INVESTIGATION OF THERMAL PROPERTIES OF OIL-BASED NANOFLUIDS FOR OIL COOLER

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Abstract—*Due to their potential use as an insulating oil as well as an improved thermophysical heat transfer fluid, nanofluids have attracted a lot of attention in recent years. Modern power networks rely heavily on mineral oil, which is employed as insulating and heat-transfer fluids.Nanofluids based on transformer oil are being investigated as an alternative to regular mineral oil. In this case Multi-Walled Carbon Nano Tubes are considered to study enhanced thermophysical properties of transformer oil, IS 335. Properties at four different concentrations for MWCNT will be studied for flow rate varying from 0.5 lpm to 1.25 lpm (Natural Convection). Results of this project can be used to develop a new class of transformer fluid for ONAF power transformers. Set up of this project is designed to help further studies in oil based nanofluid for various cooling applications. This report discusses the results of mathematical model for oil based nanofluid and they are compared with the results obtained by the CFD model and experimental trials.*

Keywords—Power Transformer Cooling,Carbon Nanotubes, Natural Convection, Transformer Oil, Nanofluid.

1. INTRODUCTION

The creation of upcoming high-voltage networks, due of their distinct properties in comparison to conventional composite materials, nanocomposite materials have been receiving greater attention. Nanocomposite materials become extremely important in a variety of industrial applications, such as cooling and electrical insulation of electrical power equipment. Nanofluids are the general term for materials that are nanocomposite and use liquid dielectrics as their basis material.

Since it is used to increase or decrease the voltage of the electrical system, the transformer is one of the most important parts of the electrical network. The transformer is regarded as having a higher priority than the other parts of the electrical network because of its high cost, direct impact on the operation of the network, location, and oil and poisonous substance content. To ensure the continuity of network operation, the protection of transformers from failure must be given higher attention. The rise in oil temperature is the primary factor in transformer failure. Therefore, in order to lower the transformer temperature, new cooling methods must be discovered.

Transformers employ mineral oil (MO) for two purposes: as a coolant at the heat transfer interface and as electrical insulation. (Taheri, A. A., et al. (2021).). As evident in multiple researches, Nanofluids have a significant effect on the cooling of electrical components. A liquid with nanosized particles homogeneously suspended in a base fluid at just a few weight/ volume percentages is called nanofluid or nanoliquid (Rafiq, M., et al. (2016).). Some of the propertiesof the oil are improved by increasing the concentration of nano-additives. The concentration of the nanofluids is directly correlated with the thermal conductivity and viscosity of the oil. However, increase in the concentration on nano-additives in the base fluid leads to reduction in lubricating properties of oil due to agglomeration and precipitation of the nano-particles (Ahmadi, H., et al. (2013)). Pure MWCNT-containing nanofluids have a greater thermal conductivity ratio than hybrid nanoparticle-containing ones(Ghaffarkhah, A., et al. (2020).). The higher flow rates the higher heat transfer coefficient (Naddaf, A., et al. (2019)).

As suggested in multiple studies, the factors affecting the heat transfer coefficient are- Concentration of nanomaterials and Flow rate of the nanofluid.

2. PROBLEM DESCRIPTION

Due to its limited thermal conductivity, transformer oil's heat transfer ability is determined to be poor. It can be improved by utilizing nanoparticles with strong heat conductivity. Increased thermal conductivity is thought to result in a higher natural convection heat transfer coefficient. To determine the improvement in natural convection, the Nusselt number can be utilized as an essential parameter.

When combined with base fluids, nanoparticles with high thermal conductivity can improve the base fluid's overall heat transfer characteristics. This may aid in resolving the oil deterioration issue in transformers.

Analysis, simulation and experimental trials are conducted on an Oil Cooler test rig in order to emulate the fin-structure on the transformer casing and relate the results to an actual transformer. The two factors affecting the heat transfer rate, i.e. Nanofluid concentration and Flow rate are varied.

3. EXPERIMENTAL SETUP

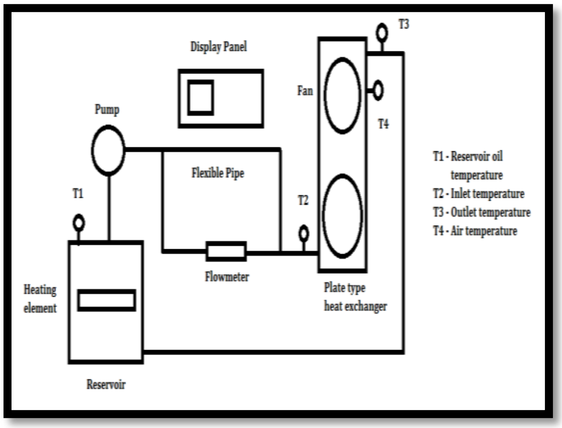


Figure 1- Flow Diagram of Experimental Setup

Design and selection of components:

3.1. PLATE TYPE HEAT EXCHANGER

Conditions applied:

1. Oil - internal flow, Air - external flow

2. Constant surface wall temperature

3. Maximum temperature rise over ambient = 40°C

Type of heat Exchanger - **Mixed cross flow heat exchanger**

In this both fluids flow perpendicular to each other. and fluid flows in well-defined path (unmixed). Temperature variation of cold fluid is in the transverse direction of the flow of hot fluid. This also implies that the cold fluid transfers heat with only hot fluid and not with itself this is because the plate type arrangement of heat exchanger. This is one of the most efficient ways of heat transfer.

Selected heat exchanger:

- Diameter = 0.015 m
- Length = 0.38 m
- No. of plates = 11
- Width of plate = 0.14505 m
- Sample Theoretical Calculations:
- Area of plates of power transformer= 10 m^2
- Minimum temperature difference for design = 10°C
- Temperature at the inlet of heat exchanger = 65°C
- Temperature of inlet of air = 27°C
- Working fluid -Transformer oil IS335 [12]

Properties:

Table 1- Properties of Transformer Oil

Density	890.1	kg/m^3
Viscosity	0.033	Pa.s
Heat Capacity	1630	J/kg.K
Thermal Conductivity	0.15	W/mK

- Effectiveness - NTU model

  Flow rate = 0.5 lpm

  = 8.33333E-06 m^3/s
- Reynold number (Re) = (ϱ V D)/μ
  = (4 ϱ Q)/ (Π μ D)
  = 19.07930166

  Here, Re< 2300
  Hence the flow is Laminar.
- Prandtl number = (μ Cp)/K
  Pr= 358.6
- Nusselt number

As flow is laminar generally we consider Sieder and Tate equation for Constant surface wall temperature conditions but here as the plates are not considered short and the Sieder-Tate correlation is useful only for relatively short lenghts we can't use this correlation.

Hence we selected Mills correlation (Subramanian, R. S. (2015)) for calculations:

$$Nu = \frac{hD}{K} = \frac{0.065 RePr\frac{D}{L}}{1 + 0.04\left(RePr\frac{D}{L}\right)^{2/3}} \quad \text{.... (1)}$$

Nu = 10.23167066

- Internal heat transfer coefficient (h_i) = 102.3167066 W/m^2K

Air -External Forced Convection

- Flow rate of fan = 1400 cfm

  = 0.6608 m^3/s
- Velocity of air = 13.46 m/s

Table 2- Properties of Air

Density	1.18	kg/m^3
Viscosity	1.80E-05	Pa.s
Heat Capacity	1005	J/kg.K

Thermal Conductivity	0.02551	W/m.K

- Reynold number (Re) = $\frac{\varrho \text{ V L}}{\square}$

  = 7.68 E+05

  Re > 2 E+05
  Hence the air flow is turbulent.
- Prandtl number = $\frac{\square \text{ Cp}}{K}$

  Pr= 7.09 E-01
- Nusselt number = 0.036 $Re^{0.8}Pr^{1/3}$

  = 1667.34966
- Nusselt number = $\frac{\text{ho L}}{K}$
- External heat transfer coefficient (h_o) = 293.2374341W/m^2K
- Overall Heat Transfer Coefficient (U)

Considerations while calculating U:

Internal and external areas of the heat exchanger are comparable emissivity = 1, Radiation losses are neglected

- Overall heat transfer coefficient (U) = 75.85 W/m^2K
- Effectiveness

  $$\varepsilon = \frac{\text{Ch (Thi} - \text{Tho)}}{\text{Cmin (Thi} - \text{Tci)}}$$

  = 0.4268

- Effectiveness for Unmixed cross flow heat exchanger

  $\varepsilon = 1 - EXP\ [NTU^{0.22}(EXP^{-C.NTU\wedge 0.78} - 1)/C]$ ... (2)

- NTU = Number of transfer units

  NTU =0.6956

  $$NTU = \frac{UA}{Cmin}$$

- Theoretically calculated Area of Heat exchanger = 9.2179 m^2

Now, to decrease the volume capacity and overall cost of the setup we scaled down the area of heat exchanger by almost 11 times, hence we reduced the number of fins to only 6 fins.

Actual area of the heat exchanger = 0.825 m^2
Now, due to the reduced area temperature difference achieved will decrease because decrease in the number of transfer units.

NTU = 0.062265562

Effectiveness = 0.058343851
Temperature Difference of working fluid = 1.3669°C

Table 3-Variation in thermal properties with respect to flow rate

Flow Rate	**Flow Rate**	**Re**	**Nu**	**hi**	**Overall HTC**	**NTU**	**ε**	**Temp. diff.**
Lpm	m^3/s			W/m^2K	W/m^2K			°C
0.5	8.33333E-06	19.0793	10.23167	102.316	75.850	0.0622	0.0583	1.3669
0.75	1.25E-05	28.61895	11.91461	119.146	84.722	0.0695	0.0647	1.5169
1	1.66667E-05	38.1586	13.27118	132.711	91.363	0.0749	0.0694	1.6279
1.25	2.08333E-05	47.69825	14.4205	144.205	96.667	0.0793	0.0732	1.7159

PROPERTIES OF NANOFLUIDS-

The properties of a nanofluid combine those of the base fluid (transformer oil) with solid nanoparticles, and they also rely on the volumetric concentration and shape of the nanoparticles.In addition to greatly improving heat transfer capacities, nanoparticles' significantly higher relative surface area compared to ordinary particles should also strengthen the stability of the suspensions. Additionally, compared to normal solid/fluid combinations, nanofluids can enhance abrasion-related properties (Wang, X. Q., et al. (2007)).

Some oil qualities get better when the nano-additives' concentration rises. The concentration of the nanofluids is directly correlated with the thermal conductivity and viscosity of the oil.

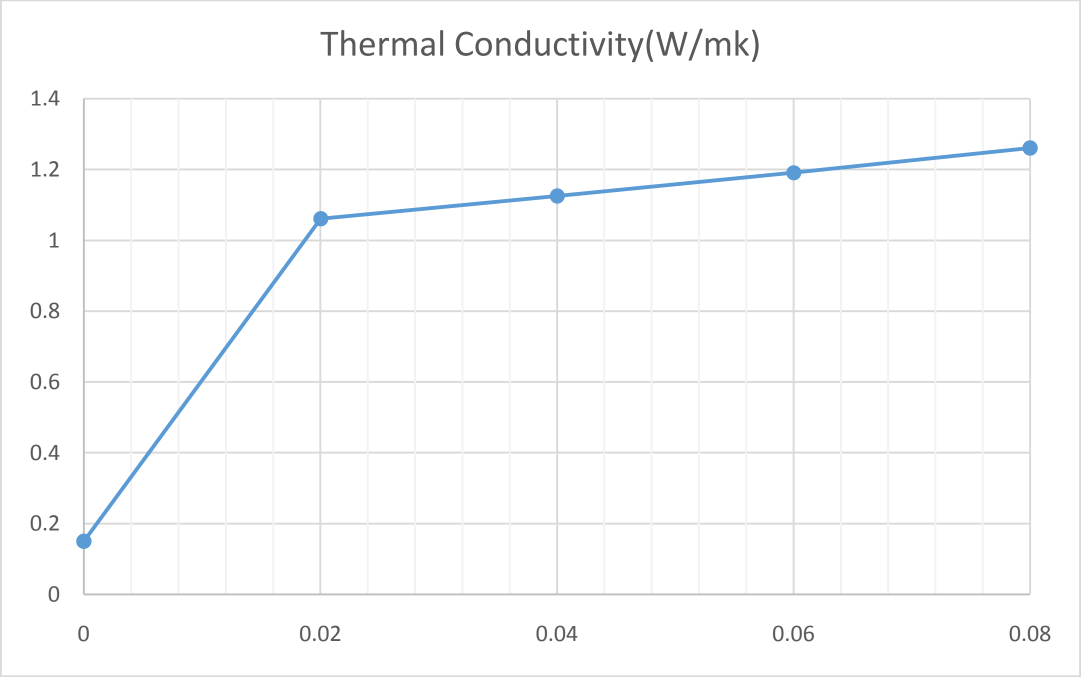
Thermal Conductivity

The thermal conductivity of nanofluids is known to be dependent on a number of factors, including **the temperature, the volume fraction, the surface area, and the shape of the nanoparticles, as well as the thermal conductivities** of the base fluid and the nanoparticles.The relationship between the concentration of nano particles in nanofluids is given by Maxwell model for Thermal conductivity of nanofluids(Wang, X. Q., et al. (2007)).

$$\mathrm{k}_{nf} = \frac{k_p + 2k_f - 2\emptyset(k_f - k_p)}{k_p + 2k_f + \emptyset(k_f - k_p)} \quad \text{.... (3)}$$

The Thermal conductivity of MWCNT is k_p= 3000 W/mK

Volume Fraction	**Thermal Conductivity**
ϕ	**k_{nf}**
v/v	W/mK
0	0.15
0.02	1.0612
0.04	1.1250
0.06	1.1915
0.08	1.2608



Graph 1- Thermal Conductivity w.r.t nanofluid concentration

Viscosity

Although increasing the thermal conductivity of a fluid by adding nanoparticles improves its ability to transport heat, the addition also causes the fluid's viscosity to rise as a result of the interaction between the nanoparticles and fluid molecules.

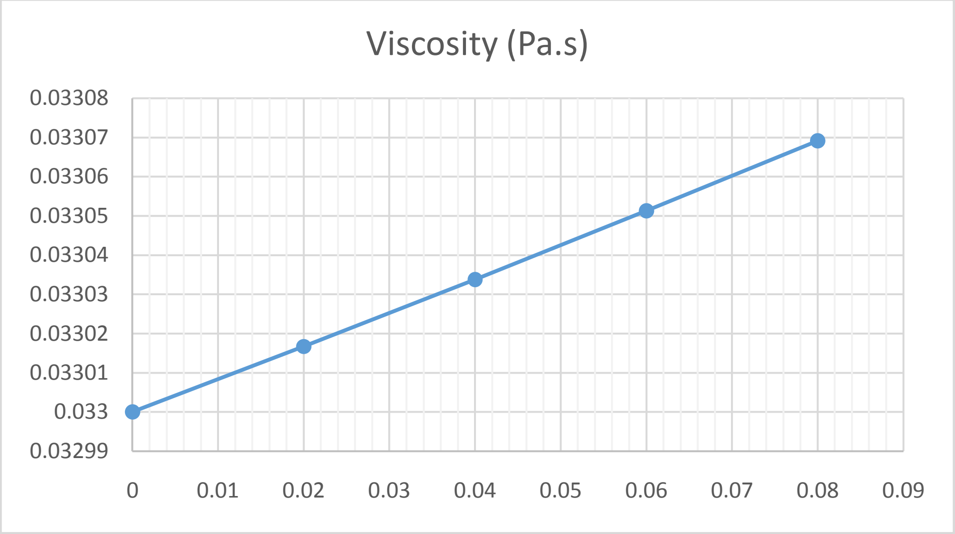
The crucial factors affecting the viscosity of nanofluids include temperature, the volume fraction of nanoparticles, size, shape, pH, and shearing rate.

The bulk stress is directly influenced by the system of thermodynamic forces acting on the particles, and it is also indirectly impacted by thermodynamic forces because they alter the statistical characteristics of the relative locations of the particles. In the case of a suspension of stiff spherical particles, these two effects are examined(Batchelor, G. K. (1977)).Batchelor added the Brownian motion effect to Einstein's viscosity equation(Mishra, P. C., Mukherjee, S., et al. (2014)).The model is given as follows:

$$\mu_{\mathrm{nf}} = (1 + 2.5\phi + 6.5\phi^2)\mu_{\mathrm{f}} \quad \dots (4)$$

Table 4- Variation of viscosity w.r.t volume fraction

Volume Fraction	**Viscosity**
ϕ	**μ_{nf}**
v/v	Pa.s
0	0.033
0.02	0.0330167
0.04	0.0330338
0.06	0.0330513
0.08	0.0330692



Graph 2- Variation of viscosity w.r.t. concentration of nanofluid

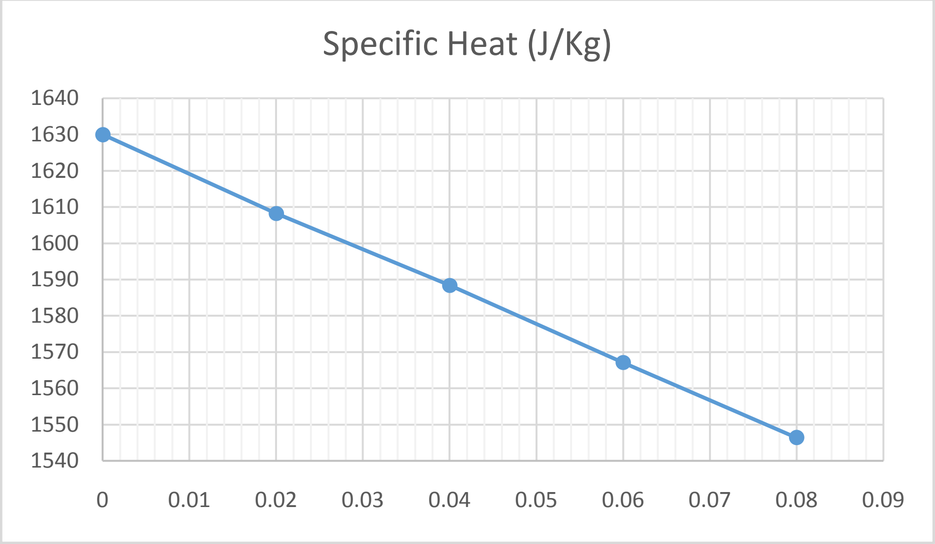
Heat Capacity and Density

The base fluid's specific heat is higher than that of the extra nanoparticles. Since metallic particles with lower specific heat occupy space in the whole volume instead of simply base fluid with relatively greater specific heat, the overall specific heat of the "nanofluid" mixture is reduced.For the synthesized nanoparticle±liquid suspension, the parameter of thenanofluid is expressed as(Xuan, Y., &Roetzel, W. (2000)). -

$$\left(c_p\right)_{\mathrm{nf}} = (1-\phi)\left(c_p\right)_{\mathrm{f}} + \phi\left(c_p\right)_{\mathrm{s}} \qquad \dots (5)$$

Table 5- Variation of Specific Heat w.r.t volume fraction

Volume Fraction	Specific Heat
Φ	**C_p**
v/v	J/kg
0	1630
0.02	1608.227
0.04	1588.369
0.06	1567.092
0.08	1546.383

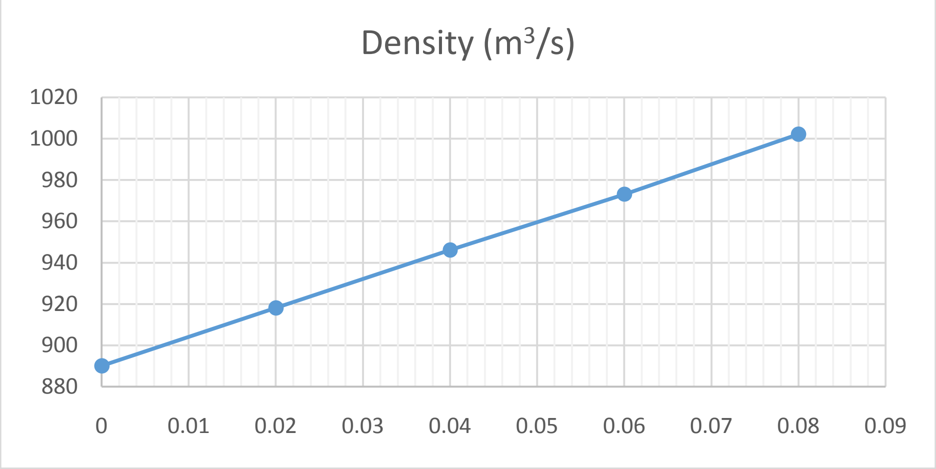


Graph 3- Variation of Specific heat with Nanofluid concentration

The density of nanofluids increases proportionally to the volume concentration of MWCNTs. The density variation is given by(Xuan, Y., &Roetzel, W. (2000))-

$$(\rho)_{\mathrm{nf}} = (1-\phi)(\rho)_{\mathrm{f}} + \phi(\rho)_{\mathrm{s}} \quad \ldots (6)$$

Volume Fraction	**Density**
ϕ	**ρ**
v/v	m^3/s
0	890.1
0.02	918.141
0.04	946.165
0.06	973.169
0.08	1002.2



Graph 4- Variation of Density w.r.t Nanofluid concentration

ANALYTICAL RESULTS-

Table 6- Results obtained from Mathematical Calculation

Flow Rate	**h_i**	**Temp. Diff.**	**Vol. Fraction** **φ**	**Temp. Diff.**	**h_i**	**Increase In Heat Transfer**
lpm	W/m^2K	^oC		^oC	W/m^2K	**%**
0.5	102.3167	1.3669642	0.02	2.84111681	381.4012	272.7653707
			0.04	2.929159117	400.0824	291.0235877
			0.06	3.017858533	419.3544	309.8591657
			0.08	3.107331287	439.2589	329.3129714
0.75	119.1461	1.51692153	0.02	2.961867883	426.2963	257.7929024
			0.04	3.047989057	446.4132	274.6771392
			0.06	3.134663065	467.1073	292.045812
			0.08	3.222012871	488.4197	309.9334274

1	132.7118	1.62796319	0.02	3.055171552	465.6717	250.8894686
			0.04	3.139964573	487.1327	267.0605806
			0.06	3.225238567	509.1643	283.6616537
			0.08	3.311120543	531.807	300.7232344
1.25	144.205	1.71592184	0.02	3.13046301	500.994	247.4179149
			0.04	3.214263108	523.7177	263.1758119
			0.06	3.298493017	547.0101	279.3280844
			0.08	3.383282379	570.9112	295.902534

Maximum temperature drop achieved = 3.383282379^{o}C

- Flow Rate - 1.25 lpm
- Volume Fraction - 0.08

Maximum increase in heat transfer = 329.3129714 %

- Flow Rate - 0.5 lpm
- Volume Fraction - 0.08

5. SIMULATION ANALYSIS

5.1. CFD ANALYSIS

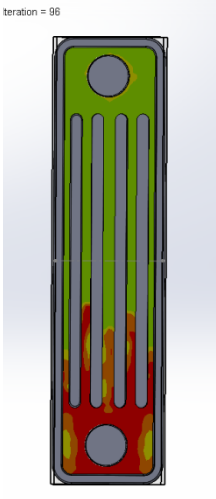
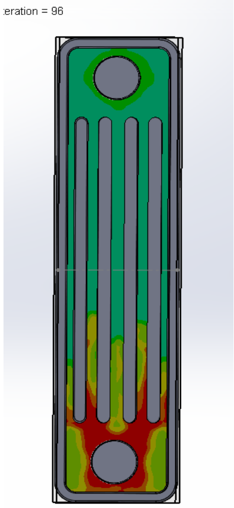
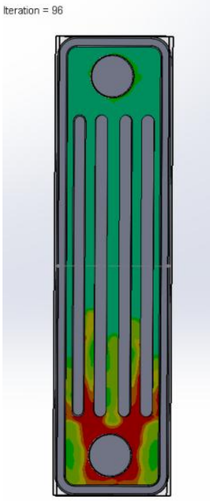
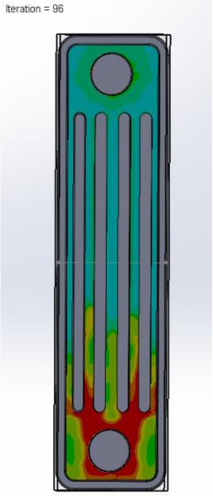
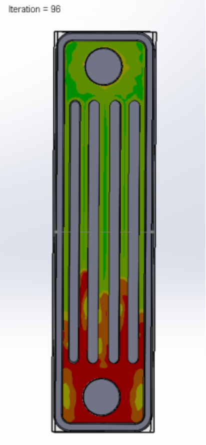
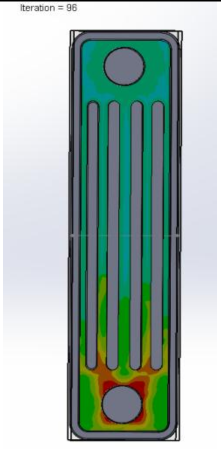
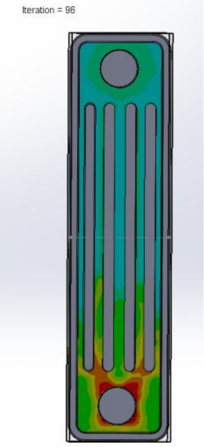
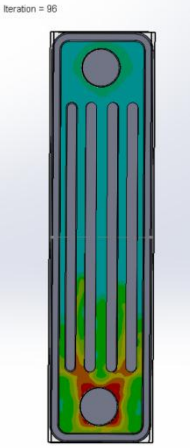
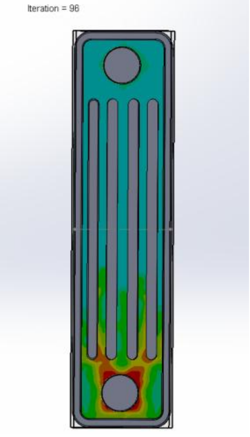
CFD analysis of one plate of the radiator is performed on Solidworks software. This process is essential to confirm the results obtained by mathematical modelling. CFD analysis shows the temperature difference obtained across the plate in varying flowrates and volume percentage of nanoparticles in transformer oil.

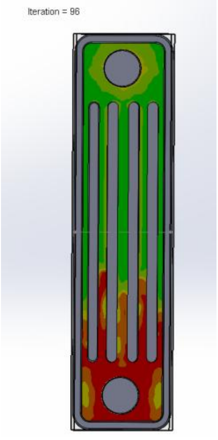
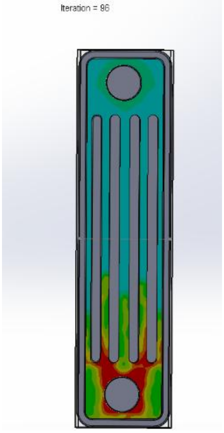
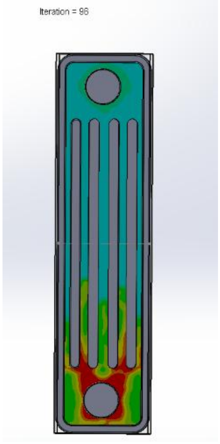
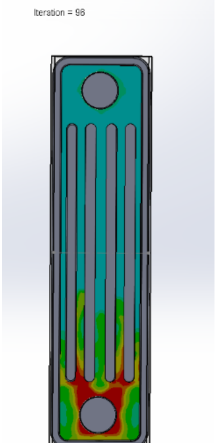
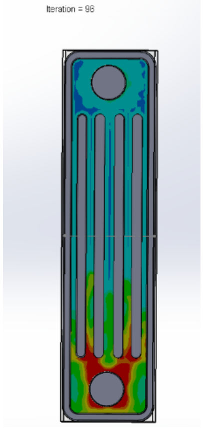
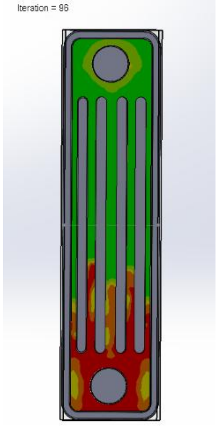
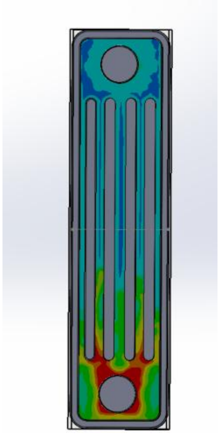
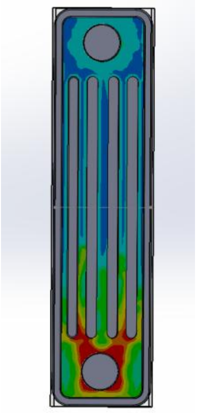
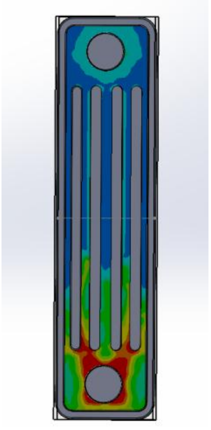
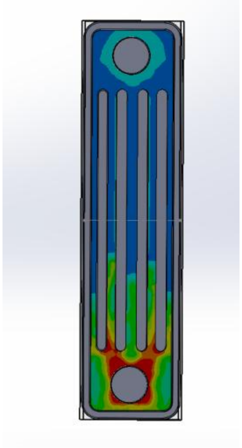
Procedure followed for CFD analysis in Solidworks:

- For CFD analysis involving two fluids, air and oil/nanofluid, CAD of plate is created in Solidworks and fluid region is confined. Air region boundries are specified.
- By selecting surfaces of each region, inlet and outlets are specified.
- Physical values of the fluid region are as follows:
  For air region:

Group Box	**Model**
Space	**Three-Dimensional Gradients**
Time	**Steady**
Material	**Fluid**
Flow	**Segregated flow**
Equation of state	**Constant density**
Viscous Regime	**Turbulent**
Reynolds-Averaged Turbulence	**K-epsilon turbulence**
Optional Models	**Segregated fluid temperature**

- In this case, mass flow rate of air and physical properties of airflow are considered as uniform. Also, properties of the metal plate are specified.
- Fluid values vary for different analysis as we add nanoparticles.
- Inlet values of fluid region are varying **mass flow rates** and fluid **temperature at the inlet**.
- Mesh size is set at **0.2mm**.
- This analysis is done at mass flow rates **0.5, 0.75, 1, 1.25 lpm.**
  And volume percentage of **0, 0.02, 0.04, 0.06 and 0.08.**
- Results of CFD analysis are compared to the results obtained by mathematical modelling.

Flow Rate (lpm)	Transformer Oil	0.02% CNT+TO	0.04% CNT+TO	0.06% CNT+TO	0.08% CNT+TO
0.5					
0.75					

1.00					
1.25					

CONCLUSION

RESULTS OF TEMPERATURE DIFFERENCE OBTAINED BY NUMERICAL ANALYSIS

Maximum temperature drop achieved = 3.383282379°C

- Flow Rate - 1.25 lpm
- Volume Fraction - 0.08

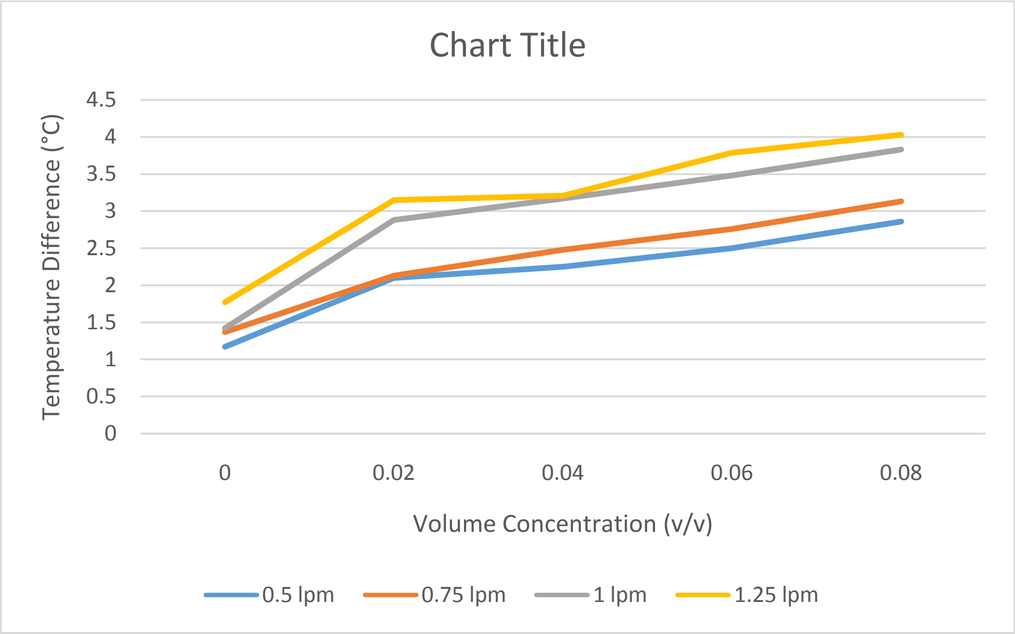
Maximum increase in heat transfer = 329.3129714 %

- Flow Rate - 0.5 lpm
- Volume Fraction - 0.08

RESULTS OF TEMPERATURE DIFFERENCE OBTAINED BY CFD ANALYSIS

Flow (lpm)	**Volume Concentration**									
	0.00		**0.02**		**0.04**		**0.06**		**0.08**	
	ΔT	**Q**	**ΔT**	**Q**	**ΔT**	**Q**	**ΔT**	**Q**	**ΔT**	**Q**
0.5	1.17	14.146	2.1	25.840	2.25	28.179	2.5	31.772	2.86	36.937
0.75	1.37	24.846	2.13	39.314	2.48	46.589	2.76	52.614	3.13	60.635
1	1.42	34.337	2.88	70.876	3.17	79.401	3.48	88.453	3.83	98.928
1.25	1.77	53.501	3.25	99.977	3.21	100.503	3.79	120.415	4.03	130.117

RISE IN TEMPERATURE DIFFERENCE BY ADDITION OF NANOPARTICLES



Graph 5-CFD results of Teperature Difference for Nanofluid Concentration

EXPERIMENTALMETHOD

Figure 2- Experimental Setup

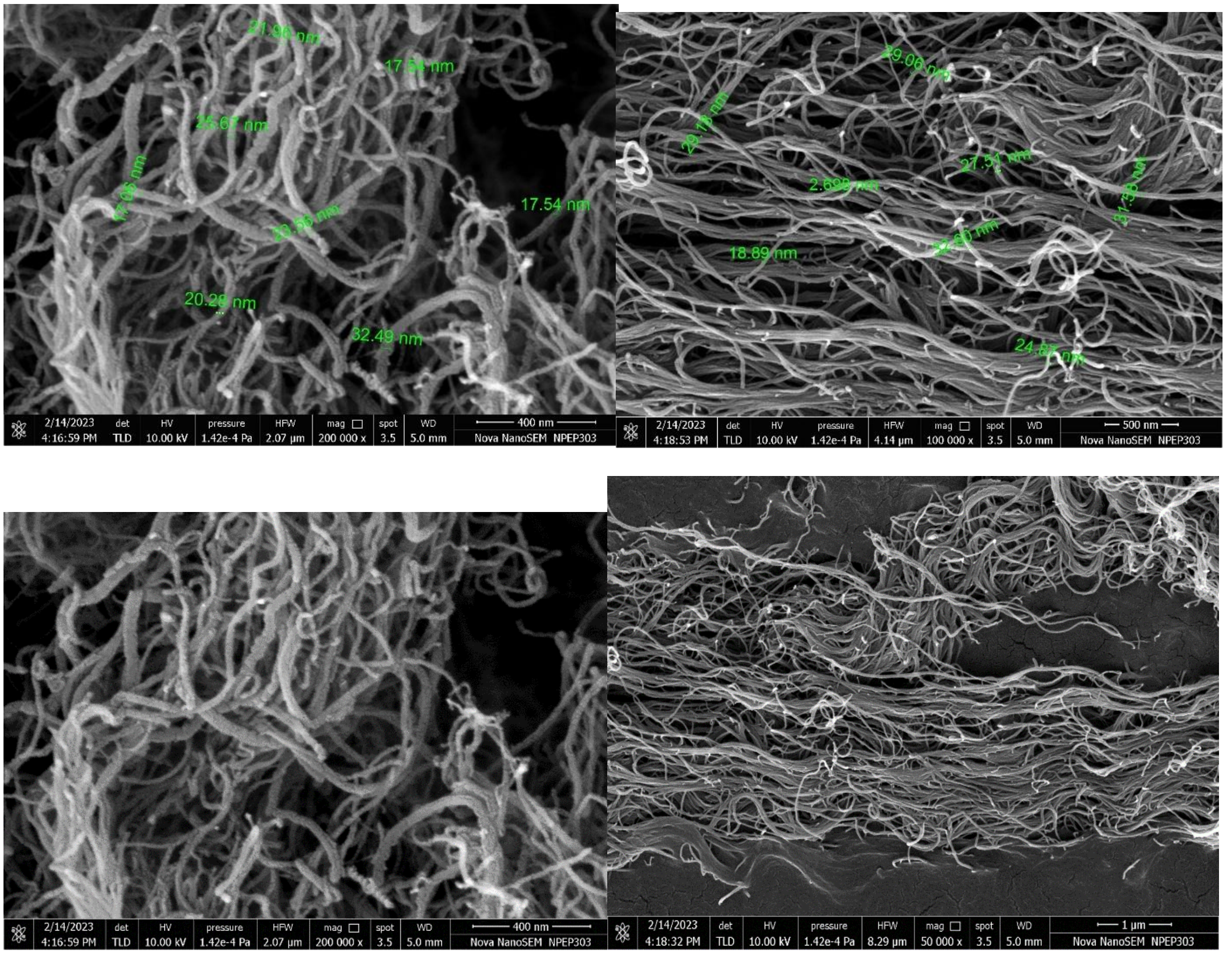


Figure 3- FESEN Images of Multi-Walled Carbon Nano Tubes

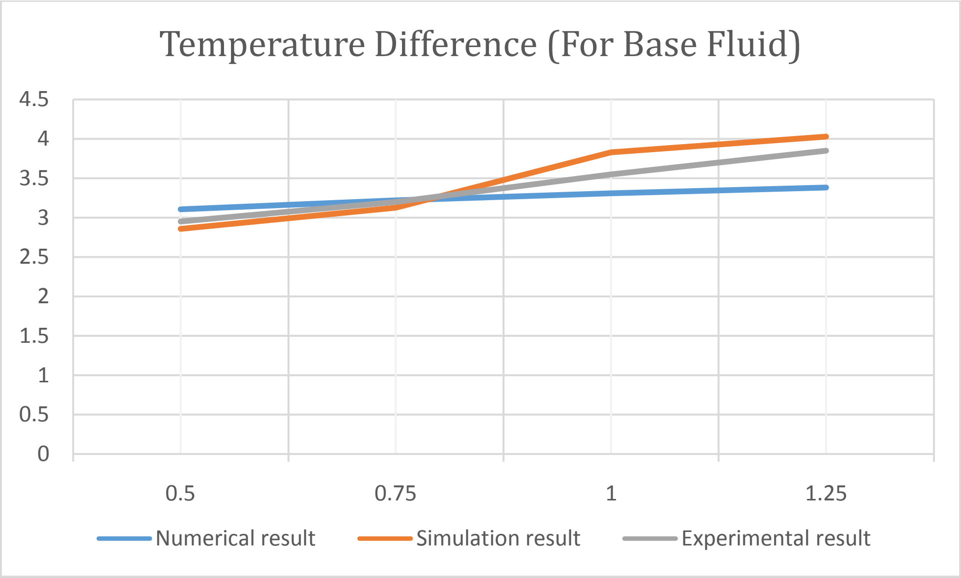
PREPARATION OF NANOFLUID

- The MWCNT- Transformer oil nanofluid was prepared with the Two-step method. Particles of MWCNT were weighted at 0.1 percent volumetric concentration and Sodium Laureth Sulfate (SLS). Amount of SLS = 10% of nanoparticles weight.
- First, 400 ml of coolant was taken, and 2 g of SLS was added to it. The solution was magnetically stirred for 15 minutes. After those 4 grams of nanoparticles were added and homogenized for another 20 minutes.
- The quick movement and agitation of this stir bar thoroughly combines the nanoparticles, SLS, and base fluid. A knob is used to change the magnetic field's speed.
- The solution is now ultrasonicated for 40 minutes.

RESULTS

Table 7- Temperature Difference for Base Fluid

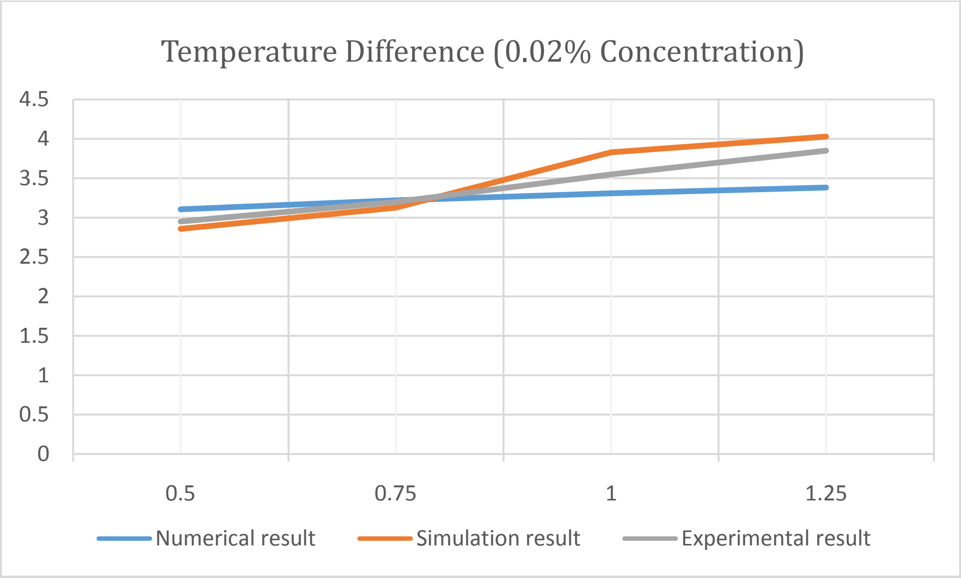
FLOW (LPM)	TEMPERATURE DIFFERENCE (FOR BASE FLUID)		
	Numerical result	Simulation result	Experimental result
0.5	1.367	1.17	1.32
0.75	1.517	1.37	1.45
1	1.628	1.42	1.56
1.25	1.716	1.77	1.8



Graph 6- Temperature Difference Comparison for Base Fluid

Table 8-Temperature Difference for 0.02% Nanofluid

FLOW (LPM)	TEMPERATURE DIFFERENCE (FOR BASE FLUID)		
	Numerical result	Simulation result	Experimental result
0.5	2.841	2.1	2.50
0.75	2.962	2.13	2.59
1	3.055	2.88	2.91
1.25	3.130	3.25	3.20



Graph 7-Temperature Difference Comparison for 0.02% Nanofluid

Table 9-Temperature Difference for 0.04% Nanofluid

FLOW (LPM)	TEMPERATURE DIFFERENCE (FOR BASE FLUID)		
	Numerical result	Simulation result	Experimental result
0.5	2.929	2.25	2.71
0.75	3.048	2.48	2.82
1	3.140	3.17	3.16
1.25	3.214	3.21	3.25

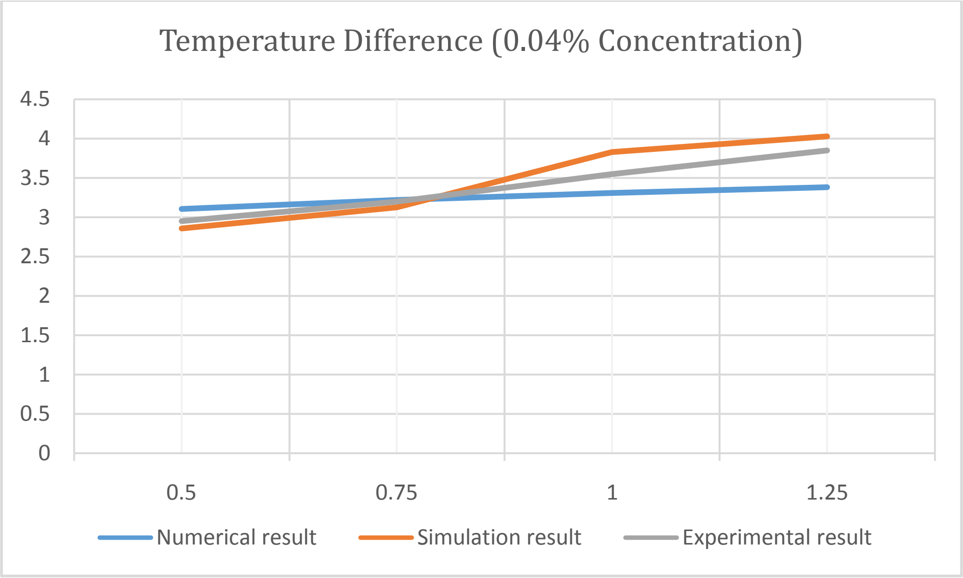
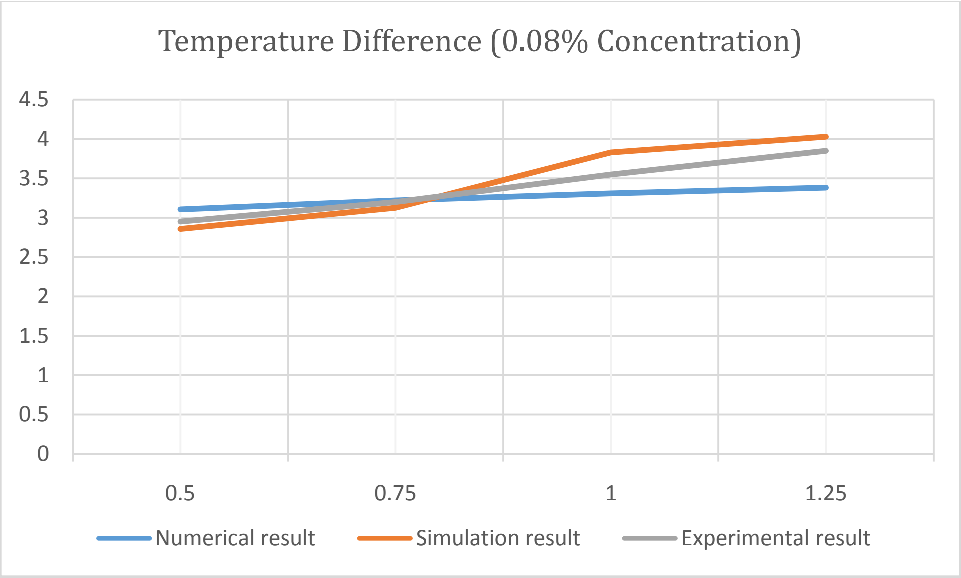


Table 10-Temperature Difference Comparison for 0.06% Nanofluid

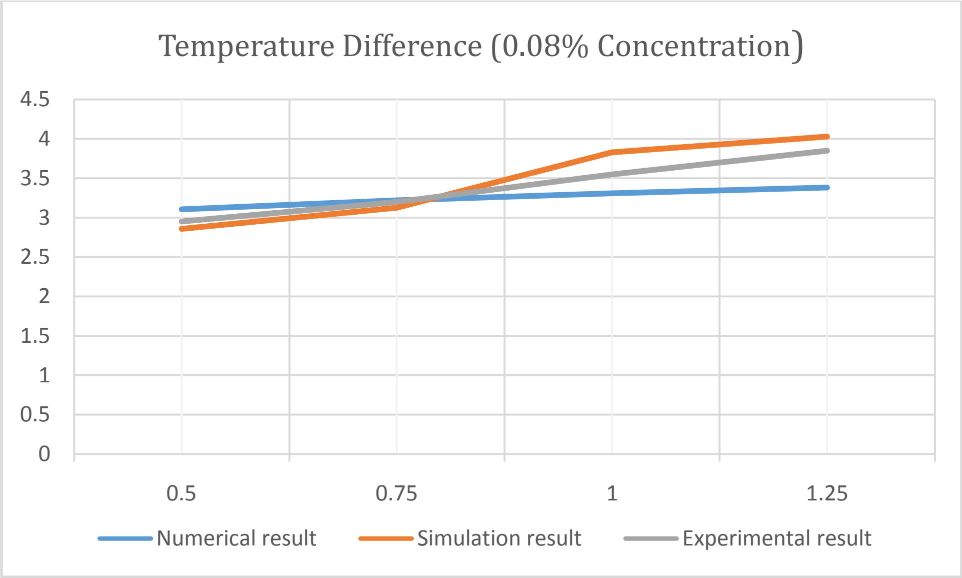
FLOW (LPM)	TEMPERATURE DIFFERENCE (FOR BASE FLUID)		
	Numerical result	Simulation result	Experimental result
0.5	3.018	2.5	2.84
0.75	3.135	2.76	2.92
1	3.225	3.48	3.35
1.25	3.298	3.79	3.58



Graph 8-Temperature Difference Comparison for 0.06% Nanofluid

Table 11-Temperature Difference for 0.08% Nanofluid

FLOW (LPM)	TEMPERATURE DIFFERENCE (FOR BASE FLUID)		
	Numerical result	Simulation result	Experimental result
0.5	3.107	2.86	2.95
0.75	3.222	3.13	3.20
1	3.311	3.83	3.55
1.25	3.383	4.03	3.85



Graph 9-Temperature Difference Comparison for 0.08% Nanofluid

CONCLUSION

1. Thermal conductivity of nanofluid is considerably greater that the thermal conductivity of transformer oil because of the high thermal conductivity of Graphene Nanoplatelates (GNP) and it is also observed that the thermal conductivity of nanofluid increases with the increase in the volume fraction.

2. Specific heat of nanofluid decreases with the increase in the volume fraction because of the lower heat capacity of GNP and better structurally oriented layers of the base fluid due to the greater regulation.

3. Based on the mathematical modelling it was observed that the highest heat transfer coefficient 570.9112W/m^2K was observed at 1.25 lpm flowrate with a volume fraction of 0.08%. However, the maximum increase in heat transfer percent was seen for a flow rate of 0.5 lpm at a volume fraction of 0.08%.

4. The heat transfer coefficient increases as the flow rate increases. This is because increase in flow rate increases momentum transfer between fluid particles, which in turn increases the convection heat transfer coefficient.

5. Heat transfer coefficient increases with increase in volume fraction upto a certain concentration because total surface area of heat transfer increases beyond which the nanofluid tends to become unstable due to higher interactions between the particles and increased pressure drop.

6. By comparing the results of mathematical models and - the CFD analysis we found that the maximum error in the temperature difference of nanofluid is 0.6468 ^{0}C.

7. The Mathematical, Simulation and Experimental results prove that Nanofluids are highly effective. Nanofluids can have a variety of cooling applications such as in pumps, battery packs, motors etc.

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