EXPERIMENTAL INVESTIGATIONS ON THE IMPACT OF BASE FLUID AND PARTICLE CONCENTRATION ON THE THERMO-HYDRAULIC PERFORMANCE OF Fe_3O_4, SiC AND HYBRID NANOFLUIDS

A SYNOPSIS

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by

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SYNOPSIS

INTRODUCTION

Efforts towards energy conservation and energy efficiency have far reaching effect due to the depletion of natural resources and global warming. Engineering as well as non-engineering industries are increasingly enthusiastic for the development of energy efficient systems. Heat exchangers are the important components of many industries that provide scope in achieving energy efficiency. There are several methods to increase the efficiency of heat exchangers. One such method is the use of nanofluids in place of conventional heat transfer fluids.

Coined by Choi [1], the suspension of nanosized solid particles in the conventional heat transfer fluids are termed as nanofluids. When nano-sized high thermal conductivity solid particles are dispersed in the conventional fluids, the themo physical properties of conventional fluids are observed to change from that of conventional fluid. The solid particles being suspended in the base fluids can be metals, viz., Al, Cu, Co Ag, Au etc., metal Oxides, viz., Al_2O_3. Fe_3O_4, CuO, SiO_2 etc, carbides like BN, SiC and Carbon nanotubes like SWCNT, MWCNT etc. Most commonly used base fluids include water, ethylene glycol, propylene glycol, oils, mixture of water and ethylene glycol or propylene glycol etc. Due to the improvement in the thermo physical properties of the nanofluids when compared to their base fluids, the heat transfer performance achieved by nanofluids is expected to be superior to their respective base fluids. Nanofluids find potential applications in various fields like automobile, electronics, power, textile etc.

The present research is an experimental investigation, to study the effect of different base fluids, different type of nanoparticles and their particle concentration on the thermo hydraulic performance of nanofluids using a double pipe heat exchanger. Fe_3O_4, SiC and Hybrid (mixture of 50% by volume of Fe_3O_4 and 50% by volume of SiC) nanoparticles are suspended separately in water, Ethylene Glycol and water mixtures in the ratios of 20:80 and 40:60 base fluids for the analysis. The thermophysical properties of the so obtained nanofluids are measured and the thermo hydraulic performance of the nanofluids is experimentally investigated and their performance is analyzed.

LITERATURE REVIEW

Nanofluids have attracted many researchers since their introduction. The following are some of the research works related to the investigation of thermo-physical properties of single and Hybrid nanofluids is given in Table 1, heat transfer enhancement of single-component nanofluids is given in Table 2 and hybrid nanofluids is given in Table 3.

Table.1 Thermo-Physical Properties of Single & Hybrid nanofluids

Author & year	**Instrument Used**	**Nanoparticle (Size of the particle in mm)**	**Particle Concentration & temperature**	**% Enhancement in thermal Conductivity & Viscosity**	**Remarks**
Yiamsawasd et al.[2] (2012)	Transient hot wire method	Al_2O_3 TiO_2	0-8%. (15-65°C)	30%-Al_2O_3 20%-TiO_2(in thermal conductivity)	Correlations were developed as functions of temperature, particle concentration and thermal conductivity of base fluid since existed models such as Hamilton-Crosser[3], Yu & Choi [4]and other models didn't predict experimental values well
Esfe et al.[5] (2014)	KD2 pro thermal property analyser (Decagon Devices)	Al_2O_3	0.2,0.5,1,2,3,4 and 5%, 26-55°C	32% in thermal conductivity at 5% volume fraction	Correlation developed as a function of concentration and temperature. Yu-Choi [4]and Hamilton-Crosser[3] models underestimated the experimental values
Afrande et al. [6]	KD2 pro thermal property analyser	Fe_3O_4/Water	0.1-3 (20-55°C)	90% enhancement in thermal conductivity at 3% volume fraction	Developed an ANN-based correlation to predict the thermal conductivity of nanofluids and this model was more accurate than the empirical correlations, in the prediction of thermal conductivity
Huminic et al. [7] (2017)	KD2 Pro	SiC/Water (<25nm)	0.5 & 1 (20-50°C) (Carboxymethyl cellulose white powder Surfactant is used)	17.62% in thermal Conductivity and 40.98% in Viscosity	Thermal Conductivity decreased and Viscosity increased with the increase of surfactant in water
Won Lee et al. [8](2011)		SiC/Water (<100nm)	0.001-3%(28-70°C)	102% in relative Viscosity and 7.2% in thermal conductivity at 3% volume concentration	pH of the solution was adjusted to 11 to attain the stability. Brinkman [9] and Batchelor [10] models for viscosity and Maxwell [11] model for thermal conductivity are not in good agreement with experimental values
Vajjha et al.[12] (2009)	Thermal Conductivity apparatus by P.A.Hilton, U.K.	Al_2O_3(53nm) CuO(29nm) ZnO(29 & 77 nm) Base Fluid: 60:40 EG-W	Al_2O_3-0 to 10% ZnO & CuO-0 to 6% Temp. range:298 to 363 K	knf/kbf Al_2O_3-69% at 10% CuO-60% at 6% ZnO-48.5% at 6%	Existing Hamilton-Crosser [3] correlation couldn't predict the experimental values. Correlations proposed
Banisahrif et al.[13] (2020)	THW-L2 Portable thermal conductivity meter	Fe_3O_4/50:50 EG-Water	0.01, 0.05, and 0.1% (253.15 K to 293.15K) (Sodium Dodecyl Sulfonate and Oleic acid was used as surfactants)	(K_{nf}/K_{bf}) 14.3% at 293.15 K for 0.1% volume concentration	Viscosity of the nanofluid decreased upto 40% at 0.1% volume concentration due to the presence of surfactant
Li et al. [14] (2016)	KD 2 pro thermal analyser	SiC/40:60 EG-Water (30nm)	0.1-0.5 (10-50°C)	53.81% in thermal Conductivity and 31.8% in viscosity	The overall effectiveness of the nanofluid reported was around 1.6, indicating that the nanofluid considered is suitable for heat transfer applications
Esfe et a.[15] (2015)	Thermal Conductiivty-KD2 pro thermal property analyzer.	Ag-MgO(50:50 by volume). Ag-25nm MgO-40nm	0 to 2%	15.8% enhancement in thermal conductivity	Correlation given by Hamilton & Crosser[3], Yu &Choi[4] and Prasher[16] failed to predict the experimental values due to the formation of clusters in the nanofluid. So new correlation

	Viscosity-Brookfield cone and plate viscometer			38.1% enhancement in viscosity	was proposed for thermal conductivity and viscosity
Baby and Ramaprabhu[17] (2011)	KD2 Pro thermal property analyser	f-MWCNT+f-HEG(Temp. range 25 to 50°C	0.005-0.05% with base fluid DI water and 0.05-0.08% with Base fluid EG	Thermal conductivity enhancement was 80% for base fluid DI water and 6% for base fluid EG	Enhancement in thermal conductivity of DI Water based hybrid nanofluid was much higher than EG based hybrid nanofluid.

Table 2. Heat Transfer Performance of Single-Component Nanofluids

Author/year	**Nanofluid & nanoparticle Size**	**Heat Exchanger**	**Particle concentration**	**% Enhancement**	**Observations**
Sajadi et al.[18] (2011)	TiO_2/Water (TiO_2-30nm) (under turbulent conditions, Reynolds number range 5000 to 30000)	Circular pipe heat exchanger	0.05 to 0.25%	h_{nf}/h_{bf} at 0.25% volume fraction is 1.22 at 5000 Reynolds number.	By increasing the Reynolds number no significant increase in ratio of heat transfer coefficient of nanofluid to base fluid. Increasing the particle concentration has no effect on heat transfer enhancement.
Xuan & Li[19] (2003)	Cu/Water (Cu<100nm) (Reynolds number ranging from 10000 to 25000)	Circular pipe heat exchanger	0.3 to 2%	Nu_{nf}/Nu_{bf} varied from 1.06 to 1.39. Heat transfer coefficient increased with volume fraction and velocity of fluid flow	The heat transfer coefficient of nanofluid may be less than base fluid [60] if the volume fraction increased beyond optimum point due to the increase in viscosity with the increase in volume fraction.
Ravi Kumar et al. [20](2017)	Fe_3O_4/Water(<50 nm)(Reynolds number ranging from 15000-30000)	Double pipe heat Exchanger	0.005 to 0.06%	14% in Nusselt number at 0.06% concentration and 28970 Reynolds number	The NTU, effectiveness and friction factor of Fe_3O_4-Water were 1.037, 1.024 and 1.092 times greater than base fluid at 0.06% volume concentration and a Reynolds number of 28970
Aghayari et al. [21](2015)	Fe_3O_4/Water (15-20nm) (Reynolds Number-14000-34600)	Horizontal Double pipe heat Exchanger	0.08-0.1%	28% in heat transfer coefficient at the volume concentration of 1%	24% in Nusselt number was obtained at the volume concentration of 1%
Yu et al. [22](2009)	SiC/Water (170nm) (Reynolds Number -3300-13000)	Circular Tube Heat Exchanger	3.7%	50 - 60% enhancement in the heat transfer coefficient	But when compared based on the constant velocity of flow a 7% decrease in the heat transfer coefficient of SiC/water nanofluid was observed due to the dominant effect of viscosity enhancement over thermal conductivity enhancement with the increase in particle concentration
Heris et al.[23][66] (2014)	CuO/40:60 EG-Water (CuO-60nm) (Reynolds number in the range of 2000 to 8000)	Car radiators	0.05 to 0.8%	55% enhancement in heat transfer coefficient is observed at 0.8% for the Reynolds number 8000	These results helped to design compact car radiators which in turn reduce the weight of the vehicle.
Nishant et al.[24](2016)[71]	Fe_2O_3/Water and Fe_3O_4/EG (Reynolds number range of 1000 to 7000)	Shell and tube heat exchanger	0.02 to 0.08%	29% in Nusselt number for Fe_2O_3/Water	The increment in convective heat transfer coefficient of water-based nanofluids is higher than EG-based nanofluid
Timofeeva et al. [25](2011)	SiC/50:50 EG-Water (16-90nm) (Reynolds number-4500-7500)	Closed loop heat transfer test facility	4%	An increase of 14.2% in heat transfer coefficient ratios is observed for 90nm particle size)	Based on the comparison of efficiency of EG-Water and Water based SiC nanofluids, it is observed that EG-Water based SiC nanofluid serves as better coolant when compared to water based nanofluid

Table 3. Heat Transfer Performance of Hybrid Nanofluids

Author/year	Nanofluid/Mixture ratio & particle diameter	Heat Exchanger	Volume Concentration	% Enhancement	Observations
Suresh et al.[26] (2014)	Al_2O_3+Cu/Water (Mixture ratio-90:10)	Circular pipe heat exchanger- under turbulent conditions	0.1%	8.02% increase in heat transfer coefficient and 10.48% increase in friction factor are obtained over base fluid at 0.1% volume concertation	5.61% enhancement in heat transfer coefficient was observed for Al_2O_3/water nanofluid indicating the advantage of adding Cu particles to Al_2O_3 in the hybrid mixture. Correlation developed for Nusselt number and friction factor
Sundar et al.[27] (2014)	MWCNT+Fe_3O_4/Water (Fe_3O_4-74% & MWCNT-26%)	Circular tube with constant heat flux under turbulent conditions	0.1 and 0.3%	Maximum of 31.1% enhancement in Nusselt number and 1.18 times increase in pumping power is obtained over the base fluid.	Correlations for Nusselt number and friction factor of hybrid nanofluids were developed
Madhesh et al.[28] (2014)	Cu+TiO_2/Water (Mixture ratio- weight%- 52.19:47.81)	Counter flow tube in tube heat exchanger, with Reynolds number ranging from 3500 to 7500	0.1 to 2%	Enhancement of 52% in heat transfer coefficient, 49% in Nusselt number and 68% in overall heat transfer coefficient at 1% volume concentration	A decrease in the enhancement is observed with further increase in the volume concertation due to the constricted movement of the particles with increased particle loading.
Yarmand et al.[29] (2015)	Graphene nanoparticles (GNP+Ag- nanocomposite), (Reynolds number 5000 to 17500)	Circular tube with constant heat flux under turbulent conditions	0.02 to 0.1%	32.7% enhancement in Nusselt number is observed at 0.1% volume concentration and 17500 Reynolds number	New Nusselt number correlation developed
Aghzoborg et al.[30] (2015)	Fe_2O_3+CNT/ Water (Hybrid Nanocomposite was prepared with an average particle size of 15-40nm)	Shell and Tube heat exchangers under laminar, turbulent and transmission conditions	0.1 and 0.5%	4272.85 W/m^2K is the maximum heat transfer coefficient obtained at 0.5% volume concentration.	Increase in the percentage of magnetic nanoparticles in the hybrid mixture decreased the enhancement in the heat transfer coefficient
Hormozi et al.[31] (2016)	Al_2O_3+Ag/Water (Mixture ratio- 97.5:2.5)	Helical coil heat exchanger under laminar conditions	0.2% (Surfactant SDS and PVP are employed in the concentration range of 0.1-0.4%)	Maximum Nusselt number ratio is 6.283% and maximum increase in thermal performance ratio is 1.163 at 5100 Reynolds number with 0.1% SDS surfactant	Thermal performance of Al_2O_3+Ag/Water hybrid nanofluid is 16% higher than base fluid. This result encourages for the design of new compact heat exchangers and economisers

Summary of the Literature Survey:

From the above literature following are the inferences drawn

- Stability of the nanoparticles in the base fluid is a big challenge and it was reported that nanoparticles were more stable in EG-Water based fluid compared to water-based fluid
- The thermal conductivity of the nanofluids increases with the increase in volume concentration and temperature due to Brownian motion of the

nanoparticles in the base fluid and the interfacial forces between the solid and liquid particles in the solution. Viscosity of the nanofluids always increased with the addition of nanoparticles

- The available classical as well as semi empirical correlations could not predict the thermal conductivity and viscosity of nanofluids
- It was observed that the comparison of heat transfer performance based on flow velocity is better than comparing based on Reynolds number, when comparing different types of nanofluids.
- It was noticed from the literature that the heat transfer performance of hybrid nanofluids is higher than their single-component counterparts, only when the proper combination of nanoparticles and base fluids is employed.
- It was observed from the literature that the heat transfer performance of single component nanofluids is higher with EG-Water as base fluid than water as base fluid

Gaps Identified in the Literature

- It is evident from the literature that most of the researchers have considered the volume concentration of nanoparticles in the base fluid greater than 0.1%. Very limited research is available on the heat transfer performance of nanofluids at low volume concentrations particularly below 0.1%.
- Limited research was available on the heat transfer performance of Fe_3O_4 and SiC nanofluids with EG-Water as base fluids, particularly at low volume concentrations.
- Very limited research is available on the heat transfer performance of hybrid nanofluids with EG-Water as base fluid. The heat transfer performance of Hybrid nanofluid with the combination of Fe_3O_4 and SiC nanoparticles is not reported in the literature to date.
- Pressure drop characteristics of Hybrid nanofluids are also least discussed by the researchers in the literature
- Effect of base fluids on the heat transfer performance of Fe_3O_4 and SiC nanofluids is limited in the literature.
- A comprehensive study on the influence of base fluid on the heat transfer performance of Hybrid (Fe_3O_4+SiC) is not reported in the literature.

OBJECTIVES OF THE PRESENT WORK:

- To experimentally investigate the heat transfer enhancement and thermo-hydraulic performance of two different single component nanofluids of Fe_3O_4 and SiC

- To experimentally investigate the heat transfer enhancement and thermo-hydraulic performance of their Hybrid (Fe_3O_4 + SiC) nanofluid in the ratio of 1:1 and compare the same with that of heat transfer performance of constituent single component nanofluids.

- To experimentally investigate the effect of base fluid on the heat transfer performance of single component (Fe_3O_4 & SiC) as well as their Hybrid (Fe_3O_4 + SiC) nanofluid at low volume concentrations and draw inferences on the combination for their applicability as working fluids

METHODOLOGY: The methodology of experimental procedure is explained in the Figure 1.

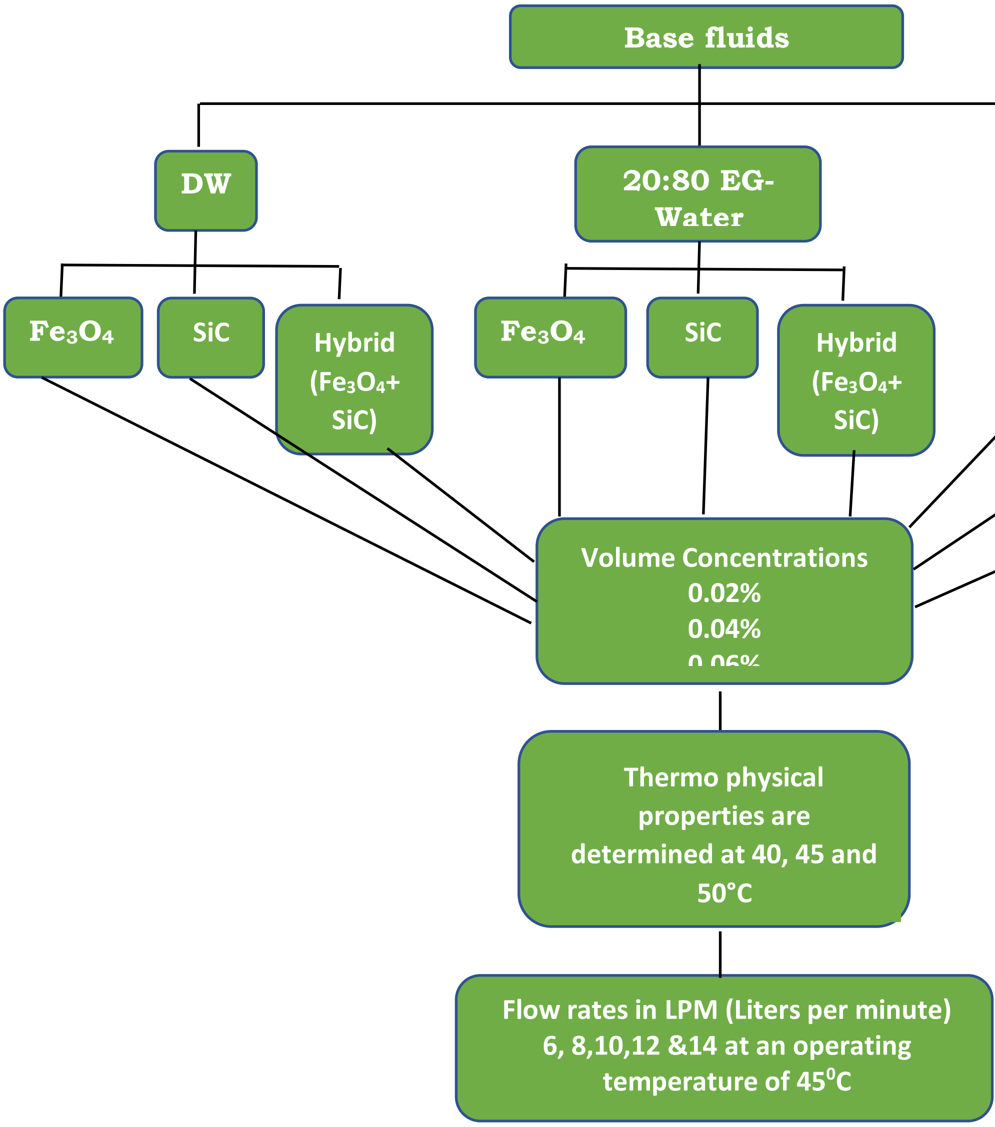


Figure.1 Flow Chart for the experimentation

NANOFLUIDS PREPARATION:

Fe_3O_4 and SiC nanoparticles are procured from Nanoamor Texas. The properties of these nanoparticles are presented in Table 4.

Table 4. Properties of Nanoparticles

Properties	**Fe_3O_4**	**SiC**
Density(ρ, kg/m^3)	4950	3227.87
Specific Heat(J/kgK)	670	675
Thermal Conductivity(W/mK)	95	350
Purity	99.5%	99%

The percentage volume concentration of nanofluid is calculated using Eq. (1), where ϕ is the volume concentration of the nanofluid.

$$\phi = \frac{\frac{W_{np}}{\rho_{np}}}{\left(\frac{W_{np}}{\rho_{np}} + \frac{W_{bf}}{\rho_{bf}}\right)} \times 100 \quad (1)$$

The percentage volume concentration of Hybrid nanofluid is calculated using Eq. (2).

$$\phi = \frac{\frac{W_{SiC}}{\rho_{SiC}} + \frac{W_{Fe_3O_4}}{\rho_{Fe_3O_4}}}{\left(\frac{W_{SiC}}{\rho_{SiC}} + \frac{W_{Fe_3O_4}}{\rho_{Fe_3O_4}} + \frac{W_{bf}}{\rho_{bf}}\right)} \times 100 \quad (2)$$

Nanofluid at various volume concentrations in the range of 0.02 to 0.08% is prepared using the two-step method. In order to avoid the sedimentation of the nanoparticles, the mechanical stirrer is used continuously for 24-48 hours depending on the volume concentration. The particle size analysis of Fe_3O_4 and SiC nanoparticles is performed using the transmission electron microscope. Figures 2 and 3 show the TEM images of Fe_3O_4 as well as SiC nanoparticles at a magnification of 50nm and 10nm respectively, which clearly indicates that each of these particles is of spherical shape.

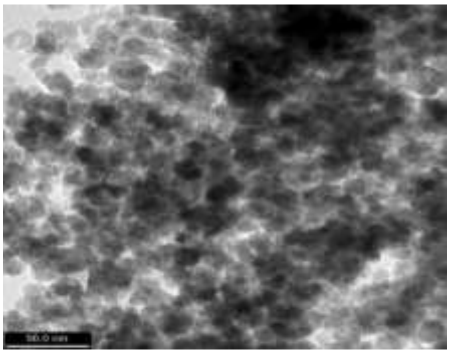


Figure 2. TEM Image of Fe_3O_4 Nanoparticles

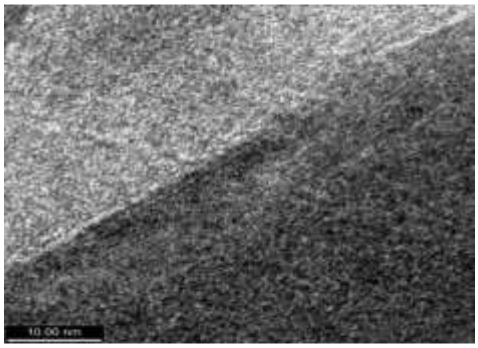


Figure 3. TEM Image of SiC Nanoparticles

The stability of the nanofluids is tested by determining the zeta potential values of the nanofluids at 0.08% volume concentration using nanoparticle analyser (Horiba, Japan) and the corresponding values are represented in Table 5. Generally, the colloidal solutions are treated to be stable if the Zeta potential values are greater than ±30mV. The values in the table indicate that all the solutions prepared are stable, while SiC and Hybrid nanofluids are observed to be more stable comparatively.

Table 5. Zeta potential Values of Nanofluids at 0.08% volume Concentration

Base Fluid	Suspended Nanoparticle	Zeta Potential(mV)
Water	Fe_3O_4	-32.7
	SiC	-48.6
	Hybrid	-36.3
20:80 EG-Water	Fe_3O_4	-50
	SiC	-50.4
	Hybrid	-46.8
40:60 EG-Water	Fe_3O_4	-23.2
	SiC	-38.6
	Hybrid	-39

EXPERIMENTATION:

Measurement of Density and Specific Heat

The density of the nanofluids is measured using Anton paar Density Measuring Instrument as shown in Figure 4. It works on the principle of Oscillating U-tube, which is a technique used to determine the density of liquids or gases based on an electronic measurement of the frequency of oscillation.

Figure 4. Density Measurement of Nanofluid

Figure 5. Specific Heat Measuring Apparatus

The specific heat of the nanofluid is measured using Mentos Heat Capacity Apparatus as shown in Figure 5. It consists of a water bath with a heater to raise the temperature of the fluid under test. The data is logged into a USB drive for every 0.1°C of temperature rise. The Specific heat of the test fluid is calculated using the Eq. 3.

$$c_p = (W_s - P_{av} / \Delta) / m \qquad (3)$$

Where W_s is the specific heat equivalent of water, P_{av} is the average power consumed in watts to raise the temperature of the fluid for a given time. $\Delta = (T_1 - T_2)/t$. Where T_1 and T_2 are the temperatures for a given time t.

Measurement of Viscosity and Thermal Conductivity

The viscosity of Fe_3O_4, SiC, and hybrid nanoparticle suspensions in 20:80 EG-Water is measured using the DV2T Viscometer shown in Figure 6, for different volume concentrations ranging from 0.02 to 0.08%. The viscosity of these nanofluids is measured at a temperature of 45^{0}C. The thermal conductivity of Fe_3O_4, SiC, and hybrid nanofluids are measured using Tempos thermal property analyser at 45°C as shown in Figure 7.

Figure 6. DV2T Brookfield Viscometer

Figure 7. Tempos Thermal Property Analyzer

Experimental Setup and Procedure

The test section consists of a Double Pipe Heat Exchanger (DPHE) with U bend as shown in the schematic diagram of the experimental setup in Figure 8. Hot fluid flows through the inner tube and water at room temperature passes through the annulus at a constant flow rate. The inner pipe of the heat exchanger is made of stainless steel with a 19 mm inner diameter and 25 mm outer diameter. The outer pipe is made up of galvanized iron with a 56 mm outer diameter and 50 mm inner diameter. The total length of the pipe is 4.52 m. The other parts of the setup include two reservoirs for hot and cold water, a temperature controller and a data logger for the measurement of all relevant parameters, viz., flow rate, temperature and pressure drop.

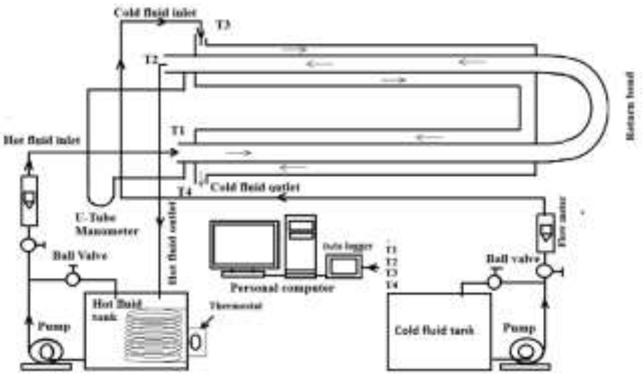


Figure 8. Schematic of the Experimental Setup

The experimental setup is validated by comparing the experimental heat transfer coefficient of water with that of Dittus [32] and Gnielinski [33] correlations as shown in Figure 9. The figure shows that the experimental data of water is predicted with good agreement by both Dittus et al. [32] and Gnielinski [33] correlations, with an average deviation of 14.25% and 4.84% respectively. After validation, the experiments are repeated with nine different nanofluids at different concentrations ranging from 0.02 to 0.08%. The flow rate of hot fluid (nanofluid) is varied from 6 to 14 lpm, in steps of 2 lpm, while maintaining the constant flow rate of the cold water in the annulus.

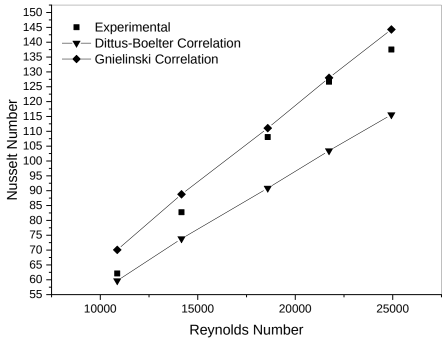


Figure 9. Validation of Experimental Setup with Water

Estimation of Heat Transfer Coefficient

The heat lost by the hot fluid and heat gained by the cold fluid is calculated using the Eqs. (4) and (5). Eq. (6) gives the average heat duty of the heat exchanger.

$$Q_h = m_h c_{\text{nf}} \left(T_{hi} - T_{ho}\right) \quad (4)$$

$$Q_c = m_c c_{pc} \left(T_{co} - T_{ci}\right)) \quad (5)$$

$$Q_{\text{avg}} = \frac{Q_h + Q_c}{2} \quad (6)$$

Based on the recorded temperature readings, Logarithmic Mean Temperature Difference (LMTD) is calculated using Eq. (7).

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \quad (7)$$

Where $\Delta T_1 = T_{hi} - T_{co}$ and $\Delta T_2 = T_{ho} - T_{ci}$. Using Eqs. (6) and (7), the overall heat transfer coefficient based on the inner surface area of the inner pipe is calculated using Eq. (8).

$$U_i = \frac{Q_{\text{avg}}}{A_{si}\left(LMTD\right)} \quad (8)$$

Where $A_{si} = \pi d_i l$ inside surface area. The Reynolds Number for annulus flow typically falls in the range of transition flow. Hence the Nusselt number for the annulus pipe is calculated using Gnielinski [33] correlation as presented by Eq.(9)

$$Nu_o = \frac{\left(\frac{f}{8}\right)(\text{Re} - 1000)\,\text{Pr}}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(\text{Pr}^{\frac{2}{3}} - 1\right)} \quad (9)$$

Where Reynolds number $\text{Re} = \frac{\rho_c V_c d_h}{\mu_c}$, Hydraulic diameter $d_h = d_o - d_i$, and Pr is the Prandtl number

Friction factor *f* is calculated using Petukhov's [34] correlation, given by Eq. (10)

$$f = \left(0.79 \ln \mathrm{Re} - 1.64\right)^{-2} \quad (10)$$

Using Eq. (9), the annulus heat transfer coefficient is calculated by Eq. (11)

$$h_o = \frac{Nu_o \times k_o}{d_h} \quad (11)$$

Eq. (12) shows the calculation of the Heat transfer coefficient of the hot fluid using Eqs. (8) and (11).

$$\frac{1}{h_i} = \frac{1}{U_i} - \frac{r_i}{k} \ln\left(\frac{r_o}{r_i}\right) - \frac{1}{h_o} \quad (12)$$

Where k is the thermal conductivity of the inner tube, r_i is the inner radius of the inner tube, and r_o is the outer radius of the inner tube.

Estimation of Friction Factor

The friction factor of the inner tube is calculated based on the experimentally determined pressure drop across the inner tube, using the Eq. (13)

$$f = \frac{2\Delta P d}{\rho l v^2} \quad (13)$$

where ΔP is the pressure drop of the inner pipe, d is the inner diameter, l is the length of the pipe, v is the velocity of flow, and ρ is the density of hot fluid.

RESULTS & DISCUSSION

Base Fluid-Water

Thermo- Physical Properties

The four most important thermo physical properties of nanofluids which play a major role in the heat transfer performance include density, specific heat, viscosity and thermal conductivity.

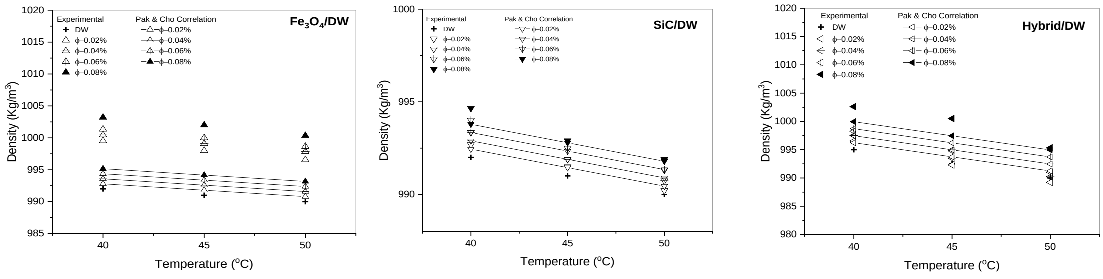
Density

The density of DW based Fe_3O_4, SiC and Hybrid nanofluids is determined experimentally using Anton Paar density measuring instrument at the temperatures of 40, 45 and 50°C for the volume concentrations ranging from 0.02 to 0.08%. The experimental values are compared with the Pak & Cho[37] correlations for the single component and Hybrid nanofluids given by Eqs.14 & 15 respectively.

$$\rho_{\mathrm{nf}} = \left(1-\phi\right)\rho_{\mathrm{bf}} + \phi\rho_{\mathrm{p}} \quad (14)$$

$$\rho_{\mathrm{hnf}} = \phi_{\mathrm{np1}}\rho_{\mathrm{np1}} + \phi_{\mathrm{np2}}\rho_{\mathrm{np2}} + \left(1-\phi_{\mathrm{np1}}-\phi_{\mathrm{np2}}\right)\rho_{\mathrm{bf}} \quad (15)$$

The experimental and theoretical values of density for DW based Fe_3O_4, SiC and Hybrid nanofluids are represented in the Figure 10.



(a) (b) (c)

Figure 10. Density of DW based Nanofluids (a) Fe_3O_4, (b) SiC and (c) Hybrid

It is observed from the above analysis that the density of nanofluids increase with the increase in volume concentration and decrease with the increase in temperature. The percentage enhancement in the density of nanofluids with respect to the base fluid is varied from 0.75 to 1.13, 0.7 to 1.1, 0.66 to 1.04 for the temperatures 40, 45 and 50°C respectively for Fe_3O_4/DW nanofluid, while the percentage enhancement for SiC/DW nanofluid varied from 0.06 to 0.26, 0.05 to 0.19 and 0.02 to 0.19 and for Hybrid/DW nanofluid the values ranged from 0.45 to 1.06, 0.13 to 0.95 and 0.07 to 0.53 for the volume concentrations ranging from 0.02 to 0.08%. The percentage deviation of the experimental density values of nanofluids with Pak & Cho [37] correlation was less than 1%, indicating the excellent agreement of the experimental values with the correlation.

Though the variation of density from the base fluid is marginal, it is noticed that the effect of temperature, volume concentration and type of nanoparticle suspended in the base fluid plays a significant role on the density of the nanofluid.

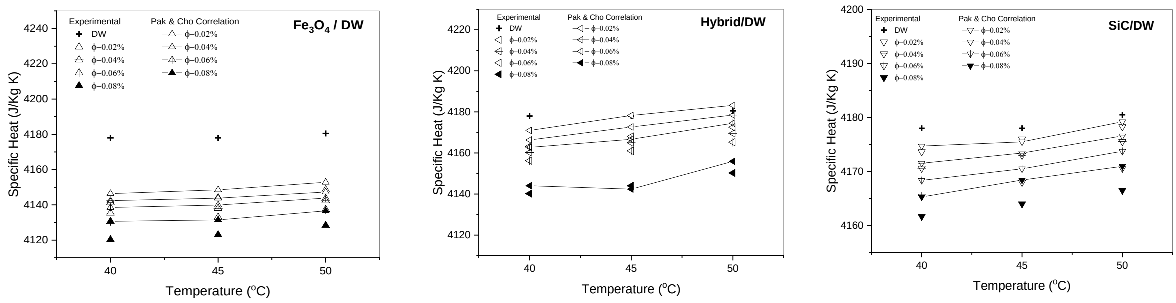
Specific Heat

The specific heat of DW based Fe_3O_4, SiC and Hybrid nanofluids is experimentally determined using Mentos Heat capacity apparatus and its variation with temperature and volume concentration is plotted in Figure 11. The measured values are compared with the Pak & Cho [37] correlations for single component and Hybrid nanofluids given by Eqs. 16 and 17.

$$c_{\mathrm{p}} = \frac{(1-\phi)\,\rho c_{\mathrm{p}} + \phi \rho_{\mathrm{p}} c_{p_p}}{\rho_{\mathrm{nf}}} \tag{16}$$

$$(\rho C_p)_{hnf} = \varnothing_{p1}\left(\rho C_p\right)_{np1} + \varnothing_{p2}\left(\rho C_p\right)_{np2} + \left(1-\varnothing_{p1}-\varnothing_{p2}\right)\rho_{bf} \tag{17}$$

Figure 11 also shows the comparison of measured values with the predicted values using the above equations, for DW based nanofluids.



(a) (b) (c)

Figure 11. Specific Heat of DW based Nanofluids (a)Fe_3O_4, (b) SiC and (c) Hybrid

It is observed from the above analysis that the specific heat of nanofluids decrease with the increase in volume concentration and marginally increase with increase in temperature.

The percentage decrement in the specific heat of nanofluids with respect to the base fluid varied from 0.8 to 1.4%, 0.8 to 1.33% and 0.77 to 1.26% for Fe_3O_4/DW, 0.1 to 0.39%, 0.04 to 0.33% and 0.05 to 0.33% for SiC/DW and 0.35 to 0.91%, 0.23 to 0.82% and 0.19 to 0.73% for Hybrid/DW nanofluids at temperature of 40, 45 and 50°C respectively, as the volume concentration varies from 0.02 to 0.08%.

Maximum deviation obtained between the experimental values and theoretical values was less than 0.26%, which indicates that Pak & Cho correlations for Specific Heat have predicted the measured values with an excellent agreement.

Viscosity

The viscosity of DW based Fe_3O_4, SiC and Hybrid nanofluids is determined experimentally using DV2T Brookfield viscometer.

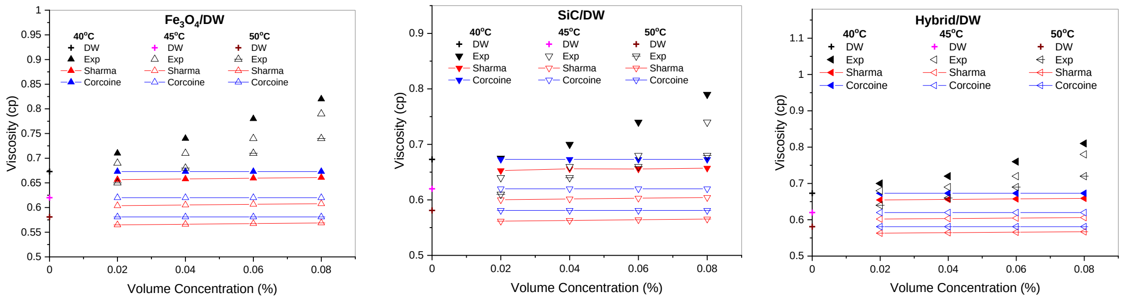
The measured values of viscosity of the nanofluids were, Sharma et al.[35] and Corcione [36] correlations are considered for the comparison with measured viscosity values of nanofluids as shown in Figure 12.

The experimental viscosity values of the nanofluids are compared with Corcione [36] and Sharma et al. [35] correlations given by Eqs.18 & 19.

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{1-34.87(\frac{d_p}{d_{bf}})^{-0.3}(\frac{\phi}{100})^{1.03}} \quad (18)$$

Where d_{bf} is the equivalent diameter of the base fluid molecule given by $d_{bf} = 0.1\left[\frac{6M}{N\pi\rho_{bfo}}\right]^{1/3}$ in which M is the molecular weight of the base fluid, N is the Avogadro number and ρ_{bfo} is the density of the base fluid at 20°C.

$$\frac{\mu_{nf}}{\mu_{bf}} = \left[(1+\frac{\phi}{100})^{11.3} (1+\frac{T_{nf}}{70})^{-0.038} (1+\frac{d_p}{170})^{-0.061} \right] \tag{19}$$



(a) (b) (c)

Figure 12. Viscosity of DW based Nanofluids (a) Fe_3O_4, (b) SiC and (c) Hybrid

The Figure 12 clearly shows that general trend that the viscosity of the nanofluids increases with volume concentration and decreases with the increase of temperature.

The percentage enhancement in the viscosity with respect to base fluid of the Fe_3O_4/DW nanofluid varies from 5.49 to 21.84%, 11.29 to 27.41% and 11.87 to 27.36% for the temperatures 40, 45 and 50°C respectively as the volume concentrations varies from 0.02 to 0.08%.

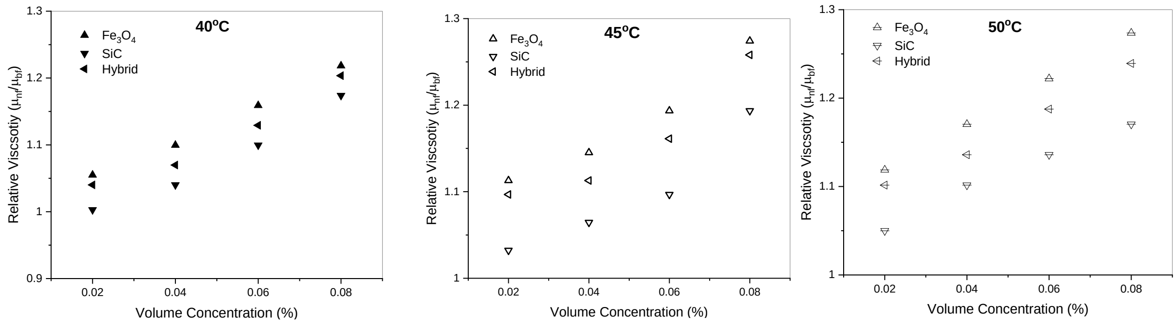
The percentage enhancement in the viscosity of SiC/DW nanofluid compared to the base fluid, DW varies from 0.29 to 17.38%, 3.22 to 19.35% and 5 to 17.03% for the temperatures 40, 45 and 50°C respectively as the volume concentration varies from 0.02 to 0.08%.

The percentage enhancement in the viscosity of Hybrid/DW nanofluid with respect to base fluid varies from 4.01 to 20.35%, 9.67 to 25.8% and 10.15 to 23.92% for the temperatures 40, 45 and 50°C as the volume concentration varies from 0.02 to 0.08%.

The above results indicate that the percentage enhancement in viscosity of Fe_3O_4/DW nanofluid is higher than Hybrid and SiC nanofluids. SiC/DW nanofluids exhibited least percentage enhancement in viscosity among the considered nanofluids. At 50°C and 0.08% volume concentration the viscosity of Fe_3O_4/DW is 1.08 times higher than SiC/DW and 1.02 times higher than Hybrid/DW nanofluid.

The average percentage deviation of predicted viscosity using Sharma et al.[106] correlation varied from 10.8 to 22.6% whereas the deviation with Corcione correlation varied from 7.9 to 19.6%, with the measured data. It is observed that the deviation between experimental and theoretical values increased with the increase in temperature and volume concentration.

The relative viscosity of the DW based Fe_3O_4, SiC and Hybrid nanofluids is represented in Figure 13.



(a) (b) (c)

Figure 13. Relative Viscosities of DW based Fe3O4, SiC and Hybrid Nanofluids (a) 40°C, (b) 45°C and (c) 50°C

The relative viscosity of Fe_3O_4/DW nanofluid was greater than Hybrid/DW and SiC/DW nanofluids at all concentrations considered. This is because of the higher density and viscosity of the Fe_3O_4 nanoparticles when compared with SiC nanoparticles. Hybrid/DW nanofluid viscosity was found to be between SiC/DW and Fe_3O_4/DW nanofluids.

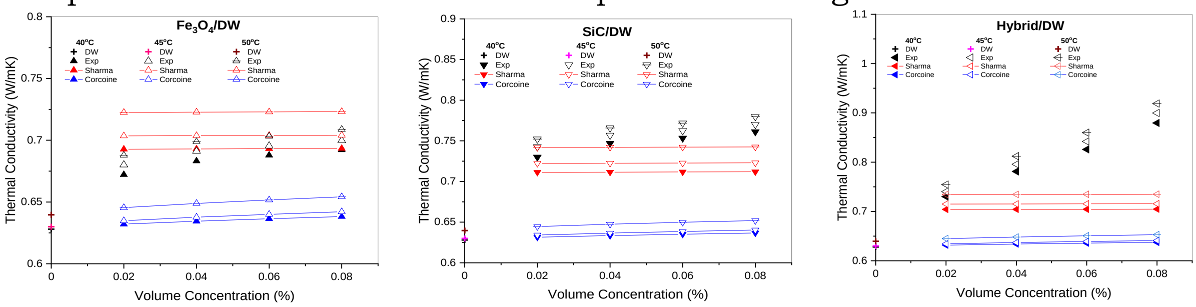
Thermal conductivity

The thermal conductivity of the Fe_3O_4, SiC and Hybrid nanofluids with DW as base fluid is experimentally determined using Tempos Thermal property analyser. The experimental values of thermal conductivity of the nanofluid considered are compared with Hamilton Crosser [36], Sharma et al. [35] and Corcione correlations. The experimental values of thermal conductivity are compared with Sharma et al.[35] and Corcione [36] correlations given by Eqs. 20 & 21.

$$\frac{k_{nf}}{k_{bf}} = \left[0.8938(1+\frac{\phi}{100})^{1.37}(1+\frac{T_{nf}}{70})^{0.277}(1+\frac{d_p}{150})^{-0.0336}(\frac{\alpha_p}{\alpha_w})^{0.01737} \right] \quad (20)$$

$$\frac{k_{nf}}{k_{bf}} = 1+4.4(\mathrm{Re})^{0.4}(\mathrm{Pr}_{bf})^{0.66}\left[\frac{T}{T_{fr}}\right]^{10}\left[\frac{k_p}{k_{bf}}\right]^{0.03}\left[\frac{\phi}{100}\right]^{0.66} \quad (21)$$

Where $\mathrm{Re} = \frac{2\rho_{bf}K_b T}{\pi(\mu_{bf})^2 d_p}$ is the Reynolds number of the nano particle, K_b is the Boltzmann constant. The thermal conductivity of DW based nanofluids and their comparison with the correlations is represented in Figure 14.



(a) (b) (c)

Figure 14. Thermal Conductivity of Nanofluids (a) Fe_3O_4, (b) SiC and (c) Hybrid

The Figure 14 shows that the thermal conductivity increases with the addition of nanoparticles considered in the analysis and that the thermal conductivity of nanofluids is sensitive to the temperature. The increase in thermal conductivity is reported to be due to the Brownian motion [3] of the nanoparticles in the base fluid and is also because of the conductivity of interfacial layer [4] of the base fluid which is attached to the nano particle suspended in the solution. The Percentage enhancement in the thermal conductivity of Fe_3O_4/DW nanofluid with respect to base fluid varies from 7.03 to 10.22%, 7.95 to 11.07% and 7.54 to 10.81% for the temperatures 40, 45 and 50°C, as the volume concentration varies from 0.02 to 0.08%.

The Percentage enhancement in the thermal conductivity of SiC/DW nanofluid varies from 16.22 to 21.21%, 17.87 to 22.23% and 17.59 to 21.91% for the temperatures 40, 45 and 50°C, as the volume concentration varies from 0.02 to 0.08%.

The Percentage enhancement in the thermal conductivity of Hybrid/DW nanofluid varies from 16.25 to 40.04%, 17.49 to 42.83% and 17.95 to 43.65% for the temperatures 40, 45 and 50°C, as the volume concentration varies from 0.02 to 0.08%.

Correlations given by Sharma et al. and Corcione have under predicted the thermal conductivity with a maximum deviation of 5%, 6.5% and 25% and 8.97%, 20.27% and 40.72% respectively for Fe_3O_4/DW, SiC/DW and Hybrid/DW nanofluids. It is observed that the deviation is maximum for Hybrid/DW nanofluids with the two correlations considered for thermal conductivity which indicates the correlations considered are suitable for single component nanofluids.

The relative thermal conductivity of DW based nanofluids is represented in Figure 15.

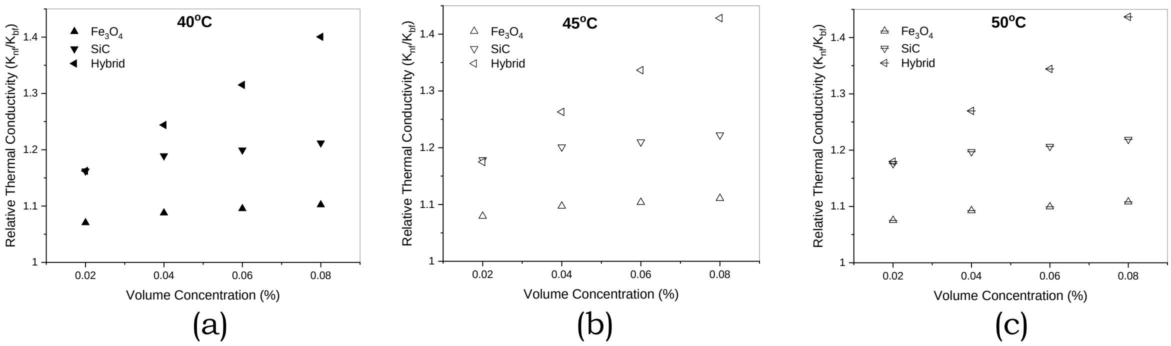


Figure 15. Relative Thermal Conductivity of DW based Nanofluids (a) 40°C, (b) 45°C and (c) 50°C

The relative thermal conductivity trends of all the three different DW based nanofluids including Hybrid nanofluid is strikingly similar at all volume concentrations and measuring temperatures considered in the analysis. The approximate variation of relative thermal conductivity of Fe_3O_4/DW is from 1.05 to 1.1, SiC/DW is from 1.17 to 1.22 and for Hybrid /DW it is from 1.17 to 1.4 as the volume concertation increased from 0.02 to 0.08% for all the temperatures considered. This shows that for the range of operating temperatures and the range of volume concentrations considered, the relative thermal conductivity is not affected by the temperature. The relative thermal conductivity of Hybrid nanofluids is observed to be much higher than Fe3O4/DW as well as SiC nanofluids. At 50°C, the average relative thermal conductivity of Hybrid nanofluid is 1.19 times higher than Fe_3O_4/DW and 1.08 times higher than SiC/DW nanofluids.

To analyse the combined effect of thermo-physical properties of nanofluids on their heat transfer performance Prandtl number is calculated and the results are as follows.

Prandtl Number

Prandtl number (Pr) is defined as the ratio of momentum diffusivity to thermal diffusivity. In order to identify the combined effect of thermo physical properties of the nanofluids Prandtl number is calculated using Eq.22

$$\mathrm{Pr} = \frac{\mu C_p}{k} \qquad (22)$$

The Prandtl number of the DW based Fe_3O_4, SiC and Hybrid nanofluids is represented in Figure 16.

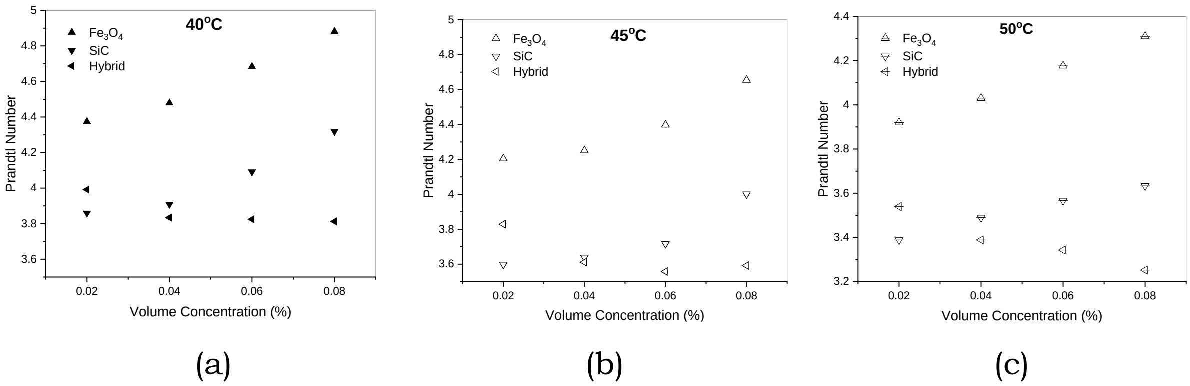


Figure 16. Prandtl Number of Nanofluids (a) 40°C, (b) 45°C and (c) 50°C

The Prandtl number of Fe_3O_4/DW and SiC/DW nanofluids increase with the increase in volume concentration irrespective of the measuring temperature considered in the analysis, whereas the Prandtl number of Hybrid/DW nanofluid decreased with the increase in volume concentration. The decrease in the Prandtl number of Hybrid/DW nanofluids indicates the increase in thermal diffusivity when compared to momentum diffusivity which is due to the higher enhancement in the thermal conductivity of Hybrid/DW nanofluid than its constituent single component suspensions compared to its viscosity. The decrease of Prandtl number of DDW based hybrid nanofluid is considered as an encouraging trend as this signifies the faster heat transfer penetration and more depth of heat transfer penetration into the fluid than the momentum penetration. Thus, it is expected that the present combination of hybrid nanofluid will yield comparatively better thermo-hydraulic performance than its constituent single component nanofluids.

Thermal Performance

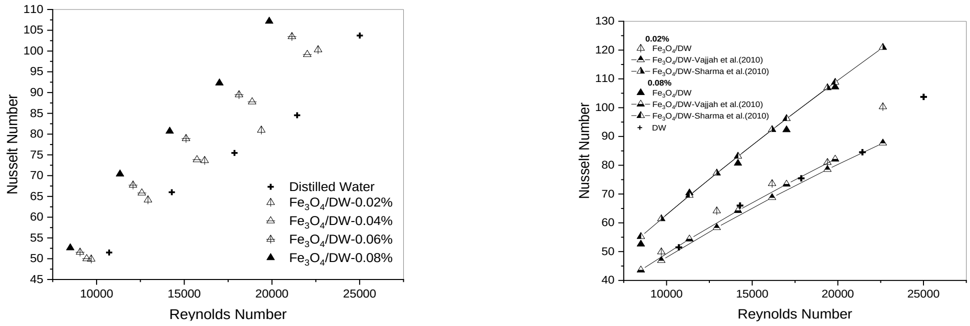
Nusselt Number

The Nusselt number of the DW based Fe_3O_4, SiC and Hybrid nanofluids are compared with the correlations of Sharma et al[35] and Vajjha et al[12]. These correlations given by Eqs.23 & 24.

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}_w^{0.4}(1+\mathrm{Pr}_{nf})^{-0.012}(1+\phi)^{0.23} \tag{23}$$

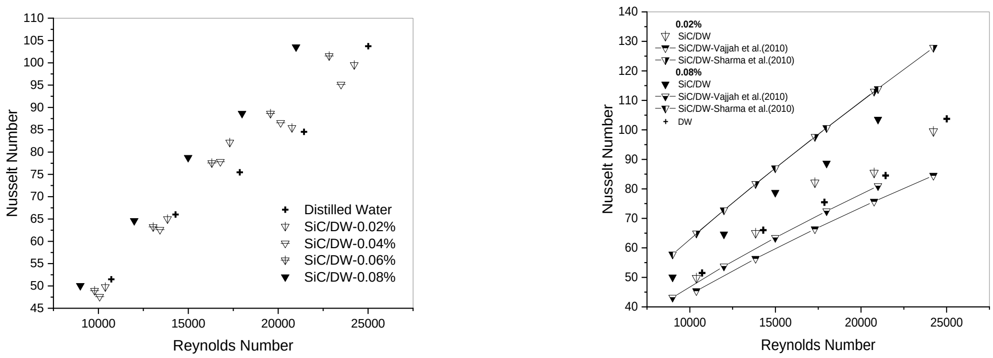
$$Nu = 0.065(\mathrm{Re}^{0.65}-60.22)(1+0.0169\phi^{0.15})\,\mathrm{Pr}^{0.542} \tag{24}$$

Figures 17 to 19 represents the analysis of experimental Nusselt number as well as comparison with the correlations for DW based Nanofluids Fe_3O_4, SiC and Hybrid nanofluids respectively for the volume concentrations of 0.02% and 0.08%.



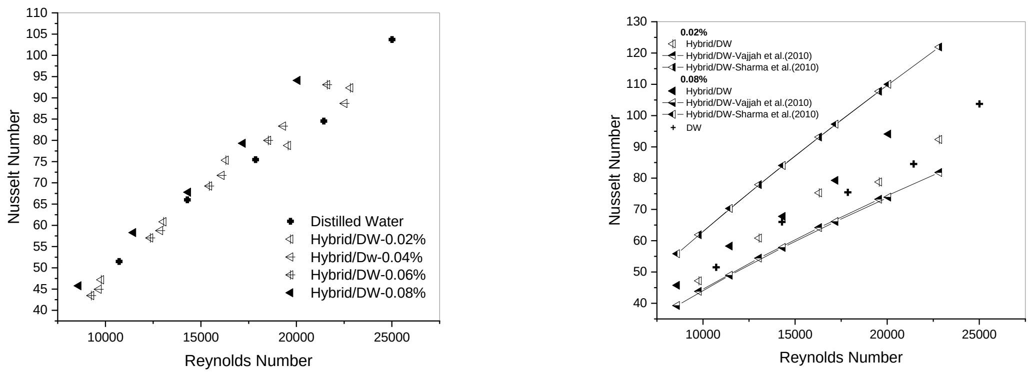
(a) (b)

Figure 17. Nusselt Number of Fe_3O_4/DW Nanofluid (a) Experimental, (b) Comparison with Theoretical Correlations.



(a) (b)

Figure 18. Nusselt Number of SiC Nanofluid (a) Experimental, (b) Comparison with Theoretical Correlations



(a) (b)

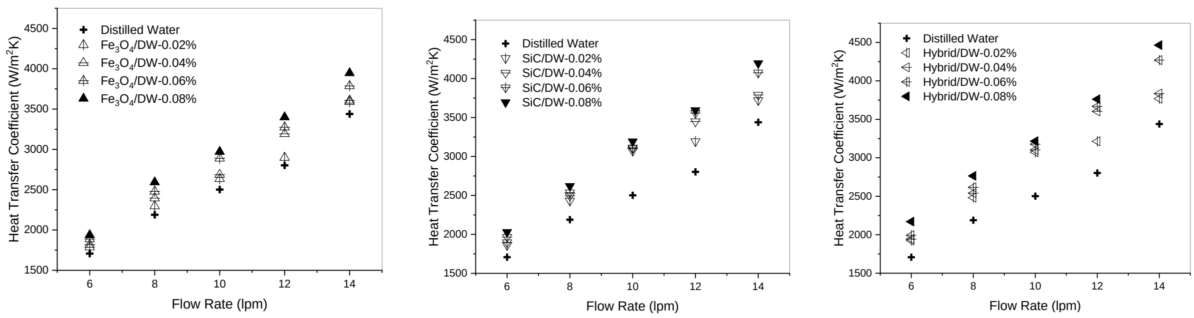
Figure 19. Nusselt number of Hybrid/DW Nanofluid (a) Experimental (a) Comparison with Correlations

The average enhancement in Nusselt number is 26.31%, 14.87% and 6.3% for Fe_3O_4/DW , SiC/DW and Hybrid/DW nanofluids respectively is obtained at 0.08% volume concentration. This shows that the effect of Brownian motion is dominant with Hybrid nanofluid.

The comparison of experimental Nusselt number with Sharma and Vajjha correlations that though these correlations predicted the experimental data with a deviation of less than 30%.

Heat transfer Coefficient

The heat transfer coefficient of the DW based Fe_3O_4, SiC and Hybrid nanofluids is analysed on the basis of the nanofluid flow rates, as shown in Figure 20.



(a) (b) (c)

Figure 20. Heat transfer Coefficient of Nanofluids (a) Fe_3O_4, (b) SiC and (c) Hybrid

The heat transfer coefficient of the DW based Fe_3O_4, SiC and Hybrid nanofluids increase with the increase of flow rate and volume concentration.

The percentage enhancement in the heat transfer coefficient of Fe_3O_4/DW nanofluids varies from 3.39% to 5.33%, 4.87% to 13.9%, 10.1% to 16.84% and 13.48% to 21.3% for the volume concentrations 0.02%, 0.04%, 0.06% and 0.08% respectively as the hot fluid flow rate varies from 6 to 14 lpm. The percentage enhancement in the heat transfer coefficient of SiC/DW nanofluids varies from 8.16% to 22.73%, 10.18% to 23.91%, 15.05% to 26.88% and 18.82% to 28.19% for the volume concentrations 0.02%, 0.04%, 0.06% and 0.08% respectively as the hot fluid flow rate varies from 6 to 14 lpm. The percentage enhancement in the heat transfer coefficient of Hybrid/DW nanofluids varies from 9.56% to 22.82%, 11.49% to 28.57%, 16.79% to 30.9% and 26.34% to 34.21% for the volume concentrations 0.02%, 0.04%, 0.06% and 0.08% respectively as the hot fluid flow rate varies from 6 to 14 lpm.

This clearly shows that the heat transfer enhancement is higher with Hybrid nanofluids, compared to its constituent single component nanofluid. The comparison of heat transfer coefficient of DW based nanofluids for a volume concentration of 0.08% is shown in Figure 21. The average percentage enhancement of Hybrid/DW nanofluid is 1.25 times higher than SiC/DW nanofluids and 1.683 times higher than Fe_3O_4/DW nanofluids at 0.08% volume concentration.

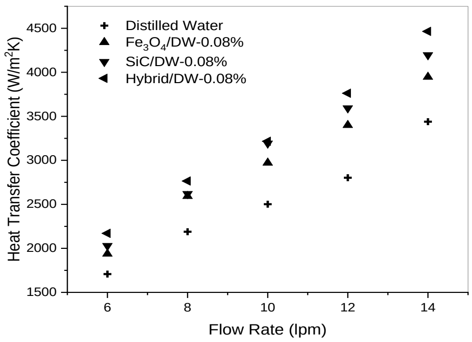
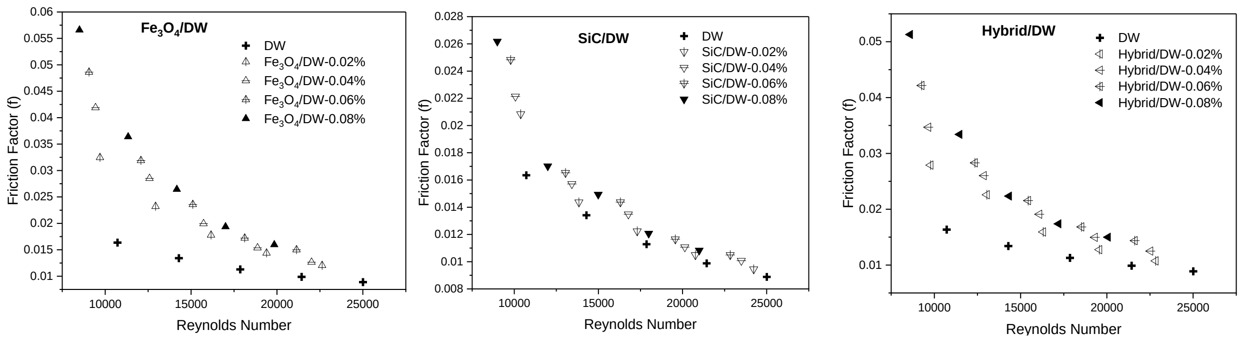


Figure 21. Comparison of Heat Transfer Coefficient of Nanofluids

Friction Factor

The friction factor of the nanofluids is represented with respect to Reynolds in Figure 22 for DW based Fe_3O_4, SiC and Hybrid nanofluids respectively



(a) Fe_3O_4/DW (b) SiC/DW (c) Hybrid/DW

Figure 22. Friction Factor of Nanofluids

The friction factor of the nanofluids varied from 52.3 to 102.4%, 9.27 to 17.01% and 39.02 to 100.4% for Fe_3O_4/DW, SiC/DW and Hybrid/DW nanofluids respectively as the volume concentration increases from 0.02% to 0.08%.

In order to compare the thermal performance of the nanofluids and to analyse the effect of enhancement in heat transfer coefficient and friction factor thermal performance factor (TPF) denoted by η is determined using Eq.(25)

$$\eta = \frac{\left(\frac{Nu_{nf}}{Nu_{bf}}\right)}{\left(\frac{f_{nf}}{f_{bf}}\right)^{\frac{1}{3}}} \qquad (25)$$

The TPF of DW based Fe_3O_4, SiC and Hybrid nanofluids at 0.08% volume concentration is represented in Figure 23.

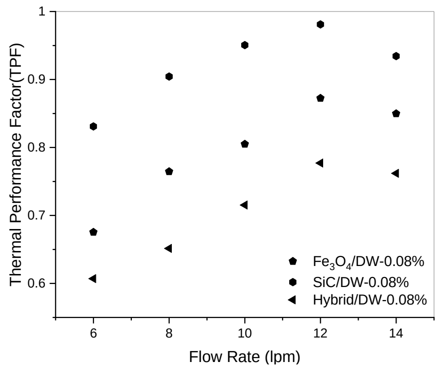


Figure 23. Thermal performance Factor of Nanofluids

It is observed that the thermal performance factor of nanofluids increase upto the flow rate of 12 lpm and decreased at 14 lpm and also the TPF values of SiC/DW nanofluid is greater than DW based Fe_3O_4 and Hybrid naofluids. This phenomena is mainly due to the combined effect of the thermo physical properties of increase in viscosity and thermal conductivity of the nanofluids. Increase in thermal conductivity enhances the heat transfer performance where as increase in viscosity in turn increase the pumping power there by reducing the heat transfer performance. Due to the opposing effects of these properties the variation in TPF values of the nanofluids is observed.

Similarly the experiments are repeated with the other two base fluids i.e 20:80 EG-Water and 40:60 EG-Water and the results are tabulated in the following table. Tables 6,7,8 and 9 indicates the percentage enhancement or decrease in thermal conductivity, Viscosity, Specific heat and density of nanofluids w.r.t base fluids

Table 6. Percentage enhancement of Thermal Conductivity

Volume concentration in %	DW based Nanofluids			20:80 EG-Water based Nanofluids			40:60 EG-Water Based Nanofluids		
	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid
0.02	7.95	17.87	23.04	24.61	29.28	35.6	23.67	24.28	28.77
0.04	9.71	20.12	30.39	25.7	33.02	45.1	25.16	26.32	35.71
0.06	10.38	21.01	38.33	26.42	36.84	54.3	28.36	29.93	42.73
0.08	11.07	22.23	43.07	26.94	40.63	**63.87**	32.85	33.87	49.22

Table 7. Percentage enhancement of Viscosity

Volume concentration in %	DW based Nanofluids			20:80 EG-Water based Nanofluids			40:60 EG-Water Based Nanofluids		
	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid
0.02	11.3	3.22	9.67	43.82	14.6	28.08	27.04	13.11	24.6
0.04	14.51	6.45	11.29	50.56	23.59	34.83	35.24	18.85	31.2
0.06	19.35	9.67	16.12	56.17	30.33	43.82	40.16	23.77	37.7

0.08	27.41	19.35	25.8	62.92	38.2	50.56	47.54	28.68	41

Table 8. Percentage decrease of Specific heat

Volume concentration in %	DW based Nanofluids			20:80 EG-Water based Nanofluids			40:60 EG-Water Based Nanofluids		
	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid
0.02	0.81	0.04	0.23	1.37	1.28	1.34	0.12	0.06	0.09
0.04	0.95	0.11	0.31	1.61	1.58	1.59	0.22	0.15	0.19
0.06	1.07	0.23	0.4	1.82	1.79	1.8	0.47	0.38	0.41
0.08	1.31	0.33	0.81	2.23	2.14	2.2	0.67	0.51	0.57

Table 9. Percentage enhancement of Density

Volume concentration in %	DW based Nanofluids			20:80 EG-Water based Nanofluids			40:60 EG-Water Based Nanofluids		
	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid
0.02	0.7	0.05	0.13	1.44	1.24	1.34	0.09	0.04	0.13
0.04	0.81	0.09	0.25	1.54	1.48	1.5	0.18	0.09	0.25
0.06	0.9	0.15	0.38	1.73	1.63	1.67	0.38	0.31	0.37
0.08	1.1	0.19	0.95	2.11	2.05	2.06	0.56	0.41	0.5

Tables 10 and 11 indicate the average percentage enhancements of heat transfer coefficient and friction factor of the nanofluids w.r.t their base fluids.

Table 10. Percentage enhancement of Average Heat Transfer Coefficient

Flow Rate	DW based Nanofluids			20:80 EG-Water based Nanofluids			40:60 EG-Water Based Nanofluids		
	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid
0.02	4.53	12.97	14.64	10	24.11	30.15	14.87	28.61	34.46
0.04	8.42	16.43	18.79	17.84	27.64	36.74	21.93	32.41	46.18
0.06	13.23	20.14	23.66	21.76	35.24	41.24	26.56	40.81	51.2
0.08	17.35	23.25	29.2	27.41	51.16	55.37	31.88	51.5	59.8

Table 11. Percentage enhancement of Average Friction Factor

Flow Rate	DW based Nanofluids			20:80 EG-Water based Nanofluids			40:60 EG-Water Based Nanofluids		
	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid	Fe_3O_4	SiC	Hybrid
0.02	62.08	7.03	46.06	55.6	9.47	10.98	27.96	4.93	18.94
0.04	88.74	15.51	73.52	83.98	14.42	23.4	38.08	15.27	28.44
0.06	117.45	21.67	98.36	109.25	16.27	27.7	47.54	22.03	43.85
0.08	145.51	25.82	121.1	139.57	18.89	35.17	62.47	26.71	55.63

Table 12 indicates the thermal performance factors of the nanofluids at all the concentrations considered for all the nanofluids in the analysis.

Table 12. TPF of Nanofluids

Base Fluid	Flow rate lpm	Fe_3O_4				SiC				Hybrid			
		0.02	0.04	0.06	0.08	0.02	0.04	0.06	0.08	0.02	0.04	0.06	0.08
DW	6	0.8	0.7	0.7	0.7	0.9	0.8	0.8	0.83	0.8	0.7	0.6	0.6
	8	0.8	0.8	0.8	0.8	1.0	0.9	0.9	0.9	0.8	0.7	0.7	0.7
	10	0.8	0.8	0.8	0.8	1.1	1.0	1.0	1.0	0.9	0.8	0.7	0.7

	12	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0	0.9	0.9	0.8	0.8
	14	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8
20:80 EG-Water	6	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.8	0.8	0.8	0.8
	8	0.8	0.8	0.8	0.8	1.1	1.0	1.0	1.1	1.1	1.0	0.9	0.9
	10	0.8	0.8	0.7	0.7	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8
	12	0.8	0.8	0.8	0.8	0.9	0.9	1.0	1.0	0.9	0.9	0.9	0.9
	14	0.8	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0	0.9	0.9	0.9
40:60 EG-Water	6	0.8	0.8	0.8	0.7	0.99	0.98	1.0	1.0	0.9	0.9	0.9	0.9
	8	0.9	0.9	0.9	0.9	1.1	1.1	1.0	1.0	1.1	1.0	1.0	0.9
	10	0.9	0.9	0.9	0.9	1.0	1.00	1.0	1.0	1.0	1.1	1.0	0.9
	12	0.9	0.9	0.9	0.8	0.9	0.9	0.9	1.0	0.9	1.0	0.9	0.9
	14	1.0	0.9	0.9	0.9	1.0	1.00	1.0	1.2	1.0	1.0	1.0	1.1

CONCLUSIONS:

The thermo physical properties and heat transfer performance of DW, 20:80 EG-Water, 40:60 EG-Water based Fe_3O_4, SiC and their hybrid combination nanofluids are experimentally investigated. The volume concentration of the nanofluids considered are in the range of 0.02% to 0.08% and the flow rates are in the range of 6 to 14 lpm. The following are the conclusions drawn from the experimentations.

- The enhancement in density of nanofluids is less than 3% and the percentage decrease in specific heat of nanofluids is less than 3%, for the range of low volume concentrations considerde in teh analysis. The Pak & Cho correlations for density and specific heat predicted the respectve measured data with excellent agreement, the deviation is observed to be less than 3%.
- Maximum of 63.87% enhancement in thermal conductivity is obtained for 20:80 EG-Water based Hybrid nanofluids at 0.08% volume concentration because of the induced Brownian motion which was obtained by mixing high and low-density particles in the base fluid.
- Maximum of 62.92% increment in viscosity is obtained for 20:80 EG-Water based Fe_3O_4 nanofluids at 0.08% volume concentration.
- Existing correlations for thermal conductivity and viscosity were found to be not adequate in predicting the measured data.
- Prandtl number of the hybrid nanofluids is observed to decrease with volume concentration while that of single component nanofluid increased. This is due to significantly higher thermal conductivity of hybrid nanofluid compared to that of its constituent single component nanofluids. The decrease of Pr is a favourable trend as it signifies the deeper penetration of heat transfer compared to that of momentum transfer.
- Among the three base fluids considered, 20:80 EG-Water showed comparatively higher enhancement in the thermos physical properties when spiked the same type and same amount of the nano particles.
- Maximum of 77.19% enhancement in heat transfer coefficient was obtained for 40:60 EG-Water based Hybrid nanofluids at 0.08% volume concentration
- Heat transfer enhancement of hybrid nanofluids is higher than single component nanofluid due to the increase in thermal conductivity of hybrid nanofluids.

- Though 20:80 EG-Water based nanofluids showed higher enhancements in the thermos physical properties, higher heat transfer enhancement was observed with 40:60 EG-Water.
- Even at low volume concentration of 0.02% the average enhancement of 34.46% in heat transfer coefficient is observed for 40:60 EG-Water based hybrid nanofluid, compared to that of 14.87% and 28.16% respectively for Fe_3O_4 and SiC nanofluids.
- Sharma et al. (2017) and Vajjha et al. (2010) correlations for the Nusselt number are having a maximum of 30% deviation with the experimental values.
- Higher frictional pressure drop penalties are observed for DW based nanofluids. Fe_3O_4 nanofluids exhibited higher friction factor penalty compared to SiC nanofluids and Hybrid nanofluids due to the higher viscosity of Fe_3O_4 nanofluids.
- The thermal performance factor of SiC and Hybrid nanofluids was found to be one or greater than one in almost all volume concetration especially with 20:80 EG-Water based and 40:60 EG-water based nanofluids.
- The hybrid combination of SiC and Fe_3O_4 nanoparticles proved to an effective combination considering both the enhancement in heat transfer and pressure drop penalty, for any of the three base fluids considered. However, EG-Water based nanofluids have represented higher enhancement in the thermos physical properties as well as thermos hydraulic performance.

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List of Papers Published

1. Title: Experimental Investigation of Thermal Performance of Ethylene Glycol-Water based Fe3O4, SiC and Hybrid Nanofluids.
Journal: Journal of Enhanced Heat transfer, Vol:27 Issue:7, page No: 595-616,(2020) Impact Factor:3.4. Publisher: Begell House Publishers

2. Title: Experimental Investigation on Thermal Performance of Double Pipe Heat Exchanger Using EG-Water based SiC Nanofluid
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3. Title: Effect of Low Volume Concentration on heat Transfer Enhancement of EG-Water Based Fe_3O_4 Nanofluid
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4. Title: Heat Transfer performance of EG-Water based Fe3O4 and its Hybrid Nanofluid in a Double Pipe heat Exchanger
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5. Title: Effect of base fluid on the Performance Enhancement of Fe3O4 Nanofluid-An Experimental Investigation
Journal : International Journal of Applied Engineering Research- Research India Publications. Volume 17, Number 2 (2022) pp. 169-179

Conference Papers

1. Title: Heat Transfer performance of Hybrid (Fe_3O_4+ SiC) Nanofluid-An Experimental Study
Conference: ISHMT-ASTFE heat and Mass Transfer Conference (IHMTC 2021) DOI:10.1615/IHMTC-2021.520, Pg.No.349-354.
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2. Title: Experimental Investigation on the Heat Transfer Performance of Iron Oxide and Silicon Carbide Nanofluids

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3. Title: Thermo-Hydraulic performance of nanofluids with Silicon Nanoparticles suspended in different base fluids

Conference: International Conference on Recent Developments in Mechanical Engineering
Conducted by K L E F on 18th and 19th December 2020.

List of Papers in Review

Title: Influence of Base Fluid on The Thermo-Hydraulic Performance Of Hybrid Nanofluids-An Experimental Investigation
Journal: Journal of Nanofluids-American Scientific Publishers