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Using the transformer oil-based nanofluid for cooling of power distribution transformer

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Abstract
Thermal behavior of electrical distribution transformer has been numerically studied with the effect of surrounding air temperature. 250 KVA distribution transformer is chosen as a study model and studied in temperature range cover the weather conditions of hot places. Transformer oil-based nanofluids were used as a cooling medium instead of pure transformer oil. Four types of solid particles (Cu, Al_2O_3, TiO_2 and SiC) were used to compose nanofluids with volume fractions (1%, 3%, 5%, 7%, and 9%). In addition to its good thermal characteristics the nanoparticles lead also to increase the dielectric of oil and increase the breakdown voltage. Results obtained show that, using of transformer oil-based nanofluids as a cooling medium instead of pure transformer oil lead to improve the cooling performance of transformer by reducing the temperature of transformer and as a consequence increasing the protection of the transformer against the breakdown. Also increasing the nanoparticles volume fraction in nanofluid cause extra decrease in transformer temperature. Among all of the selected nanofluids the SiC-Oil nanofluid give lower transformer temperature.

Keywords: Nanofluid; Electrical transformer; Transformer oil; Cooling performance; Distribution transformer; Transformer cooling.

1. Introduction

Among all of the electrical network components the transformer plays a central role since it used to rise up or down the voltage of electrical system. Due to its high cost, direct effect on network operation, location and its contents of oil and toxic materials the transformer is considered of higher importance compared to the other components of the electrical network. Therefore the protection of transformer from breakdown must have higher priority to ensure the continuity of network operation. The main cause for transformer breakdown is the oil temperature rise. Therefore it is necessary to find out new cooling techniques to reduce the transformer temperature. Transformers utilize transformer oil as a cooling medium and electrical insulation material, together with cellulose paper. Breakdown voltage (dielectric strength) is one of the most important characteristics of transformer oil.

To ensure a normal operation of transformer, the oil temperature must not exceed the limits set by industry standards. The temperature of solid insulation is the main factor of transformer aging. With temperature and time, the cellulose insulation undergoes a depolymerization process. This situation characterizes the end of life of the solid insulation. Since it is not reversible, it also defines the transformer end of life. Increasing transformer load increases the temperature of the insulating oil, so loading above the nameplate rating involves some risks. Transformers are rated at a maximum oil temperature rise over ambient with modern transformers rated about 65 ºC rises above ambient [1]. The normal operation of transformer depend on the dielectric strength and thermal properties (cooling capacity) of the transformer oil, therefore it is important to modify both the thermal and electrical properties of oil in order to get higher performance of the transformer.

Nanofluid is a mixture of nanometer sized metal or nonmetal particles in traditional base fluids. Nanofluid considered a novel cooling fluid which has good heat transfer characteristics especially higher thermal conductivity compared with base fluid.

Many researchers in literature showed that, adding nanoparticles into transformer oil leads to enhancement of dielectric strength by increasing the breakdown voltage. Thermal improvements in transformer oil by dispersing nano solid particles and its effects on transformer cooling needs to be extensively studied.

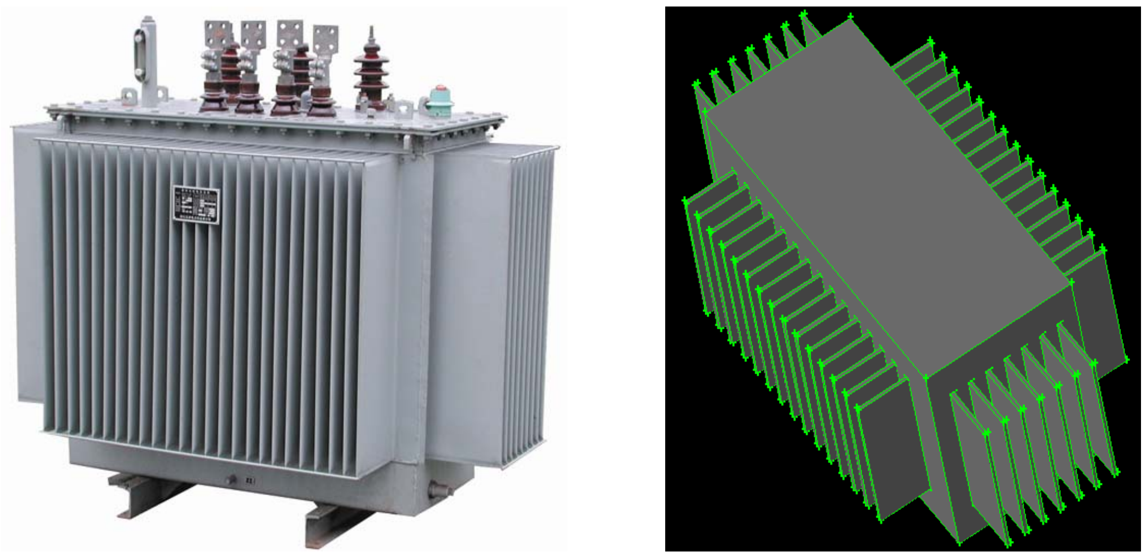
The basic principles of transformers and transformer oil specifications with nanofluids are presented in many researches in literature. Dejan [2] present new and more accurate temperature calculation methods in transformer oil, using heat transfer theory, used of lumped capacitance method, the thermal electrical analogy and a new definition of nonlinear thermal resistance at different locations within a power transformer. He takes into account oil viscosity changes and loss variation with temperature. The change in transformer time constant due to changes in the oil viscosity is also accounted for in thermal models. He found that the hot-spot temperature rise over top-oil temperature is an exponential function with a time constant equal to the winding time constant. Choi et al. [3] prepared three types of nanofluids by dispersing Al_2O_3 and AlN nanoparticles in transformer oil. They found that, the thermal conductivity of the nanofluids increases with particle volume fraction and thermal conductivity of the solid particle. They also observed that, the AlN nanoparticles with volume concentration of 0.5% lead to increase the thermal conductivity of the mixture by 8% and the overall heat transfer coefficient by 20%. Du Yuefan et al. [4] formulated new type of colloidal dielectric fluids by mixing TiO_2 nanoparticle with transformer oil. They found that, the mean value and 1% probability breakdown voltage of nanofluid increased by 1.15 and 1.43 times compared with pure transformer oil respectively. Also for lightning breakdown voltage, nanofluid was 13.3KV higher than that of transformer oil. Their results confirmed that transformer oil mixed with TiO_2 nanoparticles hold a promise to improve its insulating properties. George Hwang et al. [5] Studied the effects of transformer oil-based nanofluids on the electrical properties of oil and its breakdown voltage. They found that, the mixing of nanoparticles with transformer oil defy conventional wisdom and their experimental results showed that such nanofluids have substantially higher positive voltage breakdown levels with slower positive streamer velocities than that of pure transformer oil. They explain this paradoxical superior electrical breakdown performance compared to that of pure oil due to the electron charging of the nanoparticles to convert fast electrons from field ionization to slow negatively charged nanoparticle charge carriers with effective mobility reduction. Arslan et al. [6] covered the research conducted in a series of testing done on distribution transformers regarding temperature rise. They discussed the ambient effects which are dependent upon relative humidity and natural wind siphon that a transformer surface creates. They evolved that relative humidity as a major environmental component effects temperature rise considerably. Yuefan Du et al. [7] Studied the effects of semiconductive nanofluids prepared by adding TiO_2 nanoparticles on the transformer oil on the insulating characteristics, AC, DC and lightning impulse breakdown voltage and partial discharge (PD) characteristics of oil. They found that, semiconductive nanofluids have AC, DC and lightning impulse breakdown voltage up to 1.2 times compared with pure oil. Meanwhile, the partial discharge resistance was also dramatically improved. Also they found that, the electron shallow trap density and charge decay rate are greatly increased in semiconductive transformer oil based nanofluid. Srinivasan [8] Proposed a new semi-physical model comprising of the environmental variables for the estimation of hot spot temperature and loss of insulation life in transformer. The winding hot-spot temperature was calculated as a function of the top-oil temperature that can be estimated using the transformer loading data, top oil temperature lagged repressor value, ambient temperature, wind velocity and solar heat radiation effect. The proposed model has been validated using real data gathered from a 100 MVA power transformer. Dong et al. [9] prepared Aluminum-nitride-(AlN)-transformer oil based nanofluid and investigated its effects on the composition-dependent electrical conductivity at different ambient temperatures. They found that, the electrical conductivity has nonlinear dependences on the volumetric fraction and temperature. In comparison to the pure transformer oil, the electrical conductivity of nanofluid containing 0.5% AlN nanoparticles has increased by 1.57 times at 60 ºC.

Murtaza [10] Performed a steady-state calculations using IEC guidelines to determine the hot spot temperatures of distribution and power transformers in the worst projected environment due to long summer periods. Moreover, the effect of increase in winding resistance due to increase in ambient temperatures has been taken into account. They found that, the power and distribution transformers should be progressively de-rated under such circumstances for their safe operations, which will not only prove cost-effective for utilities but also improve the reliability of the power supply to their valued customers in the challenging future smart grid environment.

As observed from the literature there were many research works regarding the effects of adding nanoparticles on the electrical behavior of transformer oil which reveal that, using of oil- based nanofluid lead to improvement in electrical characteristics of oil by increasing its breakdown voltage. But there is a shortage in research that studied the thermal effects of transformer oil based nanofluids and there is no research that included modeling of the complete transformer. In this paper a transformer oil-based nanofluid is studied as a cooling medium in distribution transformer instead of pure transformer oil and the cooling modification is investigated by analyzing and modeling a complete transformer with pure oil and with four types of nanofluids (Cu-oil, Al_2O_3-oil, TiO_2-oil, and SiC-oil).

2. Problem description

250 KVA distribution transformer is selected as a case study in this paper which is widely used in Iraqi electricity network. Figure 1a shows a picture for this transformer while Figure 1b represents a schematic drawing to illustrate the outer view of this transformer. The transformer consists of (coils and core assembly) which consists of three copper coils and a steel core linking them, all these items are immersed in transformer oil contained in the transformer body which equipped with fins to increase the heat transfer area. The transformer oil play two important roles, a cooling medium transfer the heat generated in coils and core into outer walls to dissipate it to the outside, and electric insulator. According to the available data the heat generated in transformer in full load situation is 1000 W from each coil and 500 W from core. This heat generated must be dissipated to maintain the temperature of oil at certain accepted level. The properties of transformer oil are listed in Table1 [11].



(a) (b)

Figure 1. (a) Picture for studied 250 KVA transformer, (b) schematic figure for studied 250 KVA transformer.

3. Mathematical formulation

Simulate numerically the complete transformer shown in Figures (1a and 1b) is complicated and need huge of processing time and memory, therefore and to simplify the numerical solution and due to the geometrical symmetry, a quarter of transformer can be used as a computational model to represent the complete transformer as shown in Figure 2a which represent the outer view of computational model (quarter of transformer) and Figure 2b which represent the computational model for coils and core assembly (quarter of coils and core assembly) since the coils are assumed as a solid cylinders.

Heat is generated in coils and core due to electrical resistance, this heat is absorbed by oil to transfer it to the outer walls by natural convection and then dissipated from outer walls to surrounding air by convection and radiation. The governing equations for 3D, steady and incompressible oil are continuity, momentum and energy equations as below [12, 13]:

$$\nabla V = 0 \tag{1}$$

$$\rho\,(V\,.\nabla V\,) = -\nabla P + \nabla.(\mu_j \nabla V_j) + F \tag{2}$$

$$\rho c_p (V\,.\nabla T\,) = k\nabla^2 T \tag{3}$$

The boundary conditions used to solve the above set of equations are: no slip velocity on all solid walls (coils, cores and all transformer walls). Coils and cores are subjected to constant heat generation source term calculated from the actual heat losses generated in real transformer and its values are calculated from the available data for electrical losses in coils and core which are converted to heat generation. All the outer walls of transformer including the fins surfaces are subjected to combined natural convection and radiation, the value of convection heat transfer coefficient is assumed (1000 $W/m^2.K$) and the external emissivity is 1. The above model is numerically solved to calculate the distributions of temperature, then the oil average and maximum temperatures and heat transfer rate can be calculated. First the transformer is simulated with pure transformer oil, and then the solution is repeated with four transformer oil based nanofluids (Cu-oil, Al_2O_3-oil, TiO_2-oil, and SiC-oil) with volume fractions of 1 %, 3 %, 5 %, 7 %, and 9 %. Considering these values of concentration is reasonable since there is no flow and as a consequence there is no attention for pressure drop increasing.

4. Properties of nanofluid

The properties of nanofluid are a combination of the properties of the based fluid (transformer oil) and the solid nanoparticles which depend also on the volumetric concentration of the nanoparticles and its shape, where the shape of used nanoparticles is assumed spherical. The properties of nanofluids can be calculated from the following relations [14-16].

Density:

$$\rho_{NF} = (1-c)\,\rho_{oil} + c\,\rho_P \tag{4}$$

Specific heat:

$$Cp_{NF} = (1-c)\,Cp_{oil} + c\,Cp_P \tag{5}$$

Viscosity:

$$\mu_{NF}=\mu_{oil}(1+2.5c) \tag{6}$$

The bulk thermal conductivity of nanofluid was calculated from the relation:

$$\frac{k_{NF}}{k_{oil}} = \frac{k_p + (PSH-1)k_{oil} + (PSH-1)c(k_p - k_{oil})}{k_p + (PSH-1)k_{oil} - c(k_p - k_{oil})} \tag{7}$$

where: *NF* refer to nanofluid, oil refer to transformer oil, *p* refer to the solid nanoparticle, PSH is the nanoparticle shape factor, where PSH = 3/ψ, ψ is sphericity which defined as the ratio of the surface area of a sphere with a volume equal to that of the particle to the surface area of the particle. For spherical particles PSH = 3.

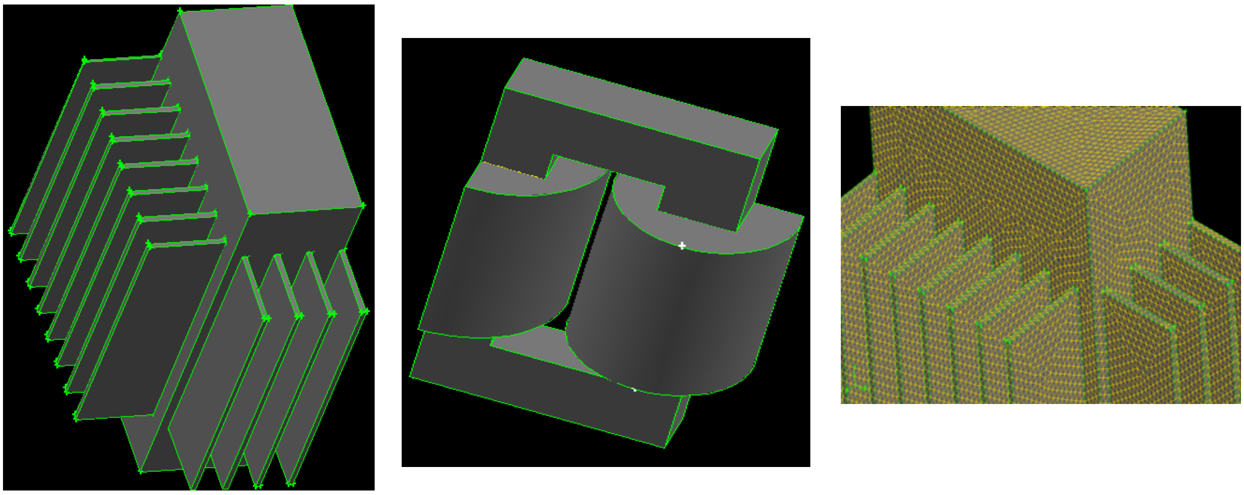
The properties of transformer oil and four types of nanoparticles (Cu, Al_2O_3, TiO_2, and SiC) are listed in Table1 [17, 18]:

Table 1. Thermo physical properties of oil and nanofluids components.

	Density (Kg / m^3)	Cp (J / Kg.K)	k (W /m. K)	μ (Kg /m.s)
Transformer oil	870	2000	0.109	0.0124
Cu particles	8930	383.1	386	-
Al_2O_3 particles	3600	765	36	-
TiO_2 particles	4250	686.2	8.953	-
SiC particles	3160	675	490	-

5. Numerical model

A finite volume method (FVM) is used to solve the governing equations numerically, and the distribution of temperature is obtained in fluid. The segregated solver is used to solve the governing integral equations for the conservation of mass, momentum and energy. A mesh was generated by descretizing the computational domain, quarter of transformer including (coils, core and oil). Mesh independent was studied by using seven mesh sizes and the results for oil average temperature for different meshes used are listed in Table 2 for outer walls temperature To = 303 K. From Table 2 it can be observed that, after sixth mesh further increase in the grids will not have a significant effect on the solution so the sixth mesh is used for all numerical computations. The mesh used is indicated in Figure 2c for the computational model. The solution residuals used as a convergence criteria for both momentum and energy equations were selected to be less than 10^{-6}.



(a) (b) (c)

Figure 2. (a) Computational model (outer view of quarter of transformer), (b) Computational model (quarter of coils and core assembly, (c) Outer view of mesh used for computational model.

Table 2. Mesh refinement results.

mesh	Average oil temperature (K)
Mesh1 (Number of nodes = 43681)	444.59
Mesh2 (Number of nodes = 57789)	398.79
Mesh3 (Number of nodes = 73680)	369.67
Mesh4 (Number of nodes = 89226)	350.14
Mesh5 (Number of nodes = 104877)	336.16
Mesh6 (Number of nodes = 109945)	331.52
Mesh7 (Number of nodes = 112013)	330.01

6. Results and discussion

The used numerical model has been previously validated in my previous work [16] by solving the numerical model presented in [19] and the results were compared. The model presented in [19] is a micro pin fin heat sink consists of square and circular pin fins, the heat sink contains an array of 19 x 66 pin fins. Inlet temperature was choose as 278.15 K and the inlet velocity depend on flow rate and heat sink dimensions. Thermal boundary condition is a constant heat flux of 1 W subjected on the bottom wall of the substrate

Figure 3 shows the comparison between results of present numerical model and the data of [19] for thermal resistance. From this figure it can be seen that, the agreement between the results of present model and that for [19] is acceptable since the average error is 2% which may be due to the difference in the selected properties of water and silicon also may be due to the difference in mesh. Then this model hase been used to study the nanofluid as in [16] therefore the present numerical model is reliable and can be used to stduty the distribution transformer with nanofluids.

Figure 4 shows the temperature contours on (x-z) horizontal plane at middle height of transformer for pure oil case at outside temperature of 30 °C. It is clear form this figure that, the temperature is distributed from its maximum values near the surfaces of coils and core to its minimum values at the outer surfaces of transformer corresponding to the surrounding air temperature due to transferring the generated heat from the coils and core to the outside air through the transformer oil.

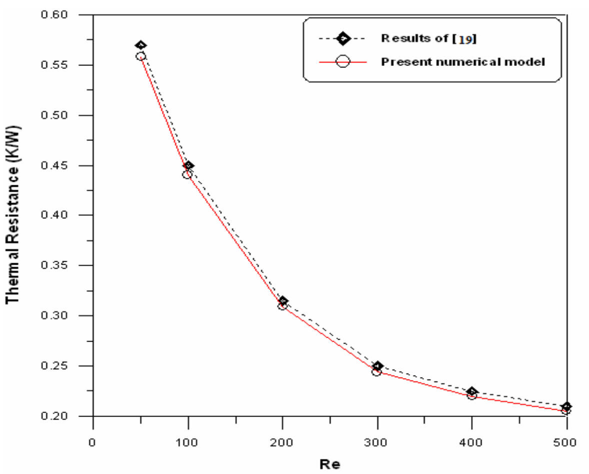


Figure 3. Comparison between results of present model and that for [19] for variation of thermal resistance with Re.

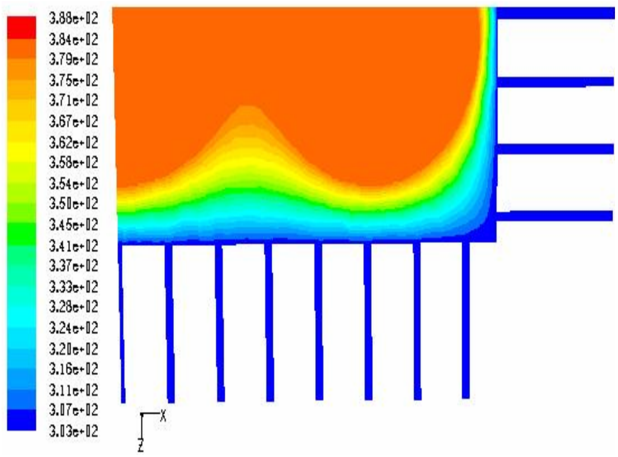


Figure 4. Temperature contour on the x-z plan at middle height of transformer.

Figure 5 indicates the variation of both of the oil maximum and average temperature with outside air temperature for pure oil case. The average temperature calculated as a volume average for whole oil and the maximum temperature represent the highest value of temperature in the transformer oil. From this figure it can be noted that, both of average and maximum oil temperatures are increased with increasing the outside air temperature due to decreasing of the heat dissipation to the outside as a results of decreasing the temperature difference which lead to accumulate the heat in the oil. The outside air temperature is selected up to expected higher values in hot climate regions (51 °C). It is observed from the results of this figure that, the maximum oil temperature reaches high and dangerous values at higher values of outside air temperature which is the main problem in transformer in hot climate regions especially at full load conditions, since the outside air temperature reach a higher level which cause decreasing the dissipation of transformer generated heat. Increasing of transformer oil temperature to a certain level lead to decrease of its dielectric and cause a transformer breakdown, also increasing the oil temperature cause decreasing of the insulation of paper used to cover and insulate the coils which lead to reduce the life of transformer. Therefore it is important to use new and efficient techniques to improve the cooling performance of transformers.

Figure 6 represents the Variation of transformer fluid average temperature with nanofluid volume fraction at outside air temperature of 30 °C. The case of zero volume fraction represent the pure oil. From this figure it can be seen that, the fluid average temperature decreased with increasing volume concentration for all studied nanofluids compared with pure oil due to enhancing heat transfer process as a results of improving of thermal conductivity of oil by dispersing nanoparticles since the thermal conductivity increased with increasing the volume fraction due to dispersing extra amount of nanoparticles in the suspension. Also it can be seen that, the SiC-oil nanofluid lead to obtain lower average temperature compared with all other nanofluids due to its higher thermal conductivity followed by Cu-oil, and the TiO_2-oil give higher temperature due to its lower value of thermal conductivity. These results indicate that, choosing of suitable nanoparticle depend on its thermo physical properties.

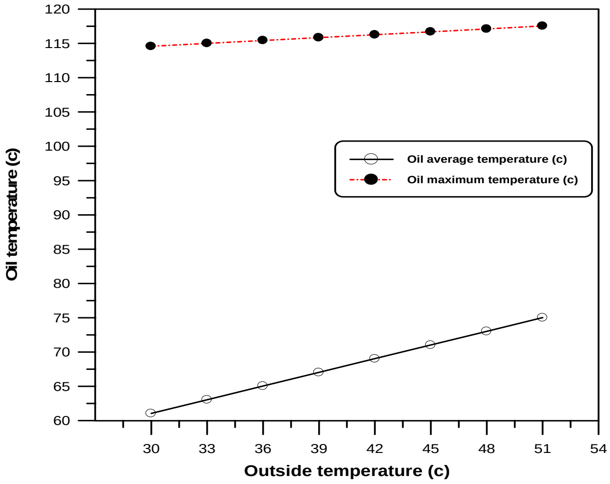


Figure 5. Variation of oil temperature (maximum and average) with outside temperature for pure transformer oil.

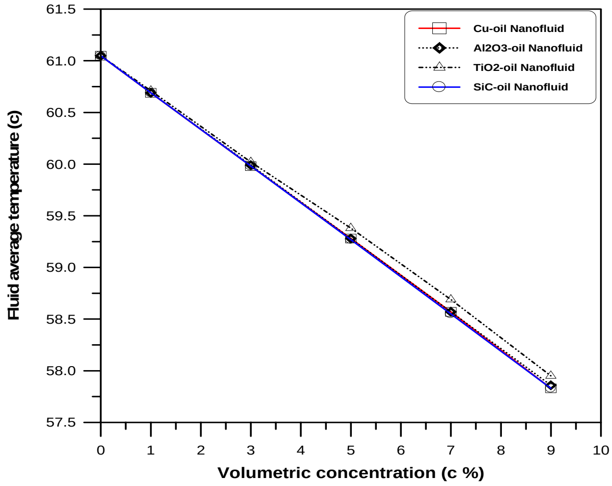


Figure 6. Variation of fluid average temperature with volumetric concentration for four types of nanofluids at outside temperature 30 ºC.

The variation of transformer fluid maximum temperature with volume fraction for four types of nanofluids at outside temperature of 30 °C is shown in Figure 7. The case of zero concentration represents the pure oil case. From this figure it can be concluded that, the fluid maximum temperature is decreased with increasing the volume concentration of all studied nanofluids as a results of increasing the heat dissipation process caused by increasing the thermal conductivity of fluid and there is a considerable reduction in maximum temperature with using nanofluids compared with pure oil. Also as discussed in Figure 6 the SiC-oil nanofluid lead to higher reduction in transformer maximum temperature due to its higher thermal conductivity.

Figure 8 shows the variation of the heat flux at the transformer outer walls with nanofluids volume fraction for four types of nanofluids at outside temperature of 30 °C. This heat flux gives an indication about the amount of heat that can be dissipated to the surrounding air. From this figure one can observe that, the amount of heat transferred when using nanofluids are larger than that of the case with pure oil and increased with increasing the solid particles concentration for all selected nanofluids due to increasing the thermal conductivity of fluids which lead to enhancement in the heat dissipation process.

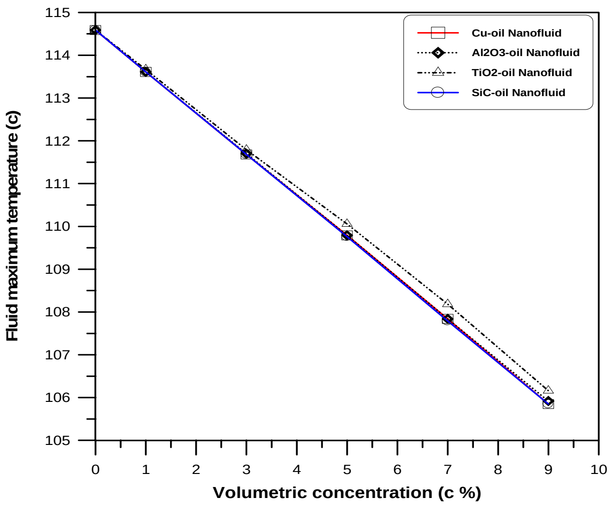


Figure 7. Variation of fluid maximum temperature with volumetric concentration for four types of nanofluids at outside temperature 30 ºC.

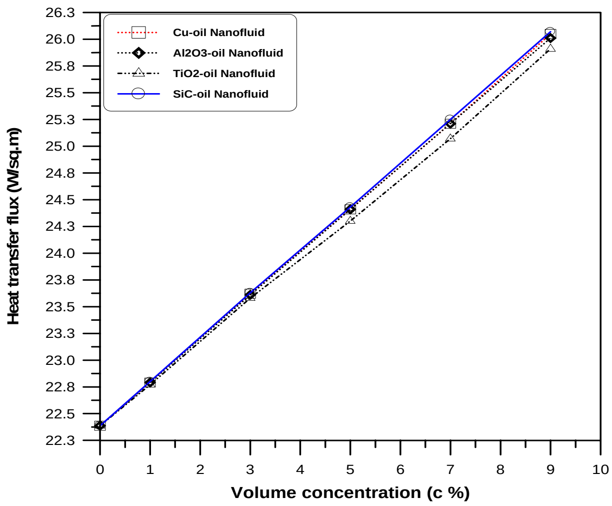


Figure 8. Variation of heat transfer rate with nanofluid volume fraction for four types of nanofluids at outside temperature 30 ºC.

Also the results of figure reveals that, over the selected range of volume fraction the SiC-oil nanofluid give higher heat transfer due to its higher thermal conductivity and the TiO_2-oil nanofluid is the lower one. The variation of fluid average temperature with outside air temperature for pure oil and four nanofluids at 9 % volume fraction is indicated in Figure 9. From this figure it can be noted that, the fluid average temperature increased with increasing outside temperature for all cases due to decreasing the heat transfer process as a result of decreasing the temperature difference and for all range of studied outside temperature the average temperatures for all types of nanofluids are lower than that of pure oil as discussed before. Also the SiC-oil nanofluid give lower average temperature compared with other selected nanofluids over the selected range of outside temperature.

Figure 10 shows the variation of fluid maximum temperature with outside air temperature for pure oil and four nanofluids at 9 % volume fraction. From this figure it can be observed that, the fluid maximum temperature increased with increasing outside temperature for all cases due to decreasing the heat transfer process as a result of decreasing the temperature difference and for all range of studied outside temperature the maximum temperatures for all types of nanofluids are lower than that of pure oil as discussed before and there is a considerable reduction in maximum temperature when using oil based nanofluid instead of pure oil. Also the SiC-oil nanofluid give lower maximum temperatures compared with other selected nanofluids over the selected range of outside temperature.

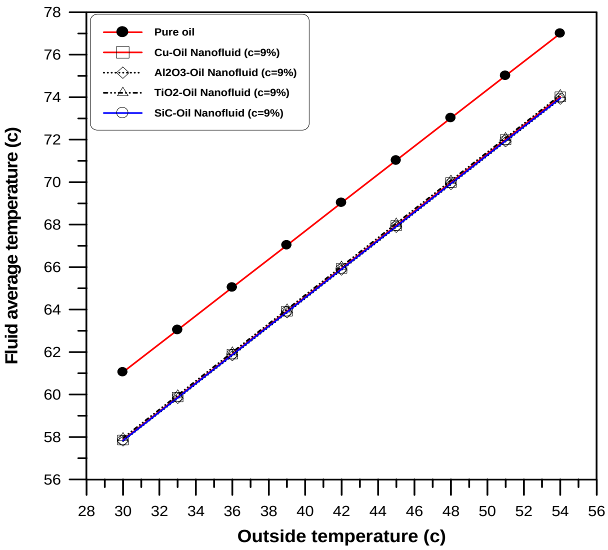


Figure 9. Variation of fluid average temperature with outside temperature for pure oil and four types of nanofluids at volume fraction = 9%.

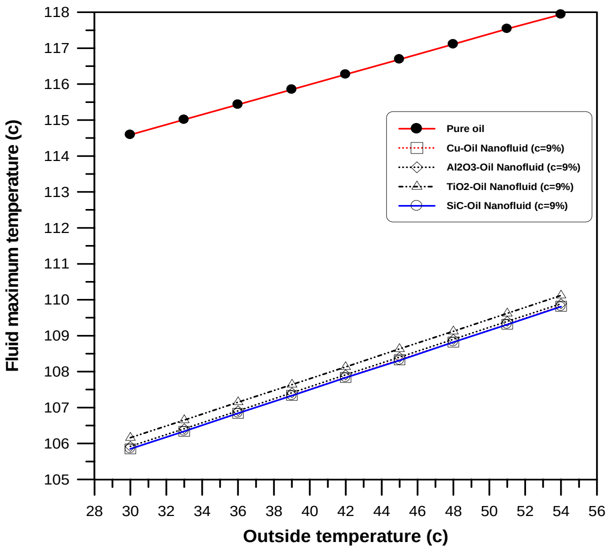


Figure 10. Variation of fluid maximum temperature with outside temperature for pure oil and four types of nanofluids at volume fraction = 9%.

Figure 11 represents the variation of fluid maximum temperature with outside air temperature for pure oil case and SiC-oil nanofluid case with different values of volume fractions. Since the SiC-oil nanofluid behaves as the best one among all of the studied nanofluids, it is important to study its effects extensively. From this figure it can be seen that, the fluid maximum temperature increased with increasing the outside temperature as explained before and the case of using SiC-oil nanofluid shows the lower values of maximum temperature over all range of outside temperature. Also the reduction in fluid maximum temperature obtained from using of SiC-oil nanofluid instead of pure oil is increased with increasing its volume fraction due increasing its thermal conductivity.

Figure 12 represen the variation of heat transfer coefficient at the transformer outer walls with outside air temperature for both the pure oil and SiC-oil nanofluid. From this figure one can see that, the heat transfer coefficient decreased with increasing the outside temperature as a result of decreasing the temperature difference which lead to reduce the value of heat that can be transferred which declare the effects of temperature of the transformer which cause storing the heat in the transformer oil and increasing its temperature and may expose the transformer on the breackdown dangaraous. Also this figure reveal that, using of SiC-oil nanofluid lead to increase the heat transfer coefficient and as a consequence lead to improve the cooling performance of transformer.

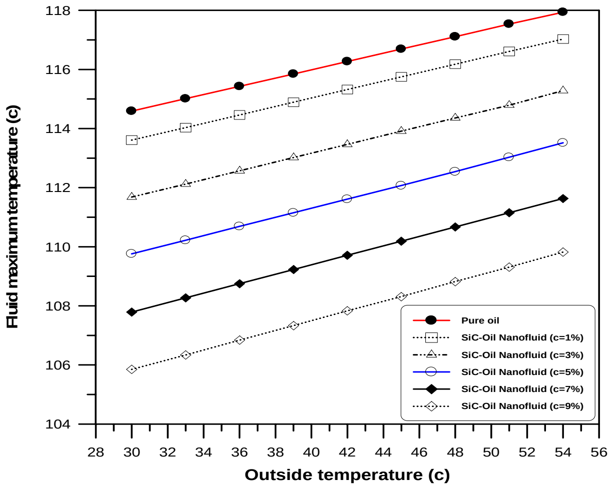


Figure 11. Variation of fluid maximum temperature with outside temperature for pure oil and SiC-oil nanofluid With different values of volume fraction.

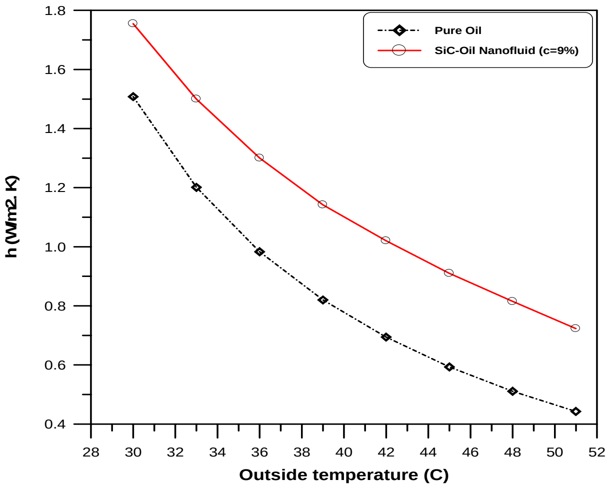


Figure 12. Variation of heat transfer coefficient with outside temperature for pure oil and SiC-oil nanofluid (c=9%).

8. Conclusions

In this paper the electrical distribution transformer is numerically studied and a transformer oil based nanofluid is used as a cooling medium instead of pure oil and the effects of adding nanoparticles into the transformer oil on its thermal behavior are studied. From the results the following conclusions can be remarked:

1. Increasing the surrounding air temperature lead to increase in the transformer temperature which may exceed the acceptable safe limits and may subject the transformer to a breakdown conditions.
2. Transformer oil based nanofluids enhance the heat transfer process in the transformer and cause a considerable reduction in its temperature.
3. The reduction in transformer temperature depends on the volume fraction at which the nanoparticles are mixed with the oil since the temperature reduction increased with increasing the nanofluids volume fraction.
4. Among all studied nanofluids the SiC-oil nanofluid give lower transformer temperature followed by Cu-oil nanofluid and so on.
5. Properties of nanoparticles used to compose the nanofluid especially thermal conductivity are the key parameters according to which the nanofluid may be chosen.

Nomenclature

Symbol

A	Area (m^2)	w	Fluid z-component velocity (m/s)
c	Nanofluid volumetric concentration (%)	x	Axial coordinate (m)
C_p	Specific heat (J/(kg K))	y	Vertical coordinate (m)
k	Thermal conductivity (W/m K)	z	Horizontal coordinate (m)
T	Temperature (K)	F	Natural convection Source term
u	Fluid x-component velocity (m/s)	μ	Dynamic Viscosity (m^2/s)
v	Fluid y-component velocity (m/s)	ρ	Density (Kg/m^3)

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