International Journal of Nanotechnology and Applications
ISSN 0973-631X Volume 2, Number 1 (2008), pp. 75–87
© Research India Publications
http://www.ripublication.com/ijna.htm

Application of Nanofluids in Thermal Design of Compact Heat Exchanger

V. Vasu[1*], K. Rama Krishna[2] and A.C.S. Kumar[3]

[1]Lecturer, Department of Mechanical Engineering,
V R Siddhartha Engineering College, Vijayawada 520002, India
[2]Professor & Dean Freshman Engineering,
KL Engineering College, Vedeswaram, Guntur District, India
Email : klce_drkrk@rediffmail.com
[3]Professor, Mechanical Engg., JNTU College, Hyderabad, India
Email : acskumar@yahoo.com
[*] Corresponding Author : Email: vvvasu@rediffmail.com

Abstract

Compact heat exchangers have been widely used in various applications in thermal fluid systems including automotive thermal fluid systems. Radiators for engine cooling systems, evaporators and condensers for HVAC systems, oil coolers and inter coolers are typical examples that can be found in ground vehicles. Recent development of Nanotechnology brings out a new heat transfer coolant called ‘Nanofluids’ these fluids exhibit larger thermal properties than conventional coolants (water, Ethylene glycol, Engine oil etc.) due to the presence of suspended nanosized particles in then such as Al_2O_3, Cu,CuO,TiO_2 etc. In this paper a theoretical analysis was carried with ε – NTU rating method by using Al_2O_3 + H_2O Nanofluid as coolant on automobile flat tube plain fin compact heat exchanger and different characteristics are graphically presented.

Keywords: Automobile Radiator, compact heat exchanger, ε – NTUmethod, Nanofluid

Introduction

The automobile industry continuously faces challenges to obtained best automobile design in aspects of performance, fuel consumption, safety etc. The thermal performance of an automobile radiator plays an important role in the performance of automobiles cooling system and all other associated systems. The air cooled heat exchanger found in a radiators, AC condenser, and evaporator etc. have an important role in its weight and also in the design of its front end module, which also has a strong impact on the car aerodynamic behavior. To improve the heat transfer from a surface it is common to apply turbulence promoters, roughness elements to the surface. In recent years a growing and intense attention has been turned to the study of new concept compact heat exchangers, as they represent a good solution in terms of dimensions and efficiency for industrial applications compared to traditional ones. Compact heat exchangers usually setup in a cross flow arrangement are characterized by extended surfaces with large surface area/volume ratios (> 700 m^2/m^3) that can often arrangements [1]. A variety of increased heat transfer surfaces are used: plain, wavy, offset strip, perforated and louvered fins [3].

Ganga et.al [4] presented a numerical model based on ε – NTU method of a radiator in diesel engine type TBD 232 V-12 and give radiator characteristics for different fin and tube materials. E. Carluccio [5] presented numerical analysis of air-oil radiator made of aluminum alloy using CFD and compared with experimental data. A. Witry et.al [6] presented thermal performance of automotive aluminum plate radiators using CFD and found to have higher heat transfer levels, lesser pressure drop, smaller size and coolant flows velocities decreases because of impingement and erosion/corrosion of the plate. J. mohmoudi [7] conducted experimental and theoretical analysis on capper base automobile radiator. He has developed a 2D CFD model and found the inlet and enter let parameter are important for design of the radiator. C.Oliet et.al [8] proposed a numerical model using ε – NTU method CFD. They presented a detailed knowledge base of parametric study on design of automotive radiations.

In radiators, which are vital component in the control of the engine temperature in automobiles, a liquid (commonly water – glycol mixture) is to be cooled by air. The liquid flows in flat tubes while the air flows in channels setup by fin surfaces. With recent developments in Nanotechnology has been widely used in traditional industries because materials with grain size of nanometers posses unique optical, electrical and thermal properties etc. Recently, nanoparticles can be dispersed in conventional heat transfer fluids such as water, Ethylene glycol, Engine oil tp produce a new class of high efficient heat exchange fluids called Nanofluids [9]. Many experimental (Eastman JA et.al [10], Sk Das et.al [11], Xuan Y et.al [12], Ding Y et.al [13] etc.) and theoretical (Ravi et.al[14] SEB. Maiga et.al [15] etc) analysis are carried and found these new heat exchanger coolants are excellent. Vasu et.al [16-17] has developed thermophysical correlations to calculated thermal conductivity, viscosity, Nusselt number in turbulent and laminar flows of different nanofluids ($Al_2O_3 + H_2O$, $Cu + H_2O$ etc) and found these fluids posses very high thermal properties than conventional coolants. In this paper numerical analysis was carried with ε – NTU method by using Nanofluid as coolants to compact automobile radiator and different radiators characteristics are presented.

Compact Heat Exchanger Geometry

As illustrated in Fig 1. the compact heat exchanger is made of four major components, coolant inlet tank, outlet tank, pressure cap and core. Coolant tanks are positioned either on top and bottom of the core. The coolant circuit is usually pressurized using pressure cap to increase the boiling point of the coolant in many applications, which allows higher operating temperatures. The major sub components of the core are coolant tubes and fins. Flat tubes are more popular for automotive applications due to their lower profile drag compared with round tubes. The directions of the coolant and air flows cross each other as in Fig. 1. Therefore, ultimate design object of the heat exchanger is to maximize the heat rejection rate while minimizing the flow resistance. Due to many parameters numerical ε – NTU method can be very useful for analysis.

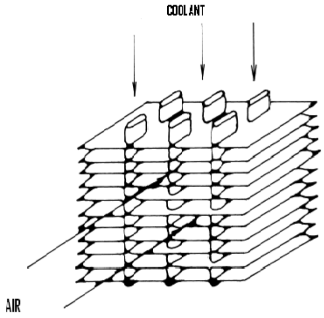

Figure 1 : Structure of typical Compact Heat Exchanger core

Problem Formulation

Considered the radiator [4] mounted on the present turbo-charged diesel engine of type TBD 232V-12 cross flow compact exchanger with unmixed fluids in Fig.1 consists of 644 tubes make of brass and 346 continuous fins made of copper. The following geometrical factors operating conditions are described in the following tables 1-2

Table 1 : Fluid parameters and Normal Operating conditions

S.No.	Description	Air	Coolant
1.	Fluid mass rate	8 -20 kg/s	6000-10000 kg/hr
2.	Fluid inlet Temperature	20-55 ^{0}C	70-95 ^{0}C
3	Fluid Temperature rise/ drop	28 ^{0}C	6 ^{0}C
4	Core width	0.6 m	
5.	Core height	0.5m	
6.	Core depth	0.4m	
7.	Tube size	1.872cm * .245cm	

Table 2 : Surface core geometry of flat tubes, continuous fins (surface 11.32-0.737-SR [2])

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	0.351cm	0.373cm
4.	Min free flow area / Frontal area , σ	0.780	0.129
5.	Total heat transfer area / Total volume, α	886 m^2/m^3	138 m^2/m^3
6.	Fin area / Total area, β	0.845	

Equations Used for Calculations

Air side

(1) Heat transfer coefficient [4] , h_a

$$h_a = \frac{j_a G_a Cp_a}{(\Pr_a)^{2/3}}$$

Where $j_a = \dfrac{0.174}{(\mathrm{Re}_a)^{0.383}}$

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

$$\mathrm{Re}_a = \frac{G_a D_{h,a}}{\mu_a}$$

(2) Fin efficiency of plate fin can be calculated as

$$\eta = \frac{\tanh mL}{mL} \quad \text{where} \quad m = \sqrt{\frac{2h_a}{k\,t}}$$

The area-weighted fin efficiency is determined by

$$\eta' = \lambda\eta + 1 - \lambda \quad \text{where} \quad \lambda = \frac{A_f}{A}$$

(3) Pressure drop for fin side

$$\Delta P = \frac{G_a}{2\rho_{i,a}}\left[\left(1+\sigma_a^2\right)\left(\frac{\rho_{i,a}}{\rho_{i,a}} - 1\right) + f\,\frac{A}{A_{\min}}\,\frac{\rho_{i,a}}{\rho_m}\right] \tag{12}$$

where $\frac{1}{\rho_m} = \frac{1}{2}\left(\frac{1}{\rho_{i,a}} + \frac{1}{\rho_{o,a}}\right)$

(4) Friction factor f is given by

$$f = \frac{0.3778}{\mathrm{Re}_a^{0.3565}}$$

(5) Air heat capacity rate , C_a

$$C_a = m_a Cp_a$$

Nanofluid as coolant side

(1) Heat transfer coefficient of the $Al_2O_3 + H_2O$ nanofluid in turbulent flow as been developed in previous studies the reference paper [18]-[20] comparison is shown in Fig. 2

$$h_{nf} = \frac{Nu_{nf} K_{nf}}{D_{h,nf}}$$

Where $Nu_{nf} = 0.023(\mathrm{Re}_{nf})^{0.8}(\mathrm{Pr}_{nf})^{0.4}$ for $Al_2O_3 + H_2O$ is developed [19] which is found to be in good agreement with the experimental data as shown in Fig. 2. with standard Deviation of 6.4% and Average deviation of 5%.

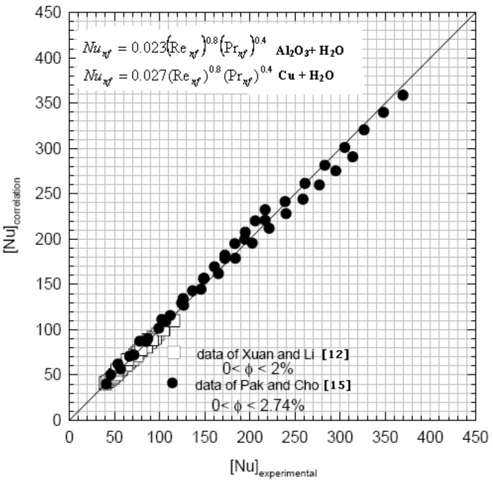

Figure 2 : Comparison of Nu Correlation with experimental data

$$\mathrm{Re}_{nf} = \frac{u_{\max} D_{h,nf}}{\nu_{nf}}$$

$$\mathrm{Pr}_{nf} = \frac{\mu_{nf} Cp_{nf}}{k_{nf}}$$

$$\frac{k_{nf}}{k_f} = \mathrm{Re}_m^{0.175}\,\phi^{0.05}\left(\frac{k_p}{k_f}\right)^{0.2324}$$

for Al_2O_3 + H_2O is developed [18] which is found to be in good agreement with the experimental data as shown in Fig. 3. with standard deviation of 1% and Average deviation of 2%.

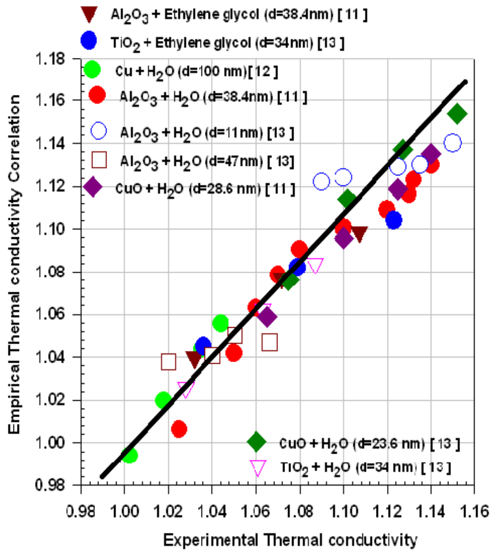

Figure 3 : Comparison of k_{nf} Correlation with experimental data

Validation with other Theoretical Models

Fig 4 (a-b) shows the prediction based on the present model (soild line) in comparison with the published models for the case of 38.4 nm Al_2O_3 at 1 Vol% in water. The symbols show the corresponding experimental data (Das S.K et al. [39]). The Xuan et al. and Koo et.al excessively overestimates and their model shows the limitation of the simple modification of Maxwell's model to apply for nanofluids. The Jang and Choi's model shows underestimated values with experimental data, this is believed attributing to their incorrect postulation in determining the Nusselt number as previously pointed out. The model by Kumar at al. wrongly postulates the mean free path of the base fluid and completely fails to predict nanofluid thermal conductivity. The model by Prasher et al. shoes good agreement with the experimental data as shown in Fig 5(b). However, with temperature variation their model breaks down showing excessive underestimation with experimental data Fig. 5(a).

These models inherently lacks the dependency of the material properties of nanoparticle other than incorporating their sizes and concentrations. Jang and Choi also shows large discrepancies possibly because of the same reason of incomprehensive parametric dependency. Xuan et al. does not show agreeable temperature dependency, and Kumar et al. model does not shown any physically meaningful representation. However, the present model of Eq () shows fairly good agreement comprehensively for both nanofluids and for all the tested conditions of temperatures and volume concentrations.

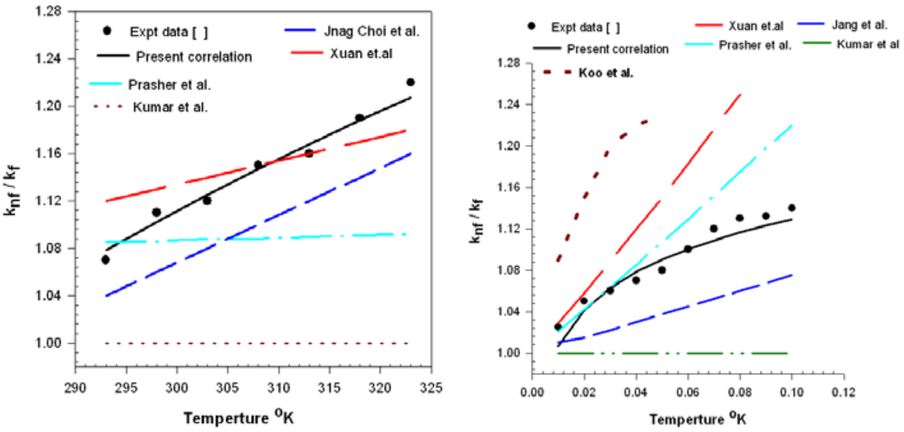

Figure 4 (a-b) : Comparison of the Present Model with the published models.

$$\mu_{\mathrm{nf}} = \mu_{\mathrm{f}}(1+39.11\phi+533.9\phi^2)$$

$$\rho_{\mathrm{nf}} = (1-\phi)\rho_{\mathrm{f}} + \phi\rho_{\mathrm{p}}$$

$$\mathrm{Cp}_{nf} = \frac{(1\text{-}\phi)\rho_{\mathrm{f}} Cp_f + \phi\rho_p Cp_p}{\rho_{nf}}$$

(2) Pressure drop is given as

$$\Delta P_c = \frac{2 G_{nf} f_{nf} H}{\rho_{nf} D_{h,nf}}$$

Where $f_{nf} = 0.079\left(\mathrm{Re}_{nf}\right)^{-0.25}$

(3) Coolant heat capacity rate , C_{nf}

$$C_{nf} = m_{nf} Cp_{nf}$$

The Heat exchanger effectiveness for cross flow unmixed fluids, ε is given as [2]

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

Where $C^* = \dfrac{C_a}{C_{nf}}$ $\quad NTU = \dfrac{U_a A_a}{C_a}$

Overall heat transfer coefficient, based on air side is given as

$$\frac{1}{U_a} = \frac{1}{\eta' h_a} + \frac{1}{\left(\dfrac{\alpha_{nf}}{\alpha_a}\right) h_{nf}}$$

Total heat transfer rate

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

For implementing the analysis, a computer program in MATLAB is developed for the compact heat exchanger. This program is useful is useful in estimating the fluid properties at operating temperatures, surface core geometry of cross flow heat exchanger, heat transfer coefficients, pressure drops, overall heat transfer coefficients and heat transfer rate. The flowchart of the numerical analysis is shown in Fig.5 .

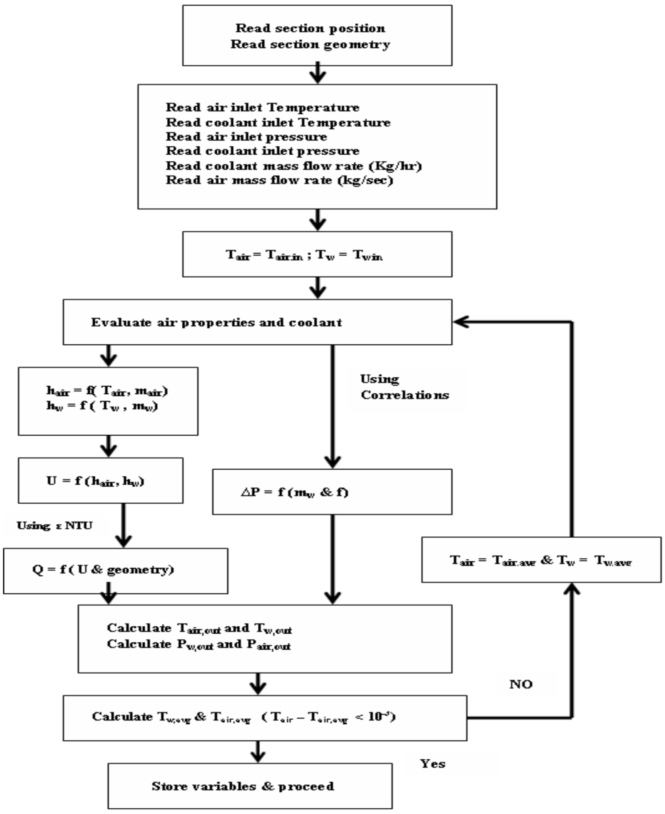

Figure 5 : Schematic of the Numerical method

Results and Discussions

Fig.6 indicates that nanofluids possess higher heat transfer characteristics than conventional coolants water and 50% ethylene glycol. The overall heat transfer coefficient is very high for Nanofluids than water and decreases with increase of the volume fraction of nanoparticles.

Effect of Air inlet Temperature

One of the most important factor in an automotive radiator system, the air inlet temperature is analysed is shown in Fig. 7 for the two limiting air flows (12kg/sec and 6 kg/sec) for a range of temperature from 0^0C to 50^0C. 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 the Al_2O_3 + H_2O nanofluids as higher cooling capacity an that of water as coolant. There is a small influence of air inlet temperature on the overall heat transfer coefficient whereas the air pressure drop reveals moderate.

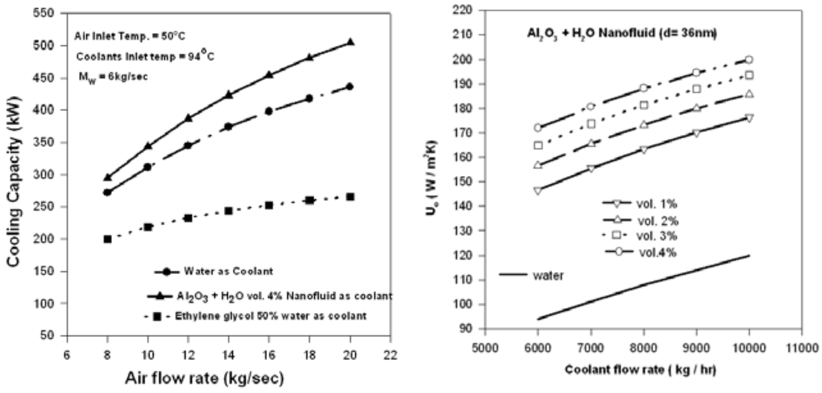

Figure 6 : Comparison of Nanofluid as coolant with conventional coolant (water)

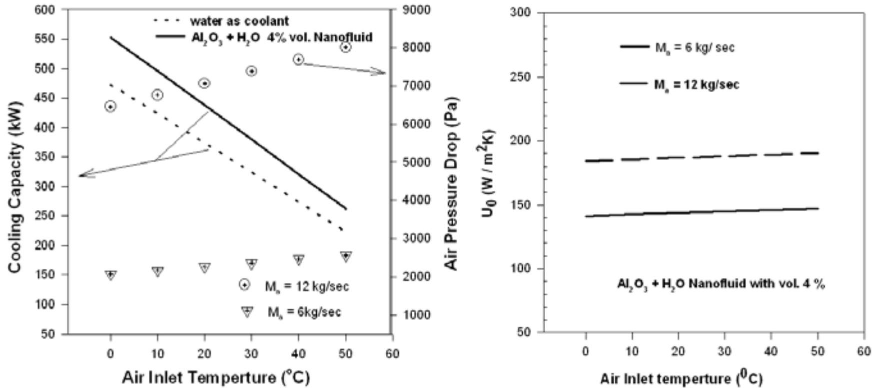

Figure 7 : Air inlet Temperature influence on the thermal and fluid dynamic performance of Compact Heat exchanger

Effect of Air and Coolant mass flow rate

The cooling capacity of the radiator is strongly dependent on both fluids mass flow rate. Fig. 8 shows the behavior of the selected radiator over a wide range, while maintaining the geometry and temperature levels at the normal situation. It is observed that cooling capacity is increasing with both air and coolant flow rates. The cooling capacity is more with air flow rate due to higher thermal resistance. The pressure drop also increases quadratically with both air and coolant mass flow rates and is almost same for all flow rate of air(6-12 kg/sec) and coolant(6000- 10000 kg/hr). It is interesting to point out that the cooling capacity and overall heat transfer coefficient of the radiator is very high with mass flow rates of the air and coolant, when Al_2O_3 + H_2O nanofluids is used as coolant as shown in Fig. 6 but the pressure drop are higher when compared with conventional coolants.

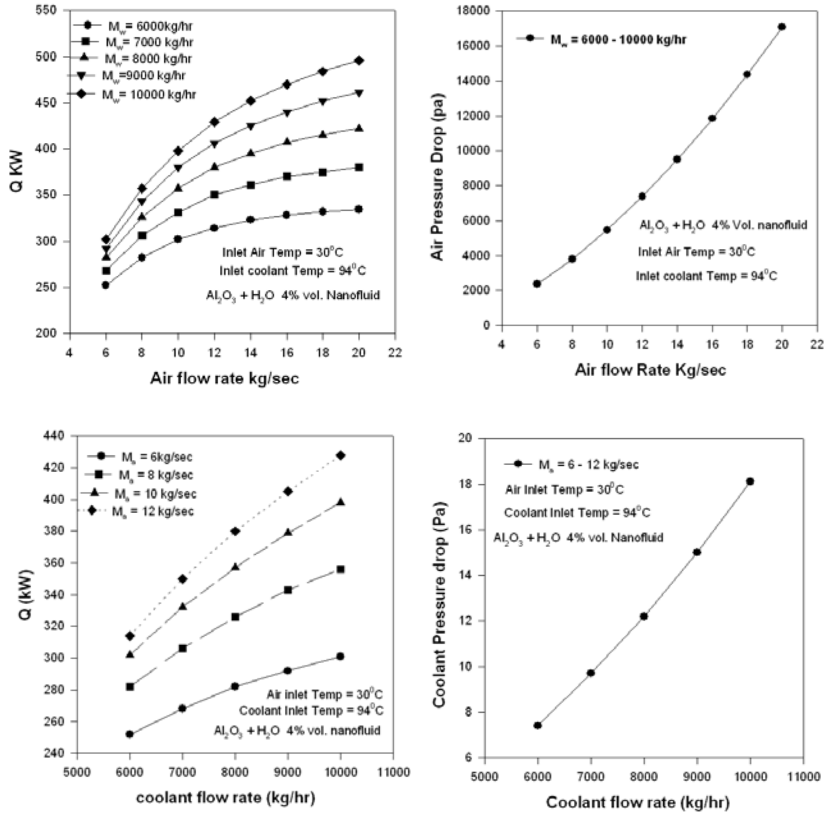

Figure 8 : Air and Coolant flow influence on the Thermal and fluid dynamic performance of Compact Heat Exchanger

Effect of Coolant inlet Temperature

Another characteristic factor of radiator is the coolant inlet temperature it is observed from the Fig. 9 that with increases of the coolant inlet temperature the cooling capacity is increase, it is also observed that the cooling capacity Al_2O_3 + H_2O nanofluids is very high when compared with water as coolant. Whereas the pressure drop are nearly double that of water.

Effect of Nanoparticle volume fraction

Fig. 10 indicates with increase of the volume fraction of the nanoparticle concentration the cooling capacity increases in moderate manner and pressure drop decreases with coolant inlet temperature, but cooling capacity is very high when compared with 0% volume fraction (pure water).

Conclusion

- A detailed study of the parametric studies on compact heat exchanger is done by using ε – NTU numerical method and using Al_2O_3 + H_2O nanofluids a coolant.
- Detailed flow chart of the numerical method and correlations used for Al_2O_3 + H_2O nanofluid are presented.
- Comparison study Al_2O_3 + H_2O nanofluid as coolant with conventional coolants, and observed that cooling capacity Al_2O_3 + H_2O nanofluid is very high.
- Different factors for compact automotive radiator are graphically presented

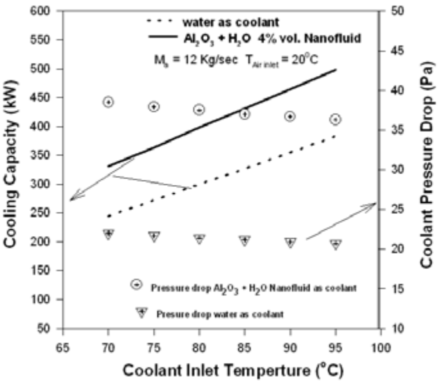

Figure 9 : Coolant inlet Temperature influence on the thermal and fluid dynamic performance of Compact heat exchanger

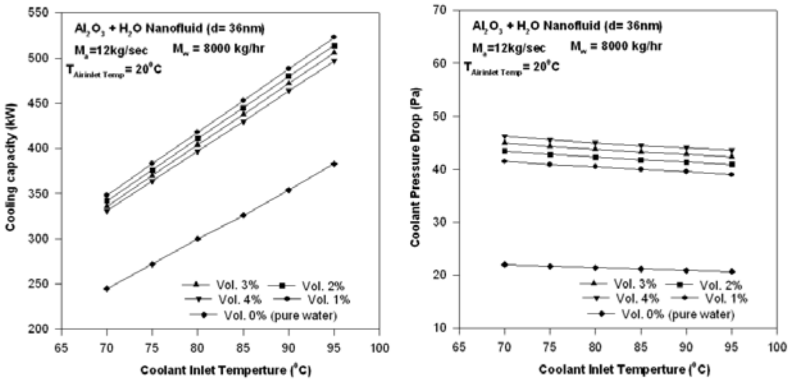

Figure 10 : Coolant inlet Temperature and volume fraction of Nanoparticle influence on the thermal and fluid dynamic performance of Compact Heat Exchanger

References

[1] W.M. Rohsenhow, J.P Hartnett, Y.I. Cho,1998, *Handbook of heat transfe* , 3rd edition, Newyork : Mc-GrawHill,

[2] W.M.Kays, A.L. London,1984. *Compact heat exchangers,* 3rd ed, Newyork: Mc-GrawHill.

[3] Shah, R.K., M.R. Heikal, Thonon, B., P. Tochon, P. 2001, Progress in the numerical analysis of compact heat exchanger surfaces. *Advances in heat transfer* 34: 363-443.

[4] Charyulu, D.G., Singh, G., Sharma, J.K. 1999. Performance evaluation of radiator in diesel engine – A case study. *Applied Thermal engineering* 19: 625-639.

[5] Carlucia,E., Starace, G., Ficarella, A., Laforgia, D. 2005. Numerical analysis of a cross floe compact heat exchanger for vehicle applications. *Applied Thermal Engineering* 25: 1995-2013.

[6] Witry, A., Al-Hajeri, H.H., Bondok, A.B. 2005. Thermal performance of automotive aluminum plate radiator. *Applied thermal Engineering*, 25:1207-1218.

[7] Mahmoudi, J. 2007. Modeling of flow field and heat transfer in copper base automotive radiator application, *Internatioanl Journal Of Green Energy* 3: 25-41.

[8] Oliet, C., Oliva, A., Castra, J., Perez-segarra, C.D. 2007. Parametric studies on automotive radiators. *Applied Thermal Engineering* 27: 2033-2043.

[9] SUS.Choi, S.U.S. 1995. Developemnt and application of non-Newtonian flows, 66: 99-105. ASME.

[10] Eastman, J.A., Choi, S.U.S., Li, S., Yu, W., Thompson, L.J. 2001. Anomalously increased effective thermal conductivities of ethylene glycol based nanofluids containing copper nanoparticles. *Applied Physical letters* 78(6): 718 – 720.

[11] SK Das, S.K., Putra, N., Thiesen, P., Roetzel, W. 2003. Temperature dependence of thermal conductivity enhancement for nanofluids, *Journal of HeatTransfer* 125: 567-574.

[12] Xuan, Y., Li, Q. 2003. Investigation of convective heat transfer and flow features of nanofluids, *Journal of Heat Transfer*. 125: 151-153.

[13] Kim, H.S., Choi, R.S., Kim, D. 2007. Thermal conductivity of Metal-oxide Nanofluids: Particle size dependence and effect of Laser Irradiation. *Journal of Heat Transfer* 129: 298- 307.

[14] Pak, B., and Cho, Y.I. 1998. Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particle. *Experimental heat transfer* 11: 151-170.

[15] Ding,Y., Wen. D. 2004. Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow condition, *International journal of heat and mass transfer* 47: 5181-5188.

[16] Ravi.P, Bhattacharya.P, Phelan. P.E 2005. Thermal conductivity of nanoscale colloidal solutions (Nanofluids), *Physical Review Letters* . 94: 25901-1-4.

[17] SEB Maiga, S.E.B., Nguyen, C.T, Galanis, N., Roy, G., Mare, T., Coqueux, M. 2006. Heat transfer enhancement in turbulent tube flow using Al_2O_3 nanoparticle suspension., International *Journal of Numerical Methods for heat and fluid flow*16 (3): 275-292.

[18] Vasu, V., RamaKrishna, K., Kumar, A.C.S. 2007. Exploitation of Thermal properties of fluids embedded with nanostructured materials, *International Energy Journal* 8: 181-190.

[19] Vasu, V., Rama, K.K., Kumar, A.C.S. 2008. Empirical Correlations to Predict Thermophysical and Heat Transfer Characteristics Of Nanofluids. *Thermal Science Journal* 12(3). (Article in Press)

[20] Vasu, V., RamaKrishna, K., Kumar, A.C.S. 2008. Analytical Prediction Of Thermophysical Properties Of Fluids Embedded With Nanostructured Materials. *International Journal of Nanoparticles* (Article in Press).