Journal of Automation and Automobile Engineering
Volume 2 Issue 2

# Analytical Investigation of Total Heat Transfer Rate and Effectiveness of Straight (Plate) Fin Compact Heat Exchanger using Nano-fluid coolants

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***Abstract***

*Compact heat exchangers are widely used in various applications in thermal fluid systems. The traditional approach of increasing the total heat transfer rate by using fins & micro channel has already reached to their limit. Hence there is a need for new & innovative heat transfer fluids for improving heat transfer called nano-fluid. This work presents a detailed numerical investigation on compact heat exchanger by using different nano-particles in base fluid 90% water-10% EG as a coolant for straight fin geometry. For the numerical investigation computer codes are developed in MATLAB language.*

*A theoretical analysis is presented to investigate the thermal performance of a compact heat exchanger by using SiO2,TiO2&ZnOnano particles in mixture of 90% water & 10% EG. Different correlations are used based on the experimental work on the same group of nano fluid. Calculation of total heat transfer rate is done on the heat transfer performance of a compact heat exchanger operating with mixture of water and ethylene glycol based nano fluid keeping in mind the impact of Brownian motion of the nano particle at higher temperature with the straight fin.. Detailed flow chart of the numerical method, correlations used for nano fluid, effects of various operating parameters are presented as well.*

*Result show that 90% water and 10% EG base fluid using nano particles is very effective coolant than 90% water and 10% EG coolant only. But cooling performance of 90% water and 10% EG based coolant can be increased effectively by the use of nano particles. On comparing cooling capacity (total heat transfer rate) for straight fin geometry it is observed that 12 % to 16% enhancement has been seen in the cooling capacity when W-EG nano fluid based coolant is used. By the present analysis it is found that $SiO_2$ based nano fluids is better than that of $TiO_2$ and ZnO based nano fluids.*

***Keywords:*** *Compact heat exchanger, Nano particles, nano fluids, Automobile compact heat exchanger, cooling capacity, pumping power and pressure drop.*

## INTRODUCTION

An automobile is used for transportation of goods and passengers. The heart of any automobile is its internal combustion engine which provides power to wheel.

Figure 1 shows that, 2016broke records for global car sales. According to a report from Macquarie Bank, in the year of 2016 approximately 88.1 million cars and trucks and other light vehicles were sold, up 4.8% from a year earlier.

That was the fastest annual rate of growth since 2013.

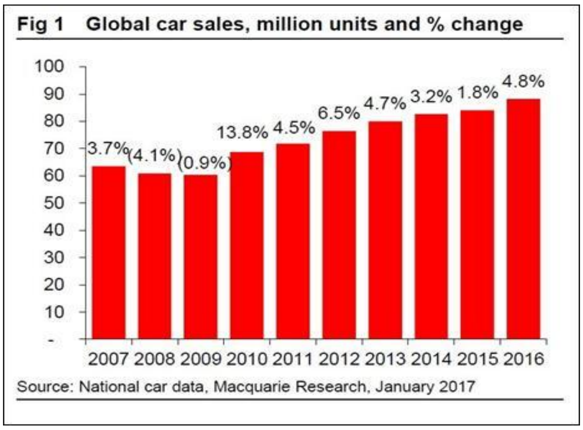


***Fig 1:*** *Global care sales from 2007 to 2016*

Global car sales data( figure 2): approximate 13% growth has been seen in the sales of automobile between the year 2012 to 2015. 73million vehicle has been sold In 2015. Earlier Global car sales totaled 52 million in 2011, 65 million in 2012, 69 million in 2013. In 2014 this increased to 71 million. So, we can easily see that car sales grow every year.

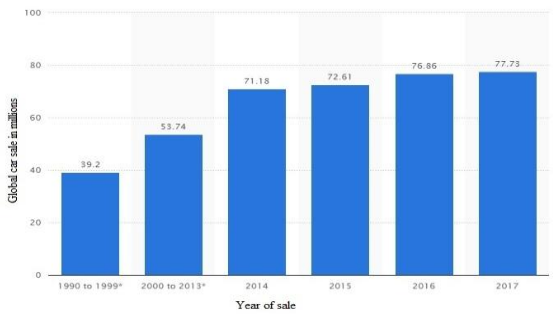


***Fig2:*** *Global care sales in millions*

So, the automobile sector is a best area for research work. Automobile sector requires more and more innovations to provide comfort and better performance to the passenger and rider. There are plenty of research areas present in automobile like engine, engine cooling, suspension system, breaking system, steering system and many more. Every sector in automobile needs an improvement to achieve better performance and comfort. In achieving the objective, engine plays an important role in vehicle as compare to other component and engine performance is depend on its cooling, which is provided by cooling system. So our project is more or less inclined towards improvement in engine cooling system with new coolant technology that is “Nano Fluids”.

**Cooling system**

Cooling system acts as backbone for the lifecycle and performance of automobile engine. If engine cooling is not proper in vehicle, then engine will overheat or may get overcooled and may cause severe damage to the parts which will result in shut down of the vehicle system.

Cooling system contains different parts like radiator, fan, thermostat, water pump, transmission cooler, reserve tank, pressure cap, heater core etc. The friction caused by mating parts result in overheating, which can be controlled by the application of the cooling system. In running time engine get overheated and the chances of failure is also increases so that it required to transfer the heat into the sink

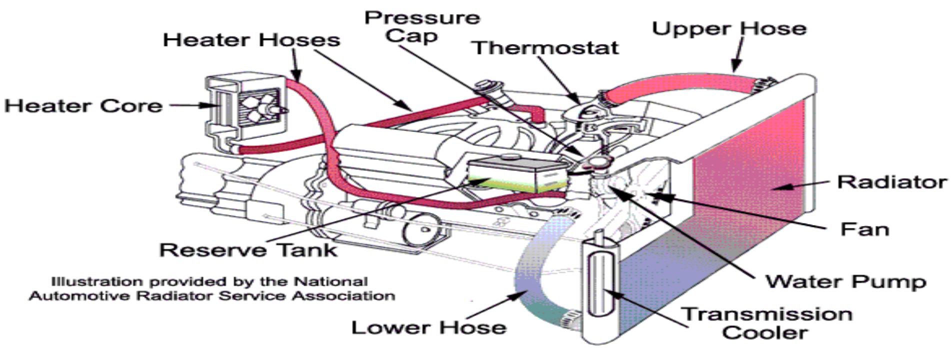


***Fig 3:*** *Automobile cooing system*

Journal of Automation and Automobile Engineering
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**Automobile Radiator**
Radiator is most important part of the cooling system to cool down the engine. The radiator is connected to the engine with channels through which a liquid is pumped. This liquid can be water or another coolant, such as antifreeze. By taking the liquid through the engine, it heats up the liquid and takes it outside of the engine to let it cool down. It is usually located in front of the vehicle's grill in order to benefit from the airflow as the vehicle moves. Water is used as a coolant but in high temperature it gets evaporated and in low temperature it get freeze. So that it's required to mix Anti-freeze substance in the water to increase the freezing point and boiling point of water. There are different type of anti-freezing agent like ethylene glycol and propylene glycol. Mixing ratio of ethylene glycol and water is depending on requirement of freezing and boiling point of coolant. If the ratio of anti-freezing agent is increased then desiring point it increases the coolant viscosity and its affects the mass flow rate. In thisproject ethylene glycolused as antifreeze agent. We use 90% water and 10% ethylene glycol which increase freezing point up to -3.4ºC and boiling point up to 101.1ºC.

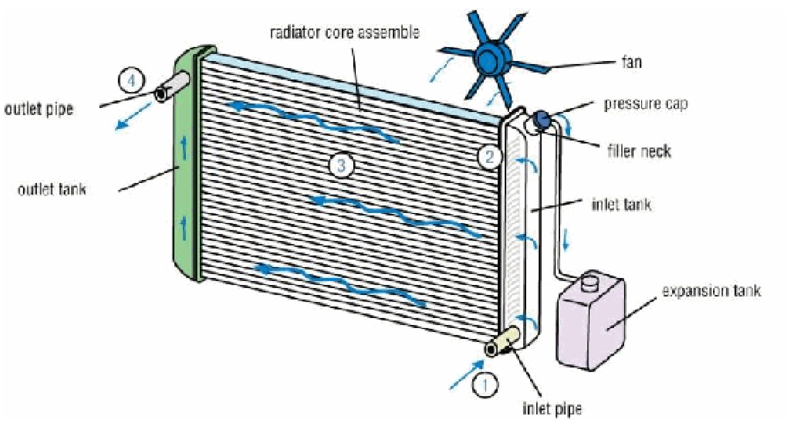

***Fig 4:** Automobile Radiator*

**Nano-Fluids**
A nano-fluid is an engineered colloidal suspension of nano-particles in a base fluid; the base fluid can be any fluid. The nano-particles are nano-meter sized particles and are primarily made of metals, carbides, or oxides.

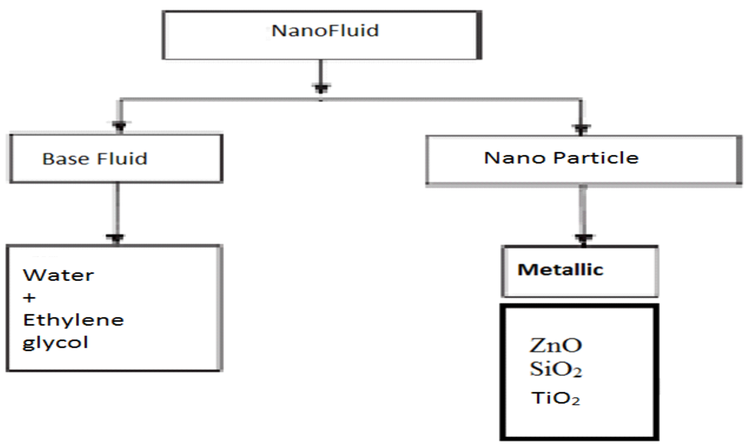

***Fig 5:** Nano Fluid Flow Chart*

The nano-fluids have many properties, which make their potential employability in various fields like micro-electronics, heat transfer, fuel cells, pharmaceuticals, refrigeration, heat exchanger, hybrid engines, grinders, machining etc.

**Classification of Nano-particle**

- Carbon Based Materials
- Metal Based Materials
- Dendrimers
- Composites
- Non-metallic Based Materials

**Carbon Based Materials**

The carbon nano-particles exist most commonly in the form of hollow spheres, ellipsoids or tubes. The spherical and ellipsoidal carbon nano-particles are known as fullerenes, whereas, cylindrical carbon nano-particles are known as nano-tubes. These particles find applications in many fields' viz. film and surface coating, electronics, material sciences etc.

**Metal Based Materials**

The metal based nano-particles are nano-gold, nano-silver, quantum dots and metal oxides like titanium dioxide. The quantum dot is basically a closely packed semi-conductor crystal comprising of millions of atoms, whose optical properties changes with the size.

**Dendrimers**

The dendrimers based nano-particles are nano-sized polymers built from branched units. The surface of a dendrimer has numerous chain ends that can be tailored to perform specific chemical functions, which can be used for catalysis.

**Composites**

The composites based nano-particles are combination of more than one type of nano-particles. In order to improve or enhance the properties nano-sized clays are added to various products like auto-parts, packaging materials.

**Objective**

In this project plate fin automobile radiator is taken as compact heat exchanger and mixture of water & ethylene glycol (90%W-10% EG) taken as base fluid. $TiO_2$, $SiO_2$ and ZnO will be taken as nano particles, which will be mix in base fluid in order to take nano-fluids.

- To calculate the cooling capacity of plat fin automobile radiator by using different type of nanofluid based on $TiO_2$, ZnO and SiO2nano-particles.
- To compare the cooling capacity of base fluid withnanofluids.

Effect of various operating parameters on cooling capacity will be studied such as inlet mass flow rate of air and coolant, inlet temperature of air and coolant and volume concentration of nano-particles

**Numerical Modeling and Computer Simulation**

Including heat transfer and fluid flow effect following assumption has been made for analysis

- Steady state process
- All the heat rejected from the Nano-fluid absorbed by airflow in side radiator.

**Air side calculation:**

Initially, air side calculation were performed to determine air heat capacity, air heat transfer coefficient, fin efficiency and total surface temperature effectiveness. This data were needed to calculated heat exchanger effectiveness, number of heat transfer unit and overall heat transfer coefficient for nano-fluids side calculation the mathematical formulations are shown below.

Air heat capacity rate, Ca can be expressed as

$$C_a = W_a c_{pa}$$

Core mass of electricity of air is expressed as {11}

$$G_a = \frac{W_a}{A_{fr}\sigma_a}$$

Heat transfer coefficient, ha can be expressed as {11}

$$h_a = \frac{j_a G_a c_{pa}}{(P_{ra})^{\frac{2}{3}}}$$

Correlation for the colburn j factor

$$j_a = \frac{0.174}{Re_a^{0.383}} \text{(For plate fin)}$$

Reynolds number expression for plate fin

$$Re_a = \frac{G_a D_{ha}}{\mu_a} \text{(For plate fin)}$$

Where air velocity is given by,

$$u_a = \frac{G_a}{\rho_a}$$

Plate fin efficiency, $\eta_f$ can be expressed as {11}

$$\eta_f = \frac{tahnml}{ml}$$

Where

$$m = \sqrt{\frac{2h_a}{kt}}$$

Total surface temperature effectiveness, can be expressed as {11}

$$\eta_o = 1 - \frac{A_f}{A}(1 - \eta_f)$$

**Nano-fluid side calculation**

Heat transfer coefficient can be expressed as {11}

$$h_{nf} = \frac{Nu_{nf} k_{na}}{Dh_{nf}}$$

Where

$k_{nf}$ is calculated from koo&kleinstruer relation {2}

$$k_{nf} = \frac{k_p + 2k_{bf} - 2(k_{bf} - k_p)\phi}{k_p + 2k_{bf} + (k_b - k_p)\phi} k_{bf} + 5 * 10^2 \beta\phi\rho_{bf} c_{pbf} \sqrt{\frac{kT}{\rho_p d_p}} f(T, \boldsymbol{\phi})$$

Where the particle related empirical parameter

$\beta = 0.0137(100\phi)^{-0.8229}$ $\boldsymbol{\phi}$<0.01

$\beta = 0.0011(100\phi)^{-0.7272}$ $\boldsymbol{\phi}$>0.01

And
$$\mathrm{f(T.\phi)} = -134063 + 1722.3 * \phi + (0.4705 - 6.04 * \phi)T_{ni}$$

Nusselt number for nanofluid is expressed as {5}
$$Nu_{nf} = 0.021(Re_{nf})^{0.8}(Pr_{nf})^{0.5}$$

Reynolds number expression for nanofluid {11}
$$Re_{nf} = \frac{G_{nf} Dh_{nf}}{\mu_{nf}}$$

Velocity of nanofluid is calculated based on correlation obtained from Maiga {3}
$$\mu_{nf} = \mu_{bf}(1 - 0.19\phi + 306\phi^2)$$

$C_{p,nf}$ and $\rho_{nf}$ were calculated based on correlation obtained from Tsai {25}
$$c_{pnf} = \frac{(1-\phi)\rho_{bf} c_{pbf+\phi\rho_p c_{pp}}}{\rho_{nf}}$$

$$P_{nf} = (1-\phi)\rho_{bf} + \phi_p$$

Core mass velocity of coolant is expressed as {11}
$$G_{nf} = \frac{W_{nf}}{A_{fr}\sigma_{nf}}$$

Prandlt number expression for nanofluid is {11}
$$Pr_{nf} = \frac{\mu_{nf} c_{pnf}}{k_{nf}}$$

Heat capacity rate, $C_{nf}$ can be expressed as
$$C_{nf} = W_{nf} c_{pnf}$$

Pressure drop can be expressed as
$$DP_{nf} = \frac{G_{nf}^2 f_{nf} H}{2\rho_{nf}(\frac{D_{hnf}}{4})}$$

Where the friction factor correlation of nano-fluid is given as
$$f_{nf} = 0.3164(Re_{nf})^{0.25}(\frac{\rho_{nf}}{\rho_{bf}})^{0.797}(\frac{\mu_{nf}}{\mu_{bf}})^{0.108}$$

**Performance calculation**

Overall heat transfer coefficient, based on air side can be expressed as below, where wall resistance and fouling factors are neglected.

$$\frac{1}{U_a} = \frac{1}{\acute{\eta} h_a} + \frac{1}{(\frac{\alpha_{nf}}{\alpha_a}) h_{nf}}$$

Number of heat transfer unit is expressed as{11}

$$NTU = \frac{U_a A_{fr,a}}{C_a}$$

Heat exchanger effectiveness for cross-flow unmixed fluid can be expressed as{11}

$$\varepsilon = 1 + \exp[\frac{1}{C^*} NTU^{0.22} \exp(-C^* NTU^{0.78} - 1)]$$

Where,

$$C^* = \frac{C_a}{C_{nf}}$$

Pumping power can be expressed as

$$P = v_{nf} DP_{nf}$$

Where,

$$V_{nf} = \frac{W_{nf}}{\rho_{nf}}$$

Total heat transfer rate can be expressed as{11}

$$Q = \varepsilon C_{min}(T_{c,in} - T_{a,in})$$

**Input Parameters**

The radiator chosen for this study is cross flow heat exchanger where fluids are unmixed. It is TBD 232V-12 type automobile radiator. Total 644 tubes made by brass material with 346 continuous fins made by aluminum material is attached with radiator. Thermal conductivity of fins material is 177 W/mK.

***Table 1:*** *Thermo physical property of air {12}*

| S.No. | Input parameters | |
|---|---|---|
| 1. | $\rho_a$ | 1.1614 kg/$m^3$ |
| 2. | $cp_a$ | 1007 J/kgK |
| 3. | $\mu_a$ | 0.00001846 N-s/$m^2$ |

***Table 2:*** *Thermo physical property of base fluid*

| S.No | Thermo physical property of base fluid | |
|---|---|---|
| 1. | $\rho_{bf}$ | 995 kg/$m^3$ |
| 2. | $cp_{bf}$ | 4157 J/kg°C |
| 3. | $\mu_{bf}$ | 0.00101 kg/ms |
| 4. | $k_{bf}$ | 0.615 W/m°C |

***Table 3:*** *Thermo physical property of Nano-particle*

| Property | $TiO_2$ | ZnO | $SiO_2$ |
|---|---|---|---|
| $c_p$ (J/kgK) | 686.2 | 514 | 745 |
| $\rho_p$ (kg/$m^3$) | 4250 | 5600 | 2220 |
| $k_p$ (W/mK) | 8.9538 | 27.196 | 1.381 |

***Table 4:*** *Fluid parameters and normal operating condition {6}*

| S.No. | Description | Air | Coolant |
|---|---|---|---|
| 1 | Fluid mass rate | 10-20 kg/s | 4-6 kg/s |
| 2 | Fluid inlet temperature | 283-323 K | 343-383 K |
| 3 | Core width | .0.6 m | - |
| 4 | Core height | 0.5 m | - |
| 5 | Core depth | 0.4 m | - |

***Table 5:*** *Surface core geometry of flat tubes, continuous fin {6}*

| S.No | Description | Air Side | Coolant Side |
|---|---|---|---|
| 1. | Fin pitch | 4.46 fin/cm | |
| 2. | Fin metal thickness | 0.01 cm | |
| 3. | Hydraulic diameter, $D_h$ | 0.351 cm | 0.373 cm |
| 4. | Min free flow area/Frontal area, $\sigma$ | 0.780 | 0.129 |
| 5. | Total heat transfer area/ Total volume, $\alpha$ | 886 $m^2/m^3$ | 138 $m^2/m^3$ |
| 6. | Fin area/ Total area, $\alpha$ | 0.845 | |

$$k_{fin} = \frac{177W}{mK}$$

**Computer Simulation**
For implementing the analysis a computer programming in MATLAB is developed for the compact heat exchanger. This program is useful in estimating the fluid properties at operating temperature, surface core geometry of cross flow heat exchanger, heat transfer coefficient, pressure drops, overall heat transfer coefficient and heat transfer rate.

**Results and Discussion**
The variation of total heat transfer rate and effectiveness with air mass flow rate from 10 to 20 kg/s, keeping constant average value for other input data ($m_{bf}$=5kg/s, $T_{ai}$=30ºC, $T_{ni}$=90ºC). It has been found that with increasing mass flow rate of air, total heat transfer rate goes on increasing because of increasing heat transfer coefficient and overall heat transfer coefficient and the effectiveness for cooling is goes on decreasing because NTU is decreasing. Also total heat transfer rate and effectiveness of nano-fluids having base fluid of 90%water- 10% EG is much higher as compared to 90%water-10% EG mixture only. On comparing total heat transfer rate and effectiveness using different nano-fluids, it has been observed that nano-fluids based on $TiO_2$, $SiO_2$ and ZnO exhibit almost same behavior and they have higher total heat transfer rate and effectiveness as compared to base fluid. However $SiO_2$ based nano fluids have higher total heat transfer rate.

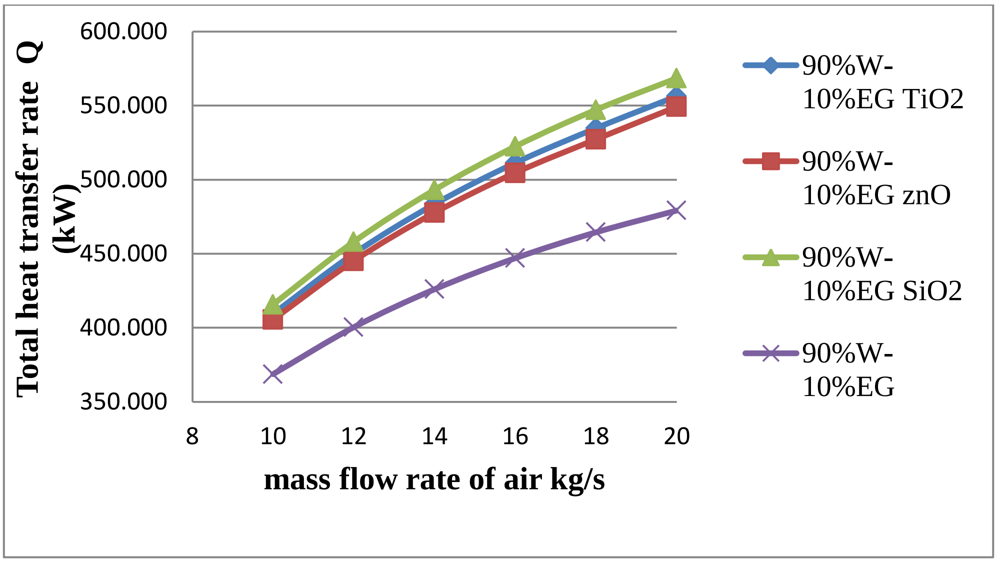


**Fig 6:** Effect of mass flow rate of air on total heat transfer rate

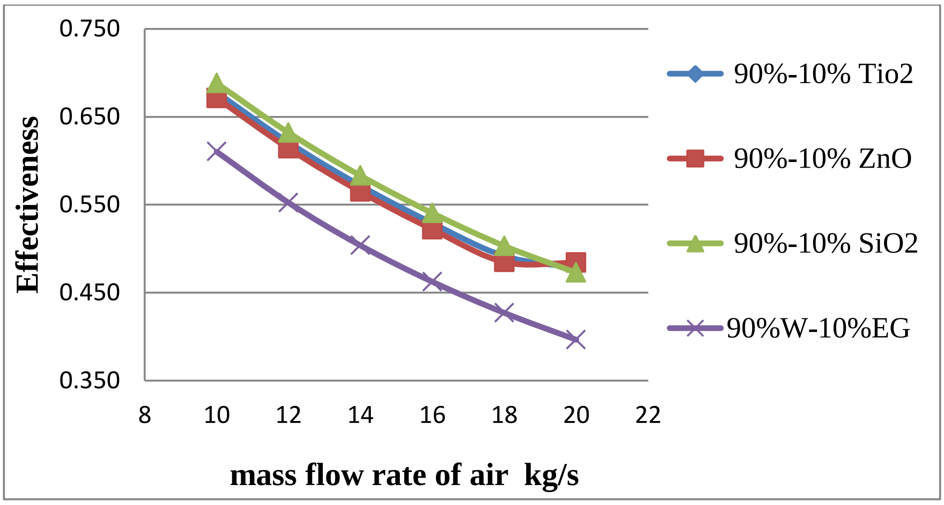


**Fig 7:** Effect of mass flow rate of air on effectiveness

**Influence of varying coolant mass flow rate**

For the variation of coolant mass flow rate, keeping constant average values for other input data ($m_a$=15kg/s, $T_{ai}$=30ºC, $T_{ni}$=90ºC). It has been observed that both total heat transfer rate and effectiveness goes on increasing and on comparing, total heat transfer rate and effectiveness of nano-fluid using base fluid 90%water-10%EG is much higher when only 90%water-10%EG mixture is used as a coolant.

 

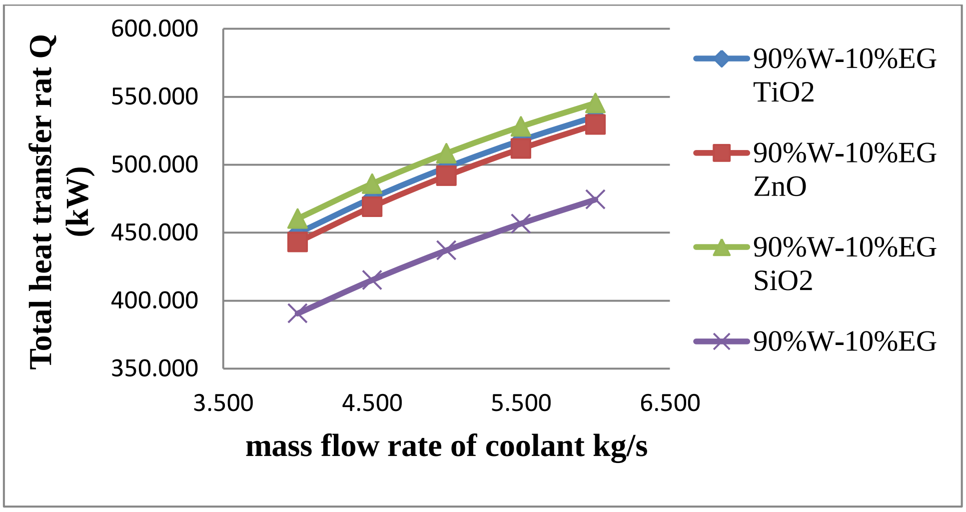


***Fig 8:*** *Effect of mass flow rate of coolant on total heat transfer rate*

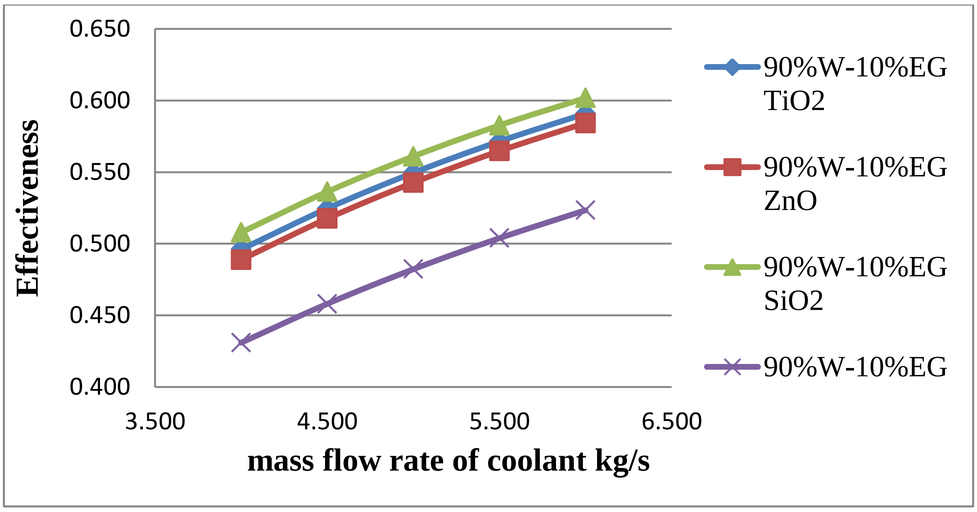


***Fig 9:*** *Effect of mass flow rate of coolant on effectiveness*

**Influence of varying inlet air temperature**

The variation of total heat transfer rate and effectiveness with air inlet temperature is shown in Fig.10 & 11 for ($m_c$=5kg/s, $m_a$=15kg/s, $T_{nfi}$=90$^0$C). As expected the heat transfer rate clearly decreases with air inlet temperature rise, as the cooling temperature difference is being reduced. It is interesting to point out that Nanofluid using 90% water-10% EG has higher total heat transfer rate than that of 90% water-10 %EG as coolant. Effectiveness is found constant throughout the variation of inlet air temperature.

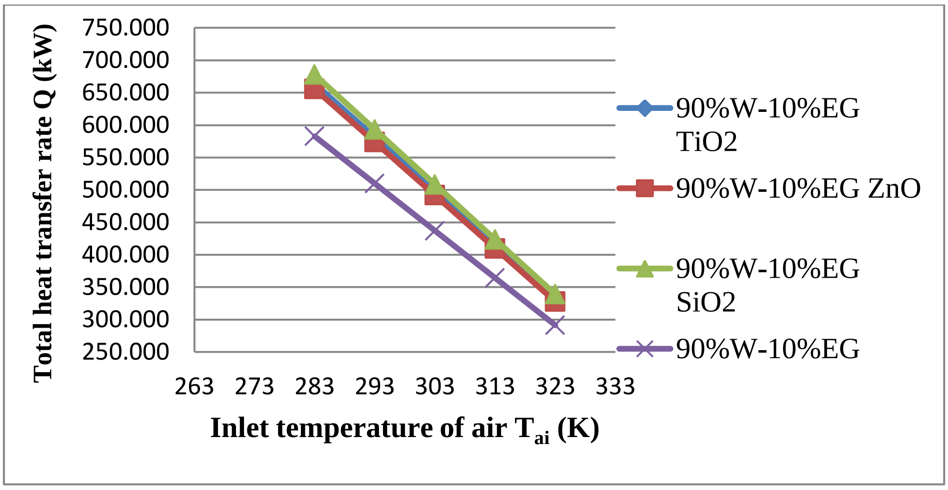


***Fig 10:** Effect of inlet temperature of air on total heat transfer rate*

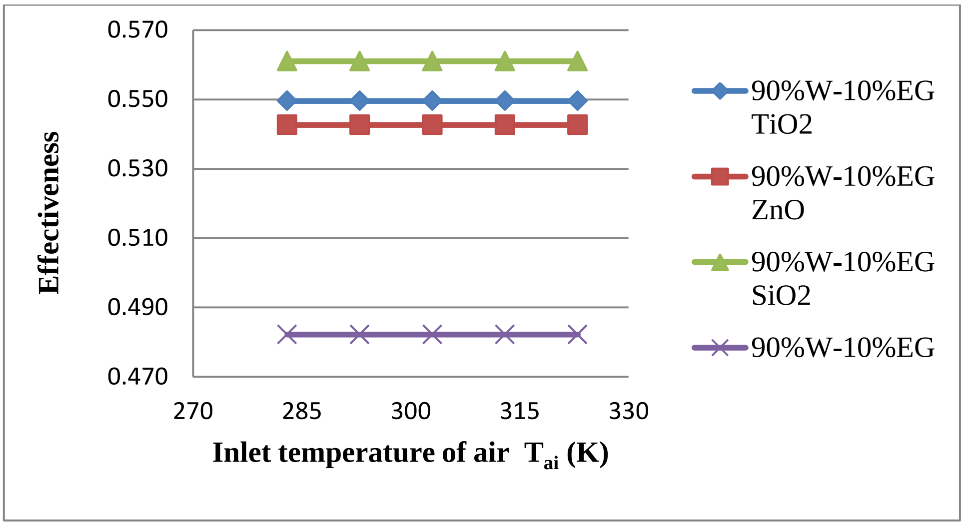


***Fig 11:** Effect of inlet temperature of air on effectiveness*

**Influence of inlet temperature of coolant**

The variation of total heat transfer rate and effectiveness with coolant inlet temperature is shown in Fig.12 & 13 for ($m_c$=5kg/s, $m_a$=15kg/s, $T_{ai}$=30$^0$C). As expected the heat transfer rate increases with coolant inlet temperature rise due to increment in the cooling temperature difference. Also, for this variation study shows there is very little increment in the effectiveness. However total heat transfer rate and effectiveness is maximum for $SiO_2$ based nano fluids and minimum for base fluid alone.

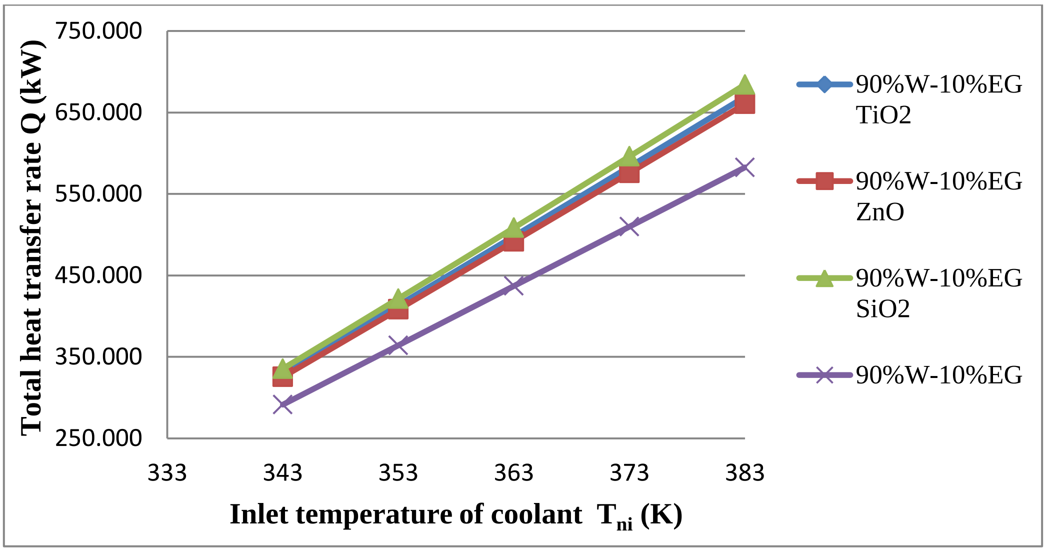


***Fig 12:** Effect of inlet temperature of coolant on total heat transfer rate*

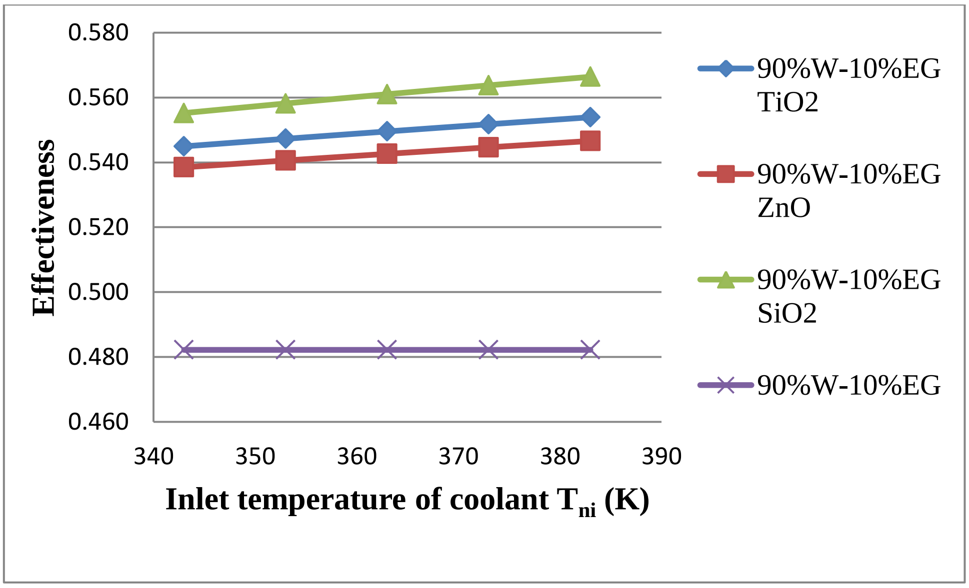


***Fig 13:** Effect of inlet temperature of coolant on effectiveness*

**Influence of volume concentration of particle**

This study observed that (Fig.14 & 15) for the variation of volume fraction of nano-particle total heat transfer rate and effectiveness is increases up to 1% volume fraction and beyond that decrement in the effectiveness and total heat transfer rate was observed duo to collection of nano particles.

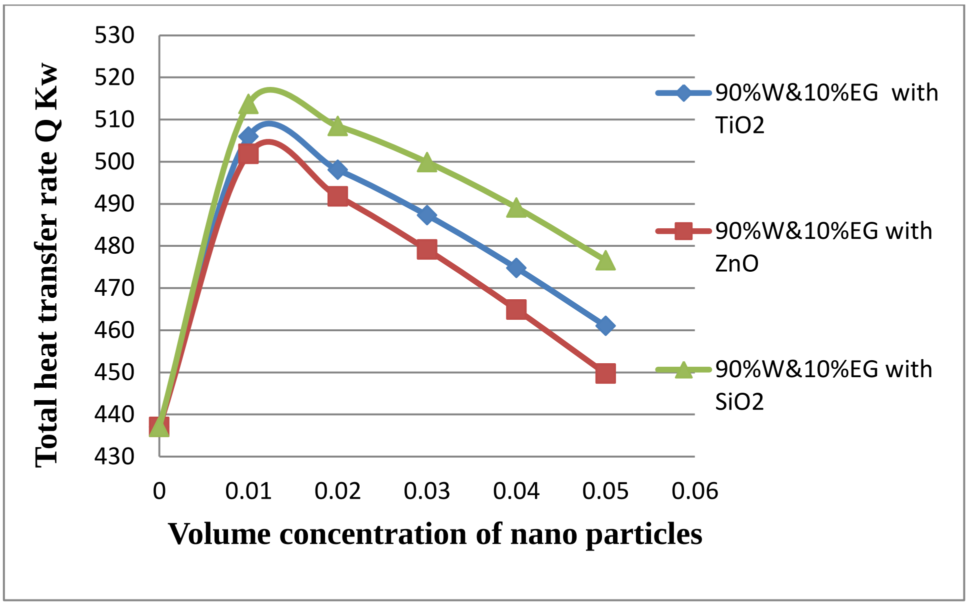


***Fig 14:*** *Effect of volume concentration of particle on total heat transfer rate*

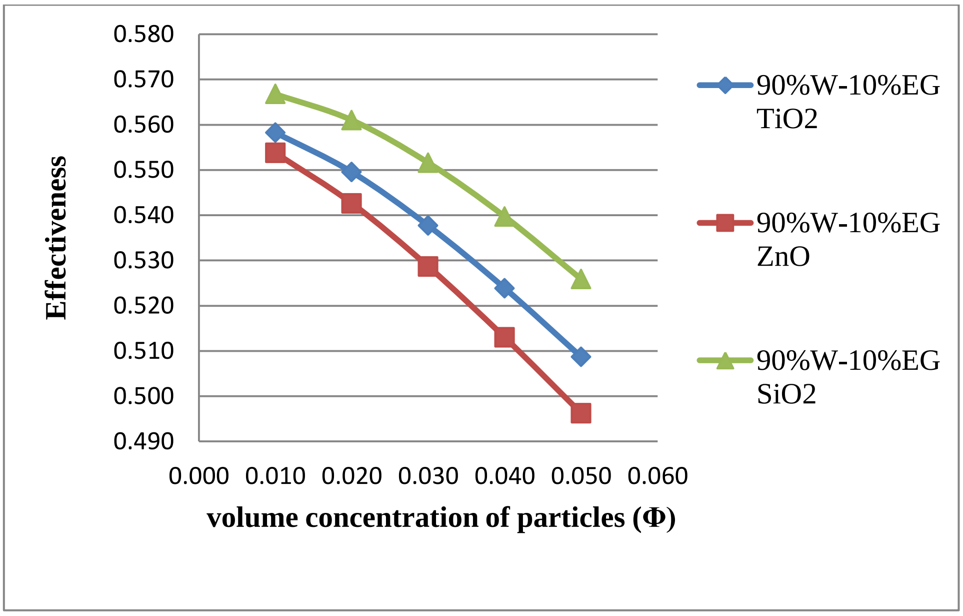


***Fig 15:*** *Effect of volume concentration of particle on effectiveness*

## COMPARISON

**Table 6:** Comparison of total heat transfer rate, effectiveness (ma=15 kg/s, mc=5kg/s, Ta=303K, Tn=363K and phi=2%)

| S.No. | Coolant | Total heat transfer rate Q (kW) | Effectiveness |
|---|---|---|---|
| 1 | $SiO_2$ base fluid | 508.450 | 0.561 |
| 2 | $TiO_2$ base fluid | 498.050 | 0.549 |
| 3 | ZnO base fluid | 491.790 | 0.542 |
| 4 | Only base fluid | 437.020 | 0.482 |

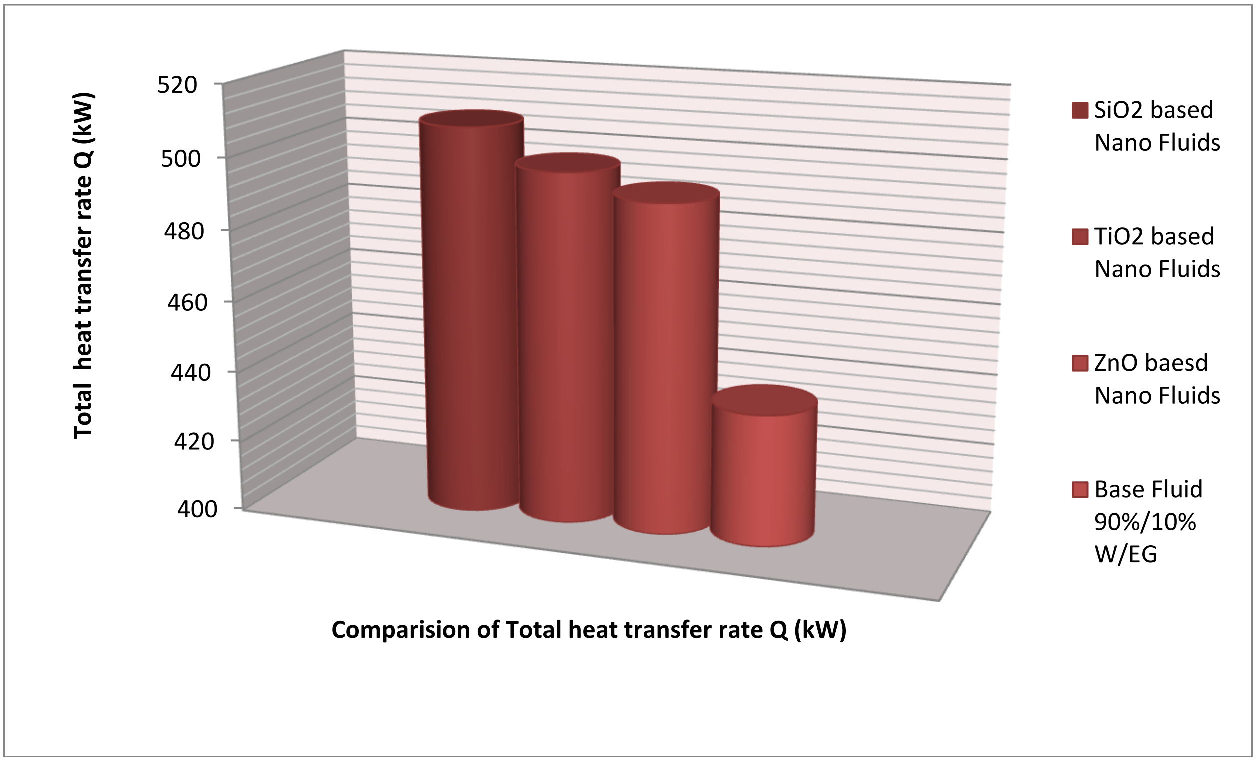


***Fig 16:** Comparison of total heat transfer rate*

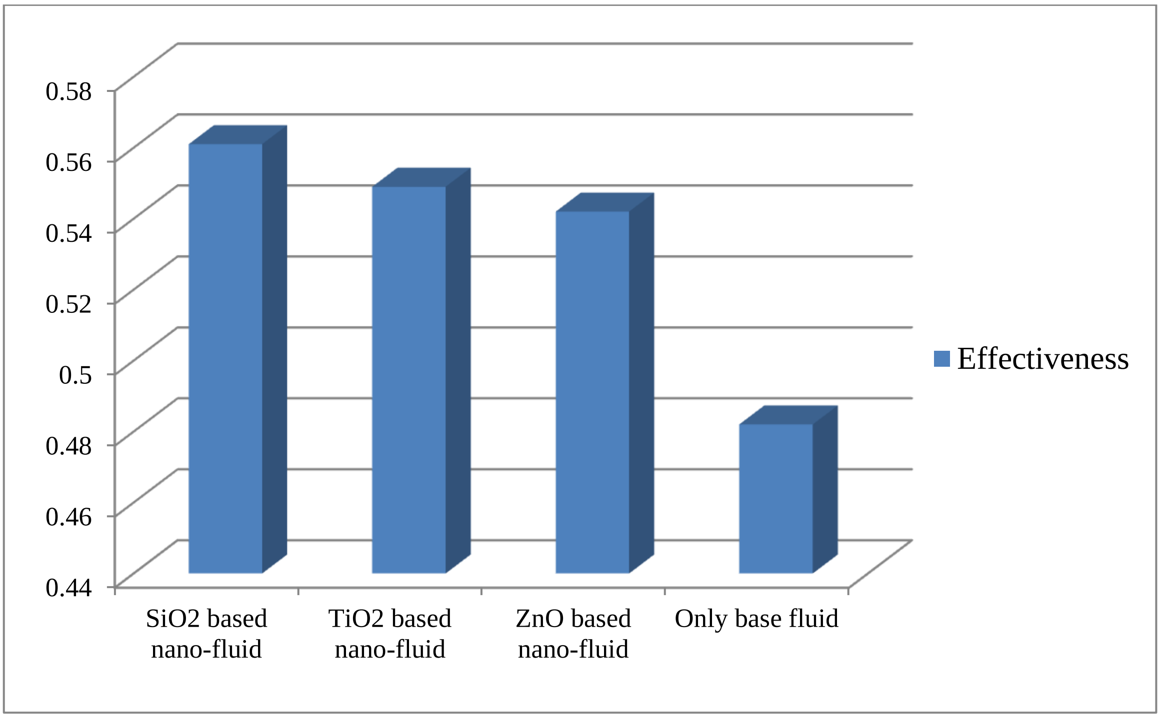


***Fig 17**: Comparison of effectiveness*

The total heat transfer rate and effectiveness of $SiO_2$, $TiO_2$ and ZnO is 16%, 14% and 12.53% more than that of 90% Water and 10% EG at $m_a$ = 15 kg/s, $m_c$ = 5 kg/s, $T_{ai}$ = 303 K, $T_{ci}$= 363 K and $V_c$ = 2%. Moreover, among the nano-fluids, total heat transfer rate of $SiO_2$ is 2% and 3.38% more than $TiO_2$ and ZnO respectively at $m_a$ = 15 kg/s, $m_c$ = 5 kg/s, $T_{ai}$ = 303 K, $T_{ci}$ = 363 K and $V_c$ =2%.

**Conclusions and Future work**

A detailed parametric study on automobile radiator has been done by using ε - NTU method using three nano-fluids ($SiO_2$, $TiO_2$ and ZnO) in a base fluid 90% water-10% EG as a coolant for plate fin geometry. Detailed flow chart of the numerical method and correlation used for nano-fluid are presented. Based on result and discussion, following conclusion can b made

- Total heat transfer rate and effectiveness increases with increase in mass flow rate of air and coolant.
- Total heat transfer rate of radiator using nano-fluid is greater than radiator using base fluid alone.
- $SiO_2$based nanofluids has grater total heat transfer rate and effectiveness as compared to $TiO_2$ and ZnO based nano fluids.

**Future work:**

- Development of experimental set up for plate fin geometry for keen observation and analysis.
- Performance analysis of engine can be done for other fin geometries.

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