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NUMERICAL STUDY ON THE PERFORMANCE OF WATER-BASED NANOFLUIDS IN FLAT TUBE OF A COOLING SYSTEM

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ABSTRACT

The main objective of the current study is to analyze the performance of water-aluminium oxide nanofluids in the flat tube, which is mostly used in the automobile cooling system. The simulation has been carried out under different conditions - Reynolds number, inlet-fluid temperature, nanoparticle concentration. The various thermal transport properties of nano-fluids i.e. thermal conductivity, density, specific heat capacity and viscosity are calculated with well-developed models of each. It was clearly observed from this study that the heat transfer capability of nanofluids at different concentration of nano-sized particles is greater than conventional fluids and also increased upon rise in inlet temperature. The pressure drop shows significant increase upon using Aluminium oxide nanofluids. This study also proved that, with the use of different nanofluids, size of vehicle cooling system also decreased.

KEYWORDS: Nanofluids, Heat Transfer Coefficient, Water, Cooling & Aluminium Oxide

Original Article

INTRODUCTION

The cooling is the one of the major problems in industry, which is the most important factor for the reliable and normally performing heat transfer device. For cooling purpose, generally air and water are used, but due to poor thermal conductivity of conventional fluids, these fluids are not suitable for the ultra-performance systems. The heat transfer fulfilment for conventional fluids can be significantly improved with enhanced thermal conductivity. In 1993, Choi presented a term “nanofluids” i.e. colloidal solution of nanoparticles into the base fluids. Nanoparticles have principle dimension less than 100 µm. With the addition of various nanoparticles into base fluid, thermal performance can be improved. In the last two decades, numerous studies were reported on addition of nanoparticles into various conventional base fluids. Due to this addition, thermal conductivity of base fluid is enhanced see (Jang et al, 2004; Mintsa et al, 2009; Sundar et al, 2013; Teng et al, 2010). In a study, Das et al, 2003 observed that temperature of base fluid and nanoparticles concentration has significant effect in thermal conductivity enhancement of nanofluids.

W. Duangthongsuk and S. Wongwises (2009) experimentally investigated that, at different concentrations of TiO_2 nanoparticle, the thermal conductivity of nanofluids increased with increase in fluid temperature and nanoparticles concentration. The viscosity of nano-fluid increases as nanoparticle concentration increased and decreased when rise in temperature took place. M. Elias et al. (2014) reported effect of Aluminium oxide nanoparticle on various thermal properties of radiator coolant and reported significant rise in the thermal conductivity. Decrease in viscosity and density was observed on addition of nanoparticle. A separate study (Sokhal et al, 2018) revealed that heat transfer capability of tube is enhanced by using Aluminum oxide-water nanofluid. The study has been performed under turbulent-flow conditions. Pressure drop increased with increasing nanoparticle concentration, but decreased with the increased inlet temperature. (Zhao et al, 2016) performed a study on the evaluation of thermal performance of flat tube along with nanofluids and reported the significant improvement in the heat transfer rate. (Singh et al, 2018) also demonstrated increase in heat transfer ratio upon increasing fluid flow rate, inlet-temperature and (Aluminium oxide) nanoparticle concentration in the flat-tube of cooling system. (Elsebay et al, 2015) carried out a study to understand resizing effect of aluminium oxide and copper oxide nanofluid on flat tube and then reported that with use of nanofluids, sizes of tubes can be significantly reduced for same heating load. The objective of current study is to evaluate performance of Aluminium oxide nanofluid in flat tube under turbulent flow regime, as the most of compact heat exchanger are operated in the turbulent flow region.

MATHEMATICAL MODELING

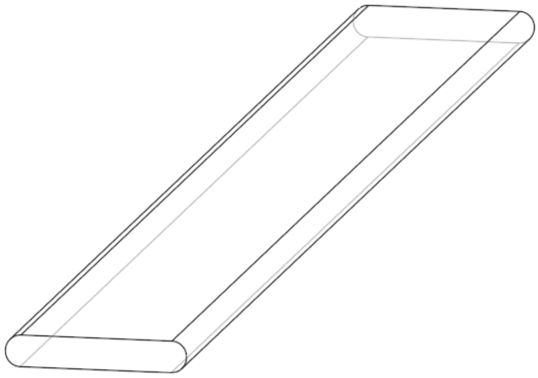

Figure 1: Schematic Diagram of Flat Tube.

The schematic diagram of flat tube of radiator is shown in Figure 1. The tube (Flat) of radiator is reported to have higher surface area to cross-section ratio, when compared with circular cross-sectioned tube which leads to better heating or cooling performance. Flat tubes have major diameter (D) and minor diameter (d). The Hydraulic diameter of this tube was calculated with Equation 1 and in the present problem, Hydraulic-diameter is 0.00539m and length of the tube is 0.610m.

$$D_h = \frac{4 \times [(\pi / 4) d^2 + (D - d) \times d]}{\pi \times d + 2 \times (D - d)} \tag{1}$$

Generalized Equations

The fluid used in the model is considered as incompressible and follows Newtonian behaviour. The viscous dissipation and compression work for the fluid flow in a radiator is negligible. The concentration of particles is very small and the size of the nanoparticle is negligible, therefore the fluid is considered as homogenous. Both, air velocity over the flat plate as well as ambient-temperature condition are assumed as constant. The viscous drag force is very high compared to the gravity force. Therefore, the gravity force is neglected in this study. Under recently mentioned conditions, this problem is analyzed numerically on ANSYS 14.5 (Fluent) and conservation equations 2, 3 and 4 were general equations utilized for analysis of problems.

- Continuity equation:

$$\nabla V = 0 \tag{2}$$

- Energy equation:

$$\rho_{nf} C_{pnf} (\nabla . V) T = k_{nf} \nabla^2 TV \tag{3}$$

- Momentum equation:

$$\rho_{nf} (\nabla . V) V = -\nabla P + (\mu_{nf} + \mu^t) \nabla^2 V \tag{4}$$

The thermal conductivity is calculated with the help of Hamilton–Crosser (1959) model which is defined as shown below:

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + (n-1)k_{bf} - \phi(n-1)(k_{bf} - k_p)}{k_p + (n-1)k_{bf} - \phi(k_{bf} - k_p)} \tag{5}$$

The expression to determine the dynamic viscosity for various nanofluids is generally as follows:

$$\mu_{nf} = \mu_{bf} (1 + 2.5\phi) \tag{6}$$

Specific heat for nanofluid studied was calculated using the relation given by Xuan and Rotzel as given in the Equation 7.

$$(\rho c_p)_{nf} = \phi(\rho c_p)_{np} + (1-\phi)(\rho c_p)_{bf} \tag{7}$$

Usually, digital density meter is used for the measurement of nanofluids density. The Eq. 8 is found to be very close to the respective measured results,

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_{np} \tag{8}$$

Boundary Conditions

The different conditions for this study are mentioned in Table 1.

Table 1: Known Parameters

Parameters	Ranges
Conventional Base fluid	H_2O
Nanoparticles	Alumina oxide
Particle concentrations	0.1–0.5 % v/v
Reynold number	10000–20000
Inlet Fluid temperature	40–70°C

- The inlet section of tube is velocity inlet and turbulence intensity was 8%.
- The wall surface is kept at constant Heat flux of 150 W/m^2K.
- The outlet of compact tube is considered as the pressure outlet only.
- The present simulation analysis is carried out with ANSYS –fluent Program (Finite volume methodology).

RESULTS AND DISCUSSIONS

Mesh Independency Test

To optimize exact number of elements in selected fluid domain, and for reducing required computation time to complete simulation analysis of problem, mesh independency test was performed. Four different set of mesh having different number of elements were used for discretization. For the mesh independence test, water is considered as the fluid and Reynolds number at 10000 and inlet-temperature at 45°C. The Table 2 shows the combinations used and the results obtained from these mesh combinations. The velocity and temperature of grid 2, 3 and 4 reported a very less difference in between them as shown in Table 2. The computation time was higher for large number of elements. Therefore, the grid type 2 is the most suitable to continue for further simulations.

Table 2: Mesh Independency Test Conditions with Results

Series	Grids	Maximum Velocities (m/s)	Maximum Temperatures (K)
1	80 x 30 x 100	0.1939125	307.64958
2	100 x 38 x120	0.1947052	307.95059
3	120 x 40 x120	0.1954152	307.95508
4	140 x 46 x160	0.1962004	307.96191

To verify first order upwind scheme, two more simulations were run and then, their results were compared with each other. Results obtained for both the methods are given in Table 3. As seen from the above, it can be concluded that there is not much appreciable variation in the results irrespective of the increase in iterations and the computation time. Therefore, first order upwind scheme was found to be convenient for proceeding further with this study.

Table 3: Mesh Independence Results

Axial Location	Parameter	First Order Upwind	Second Order Upwind	Percentage Change
Z=0.155m	Temperature (K)	308.06839	308.06956	0.00037978
Z=0.155m	Velocity (m/s)	0.19418718	0.19419551	0.00428949

Formulations Used

The Equation 9 was used for calculating the Reynolds number,

$$\mathrm{Re} = \frac{\rho_{nf} \times v \times D_h}{\mu_{nf}} \tag{9}$$

The Nusselt number for this study is obtained using the following equation,

$$Nu = \frac{h \times D_h}{k} \tag{10}$$

Friction factor (f) is calculated with Equation 11 as given below,

$$f = \frac{2 \times D_h \times \Delta P}{\rho \times v^2 \times L} \tag{11}$$

Result Validation

To confirm the results of simulation, computational results of pilot study is compared with Dittus – Boelter equation. The results in Figure 2 show that there was only 5% error between the computed results and Dittus – Boelter equation results which confirms the good agreement. The error between the Dittus – Boelter equation and computation results has been reduced at high Reynolds number as compared to low Reynolds number.

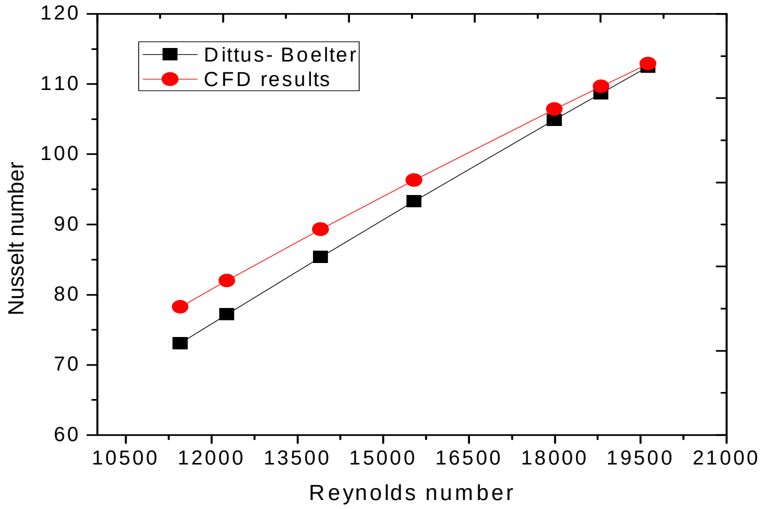

Figure 2: Comparison of Analytical Results of Water with Dittus-Boelter Correlation.

Thermal Performance

The heat transfer behaviour of Al_2O_3 nanofluid is evaluated at different nanoparticle concentration with variation of inlet temperature and Reynold number. Both parameters mentioned above have significant amount of effect on thermal performance of various fluids in flat tube.

Effect of Various Concentrations on Thermal Performance

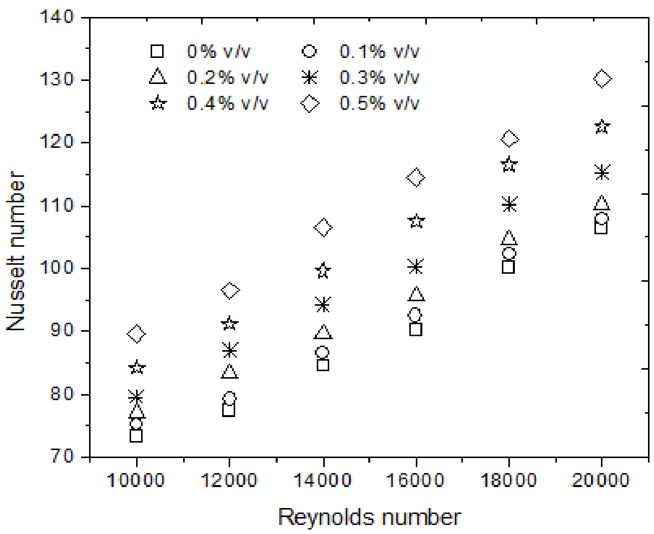

Figure 3: Effect of Variation in Nanoparticle Concentrations on Nusselt Number with Different Reynold Number.

The heat transfer performance is found to be improving upon increase in concentrations of nano-particles. The variation in Nusselt number is due to varying Reynolds number. The nanoparticle concentration is represented in Figure 3. It is inferred that the presence of nanoparticle in conventional fluid plays essential role in enhancing the heat transfer of flat tube used within a radiator. The heat transfer enhancement was only 3% higher with 0.1% v/v concentration nanofluids as compared to base fluid and this enhancement increased up to 18% with 0.5% v/v concentration of nanoparticles for same operating conditions. The higher thermal conductivity of nanoparticles is the one of responsible factors for heat transfer enhancement. This higher thermal conductivity is further said to be one of the significant factors responsible for the enhancement of thermal performance of fluids. The Nusselt number is also seen to increase with the increased Reynolds number, while on the other hand, percentage of enhancement in heat transfer is seen to decline with the increased Reynolds number.

Effect of Temperature on Thermal Performance

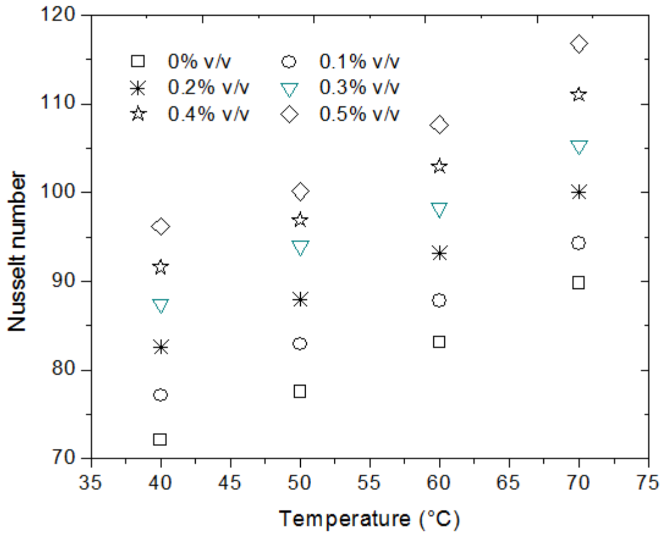

Figure 4: Variation in Nusselt Number with Fluid Temperature and Concentrations.

The heat transfer is also seen to increase with the rise of inlet-fluid temperature, as clearly observed from the figure 4. As the fluid temperature increased from 40°C to 70°C, the Nusselt number is enhanced by 10%. The enhancement is also observed for fluid inlet temperature at 50°C and 60°C. Thermal conductivity has increased with rising inlet temperature which plays an essential role in improved heat transfer. Besides the thermal conductivity of nanoparticles, Brownian motion of nanoparticles in base fluid at high temperature is also a responsible factor for the heat transfer enhancement. The thermal boundary surface layer is also found to be delayed due to presence of chaotic motion or Brownian motion in nanoparticles present near the surface of tube.

Fluid Flow Performance

Pressure Drop Performance

In various applications of nanofluid, thermal performance as well as estimation of Pressure drop is essentially important. In actual applications, Pressure drop depends completely upon various properties like viscosity, density and Reynolds number. Figure 5 given below reported variation in Pressure drop due to variations in nanoparticle concentrations under different Reynolds number. The pressure drop was found to be increased along with rising Reynolds number and with increasing nanoparticle concentrations.

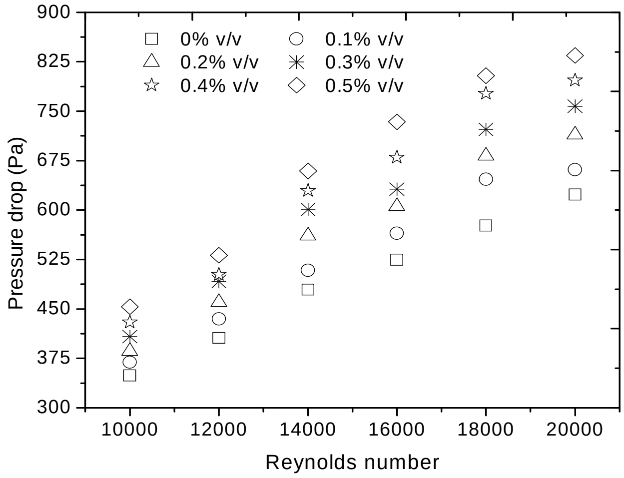

Figure 5: Change in Pressure-drop at Various Reynolds Numbers along with Varying Nanoparticle Concentrations.

The pressure drop increased from 5% to 10% with the addition of 0.1% v/v and 0.5% v/v aluminum oxide nanoparticles in base fluid for fixed Reynolds number~ 10000 and for the same concentrations of nanoparticles, pressure drop increased up to 10% and 20% respectively at Reynolds number 20000. The pressure drop decreases slightly with the increased inlet temperature. Density of nanofluid used decreased with the increased fluid-inlet temperature. Similarly, viscosity of used nanofluid is also found to have decreased with the increase in fluid-inlet temperature.

Friction Factor Variation

The friction factor shown in Figure 6 will increase when nanoparticle concentration increases and friction factor is seen to decrease with the rise in Reynolds number. Minimum value obtained for friction factor is observed at Reynolds number 20000 for the conventional base fluid and slightly increases with the presence of nanoparticles. The deviation between the nanofluids and conventional base fluid is decreased upon increasing Reynolds number.

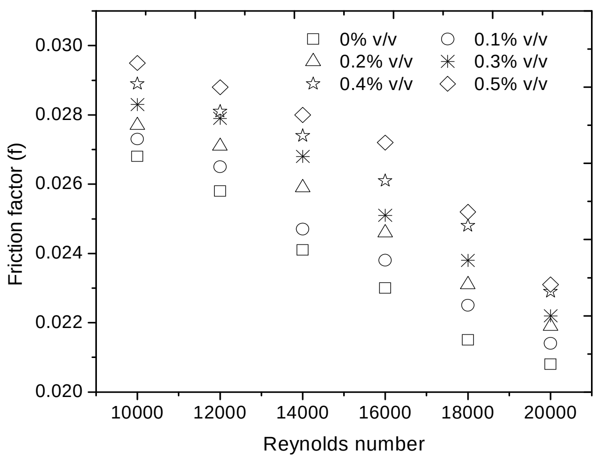

Figure 6: Change in Friction Factor because of Variations in Concentrations and Reynolds Number.

CONCLUSIONS

The performance of fluids with added nanoparticles in flat-tube with variation in concentrations of nano-sized particles, fluid-inlet temperature and Reynolds number are numerically investigated. The heat transfer capacity of fluid is increased with the significant increase in concentrations of nanoparticle in base fluid from 0.1% to 0.5%. The increase in inlet-fluid temperature and Reynolds number also shows enhancement in heat transfer capability of nanofluid. The highest heat transfer was observed approximately 23% for 05% v/v concentration of nanoparticle and fluid inlet temperature 70^{o}C for fixed Reynolds number i.e. 20000. The pressure is also seen to increase with the increase in nanoparticle’s concentrations as well as with higher Reynolds number, however, it slightly decreases with the rise in fluid- inlet temperature. The maximum value for pressure was found to be 12% higher when compared with base-fluid for flat tube. The friction factor is also increasing with higher nanoparticle volume concentration and decreases with lower Reynolds number. The heat transfer performance is more enhanced as comparison to fluid flow performance. The study clearly proves that overall size of radiator device decreased significantly upon utilizing nanofluids instead of conventional cooling mediums i.e. water, ethylene glycol etc.

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Nomenclature

Cp	Specific heat capacity (J/kg K)
Dh	Hydraulic diameter (m)
dP	Nanoparticles diameter (nm)
f	Friction factor
h	Heat-transfer coefficient (W/m2 K)
k	Thermal conductivity (W/m K)
P	Pressure(Pa)
V	Average velocity (m/s)