CHAPTER-6

RESULTS AND DISCUSSIONS
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CHAPTER - 6

RESULTS AND DISCUSSIONS

6.1. Introduction

In this chapter, results of the experiments conducted in chapter 4 & 5 are compared with the theoretical models of existing data, the analysis of conduction and convective heat transfer of nanofluids are presented in detail. The analysis is done by using the calculations which were performed in chapter 4 & 5. Some important issues about the analysis, such as the geometry in consideration, calculation of thermo physical properties, governing equations and numerical method are discussed in Chapter 5.

6.2 Thermal conductivity enhancement

6.2.1 Comparison of Results with Experimental Data

The graphs show the comparison between the variations of particle size with thermal conductivity ratio with respect to different particle volume fractions. the solid lines represents the thermal conductivity enhancement ratio for Graphene/water +EG nanofluid and the dashed lines represent the experimental values of Hamilton & Crosser model[18] for Al₂O₃ with water and ethyl glycol. By observing the graphs it is clear that the enhancement of thermal conductivity ratio depends upon particle size and its volume fraction. When the particle size and volume fraction increase the thermal conductivity enhancement ratio also increases. This is also one of the reasons for attaining the enhancement in convective heat transfer. The Graphene nanoparticles shows greater enhancement when compared to Al₂O₃. The experimental procedure and the calculation procedure of thermal conductivity ratio are done in chapter 4.
Fig: 6.1. Comparison of the Graphene results of the thermal conductivity ratio for Graphene (Cn)/water+EG nanofluid with Hamilton and Crosser model [18] as a function of the particle size at various values of the particle volume fraction. Solid lines indicate present work and dotted lines indicates Hamilton and crosser model for Al₂O₃. 

It is found that Graphene (Cn)/Water+EG nanofluid behaves similar to Al₂O₃ nanofluid and the enhancement in thermal conductivity ratio is higher than the Al₂O₃ nanofluid for all particle volume fractions. It is also observed that at higher particle size the enhancement is greater.

Fig 6.2: Comparison of the Graphene results of the thermal conductivity ratio for Graphene (Cn)/water+EG nanofluid with Xue and Xu model [68] as a function of the particle size at various values of the particle volume fraction. Solid lines indicate present work dotted lines indicate Xue and Xu model for Al₂O₃.
Another model Xue-Xu is also evaluated the experimental results are compared with the theoretical results. This model gives a decrement in the thermal conductivity ratio, with the increase in particle size and particle volume fraction. Solid lines represents the experimental values of Graphene (Cn)/Water + EG nanofluid and the dashed lines are representing the Xue & Xu model [68] related to the study of Cu nanofluid, by considering the clustering and Brownian motion.

With the Xue-Xu model it is found that while the behaviour of both nanofluids is similar the enhancement is much greater for Graphene (Cn)/Water+EG nanofluid. Strikingly the thermal conductivity ratio decreased with particle size increase. This may due to consideration of clustering and Brownian motion in the model. Hence the present results give reliable new data on the new generation of nanofluid Graphene (Cn)/Water+EG in the world of nanofluids,

Temperature dependence of thermal conductivity of the nanofluid is stressed upon from studies done by the Jang and Choi [65], Koo and Kleinstreuer model [66] for Al₂O₃ nanofluid, hence the thermal conductivity of the Graphene (Cn)/Water+ EG nanofluid with different particle volume fractions is considered at different temperatures, solid lines represents the results and the dotted lines represent the studies of Jang and Choi, Koo and Kleinstreuer model.
Fig 6.3: Comparison of the Graphene results of the thermal conductivity ratio for Graphene (Cn) 20nm/water+EG nanofluid with Jang and Choi model [65] as a function of temperature at various values of particle volume fraction. Dotted lines indicate the Jang and Choi model for Al₂O₃, solid lines represent present work.

It is clear from the graphs at higher temperature the thermal conductivity enhancement ratio also increases, In contrast to Jang and Choi findings for Al₂O₃ nanofluid the present studies show higher enhancement at lower temperatures and lower enhancement at higher temperatures, that is to say that the present work with Graphene (Cn)/Water+EG nanofluid show flatter trends. This may be due to the different fluids and also due to different ranges of temperature of the works.
Fig: 6.4. Comparison of the Graphene results of the thermal conductivity ratio for Graphene (Cn) 20nm/water+EG nanofluid with Koo and Kleinstreuer model [66] as a function of temperature at various values of particle volume fraction. Dotted indicate Koo and Kleinstreuer model for Al₂O₃. Solid lines represent present work with different values of particle volume fraction; 1%, 2%, 3% and 4%.

The trends with Koo & Kleinstreuer [66] with Al₂O₃ match with the present findings i.e. Graphene (Cn)/Water+EG. Interestingly with this model the enhancement is nearly same at lower temperatures while at higher temperatures the Graphene (Cn)/Water+EG shows slightly lower values. Again there is difference in ranges of temperatures and the fluids used.

To summarize it is inferred that the new Graphene (Cn)/Water+EG shows similar enhancement as that Al₂O₃ results.

6.3 Convective Heat Transfer Enhancement

When coming to the convective heat transfer characteristics, the discussion is presented in two main headings, constant wall temperature boundary condition and constant wall heat flux boundary condition, respectively.
6.3.1 Constant Wall Temperature Boundary Condition

For the constant wall temperature boundary condition, the results are first analyzed in terms of the average heat transfer coefficient enhancement ratio (heat transfer coefficient of nanofluid with that of the heat transfer coefficient of corresponding base fluid). The associated results are compared with the experimental and numerical studies of Heris et al. [12]. Then the variation of local Nusselt number in axial direction is examined for different particle volume fractions. Finally, effects of particle size, heating and cooling are discussed in terms of heat transfer coefficient enhancement ratio.

6.4 Heat Transfer Coefficient Enhancement

6.4.1 Comparison of Results with Experimental Data

There is very little experimental data for nanofluid flow under the constant wall temperature boundary condition available in the literature. In this part, experimental results of the present study are compared with the experimental data of Heris et al. [12]. Heris et al. considered the laminar flow of Al\textsubscript{2}O\textsubscript{3} (20 nm)/water nanofluid. The flow is hydrodynamically developed and thermally developing. Nanofluid flows inside a circular tube with a diameter of 5 mm and length of 1 m. The experimental analysis is performed by using exactly the same nanofluid parameters and flow configuration for obtaining a meaningful analysis.
In Fig. 6.5, experimental results of the present analysis and experimental data of Heris et al. are presented in terms of the variation of average heat transfer coefficient enhancement ratio with Peclet number for different particle volume fractions. Enhancement ratios are calculated by comparing the nanofluid with the pure fluid at the same Peclet number in order to focus on the sole effect of the increased thermal conductivity and thermal dispersion.

The small discrepancies between experimental data and the solution with thermal dispersion might be explained by the fact that the particle volume fraction of a nanofluid may unexpectedly affect the thermal conductivity due to the complicated variation of clustering characteristics with particle volume fraction. Another important point is that, although an empirical constant, $C$ is present for the determination of the effective thermal conductivity in the analysis (Eq. 5.2), which simultaneously defines the magnitude of dispersed thermal conductivity and the variation of it with Peclet number; it does not assure the complete agreement with experimental data. Therefore,
the present agreement between theoretical analysis and experimental data can be considered as an indication of the convenience of the single phase approach combined with thermal dispersion model for the analysis of convective heat transfer of nanofluids.

6.5 Further Analysis

6.5.1 Local Nusselt Number

In this section, the same flow configuration analyzed numerically in the previous sections is investigated in terms of the axial variation of local Nusselt number. However, in order to determine the fully developed Nusselt number as well, the flow inside a longer tube is considered (5 m). Figure 6.6 shows the associated results for the flow of pure water+EG and Graphene (Cn)/water+EG nanofluid at a Peclet number of 6500.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$Nu_{fd}$</th>
<th>$Nu$ Enhancement Ratio($Nu_{fd,nf}$/$Nu_{fd,f}$)</th>
<th>$h_{fd}$ [$W/m^2K$]</th>
<th>$h$ Enhancement ratio($h_{fd,nf}$/$h_{fd,f}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water+EG</td>
<td>3.76</td>
<td>-</td>
<td>490</td>
<td>-</td>
</tr>
<tr>
<td>Nanofluid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0 %Vol</td>
<td>3.98</td>
<td>1.069</td>
<td>589</td>
<td>1.362</td>
</tr>
<tr>
<td>1.5 %Vol</td>
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<td>1.078</td>
<td>641</td>
<td>1.571</td>
</tr>
<tr>
<td>2.0 %Vol</td>
<td>4.36</td>
<td>1.082</td>
<td>662</td>
<td>1.728</td>
</tr>
<tr>
<td>2.5%Vol</td>
<td>4.72</td>
<td>1.098</td>
<td>693</td>
<td>1.931</td>
</tr>
</tbody>
</table>

Table 6.1: Fully developed Nusselt number and heat transfer coefficient values obtained from the numerical solution for pure water and Graphene (Cn)/Water + EG nanofluid with different particle volume fractions $p_{ef} = p_{nf} = 6500$
Fig 6.6: Dissimilarity of local Nusselt number with dimensionless axial position for pure water +EG and Graphene (Cn)/water+EG nanofluid. $Pe_{nf} = Pe_f = 6500$.

In the figure, it is seen that the local Nusselt number is larger for nanofluids throughout the tube. This is mainly due to the thermal dispersion in the flow. Thermal dispersion results in a higher effective thermal conductivity at the center of the tube which flattens the radial temperature profile. Flattening of temperature profile increases the temperature gradient at the tube wall and as a consequence, Nusselt number becomes higher when compared to the flow of pure water+EG. Figure 6.6 also shows that increasing particle volume fraction increases Nusselt number. This is due to the fact that the effect of thermal dispersion becomes more pronounced with increasing particle volume fraction. It may be noted that the fully developed nanofluid Nusselt number values are also higher than pure water+EG case. Associated values for different particle volume fractions of the Graphene (Cn)/water+EG nanofluid are presented in Table 6.1 It is seen that increasing particle volume fraction increases the fully developed Nusselt number. The results presented in the table are for $Pe = 6500$.
and since thermal dispersion is dependent on flow velocity (Eq. 5.2), fully developed Nusselt number increases also with Peclet number for the case of nanofluids. In Table 6.1 fully developed heat transfer coefficient values are also provided. It should be noted that heat transfer coefficient enhancement ratios are larger than Nusselt number enhancement ratios since the former shows the combined effect of Nusselt number enhancement and thermal conductivity enhancement with nanofluids.

6.5.2 Effect of Particle Size

In Chapter 4, it was shown that most of the experimental data in the literature indicates increasing thermal conductivity with decreasing particle size. On the other hand, decreasing particle size decreases the effect of thermal dispersion through Eq. (5.2). In order to understand the relative significance of these effects, average heat transfer coefficient enhancement ratio is plotted in Fig.6.7 with respect to Peclet number for 1%Vol Graphene(Cn)/water+EG nanofluids with different particle sizes. The flow configuration in consideration is the same as the one utilized in the previous sections.

![Fig: 6.7: Experimental Results indicating that Variation of average heat transfer coefficient enhancement ratio with Peclet number for different particle sizes of the 1vol % Graphene (Cn)/Water+EG nanofluid](image)
When Fig. 6.7 is examined, it is seen that heat transfer coefficient enhancement ratio generally increases with increasing particle size, which shows that particle size dependence of thermal dispersion is more pronounced than the associated dependence of thermal conductivity. There is an exception for particle sizes below 25 nm at low Peclet numbers; therefore variation of thermal conductivity with particle size is more effective for those cases. Although there is very limited experimental data about the effect of particle size on convective heat transfer, Anoop et al. [86] showed that increasing particle size decreases heat transfer for the laminar flow of Al₂O₃/water nanofluids under constant wall heat flux boundary condition, which indicates a disagreement with the results of the present analysis. The results presented in Fig. 6.7 are obtained by utilizing the same value for the empirical constant C in Eq. (5.2) for all particle sizes, which results in a linear increase in dispersed thermal conductivity with particle size. However, it should be noted that the effect of Brownian motion of nanoparticles increase with decreasing particle size and decreasing particle size also increases the specific surface area of nanoparticles in the nanofluid, which improves heat transport. Therefore, the present analysis might be modified by considering the empirical expression C as a function of particle size so that its value decreases with increasing particle size. For proper application of such an approach, a theoretical model should be developed that defines the relation between C and particle size. Moreover, a systematic set of experimental data is required for the verification of the results of the approach, which is missing in the literature presenting.

6.5.3 Effects of Heating and Cooling

Thermal conductivity distribution of the working fluid inside the tube is an important parameter in heat transfer. Especially, thermal conductivity at the wall significantly affects heat transfer. Since thermal conductivity of nanofluids is a strong
function of temperature, heat transfer performance of nanofluids depends on whether the working fluid is heated or cooled. Thermal conductivity of nanofluids increases with temperature and as a consequence, convective heat transfer coefficient and associated enhancement ratio are larger for the heating of the nanofluid in which $T_w$ has a higher value. In Fig. 6.8, this difference is illustrated in terms of the variation of average heat transfer coefficient enhancement ratio with Peclet number for heating and cooling of 2.0% Vol Graphene (Cn)/water+EG nanofluid. The flow configuration in consideration is the same as the one utilized in the previous sections. For heating case, $T_i = 40°C$ and $T_w = 80°C$ where as for cooling $T_i = 80°C$ and $T_w = 40°C$. It is seen that the enhancement difference between the two cases exceeds 5% at low Peclet numbers. Increasing the difference between inlet and wall temperatures and increasing the particle volume fraction of the nanofluid might result in larger differences in enhancement values.

Figure 6.8: Variation of average heat transfer coefficient enhancement ratio with Peclet number for heating and cooling of the 2 vol. % Graphene (Cn)/water+EG nanofluid
The results presented in this section show that nanofluids provide higher heat transfer enhancement in heating applications when compared to cooling cases. This fact necessitates take into account for the proper design of heat transfer processes with nanofluids.

6.6 Constant Wall Heat Flux Boundary Condition

For constant wall heat flux boundary condition, results are usually presented in terms of the variation of local heat transfer coefficient in axial direction in the literature. Same approach is followed in the present discussion. Similar to the constant wall temperature boundary condition case, the results are compared with experimental and numerical data and effects of particle size, heating and cooling are also discussed.

6.6.1. Local Heat Transfer Coefficient

6.6.1.1. Comparison of Results with Experimental Data

The results of the present experimental analysis are compared with the experimental data of Kim et al. [86]. In the study, Kim et al. investigated the laminar and turbulent flow of Al₂O₃/water nanofluid. Constant wall heat flux boundary condition is analyzed in the study by utilizing a test section with 4.57 mm inner diameter and 2 m length. In the experiments, nanofluid entered the tube at 22°C and total heating power was 60W throughout the analysis. It was indicated that nanoparticle size distribution is 20 – 50 nm. By using the same flow parameters, except changing the entry temperature at 30°C the experiment performed by Kim et al. [86] was simulated numerically. For the particle size, the average value of 35 nm is used in the calculations. In Fig. 6.9, the associated numerical results are compared with the experimental data, in terms of the local heat transfer coefficient. The presented results are for 3 vol. % Graphene (Cn)/water+EG nanofluid, Experimental data for the flow of pure water+EG and associated numerical results are also
presented in the figure. It is seen that good agreement exists between numerical and experimental data for both pure water+EG and nanofluid cases.

![Graph showing variation of local heat transfer coefficient with dimensionless axial position for pure water+EG and 3 vol. % Graphene (Cn)/water+EG nanofluid Re\text{nf} = \text{Re} = 1460. Markers indicate Theoretical results of Kim et al. [86].](image)

**Fig 6.9:** Variation of local heat transfer coefficient with dimensionless axial position for pure water+EG and 3 vol. % Graphene (Cn)/water+EG nanofluid Re\text{nf} = \text{Re} = 1460. Markers indicate Theoretical results of Kim et al. [86].

In the paper of Kim et al. [86], the variation of local heat transfer coefficient in axial direction was only presented for \( Re = 1460 \). Therefore, it is not possible to provide a similar comparison for other Reynolds numbers. Nevertheless, further comparison is made by using the experimental data regarding the variation of local heat transfer coefficient at a specific point with Reynolds number. The available data is the local heat transfer coefficient at \( x^* = x / r_0 = 44 \) for the flow of pure water+EG and 3 vol. % Graphene (Cn)/water+EG nanofluid. Associated experimental results are compared with the numerical data in Fig. 6.10. It is seen that there is good agreement between numerical results and experimental data.
6.6.2. Further Analysis

6.6.2.1. Local Nusselt Number

In this section, the same flow configuration analyzed theoretically in the previous sections (test section of Kim et al. [86]) is investigated in terms of the axial variation of local Nusselt number. Figure 6.10 shows the associated results for the flow of pure water+EG and Graphene (Cn)/water+EG nanofluid at a Peclet number of 12000 ($Re \approx 2000$). In the figure, it is seen that the local Nusselt number is larger for nanofluids throughout the tube, similar to the case of constant wall temperature boundary condition. The underlying reasons of the observed trends are the same as those discussed in the case of constant wall temperature and they are not repeated here. The difference between the nanofluid Nusselt number and pure water Nusselt number is smaller for the present case when compared to constant wall temperature boundary condition. This is mainly due to the fact that the utilized empirical constant $C$ (Eq. 5.2) is smaller for the present case when compared to constant wall temperature case, which is selected to be so in order to match the experimental data of Kim et al. [86]. It should be noted that the fully developed nanofluid Nusselt number values are also higher than pure water+EG case. Associated values for different particle volume fractions of the Graphene (Cn)/water+EG nanofluid are presented in Table 6.2. It is seen that increasing particle volume fraction increases the fully developed Nusselt number. The results presented in the table are for $Pe = 12000$. In Table 6.2, fully developed heat transfer coefficient values are also provided. It may be noted that heat transfer coefficient enhancement ratios are larger than Nusselt number enhancement ratios since the former shows the combined effect of Nusselt number enhancement and thermal conductivity enhancement with nanofluids.
Fig 6.10 Experimental values indicating that Variation of local Nusselt number with dimensionless axial position for pure water+EG and Graphene (Cn)/water +EG nanofluid. \( Pe_{nf} = Pe_f = 12000. \)

Table 6.2: Fully developed Nusselt number and heat transfer coefficient values obtained from the numerical solution for pure water+EG and Graphene (Cn)/water+EG nanofluid with different particle volume fractions. \( Pe_f = Pe_{nf} = 12000. \)

<table>
<thead>
<tr>
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<td>-</td>
</tr>
<tr>
<td>Nanofluid</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1.0 vol.%</td>
<td>5.21</td>
<td>1.026</td>
<td>723</td>
<td>1.364</td>
</tr>
<tr>
<td>2.0 vol.%</td>
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<td>1.031</td>
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</tr>
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<td>3.0 vol.%</td>
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<td>832</td>
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<td>4.0 vol.%</td>
<td>5.51</td>
<td>1.062</td>
<td>874</td>
<td>2.320</td>
</tr>
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</table>
6.6.2.2. Effect of Particle Size

Effect of particle size on heat transfer is previously investigated for constant wall temperature boundary condition. A similar analysis is performed in this section for constant wall heat flux boundary condition. In the analysis, the flow configuration and associated parameters are the same as the ones utilized in the experiments of Kim et al. [86]. Numerical results are presented in Fig. 6.11 in terms of the variation of local heat transfer coefficient with axial direction. In the figure, $Pe = 2500$ and 4 % vol. Graphene (Cn)/water+EG nanofluid is considered. When the figure is examined, it is seen that heat transfer coefficient increases with decreasing particle size. This is mainly due to the fact that the particle size dependence of thermal conductivity is more pronounced than the particle size dependence of thermal dispersion due to the relatively low empirical constant $C$ used in Eq. (5.2). In constant wall temperature case, $C$ was chosen to be higher to match experimental data and thermal dispersion dominated the particle size dependence of heat transfer as a consequence. This resulted in increasing enhancement with increasing particle size in constant wall temperature case. For higher values of Peclet number, a similar trend can also be observed for the constant wall heat flux boundary condition.
Fig: 6.11: Variation of local heat transfer co efficient with dimension less axial position for different particle sizes of 4 % vol Graphene Cn)/Water+ EG nanofluid.

Particle size dependence of heat transfer enhancement with nanofluids depends on empirical constant $C$ and Peclet number due to the thermal dispersion model. As these two parameters increase, the dependence tends to become increasing enhancement with increasing particle size.

### 6.6.2.3 Effects of Heating and Cooling

Effects of heating and cooling on heat transfer enhancement are previously discussed for the case of constant wall temperature boundary condition. In that case, heating of the working fluid provided higher enhancement since thermal conductivity of the working fluid at the wall significantly affects the heat transfer. When it comes to the constant wall heat flux, the analysis is performed by firstly considering the heating case according to the parameters in the study of Kim et al. [86] (with a longer tube to emphasize temperature variation) and exit temperature is determined (80°C). For cooling case, that exit temperature is substituted as inlet temperature and the
direction of heat flux at the wall is reversed. As a consequence, exit temperature of the cooling case (30°C) is equal to the inlet temperature of the heating case. The results for these two cases are presented in terms of the variation of local heat transfer coefficient with axial direction in Fig. 6.12. 4% Vol Graphene (Cn)/water+EG nanofluid is considered and the results for the flow of pure water+EG are also presented for comparison purposes.

![Graph showing variation of local heat transfer coefficient with axial position](image)

**Fig 6.12:** Variation of local heat transfer coefficient with dimensionless axial position for heating and cooling of the 4% vol. Graphene (Cn)/water+EG nanofluid and pure water. $Pe = 2500$.

It is observed that for both the nanofluid and pure water+EG, heat transfer coefficient is higher for cooling case at the beginning since temperature of the fluid is higher in the associated region when compared to heating case. At larger values of axial position, heating case has higher heat transfer coefficient since the temperature of the flow exceeds the corresponding temperature of the cooling case. The important issue here is that the difference between the cooling and heating cases for the nanofluid is much higher than the associated difference for the pure water+EG.
Therefore, for the case of nanofluids, heat transfer performance is significantly more dependent on temperature when compared to pure fluids. This fact has to be taken into account for the proper design of heat transfer processes with nanofluids.