Calculations have been done for different flow rates starting from 5 liter per minute up to 15 liter per minute and for each flow rate three different powers have been applied from 100W to 700W. At the end the results has been studied for a sub-channel between the heaters, by determining heat transfer coefficient, Reynolds number and calculating the correlation equations for Nusselt number.

Keywords: CFD calculations, Nanofluid, Forced convection, Nusselt number, Correlation equations

1. INTRODUCTION

Nano particles are added to the traditional fluids to improve the heat transfer properties. In this research Zr\textsubscript{O\textsubscript{2}} is used as the Nano material and it is added to water which is the base fluid in this research. To observe the effect of Nano particles on heat transfer, the research is done for three different concentrations which are 0\%, 0.1\% and 3\%. The 0\% concentration is simply considered as pure water and the other fluids are Nanofluids. These fluids are flown in a hexagonal configuration with 7 vertical heaters. Temperature is the property which is calculated in advance and used for calculation of the following properties. All temperatures are observed in a triangular sub-channel, which is designed in between the heaters, it is shown in Figure 2.

This paper studies the forced convective heat transfer, so the geometry is designed for this kind of convection. Different cases were studied during the research, the two main properties which are changed in every single case are, the flow rate and the power of the heaters. Calculations have been done for different flow rates starting from 5 liter per minute up to 15 liter per minute and for each flow rate different powers have been applied from 100W to 700W. Every case is repeated for different concentrations and for
each case the heat transfer coefficient, Reynolds number, Nusselt number and other dimensionless numbers are measured. At the end the results has been studied by determining heat transfer coefficient, Reynolds number and calculating the correlations for Nusselt number.

2. METHODOLOGY

2.1. Geometry

The model is generated and meshed by GAMBIT 2.3.16. There are seven heaters in the model which are installed in a hexagonal configuration as shown in Figure 1. Each cylindrical heater is 45cm high and the diameter is 2.7cm. For the distance between heaters the P/D (pitch per diameter) is 1.32.

2.2. Meshing

After designing the geometry it is time to mesh the configuration so the CFD calculations can be taken place. For this step first the lines, then faces and at the end the volumes were meshed. The hex-cooper mesh type is used in this step. After checking the mesh quality, the zones are specified and named. The important zones which are defined, are the zones inside the sub-channel, these zones are used for reading the results of CFD calculation. In this project the zones are named Tw1, Tw2 until Tw8.

There are four thermocouples located in sub-channel 2, 3, 4 and 5 and it is assumed that the thermocouples are located in the middle of the zones.
2.3. Boundary Conditions

In this study three flow rates are flown in the model which are 7lpm, 11lpm and the maximum flow rate applied in the system is 15lpm. By calculating the Reynolds number for these flow rates it is observed that the flow is laminar therefore in CFD calculations all of the cases are run with laminar model assumption. The velocities of the fluids in the inlet, in order are 0.23 m/s, 0.36m /s and 0.49m /s.

The input temperature is constantly 300K. There are three different powers applied to the heaters which are 100W, 400W and 700W and associated to heat fluxes of 3368.3W/m², 13473.4W/m² and 23578.5W/m² respectively.

Besides the boundary conditions mentioned above, there are some assumptions such as:

- The heat flux on the cylinders surfaces is constant and uniform.
- The fluids, including Nano fluids are assumed single phase.
- The calculations are taken place in steady operating condition.
- Since the velocity of the fluids is low, thus the viscous dissipation is negligible [1].

2.4. CFD Simulation

Simulation is done by using ANSYS FLUENT version 14.5. All the calculations are repeated for three fluids which are water, Nano fluid 0.1% and Nano fluid 3%.

For every fluid the calculations are repeated nine times due to the different flow rates and different powers applied, so it will lead to better results and correlations, to observe the effect of Nano particles in enhancing the heat transfer.

For every case which is run in ANSYS FLUENT the bulk temperatures, wall temperatures and volume average velocities are noted. From these properties the dimensionless numbers including Reynolds and Nusselt are measured and these data lead to the correlation equations for Nusselt number.

2.5. Nano fluid properties

It is very important to determine Nano fluids physical properties, since it is necessary to analyze the heat transfer properties in the fluids.

For the Nanofluids in this study which are ZrO₂ with the concentrations of 0.1% and 3% respectively, the properties are measured using the Rea method [2].

Thermal conductivity (k) and viscosity (μ) are functions of the temperature and concentration of the fluid and can be calculated using Eq.1 and Eq.2 respectively.

\[ k(\phi, T) = k_f(T)(1 + 2.4505\phi - 29.867\phi^2) \] (1)

\[ \mu(\phi, T) = \mu_f(T)(1 + 46.8\phi - 556.82\phi^2) \] (2)

In these equations \( \phi \) is the volume percentage, Eq.3 shows relation between volume percentage and weight percentage (w).

\[ \phi = \frac{w \mu_j}{\rho_p(1-w) + w \rho_j} \] (3)

Which \( \rho_p \) and \( \rho_f \) are bulk density and fluid density respectively. For measuring the density of Nano fluid we use Eq. (4)

\[ \rho = \phi \rho_p + (1 - \phi) \rho_j \] (4)

The other two properties used in the calculations are specific heat (c) and thermal expansion coefficient (β) which are measured using Eq. (5) and (6) respectively.

\[ c = \frac{\phi \rho_p c_p + (1-\phi) \rho_j c_j}{\rho} \] (5)

\[ \beta = \frac{\phi \rho_p \beta_p + (1-\phi) \rho_j \beta_j}{\rho} \] (6)

The specific heat and bulk density for ZrO₂ are 418 J/Kg and 5600 Kg/m² respectively [3]. The applicable temperature range of the equations in 2.5 part is \( 20^\circ C < T < 80^\circ C \) [1].
3. RESULTS AND DISCUSSION

Theoretical results obtained in this research have been compared to each other for three different cases according to the concentrations of the Nano fluid. The comparisons have been done for simulation results between pure water, 0.1% weight concentration of $\text{ZrO}_2$ and 3% weight concentration of $\text{ZrO}_2$. To analyze the influence of Nano particles for each fluid several properties and dimensionless numbers are calculated. From bulk and wall temperatures achieved after simulation, heat transfer coefficient ($h$) and Nusselt number ($\text{Nu}$) are calculated. Afterwards from the velocity of the fluid in the sub-channel, Reynolds number ($\text{Re}$) is measured. Other dimension numbers, which help for better understanding of the heat transfer enhancement, are Graetz ($G_z$), Richardson ($R_i$) and Prandtl ($P_r$). By the time all these data is calculated, it is time for correlation equations. The correlation which is analyzed in this paper is correlation between $\text{Nu}$, $R_i$ and $G_z$. This correlation is chosen, because this paper is studying the force and mix convections and the flow rate is laminar as well.

The first case is pure water. The correlation equation graph of Nusselt number for water against $G_z$ and $R_i$, is shown in Figure 3.

![Figure 3. Correlation graph for water](image)

According to the figure 3 the correlation equation for Nusselt number is Eq.7.

$$\text{Nu} = 2.4\sqrt[12]{G_z^{0.588} R_i^{0.107}}$$  \hspace{1cm} (7)

Second fluid analyzed is $\text{ZrO}_2$ with the weight concentration of 0.1%. In this case the correlation equation graph of Nusselt number against $G_z$ and $R_i$, can be observed in Figure 4.

![Figure 4. Correlation graph for Nanofluid 0.1%](image)

According to the figure 4 the correlation equation for Nusselt number is Eq.8.

$$\text{Nu} = 2.4854 G_z^{0.588} R_i^{0.107}$$  \hspace{1cm} (8)

Comparing the figure 3 and 4, it is obvious that the results are very similar to each other because the concentration of the $\text{ZrO}_2$ is very low in this case which leads to results close to the base fluid.

The last concentration used in the simulation is 3% which is enormously higher than the previous concentration of $\text{ZrO}_2$. The correlation equation graph of Nusselt number for this case against $G_z$ and $R_i$, is shown in Figure 5.

![Figure 5. Correlation graph for Nanofluid 3%](image)

According to the figure 5 the correlation equation for Nusselt number is Eq.9.
The higher slope of the trend line makes $Gz$ number to be raised by a higher power. But at the same time the intersection between trend line and Y-axis in Figure 5 is lower than the two previous cases which also can be observed in correlation equation that the coefficient is lower for Nano fluid 3% than the other two cases. In total considering this two changes the results for Nusselt number is not that different for Nano fluid with 3% concentration and water, which means there is no significant influence in using the ZrO$_2$ 3%.

In all three correlation equations mentioned the Ri number is raised to a power which is almost zero and this makes the effect of Ri negligible.

Figure 6 shows the correlation of $\frac{Nu}{Gz^b}$ against Ri for water.

![Figure 6. Correlation of $\frac{Nu}{Gz^b}$ against Ri for Water](image)

And the same correlation for Nano fluid 0.1% is shown in Figure 7.

![Figure 7. Correlation of $\frac{Nu}{Gz^b}$ against Ri for Nanofluid 0.1%](image)

At the end Figure 8 is for the last case with higher concentration of 3%.

![Figure 8. Correlation of $\frac{Nu}{Gz^b}$ against Ri for Nanofluid 3%](image)

From the last three figures it is observed that for all fluids the slope of the trend line in correlation of $\frac{Nu}{Gz^b}$ against Ri, is very close to zero. This fact means that the effect of Ri number in this study is negligible and Nu number mostly depends on the amount of Graetz.

**4. CONCLUSIONS**

A numerical study on heat transfer characteristics of ZrO$_2$-water Nanofluid in vertical hexagonal geometry under steady state flow has been successfully conducted in this study. The research was done for three different fluids with different concentrations and in every case the study has been taken place for forced convective heat transfer.

The results of this study gave new correlation equations for forced convection in hexagonal configuration as presented in Table 1.

<table>
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<th>Correlation Equation</th>
<th>Nanofluid Concentration</th>
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Comparing the equations in Table 1 shows that for 0.1% concentration of ZrO\textsubscript{2} the effect of Nano particles is very small and the Nusselt number is very close to the pure water.

When it comes to the higher concentration of 3% the correlation equation is different from other two cases but the result is almost the same again and there is no significant change in Nusselt number. It can be concluded that for 3% concentration the density is too high so considering the effect of the gravity in the vertical sub-channel the convective heat transfer tends to be less forced convection and more natural. So based on the correlation graphs and equations these two concentrations studied in this paper have no significant influence on heat characteristics.

4.2. Recommendations

In order to study on further topics examined in this study, to improve the results there are following improvements which can be work on:

1. Simulations can be done for ZrO\textsubscript{2} with concentrations somewhere between 0.1% and 3%. To find the optimum concentration that gives better heat transfer characteristics.

2. Modifications can be done on the shape of the heater to increase the turbulence flow, which makes improvements in convective heat transfer.

3. Studying on other Nano materials available in laboratory such as Alumina-water Nanofluid and comparing the results with Zirconia-water Nanofluid.

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REFERENCES

