HEAT TRANSFER ENHANCEMENT FROM POWER TRANSFORMER IMMERSED IN OIL BY EARTH AIR HEAT EXCHANGER

by

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In this study, the modelling of power transformer with (250 kVA) by using (ANSYS17.1/FLUENT) code program was done. The power transformer was connected with earth air heat exchanger to decrease the temperature of (oil, core, and coils) of transformer which will increase its efficiency for preventing the damage and/or failure. The case study used the weather conditions of Nasiriya city, Iraq, at July 1st with 50 °C as maximum ambient temperature and full electrical load of the power transformer. In addition to different pipe diameter, length of earth air heat exchanger and different air velocity entering to pipe. The results showed the temperature of (oil, core, and coils) for power transformer decreased with increase the pipe length and earth air heat exchanger depth underground. The air velocities inlet to earth air heat exchanger that used in the study were (2, 4 , and 6 m/s, respectively) and the results showed the increasing of air velocity inlet to earth air heat exchanger should decrease the temperature of (oil, core, and coils) for power transformer and increase the thermal conductivity of oil. The study concluded when using earth air heat exchanger in the power transformer and performance of power transformer will be increasing and led to decrease the temperature of oil about (18.5 °C).The results showed a significant convergence with previous researches.

Key words: *transformer, cooling, EAHE, core, coil, oil, heat transfer*

Introduction

A power transformer is a major item for the processing of electrical energy in transmission and distribution grid systems for local and international power to many manufacture applications. In electrical power transformers, a part of furnished energy is degraded into lost heat. The coils and core increase interior power transformer temperature. The oil usually used to cool internal parts of power transformer.

Zhang *et al.* [1] presented numerical study for oil stream and temperature distribution for disc-type of power transformer in an oil natural (ON) cooling mode. The study including the dimensional analysis by using Boussinesq approximation, for fixed the power loss distribution, winding geometry, volumetric flow fraction in each horizontal cooling duct and the dimensionless temperatures in the winding, they noted that in a relatively small and fixed range of Richardson number (from 0.4 to 0.6) regardless of the values of Reynolds and Prandtl num-

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bers in their practical ranges. A benchmark case study has been performed which elucidates the apparition of reverse flow and hot-plumes. The hot-spot temperature in this case was 141.6 ºC. A new case study has been achieved on the bench mark winding with Richardson number being displaced from 1.46 to 0.6. The new oil flow and temperature distribution becomes much more superior, with the hot-spot temperature and the hot-spot factor being 77.4 ºC, 1.13, respectively. Garelli *et al.* [2] introduced simulation and analytic the behaviour of thermos fluid dynamic for electric power transformer in an oil natural air force (ONAF) cooling mode. In these studies, the heat convection transferred by two methods one by radiator of power transformer which removed the heat by forced convection while other by the oil inside the tank of power transformer which removed the heat by natural convection. The miniature model can be guess with suitable accuracy the worth of the most remarkable design variables like oil velocity, oil temperature, and air temperature. The theoretical and experimental study showed that the air velocity along the body of transformer by using fan is not active since about half of transformer radiator are not blown. Fernandez *et al.* [3] introduced an experimental study for dielectric paper (Kraft paper) by using two types of insulating oil, a vegetable oil and mineral oil by simulation it in technical laboratories to record the hot-spot of oil temperature in power transformer. The results showed the variation of hot-spot temperatures of mineral oil decreased about 20 ºC than the ones recorded with vegetable oils because increases the thermal stress endure by Kraft (dielectric paper) inside power transformers when used vegetal oil. Kondrashova *et al.* [4] improved the thermal modes to calculate the insulation paper and the life of power transformer. The results showed the climate parameters, thermal mode and nonlinearity of the thermal property are experimental. The framework of algorithm for calculating temperature graphs according to the load parameters with regard to the effect of the factors is suggested. Kim *et al.* [5] studied the operation life of power transformer which depended on cooling modes that caused collapse of dielectrics. The work showed the design of cooling mode is very important to increasing the lifetime and reliability for parts of power transformer. The study include two types of flow in radiators, the non-direct oil flow for oil natural-air natural (ONAN) type and direct oil flow for ODAN type. The results showed the cooling ability by using ODAN type increased 20.1% more than ONAN type. Gastelurrutia *et al.* [6] introduced a numerical model of thermal behaviour for power transformer. This model can be predictable the temperature distribution and oil stream inside power transformer for ONAN.This model can be used to analyse the natural convection of oil flow within power transformer and optimal design for internal parts of electric transformer. Taghikhani *et al.* [7] studied a numerical simulation a 32 MVA power transformer with mode cooling non-directed oil-forced (NDOF) and directed oil-forced (DOF) by using the finite element method. Their study introduced new method to increase precision the value of hottest spot temperature (HST) and its position. The results were identical compared with virtual data tests. Hosseini *et al.* [8] introduce simulation of thermal modelling of power transformer with type of disk winding and with several geometrical parameters of winding to correct the optimum cooling system for winding in power transformer and reduced the heat losses. The several theoretical model of winding designed by using software programs, it helped to predict the location of oil hot spot.

Akbari *et al.* [9] introduced a new algorithm to analyze the thermal behaviour of the bushings in power transformer. Through mathematical model by using the finite element method for both transient and steady-states to calculate the temperature distribution in the bushings. The type of paper bushing carried out by the algorithm was immersed with oil. The impact of the wind velocity and electric load was considered in this study. They investigated the different currents effect on the magnitude and location of the hot spot temperature. The simulation of three overload scenarios in the transient state was done to conclude two of these scenarios were from the IEC 60076-7 and IEEE C57.19.100 standards. Garelli *et al.* [10] suggested reduced model for the thermofluid dynamic analysis of a power transformer. The power transformer in this study has radiator working in either ONAF mode or ONAN. The heat removed from reduced model was two methods natural and forced convection. The experimental results of reduced model compared with CFD simulations and a significant convergence of results was found. Zhang *et al.* [1] studied a numerical model of a disc-type transformer windings for ON cooling mode. The case study was proposed by using CFD programs. Their results showed all functions (Reynolds, Richardson, and Prandtl numbers) can be controlled at constant power loss distribution, winding geometry, the hot-spot factor, and volumetric flow fraction.

The present study aims to simulate the earth air heat exchanger (EAHE) system which connected to electrical transformer. The effect of underground soil temperature around the EAHE on oil, coils, core transformer temperature is calculated especially at hot ambient temperature. This is to overcome low electrical efficiency (at hot climate temperature) and transformer damage in summer season (hot ambient season) by convective heat transfer among the earth heat exchanger pipe (cold contact soil) and outside transformer parts (fins and body).

Material and methods

The (250 kVA JOYSAN Turkish Transformer type) power transformer is theoretically analysed in this study by (ANSYS17.1/FLUENT) code program. Figure 1 illustrates this transformer. The power transformer contains (body, three coils, and core). Power transformer body includes the tank which keep the oil inside the power transformer which it connected to 44 fins to reject the generated heat in coils and core to surrounding as shown in the fig. 2. The three coils (copper wire wrapped as cylindrical shape) and iron core (magnetic iron chips) are connected together. According to the practical specifications of [11] and for full electrical load, the heat generation in the three coils and core are (3000 W and 500 W, respectively). To increase the operation life and minimize the faults of the electric transformer, the heat generated within the transformer should be as low as possible.

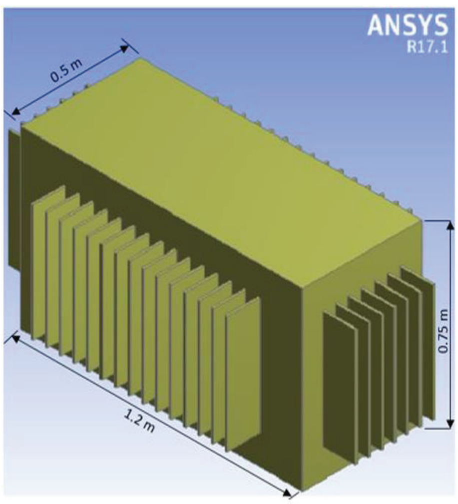

Figure 1. The power transformer model (250 kVA)

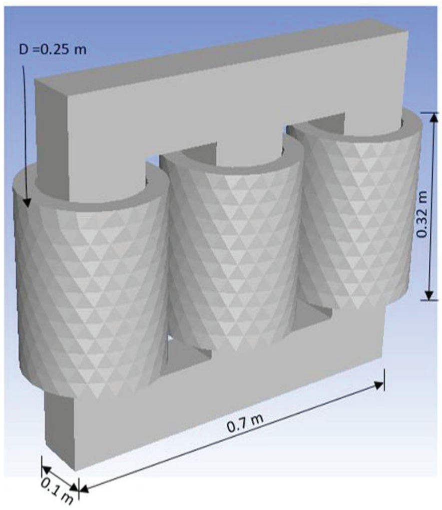

Figure 2. The internal parts of power transformer

The case study can be represented to two physical models as shown in figs. 1-3, respectively. The two models simulated by using (ANSYS17.1/FLUENT) code program.

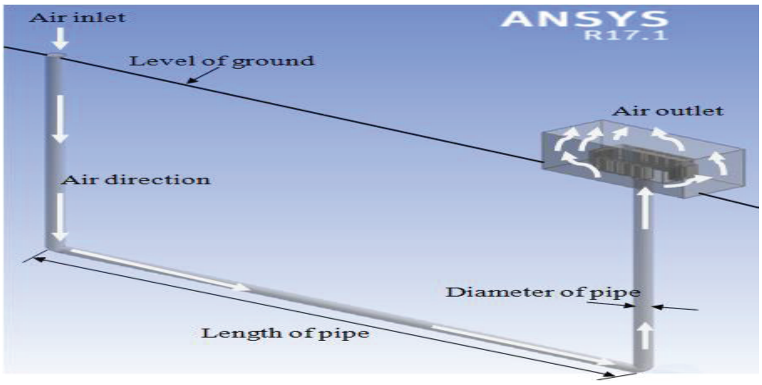

Figure 3. The power transformer with EAHE

First model

The model deals with power transformer. The heat transferred from it by natural convection because there is no oil pumps to push the oil to another its parts as shown in figs. 1 and 2. In this case the heat dissipated to outside by natural convection too with low convection heat transfer coefficient (h = 2 W/m^2°C) and ambient temperature of (50 °C) which is the average atmospheric air temperature at many days of summer season in Iraq (Nasiriya province).

At 100% load of (250 kVA Joysan Transformer), the heat flux in core is 476.1092 W/m^2 and heat flux for coils are 2236.6 W/m^2 [11]. In this model, we recorded the outer temperature of transformer body at constant of heat flux of core and coils.

Second model

In this model, the transformer is modelled with closed system included the whole body of transformer circumference by container to facilitate the transformer body and forced air coming from underground pipe working as EAHE to decrease the air temperature help in lessening the transformer temperature throughout the high atmospheric air temperature and high electrical power load in hot places. The depth of EAHE pipe is constant to be 4 m underground level to ensure minimum clay temperature [12] to decrease the air temperature inside pipe, which is thermally exchanged with clay layers by forced heat transfer as shown in fig. 3. Different length and diameter pipe are used with (2, 4, and 6 m/s) velocity of air at pipe inlet in this work.

The EAHE cools the hot air while it passes from the bottom of the EAHE. Where the Earth temperature is kept up to 26 ^{o}C the EAHE works as a heat exchanger. So, heat transferred from the air to the surrounded soil to the tube and thus will drop the temperature of the air to come out of the other outlet hole at low temperature.

Mathematical formulation

The transformer parts and boundary conditions can be analysed in present study by using the following equations.

Mathematical formulation of first model

The heat generated inside the power transformer is by coils and core because of power transformer electrical load. The heat generated in coils and core transferred to the internal body walls by oil inside power transformer (natural convection) and then the generated heat rejected from outer walls to surrounding by fins (convection and radiation). The governing eqs. (1)-(3) for 3-D, steady-state, and constant density (incompressible oil) [13, 14]:

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

$$\rho c_p\left(V\nabla T\right)=k\nabla^2 T \tag{2}$$

$$\rho\left(V\nabla\vec{\mathrm{V}}\right)=-\nabla P+\nabla\left(\mu\nabla\vec{\mathrm{V}}\right)+\frac{\rho-\rho_\infty}{\rho_\infty}g \tag{3}$$

The properties of the transformer oil can be calculated as function of the temperature according to the relationships [15]:

$$\rho\left(T\right)=1098.72-0.712T \tag{4}$$

$$k\left(T\right)=0.1509-7.101\times10^{-5}T \tag{5}$$

$$c_p\left(T\right)=807.163+3.58T \tag{6}$$

$$\mu\left(T\right)=0.08467-0.0004T+5\times10^{-7}T^2 \tag{7}$$

Mathematical formulation of second model

The equations that used to analyse the air inside tube of EAHE.

Navier-Stokes equation

Launder and Spalding introduced two-equation turbulence model that allowed the calculation of two factors length and time scale by disbanding the equations of separate transport. The standard (κ-ε) model used in ANSYS FLUENT for many heat transfer simulations because it is valid and has high accuracy. Model transport equations are very important in standard (κ-ε) model for the turbulence dissipation rate, ε, and its kinetic energy, κ. The delicate equation was used to derive the model transport equation for κ, while the model transport equation for ε, was obtained using the physical conclusion and includes a few similarities to its mathematically delicate rival. The assumption of derivation of the (κ-ε) model is completely turbulent with neglecting the influences of molecular viscosity. Therefore, the standard (κ-ε) model can be used for fully turbulent flows only. Many improvements have been made to enhancement the standard (κ-ε) model [16].

Transport equations for the standard κ-ε model

The transport equations for the standard for (κ-ε) model contain the turbulence kinetic energy, κ, and its rate of dissipation, ε, which can be found from the following transport equations [16]:

$$\frac{\partial}{\partial t}\left(\rho\kappa\right)+\frac{\partial}{\partial x_i}\left(\rho\kappa u_i\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{8}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{9}$$

where the parameters can be found from tab. 1 [16]:

Table 1. Some values of parameters

The parameter	Value
σ_ε	1.3
σ_k	1.0
C_μ	0.09
$C_{2\varepsilon}$	1.92
$C_{1\varepsilon}$	1.44

The Reynolds number can be found [17]:

$$\mathrm{Re}=\frac{V_{\mathrm{air}}\,K_{\mathrm{air}}}{d_{\mathrm{pipe}}} \tag{10}$$

Gnielinski [19] suggested empirical relationship can be employed to calculate the Nusselt number for fully developed in pipes turbulent and laminar flow in the ranges $2300 \leq \mathrm{Re} \geq 5\times10^6$ and $0.5 \leq \mathrm{Pr} \geq 2000$ as illustrated (assuming the Prandtl number is constant for air 0.7):

$$\mathrm{Nu}=\frac{\dfrac{f(\mathrm{Re}-1000)\mathrm{Pr}}{8}}{1+12.7\left(\dfrac{f}{8}\right)^{\frac{1}{2}}\left(\mathrm{Pr}^{\frac{2}{3}}-1\right)} \tag{11}$$

The thermal resistance between air flow and pipe inner surface [12]:

$$R_{th}=\frac{1}{2\pi r\,h\,L} \tag{12}$$

where h is convective film coefficient can be found [12]:

$$h=\frac{\mathrm{Nu}K_{\mathrm{air}}}{d_{\mathrm{pipe}}} \tag{13}$$

Modelling the turbulent viscosity

The turbulent viscosity, μ_t, is found:

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{14}$$

Soil temperature of EAHE

Kusuda *et al.* [19], Moreland *et al.* [20], and Labs [21] introduced mathematic relationship to predict the soil temperature depended on the annual ambient temperature change. The prediction reliability of the soil temperature is very sensible to the values of the input parameters as shown:

$$T_{(z,t)}=T_m-A_s\mathrm{e}^{[-z(\pi/8760\alpha)^{0.5}]}\cos\left[\frac{2\pi}{8760}\left(t-t_o-\frac{z}{2}\left(\frac{8760}{\pi\alpha}\right)^{0.5}\right)\right] \tag{15}$$

The errors of eq. (15) do not exceed ±1.1 °C [21].

The soil nature, environment and atmosphere of Nasiriya is the same as that of Kuwait. The values found form tab. 2 [22].

Therefore the following formula might be depended on eq. (15):

$$T_{(z,t)} = 27 - 13.3\mathrm{e}^{-0.31z} \cos\left[\frac{2\pi}{8760}\left(t - 552 - 428.31z\right)\right] \tag{16}$$

The fins, basin and outer walls of transformer are exposed to natural convection which assumed to be (2 W/m^{2}K) and emissivity of 0.9.

The study used the weather conditions of Nasiriya city in July 1st with 50 °C ambient temperature because the weather at this time is very hot and the electrical energy consumption is very large.

Table 2. Some values of parameters

The parameter	Value
Annual surface temperature amplitude, α	0.0038
Soil thermal diffusivity, A_s	13.3 °Cm^2/h
Phase constant, t_o	552 hours
Annual mean ground temperature, T_m	27 °C

Numerical model

The finite volume method is used numerically to solve the two theoretical model by using (ANSYS17.1/FLUENT) code program. Then, the governing eqs. (1)-(3), (8), and (9) are solved. The first order upwind scheme is used to solve the governing equations while using the algebraic form for solving the segregation. For the continuity equation formation and analysing velocity-pressure coupling case, the SIMPLE algorithm used. The convergence criterion used for the momentum and energy equation solution residuals to be less than 10^{-6} to ensure a high accuracy in comparison to power transformer practical specification.

Tables 3 and 4 shows the results of first model mesh to obtain better results from (ANSYS17.1/FLUENT) code program. The meshing number 8 is the better for accumulating the results because it approached to values of practical temperature [23].

Table 3. Attempts of mesh to accuracy of the results

Attempt	Relevance	No. of nodes	No. of elements	The value of max. oil temperature
1	100	211885	139632	373.2
2	75	156365	101919	374.7
3	50	114640	73979	375.6
4	25	85215	53960	376.3
5	15	78322	46195	375.1
6	10	73397	43921	374.6
7	5	68390	41033	374.4
8	0	66465	39078	374.2

Table 4. The properties of mesh

Min. edge length	Max. face size	Growth rate	Size function	Relevance centre	Curvature normal angle	Transition ratio	Max. layer	Pinch tolerance
0.009 m	1.6 m	1.2	curvature	coarse	12°	0.272	5	1.46×10^{-2} m

Results and discussion

The study is done by using code program (FLUENT/ANSYS 17), the model of power transformer is made for actual dimensions of power transformer and for maximum heat losses from the coils and core of power transformer. The study used the weather conditions of Nasiriya city in July 1st with 50 °C ambient temperature.

Figure 4 indicates the effect of pipe length EAHE on thermal resistance of convective heat transfer between pipe body and air inside it. A sharp drop happiness at the first part of pipe length (0-5 m) then this slope decreased from (5-20 m), and after 20 m the curve angle will decreased to reach to approximately zero according to eq. (12).

Figure 5 shows the effect of pipe length in maximum oil temperature in EAHE by exerting different inlet air velocity (2, 4, and 6 m/s), it is seen the oil temperature of temperature of transformer decreases with increasing the pipe length and since the heat transfer area increase vice versa. Also, the average temperature decreases with increasing the air velocity passing throughout the pipe because the convective heat transfer coefficient increases directly with increase the velocity, Reynolds and Nusselt numbers. The curve slope appears to be changed before and after 20 m of pipe length because of thermal resistance mentioned in fig. 4 above.

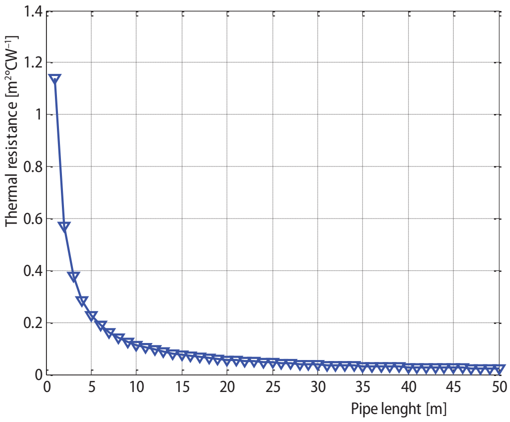

Figure 4. Thermal resistance between air-flow and pipe inner surface for different pipe length

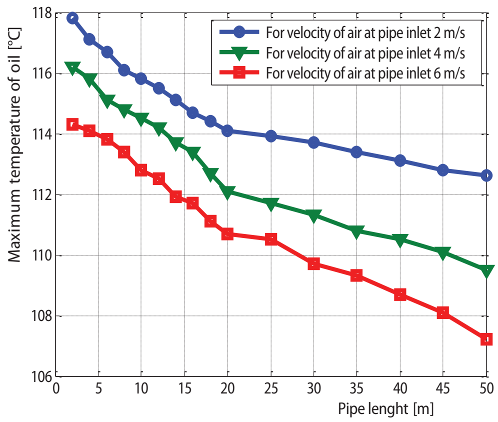

Figure 5. Maximum temperature of oil with pipe length of EAHE for different air velocity of pipe inlet for 0.5 m diameter of pipe

Figure 6 depicted the maximum oil temperature of transformer against the pipe length of EAHE but with decreasing the pipe diameter to half that in fig. 5, it is shown decreasing the oil temperature with increasing the pipe length but with higher temperature gradient than the previous figure because of decreasing convective heat transfer area between the pipe metal which in contact with soil and air passes inside it by more than 3 °C that has effective range in heat exchange to decrease transformer temperature. The same trend of figs. 5 and 6 that for fig. 7 for the relationship between the maximum oil temperature inside the transformer and pipe length but with decreasing the pipe diameter as half the diameter in fig. 6 to be 0.125 m to be temperature difference between the same curves of the same velocity in comparison with fig. 6. is about 3 °C to as a result it to decreasing the heat transfer exchange area. The thermal resistance mentioned in fig. 4 above affects curve trend before and after 20 m of pipe length which also affect the curve in fig. 7.

The same case in fig.7 for pipe diameter that used with depth 4 m underground in fig. 8, the air velocity 6 m/s, pipe length 50 m to demonstrate the maximum temperature of oil, coils, and core of transformer with different convective heat transfer coefficient. The coils and core have the same contact temperature with maximum value 116 °C at low convective heat transfer coefficient (h = 2 W/m^2°C) than it continue to decrease with increase heat transfer coefficient a result to increase the Nusselt number, so, there values are high because they are the parts that responsible to transformer the voltage and the current and iron losses starts by them,

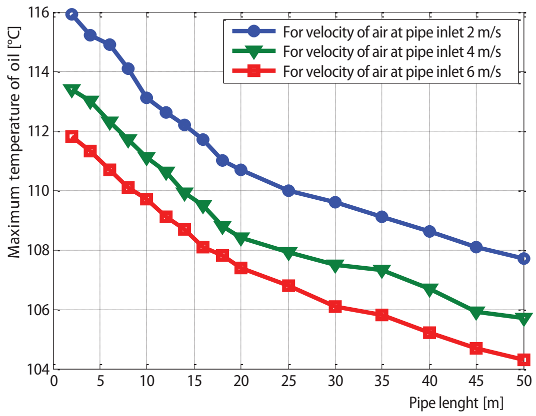

Figure 6. Maximum temperature of oil with pipe length of EAHE for different air velocity of pipe inlet for 0.25 m diameter of pipe

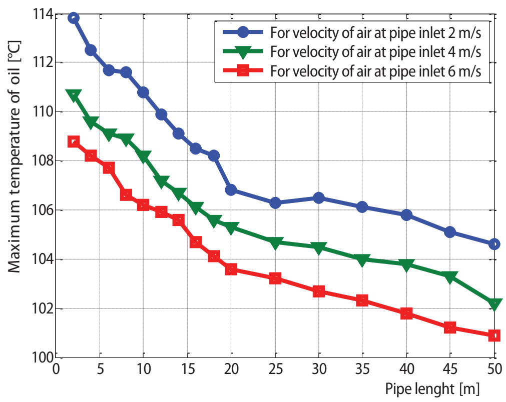

Figure 7. Maximum temperature of oil with pipe length of EAHE for different air velocity of pipe inlet for 0.125 m diameter of pipe

while the oil temperature is lower than them by about 11 °C because it is the mediator in transformer to dissipate the heat lost from the core and coils to outside surrounding.

Figure 7 represents proffered findings with low oil temperature than figs. 5 and 6 with smaller diameter of pipe with the same velocity of air inside the pipe (2, 4, and 6 m/s) because of larger heat transfer coefficient with area that in contact with soil layers underground which have low temperatures.

The maximum oil temperature against ambient temperature is represented by fig. 9. It is usually to see augment in oil temperature with increment of ambient temperature and the difference between two curves of using EAHE pipe system with transformer and without it. The effect of underground EAHE system is very high to reduce the oil temperature by more than 17 °C. It is very high effect diminish oil temperature which effects or may be lead to transformer failure as a result to rising the core and windings temperature.

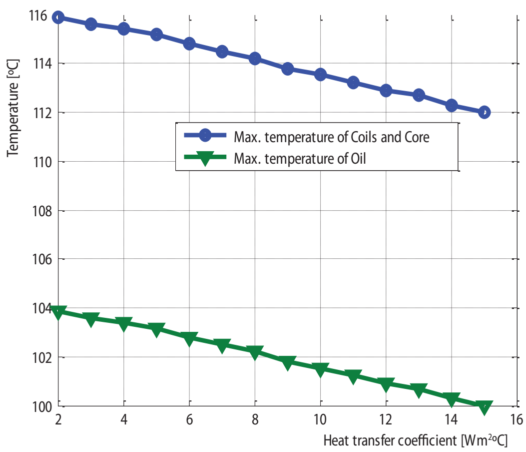

Figure 8. Maximum temperature of oil, coils, and core with use EAHE with heat transfer coefficient, for pipe length 50 m, velocity 6 m/s, depth 4 m, diameter of pipe 0.125 m

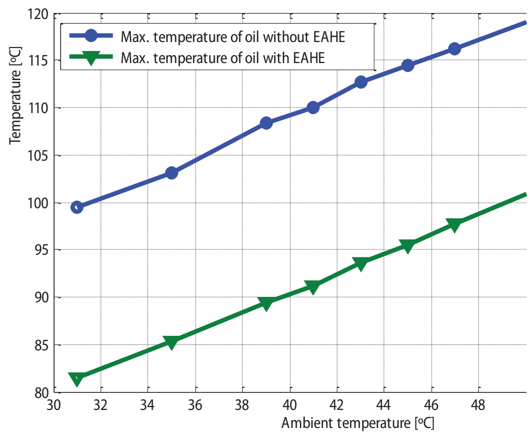

Figure 9. Maximum temperature of oil with and without EAHE for different ambient temperature, for pipe length 50 m, velocity 6 m/s, depth 4 m, diameter of pipe 0.125 m

Figure 10 indicates the oil dynamic viscosity with ambient temperature at pipe length of 50 m, 6 m/s air velocity, 4 m pipe depth, and 0.125 m pipe diameter when using EAHE in compression with no EAHE system connected to transformer. The dynamic viscosity is a criterion to molecules freedom in momentum, so, increasing the temperature will reduce the dynamic viscosity. When the EAHE system used the oil temperature decreases while dynamic viscosity is high and continue to decrease gradually with increases of ambient temperature for both cases of using this system and without it. The difference between two curves since the difference in oil temperature for both. It is fortunately to follow the same trend of this figure with thermal conductivity of oil in fig.11 with the same cases. This property of oil utilized in thermal dissipation of heat inside the transformer. The cold liquids have high thermal conductivity than hot, so, increasing the ambient temperature will decrease thermal conductivity and vice-versa.

The interior parts temperature of (250 kVA) transformer core and coil is not obviously appearing by using (ANSYS code) without using section plan to cut these parts to see their tem-

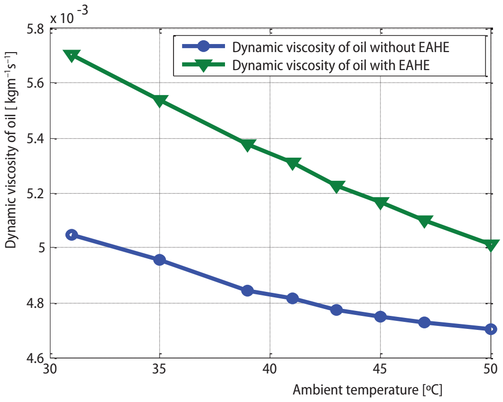

Figure 10. Dynamic viscosity of oil with ambient temperature for pipe length of pipe 50 m, velocity 6 m/s, depth 4 m, diameter of pipe 0.125 m

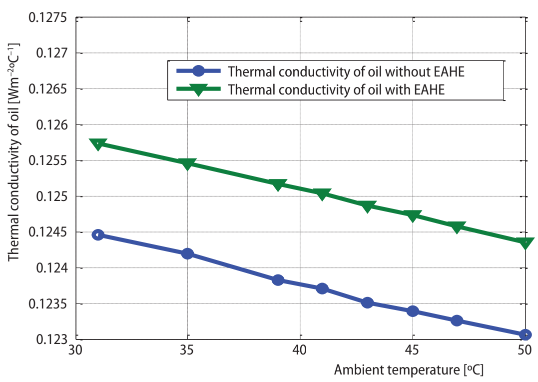

Figure 11. Thermal conductivity of oil with ambient temperature, for pipe length 50 m, velocity 6 m/s, depth 4 m, diameter of pipe 0.125 m

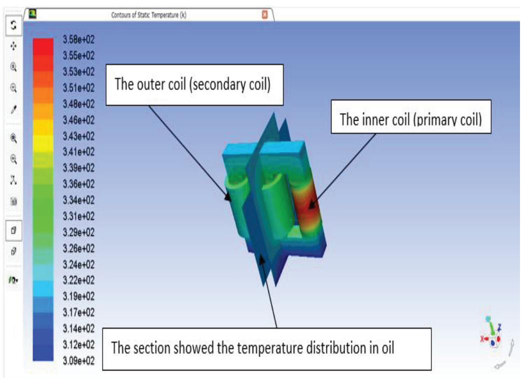

Fig. 12. Internal parts of transformer shows the section of temperature distribution by using (ANSYS 17)

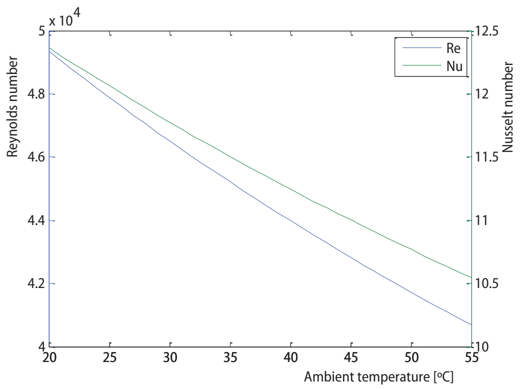

Fig. 13. Reynolds and Nusselt numbers with ambient temperature, for pipe length 50 m, velocity 6 m/s, depth 4 m, diameter of pipe 0.125 m

perature. This manner is exhibited in fig. 12. The maximum temperature of system is sown in primary coil of transformer to be 85 °C.

Comparison

Figure 14 showed the comparison between Hasan's work (for SiC-oil with 9% volume fraction of nanofluid) [24], and present study (fig. 13, for pipe length 50 m, velocity 6 m/s, depth 4 m, diameter of pipe 0.125m) and the pure oil. The findings of the present curve behaves as the same trend of the previous works in literature with high efficient results to decrease the oil temperature of transformer.

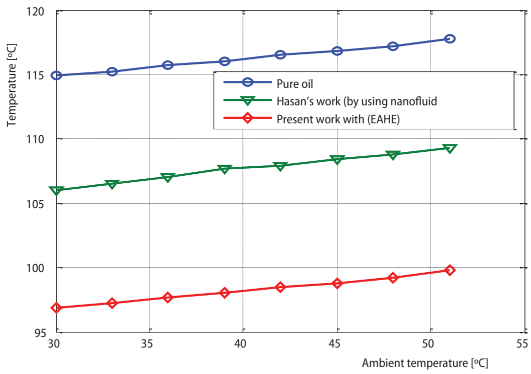

Figure 14. The cooperation between Hasan's work [24] and present work with (EAHE)

Conclusions

- By using EAHE system in power transformer, the temperature of oil, coil, and core decreased.
- The decreasing of temperature in power transformer is depending on length, diameter, and depth of pipe of EAHE.
- The velocity of air inlet of pipe EAHE directly proportional to temperature of oil, core, and coils of power transformer. *i. e* the air velocity must be increased to overcome high transformer temperature always.
- The heat transfer coefficient of ambient air inversely proportional to temperature of oil, core, and coils of power transformer by using EAHE.
- The dynamic viscosity and thermal conductivity of oil will increase with using EAHE system in power transformer.
- The present method for case study has high effectiveness than other methods in decreasing the power transformer parts to raise its efficiency and protect it against the failure and damage especially at hot climate temperature conditions.

Nomenclature

c_p – specific heat at constant pressure of air, [Jkg^{-1}K^{-1}]
d_{pipe} – diameter of pipe, [m]
G_b – is the generation of turbulence kinetic energy due to buoyancy
G_k – the generation of turbulence kinetic energy due to the mean velocity gradients
h – convective film coefficient, [Wm^{-2} °C^{-1}]
k – thermal conductivity, [Wm^{-1} °C^{-1}]
L – length of pipe, [m]
R_{th} – thermal resistance between air and pipe inner surface, [m^2 °CW^{-1}]
T – temperature, [K]
t – time of the year, [hours]
V_{air} – velocity of air in pipe, [ms^{-1}]
Y_M – the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
z – depth below ground, [m]

Greek symbols

ρ – density, [kgm^{-3}]
μ – dynamic viscosity, [kgm^{-1}s^{-1}]

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