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Experimental investigation of free connective heat transfer augmentation using transformer oil-Al_2O_3 nanofluid

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Abstract. There is a definite need to improve the heat transfer capability of the transformer oil as it plays a vital role in the life span of transformers. As the thermal conductivity of the transformer oil is very less compared to the conventional liquids and those liquids cannot be used as dielectric liquids as they do not possess electrical insulation properties. It is very much essential to improve the thermal conductivity of the transformer oil in any manner in order to augment the "heat transfer or thermal management performance" of the transformer oil. Dispersion of metallic or metallic oxide nanoparticles into the base fluid in a systematic way is a proven method to enhance the thermal properties for various practical heat transfer applications like forced convection, boiling, refrigeration, solar and electronic cooling. In this study, alumina nanoparticles are dispersed in transformer oil to synthesize stable, homogenous transformer oil – Al_2O_3 nanofluid and to investigate the free convection "coefficient of heat transfer performance" along a vertical slender cylinder submerged in the liquid. Experiments are conducted using the transformer oil - Al_2O_3 nanofluid at different particle loadings or fractions starting from 0.05 % to 0.6 %. It is learnt that the highest "coefficient of heat transfer performance" occurs at 0.1 Vol% among all the volume fractions. It has been acknowledged that the "coefficient of heat transfer" is got better up to 0.1 % particle loading and then decreased with additional accumulation of nanoparticles.

1. Introduction

Transformer oil is a protecting oil and it possesses great electrical shielding insulating properties, cools transformers and stable even at significantly at higher fluid temperatures. So, it must possess "high dielectric strength", "chemical stability", "thermal conductivity k", "viscosity μ" and very much importantly it must keep its thermodynamic and electrical properties for longer spans of time and at higher temperatures [1, 2]. In general, for practical transformer applications purified form of mineral oil will be used as a transformer oil. In practical, due to higher fluid temperatures, after consuming it for some time the transformer oil loses its properties [3, 9]. If the transformer oil loses its properties, thermal management or heat transfer from transformer will not happened effectively and this leads to generate excessive heat inside transformer and eventually causes the failure of it. For several years ago, researchers tried to mix micro sized particles and observed more settling and then they tried mixing nano sized particles in carrier fluid in order to improve their properties in addition to retain them stable for several days at constant heat flux without settling. Then after researchers have tried to synthesize transformer oil-based nanofluids (TONF) by dispersing the nano sized particles in the transformer oil [9].

2. Literature Review

Asefi et.al, [2] synthesized Transformer oil-diamond nanofluids and observed fluid properties for various concentrations of nanoparticles and observed that at 0.15 vol%, 38% enhancement in breakdown strength and 73% increase in thermal conductivity. Hwang et.al.,[3] equipped TONF nanofluids and compared the electrical breakdown strength with pure oil and observed the enhancement. Lv et.al.,[4], Rafiq et.al.,[7] reviewed various studies based on transformer oil TONF nanofluids and electrical insulation properties. Wang et.al.,[5] prepared three different types of TONF nanofluids and compared the effect of nanoparticle concentration on electrical properties. Du et.al,[6] prepared transformer oil-boron nitride and observed electrical properties and thermal properties and observed enhancement. Dong et.al.,[8] analyzed the “breakdown or dielectric strength of transformer oil-SiO_2 nanofluids” and witnessed the improvement in augmentation of “breakdown or dielectric strength” up to 0.06 vol% and later it decreases. In author’s previous works [9] transformer oil based Al_2O_3 nanofluids is synthesized and electrical insulation properties are measured using TAGUCHI design of experiments for finding optimum parameters and observed that at 0.1 vol% enhancement in breakdown strength is more also heat transfer performance is analyzed experimentally using water based Al_2O_3 nanofluid. From the literature, it is observed that very few works are done on the “natural convection heat transfer performance” using transformer oil based Al_2O_3 nanofluid. In the present work, transformer oil based Al_2O_3 nanofluid is prepared and experiments are conducted to determine the “natural convective thermal or heat transfer performance” as it is very much importance in case of transformer applications [10].

3. Synthesis and Characterization of Nanofluids

Nanofluids are prepared using two step method [11] by taking transformer oil as base fluid and Al_2O_3 nanoparticles are dispersed in the required proportion. The quantity of Al_2O_3 nanoparticles to be added can be determined from the eq., (1) for a particular volume fraction. Initially after adding nanoparticles it is stirred for 1 hour using magnetic stirrer and then it is sonicated using ultrasonic sonicator for 3 hours with a model like 15 minutes sonication and then 15 minutes break alternatively to avoid the excess temperature in the nanofluid. Thermo-physical properties of transformer oil and Al_2O_3 nanoparticles at room temperature is specified in table 1 and 2 respectively.

$$\text{Volume fraction} = \frac{v_{np}}{v_{np} + v_{bf}} = \frac{(m_{np} / \rho_{np})}{(m_{np} / \rho_{np}) + (m_{bf} / \rho_{bf})} \tag{1}$$

Table 1. Thermo-physical properties of Transformer oil [11]

Base fluid	Density ρ (Kg/m^3)	Thermal conductivity k (W/mK)	Specific heat Cp (J/kgK)	Thermal expansion coefficient β (K^{-1})	Dynamic viscosity μ (Ns/m^2)
Transformer oil	873	0.11	1982	0.78×10^{-3}	13.44×10^{-3}

Table 2. Thermo-physical properties of Al_2O_3 nanoparticles at room temp. [11]

Thermal conductivity k (W/mK)	Density ρ (kg/m^3)	Specific heat Cp (J/kgK)	Thermal expansion coefficient β (K^{-1})
38	3970	765	$0.85\ 10^{-5}$

4. Experimental Setup

Experimental setup is equipped to conduct the experiments to determine the heat transfer or heat transfer coefficient for various test fluids. In earlier experiments, authors conducted experiments using water, water + Ethylene glycol (3:1 ratio) as base fluids and as nanofluids with the addition of Al_2O_3 nanoparticles in the required quantity based on the volume fraction to determine the heat transfer performance [10]. Photograph and schematic diagram of the experimental arrangement are shown in Fig.1. Physical dimensions of the set-up are also given in Fig.1. Surface area of the vertical cylinder is 0.0099 m^2 and l/d ratio is 19.68. In order to get the steady state conditions a shell with cooling water circulation arrangement. K-type thermocouples are used in order to measure the temperature on the surface of vertical cylinder. Before conducting experiments all thermocouples are calibrated and fans are switched off to ensure that there is no movement of fluid due to external agencies. Power supply is given to the heater, which is present exactly inside the vertical cylinder without any gap in between them. MgO is filled in between heater and cylinder in order to ensure that there is no heat loss between them as it is having high thermal conductivity. At a particular heat input, flow rate of cooling water is adjusted such that the heat is received by the test fluid is taken away by cooling circulated water in order to get the steady state condition. Temperature readings are noted down after steady state conditions prevailed. The cold water temperature is maintained constant at 25°C.
For the heat inputs or heat fluxes given to the cylinder from 3030 W/m^2 to 5050 W/m^2, the "flow rate of cooling circulated water is wide-ranging from 1.43 lpm to 2.23 lpm. At conditions of steady state, the amount of heat input given to the cooling water circulation will carry the metallic cylinder away and thereby it is assumed that steady state condition is attained" [10]. When steady state conditions are prevailed, temperature readings of the surface of vertical cylinder are noted down. Experimental setup is validated by taking water as test fluid, determined the average Nusselt number, and compared with McAdam's equation [10].

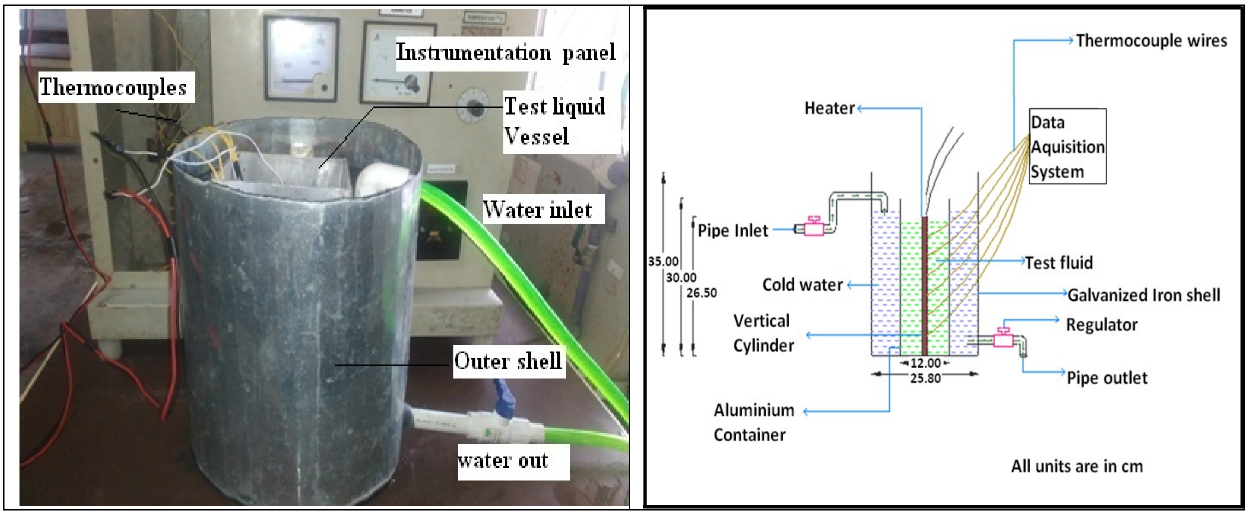
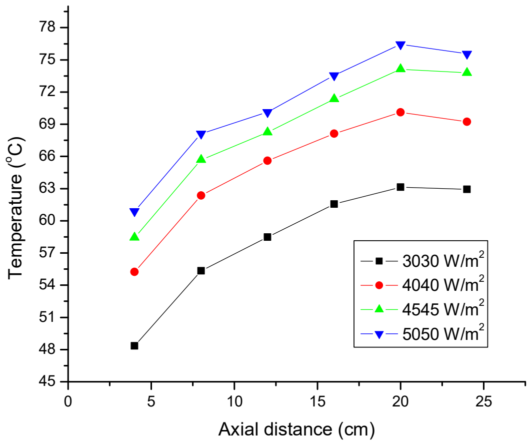


Fig.1 Photograph and Schematic diagram of experimental setup [10]

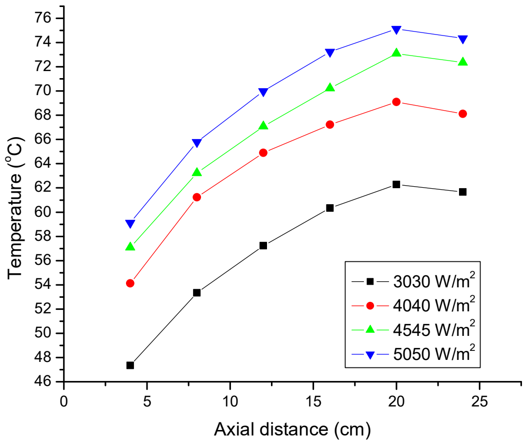
5. Results and Discussion

Experiments are carried out at various heat input given to the heater ranging from 30 W to 50 W. Surface temperatures are noted down after steady state conditions prevailed. Initially experiments are performed transformer only as a test fluid for different heat inputs and then with transformer oil – Al_2O_3 nanofluid at various concentrations of nanoparticles and at various heat inputs. Variation in surface temperatures of cylinder along axial directions is noted and presented in Fig.2.

It is observed that in both cases the trend is similar but in case of nanofluid, surface temperature is less compared to pure transformer oil. Test fluid temperature is varied with heat input and temperature difference of cylinder and test fluid at middle of cylinder is shown in fig.3. Reason for this could be reduction in temperature is due to more heat from the cylinder is carried by the nanofluid. Using eq (2) "local heat transfer coefficient" for thermal management performance is calculated for both base fluid and transformer oil – Al_2O_3 nanofluid and presented in Fig.4. Where ΔT_x is the temperature difference between a point on cylinder and a point in the fluid at same level outside the boundary layer formation.



(a)



(b)

Fig.2.Variation in "surface temperatures of vertical cylinder" along its length for (a) transformer oil (b) transformer oil – alumina nanofluid at 0.1 vol%.

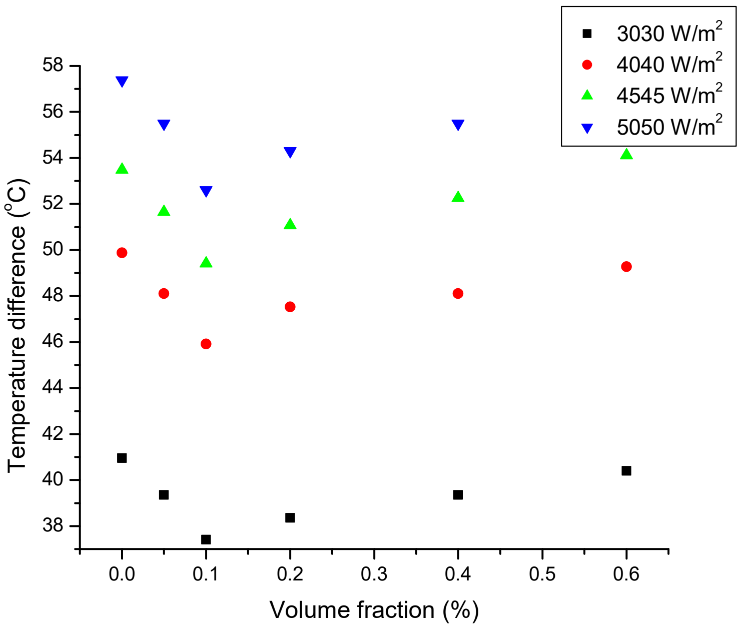
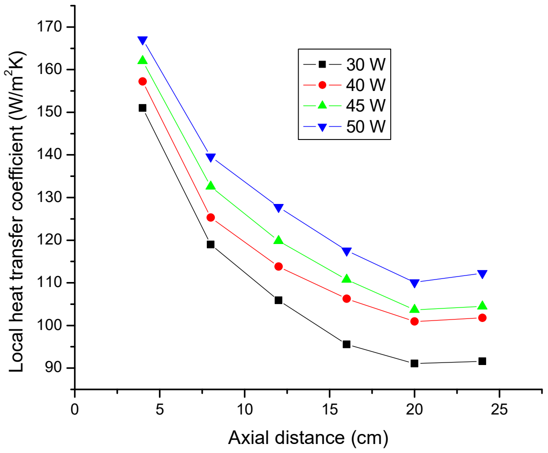
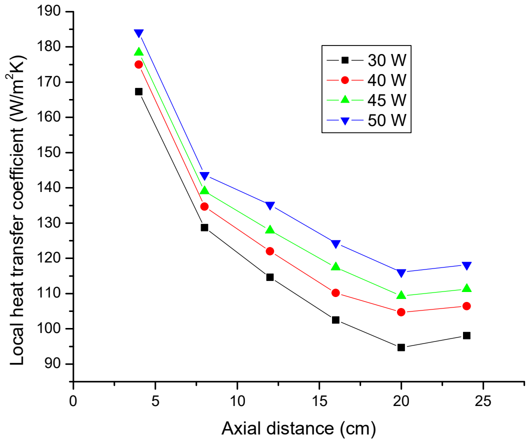


Fig.3 Temperature difference of cylinder and test fluid at middle of cylinder



(a)



(b)

Fig.4 Local heat transfer coefficient for (a) transformer oil (b) transformer oil - Al_2O_3 as medium as medium

$$h_x = \frac{Q}{A(\Delta T_x)} \tag{2}$$

It is also identified that at the lower part of the cylinder “coefficient of local heat transfer performance” is high and low at the higher cylindrical parts. It is happened because of, at the bottom portion of cylinder the thickness of the boundary layer is very small and more thickness at the higher parts of the cylinder [10]. All thermos-physical properties are measured at average temperature of surface temperature and fluid temperature i.e., film temperature. At this film temperature and at various particle loadings of nanoparticles thermal conductivity k, viscosity μ, density ρ are measured. Volumetric expansion coefficient β is determined from the model taken from eq. (3) [1].

$$\beta_{nf} = (1-\varphi)\,\beta_f + \varphi\,\beta_{np} \tag{3}$$

Average “coefficient of local heat transfer performance” of transformer oil based alumina nanofluids is determined and its variation with alumina nanoparticle loading for various heat inputs is depicted in fig.5. It has been acknowledged that “average heat transfer performance coefficient” is amplified up to 0.1 vol% concentration of nanoparticles and then with additional accumulation of nanoparticles starts diminishing. The maximum improvement observed in the natural convective “coefficient of local heat transfer performance” is 8.7 % as “coefficient of heat transfer” is augmented from 127 W/m^{2}K to 138 W/m^{2}K at 0.1 % volume of particle loading for transformer oil - alumina nanofluids. The enrichment in the thermal performance of the transformer oil based alumina nanofluid occurs because, thermal conductivity dominates at lower concentrations than viscosity of nanofluid and at higher concentrations, and viscosity plays significant role rather than thermal conductivity [10].

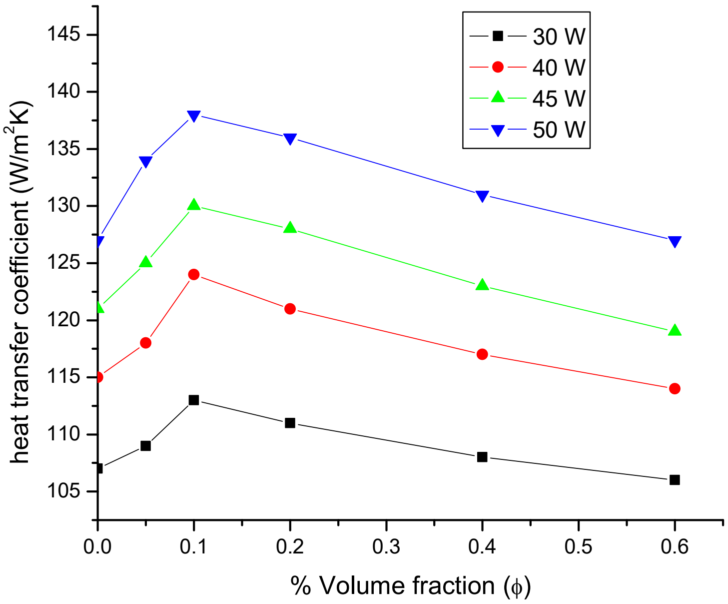


Fig.5 Variation of "average heat transfer coefficient" with particle loading of alumina nanoparticles for various heat inputs.

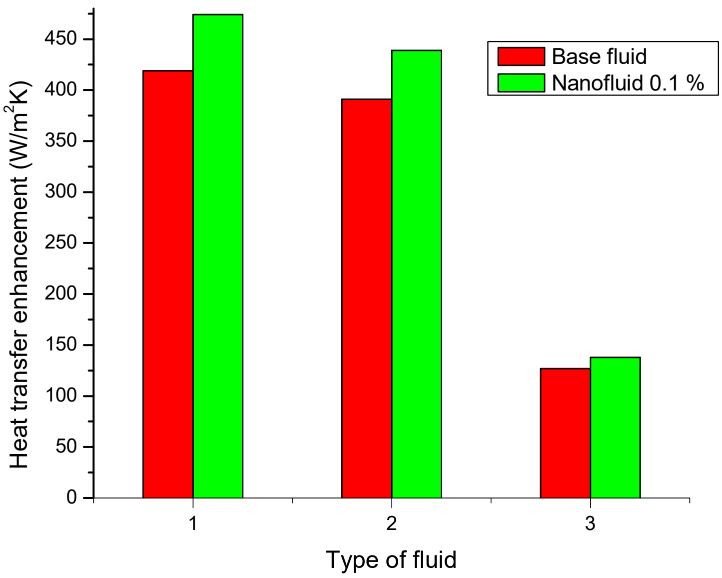


Fig. 6 Heat transfer enhancement for (1) water (2) water + EG (3) Transfer oil based Al_2O_3 nanofluids

But the enhancement in heat transfer coefficient is less compared to water- Al_2O_3 nanofluid because of high viscosity of the transformer oil. Due to this high viscosity, nanoparticles do not move fast in case of transformer oil unlike water. Heat transfer augmentation is compared for water, water + EG, Transformer oil based Al_2O_3 nanofluids at 0.1 % volume fraction and presented in fig. 6. In case of water- Al_2O_3 nanofluid the augmentation is 13.7%, water +Ethylene glycol (3:1 ratio) is 11.5% [10], in transformer oil - Al_2O_3 nanofluid it is observed as 8.7%.

6. Conclusions

In this work, transformer oil based Al_2O_3 nanofluids are synthesized using two step method for conducting the experiments for determining the performance of thermal management of the prepared nanofluids. Alumina nano sized particles are dispersed in transformer oil to synthesize stable, homogenous transformer oil – Al_2O_3 nanofluid and to investigate the free convection "heat transfer performance" in terms of "heat transfer coefficient" of a vertical cylinder submerged in the test liquid. Experiments are conducted using the transformer oil - Al_2O_3 nanofluid at various particle loadings of nanoparticles starting from 0.05 % to 0.6 %. It is perceived that the highest "coefficient of heat transfer" occurs at 0.1% volume particle loading among other volume fractions. It is also witnessed that the "heat transfer coefficient" is amplified up to 0.1 % volume concentration and then decreased with extra accumulation of alumina nano sized particles. Performance of water, water + EG, transformer oil based Al_2O_3 nanofluids is compared and presented.

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