

Using of PCM as an energy storage material to improve the cooling process in electrical transformers

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Abstract

In this paper, using (PCMs) the phase change materials in electrical transformer is numerically solved by CFD ANSYS fluent 17.1. As assistance, cooling mediums The PCMs (paraffin wax, p116 and RT44) have been used with transformer cooling oil. PCMs about 10 kg used as shield around the coils and windings. Surrounding temperature taken at (298, 310, 318 and 328) K the transformer temperature at added PCM shows clear decreasing in the average temperature due to the latent heat which absorbed the heat that got it from PCM. Constant heat generation is applied on the transformer from the heater and mixed (convection and radiation) boundary condition is applied at the outer surfaces of transformer. The results showed that, using of PCM with different types caused a reduction in temperature of transformers

Keywords: Phase change materials, transformer, boundary condition, numerical investigation Phase change materials, transformer, boundary condition, numerical investigation

NOMENCLATURE:

PFMCHE parallel flow microchannel heat exchanger

C_p specific heat (J/kg.K)

k thermal conductivity (W/m.K)

$\dot{m}$ mass flow rate (kg/s)

P total pressure (Pa)

q heat transfer rate (W)

T temperature (K)

u fluid x-component velocity (m/s)

v fluid y-component velocity (m/s)

w fluid z-component velocity (m/s)

W width (m)

H height (m)

h heat transfer coefficient

ΔH Latent heat (W)

$H H$ Enthalpy of suspension (W)

$hehe$ Sensible heat (W)

x axial coordinate (m)

y vertical coordinate (m)

Z horizontal coordinate (m)

ΔP pressure drop across heat sink (Pa)

ρ density (kg/m³)

μ dynamic viscosity (m²/s)

β Melting fraction

ϕ Mass fraction

Abbreviation

Temp. temperature Paraf. Paraffin wax

PCM phase change material

V volume

1- Introduction:

Electrical transformers are an important and necessary equipment's in our daily life and constitute the main and essential part of electricity network. Generally, transformers are made from high thermal conductivity materials such as aluminum. The age and efficiency of the electrical transformer are greatly affected by the rise in temperature.

The phase change materials can be used to improve the thermal performance of a transformer and used to absorb extra heat through peaks in dissipation power. The heat absorption by a phase change material generally, occur between the liquid and the solid states.

The successful using of the phase change materials is due to a high density of energy storage. Therefore, using PCMs in electrical devices to reducing temperature for preferred applications. There are many researchers in literature studied the performance of transformers and improve its efficiency at high temperatures.

Jon G. et al. (2011) [1]. Studied the thermal behavior of many ONAN (Natural oil) (Natural air) transformers. A

Greek Symbols:

simplified presented detailed model with complete geometric description. In order to reduce the computational cost required, and through this model they were able to study the flow of oil and the thermal distribution inside the transformer. Finite volume method (FVM) used to solve model. The results indicated that, the developed slice oil model has been gives a good capacity to present the thermal behaviors of the entire transformer. Also, the maximum difference of temperature probe oil with the measured value is less than 2.4°C.

Garlos M. et al. (2011) [2]. Studied the distribution and flow of temperature in electrical transformers. Because it is not easy to study electrical transformers experimentally therefore, they used the CFD simulation for solving model. CFD simulations were carried out to analyses the heat removal and flow distribution in core type power transformers. The results obtained showed that, CFD used has been shown to be suitable for analysis and can give a major role in improving to study difficult states as transformers thermal analysis. Also, it suitable for designing transformers, giving detailed information on flow and distribution of temperature. When the temperature distribution including the location and the amount of the highest temperature in the transformer (hot spot temperature).

Amit M., et al. (2011) [3]. Studied the insulation system of the power transformer bushing. Therefore, used double M4000 capacitance of insulation analyzer. Bushings were represented a critical component in the electricity transportation. And used in substation buildings, locomotives, transformers, and switchgear. Bushings caused more than 15% failures of the transformer. The main purpose of bushing was to transfer current load in and out of the metal (grounded) enclosures at a system voltages. Thier results showed how the dielectric properties changes and moisture with the variation of the power factor and the capacitance of insulation system. The variation in the capacitance due to variation in the dielectric properties of insulation which could be affected by moisture and other impurities or shorten some layers of paper by conducting paths.

Satyanarayan A . et al. (2014) [4] studied the variation in the temperature with in the transformer and how effect on the efficiency and life of the distribution transformer. Also, studied the method of cooling ONAN cooling through ducts and different dimensions and locations to increase the rate of heat transfer. Their results presented that, the cooling system of the transformer is improved in the term of better layout of the tube/ radiators and improving transformer thermal performance. Also, the increasing in pitch of the tube/ radiators improve the heat transfer rate and decreased in the top oil temperature.

Guan et al. [5] 2014 also presented the CFD study by adding nano particles to transformer oil and studied the natural and forced convections and their effect on velocity, temperature and density. Their study demonstrated improve heat transfer efficiency by nanoparticles. For particles, Position and oil temperature.

R. SRILEKHA [6] (2016) presented a study aimed to studying the distribution of temperature in the transformer as well as the velocity of the oil in the transformer and through modeling by MATLAB program using two methods to study the effect of velocity and temperature on the flow within the first, focused on Equation derived from previous work on the flow of oil and the distribution of temperature and the second way to deal with this problem as a global problem is the improvement distribution and flow and was solved using numerical methods. His study has shown that solutions are available in the details of the designs, which can be applied in practice

Mushtaq I. Hasan [7] (2017) Numerically studied the thermal behavior of electrical distribution transformer with the effect of air temperature. 250 KVA distribution transformer was studied as a 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. He used four types of solid particles (Cu, Al₂O₃, TiO₂ and SiC) to compose nanofluids with volume ratio (1%, 3%, 5%, 7%, and 9%). Due its good thermal characteristics the nanoparticles lead to increase the dielectric of oil and increase the breakdown voltage. His results determined show that, using of transformer oil-based nanofluids as a cooling medium instead of pure transformer oil lead to enhancement the cooling performance of transformer by decreasing the temperature of transformer and as a consequence increasing the work of the transformer against the hot weather. Also increasing the nanoparticles volume ratio in nanofluid caused extra decrease in transformer temperature. The SiC-Oil among all of the selected nanofluid give lower transformer temperature

Mushtaq I.Hasan[8] (2017) numerically modeled the electrical transformer with transformer oil based MEPCM suspension as cooling medium instead of pure transformer oil. Transformer cooling oil consists of micro capsules containing phase change materials enclosed by cover made of polymers mixed with pure transformer oil, resulting in a new mixture Contributes to the cooling of transformer parts more than pure oil and thus will increase the cooling efficiency of electrical transformer and also increase the operational life of the transformer parts. A 250 kVA transformer was modeled using CFD, code with the real transformer dimensions. Where the microcapsule contains the paraffin wax as a PCM phase change

material, which dissolves inside the capsule after absorbing the heat from the cooling oil. In his study, the capsules were mixed with cooling oil at volume rates ranging from (5% to 25%). The results of this study showed a clear reduction in the temperature of the mixture and the internal parts of the transformer and thus will maintain the oil dielectric and keep the oil from collapse and thus protect the transformer from damage.

Mushtaq I. Hassan et al. [9] (2018) numerically studied the PCM in the micro heat sink, where they used air first in Heat Sink and then used different types of PCM (paraffin wax, n-eicosane, p116, RT4) as cooling mediums at different conditions of weather and concluded that the use of these materials PCM contribute to improving the performance of cooling in the micro heat sink as well as the selection of these materials depending on the degree of melting and according to the applications.

Results obtained show a decrease in indoor temperature of the zone and the reduction in cooling load and as a result saving in electricity.

2- Problem description:-

100 KVA distribution transformer is chosen as a case study in this paper, which is mainly used in Iraqi electricity network. Picture at Fig. 1a shows real transformer while Fig. 1b from workbench ANSYS R17.1 represents a schematic drawing to illustrate the outer view of this transformer. The transformer consists of (coils and core assembly) its consists of three copper coils and a steel core linking it, all these items are immersed in transformer oil contained in the transformer body which supplied 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 standard (IEC60076), the heat generated in transformer at full load situation is about 1850 W. This heat generated must be rejected to maintain the temperature of oil at acceptable level. The properties of oil for transformer are listed in Table1 (1). In this paper the studied transformer is simulated numerically since a model of transformer has been plotted with exact dimensions and shape. Hexagonal bar heater has modeled the coils and core and the amount of heat generation is applied corresponding to the real heat losses accrued in real transformer

In this paper, the novel approaches have been used to increase the cooling efficiency of transformers using PCM. It's include using 10 kg of the PCM as sheild around the hexagonal bar heater with different types of PCM.

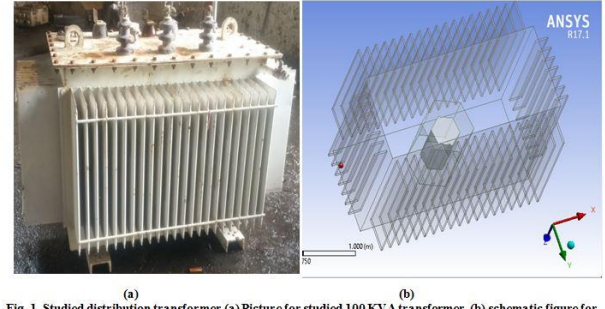


Fig. 1. Studied distribution transformer (a) Picture for studied 100 KVA transformer, (b) schematic figure for

3- Governing equations:-

The governing equations used for solving this model are continuity, momentum and energy equations which can be written as following [10][11][12][13]:

The continuity equation:

$$\nabla \cdot \mathbf{V} = 0 \quad \dots(1)$$

Momentum equation:

$$\rho(\mathbf{V} \cdot \nabla \mathbf{V}) = -\nabla P + \nabla \cdot (\mu \nabla \mathbf{V}) + \frac{\rho - \rho_{\infty}}{\rho_{\infty}} \quad \dots(2)$$

Energy equation:

$$\rho C_p C_p (\mathbf{V} \cdot \nabla H) = K \nabla^2 T \quad \dots(3)$$

The enthalpy of the PCM (H) is indicated by Eq. (4) and calculated as the sum of the latent heat (ΔH) and the sensible heat (h_e) of the PCM

$$H = \Delta H + h_e \quad \dots(4)$$

The sensible heat is described by Eq. (5), where h_{ref} ,

h_{ref} is the reference enthalpy at T_{ref} .

$$h_e = h_{ref} + \int_{T_{ref}}^T C_{pF} dt \quad \dots(5)$$

The energy (sensible & latent) stored in PCM (Q) can be calculate by (6):

$$Q = \int_{T_s}^{T_{pc}} m C_{ps} dT + m \Delta H + \int_{T_l}^{T_{pc}} m C_{pl} dT \quad \dots(6)$$

The latent heat of the PCM (ΔH) is described by Eq. (7) as a function of the latent heat of fusion of the PCM (L) and the melting mass fraction (β). The melting mass fraction (β) is defined as the mass ratio of melted PCM to the total

mass of PCM in the mixture. The PCM start to melt at $T_{solidus}$ and completing melting at $T_{liquids}$ where the liquid fraction can vary from 0 at $T_{solidus}$ to 1 at $T_{liquids}$. Eq.(8),describes the melted mass fraction (β).

$$\Delta H = \beta L \quad \dots(7)$$

Where :

$$\beta = 0 \quad \text{if } T_f \leq T_{solidus} \quad \dots(8)$$

$$\beta = 1 \quad \text{if } T_f \geq T_{liquids}$$

$$\beta = \frac{T_f - T_{solidus}}{T_{liquids} - T_{solidus}} \quad \text{if } T_{solidus} < T_f < T_{liquids}$$

$$T_{solidus} \leq T_f \leq T_{liquids}$$

4- Boundary conditions:-

The boundary conditions used to close the model are:

1. No slip at wall $u=v=w=0$.
2. Constant heat generation B.C at the core and coils
3. Mixed boundary condition (convection and radiation) is applied on the all outer walls.

The walls separated two zones solid and liquid are treated as conjugated heat transfer (coupled).

5- Properties of phase change materials:

A phase change materials are substances with a high heat of fusion, which are melt and solidification at a certain temperature, the PCMs had ability of storage and release large quantities of energy. Heat is released or absorbed when material changes from a solid to the liquid and vice versa. The PCMs continues to absorbing heat without any significant rise in a temperature until all the materials are converted to a liquid phase. When ambient temperature falls around the liquid material, the PCM solidifying, releasing its stored heat. A large number of a PCMs are presented in any essential temperature range from -5°C up to 190°C . They store from 5 to 14 times more the heat per unit volume, compared with conventional storage materials such as rock, water or masonry [13] the PCMs are classified to: organic, in-organic and eutectics. The properties of the phase change materials used in this paper are listed in table 1 below [14, 15, and 16].

Table1 Properties of materials studied in this paper

Material	Thermal conductivity (W/m.K)	Specific heat(kJ/kg.K)	Density (kg/m3)	Temp. $^\circ\text{C}$		Melting heat(kJ/kg)	Viscosity for liquid phase (kg/m.s)
				T_s	T_L		
Transformr oil	0.109	2	880	—	—	—	0.0124
Paraffin wax	0.212	2.3	880	50	57	173.6	0.0063
RT44	0.2	2	802	37.5	42.9	141.7	0.003
P116	0.21	2.1	830	50	50	190	0.00076
Aluminum	273	8.71	2719	—	—	—	—

6- Numerical Solution:

The above model of governing equations and boundary conditions are numerically solved by using the finite volume method. Using the SIMPLE algorithm for solving the problem of coupling for computing the flow variables by solving the continuity, momentum and energy equations. The mesh is chosen for solving the model by recognizing grid size since a mesh refinement had been made to find suitable mesh size gives a high accurate solution. Mesh independent was made by using six mesh sizes and the results for transformer oil average temperature for different meshes used are mentioned in Table 2 for ambient temperature $T_o = 310\text{ K}$.

Table 2 shows the different meshes selected and from this table it can be seen that, the solution becomes independent of mesh size after the fifth mesh. Therefore, the fifth mesh will be used for all next solutions. Fig 2 shows numerical domain and the used mesh. The convergence conditions used to control the numerical solution is 10^{-6} for both energy and momentum equations.

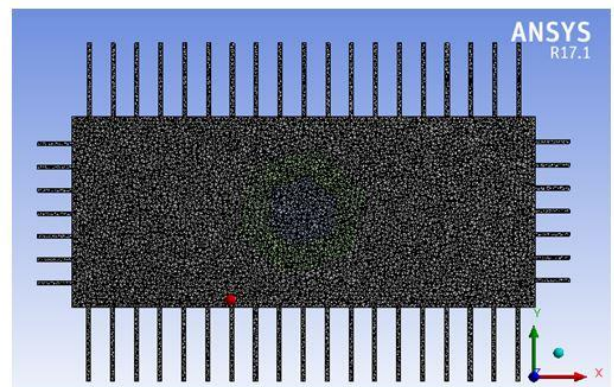


Figure 2. Half Outer view of mesh used for computational model.

Table 2 Grid independent study

Mesh	Average oil temperature (K)
Mesh1 (Number of nodes = 106851)	514.4
Mesh2 (Number of nodes = 152831)	484.5
Mesh3 (Number of nodes = 246821)	444.78
Mesh4 (Number of nodes = 320681)	394.17
Mesh5 (Number of nodes = 462700)	341.021
Mesh6 (Number of nodes = 627681)	340.812

In this study, a 3-D electrical transformer model with PCMs is numerically solved. Firstly, the model is solved with oil as a cooling fluid with constant properties are selected according to the ambient temperature, then the solution is repeated by using PCMs as a cooling assistance the oil.

To check the validity of used numerical model, this model is validated against the numerical study and the results are compared with that of present model. The numerical model represented in [8] electrical transformer 250KVA taken to study. The heat generation in transformer in full load situation is 500 W from each core and 1000 W from coil. For this study, the maximum temperature was measured in fluid with Microencapsulated PCM suspension value 5% of concentration with (30-45) Co outside temperature. Fig.3 show the comparison present numerical model and the data of [19] for the temperature. It can be noted; from a figure that the agreement between two results is acceptable.

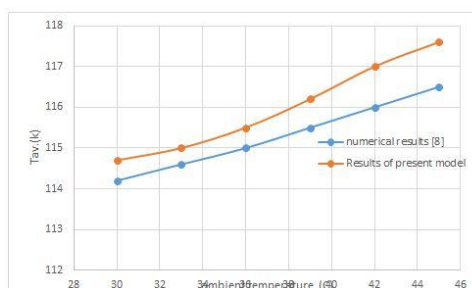


Fig.(3) comparison between the numerical results[8] and present model results

The temperature contours it is shows figures 4 and 5 at (x-y) and (y-z) planes at middle height and width of transformer respectively for pure oil at outside temperature of 25 oC. It is clear form these figures that, the temperature is distributed from its maximum values near the surfaces of heater to its minimum values at the outer walls of transformer corresponding to the surrounding air

temperature due to transferring of the generated heat from the heater to the outside air through the transformer oil.

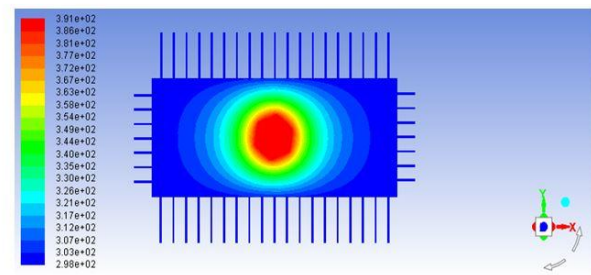


Fig.4 Temperature contour on the x-y plan at middle height of transformer

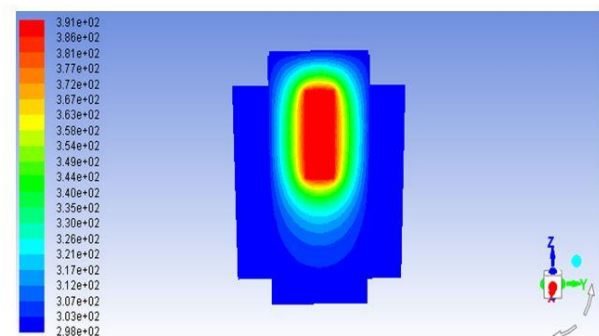


Fig.5 Temperature contour on the y-z plan at middle width of transformer

The figure (6) shows the temperature contour for using 10 kg of PCM as shield around the coils and windings (wax) at 25 C° it is clear to compare with figures (4 &5) the decreasing the temperature from the contours the host temperature and the borders due to using PCM as storage heat and the latent heat in this case it will be available where in the pure case only oil and without latent heat the heat generation transferring from coils and windings to oil and to outer so some time the outer temperature is higher that is mean the transformer temperature it will trapped inside transformer tank. Also there is some little different in contours from PMC to another due to the properties for this materials.

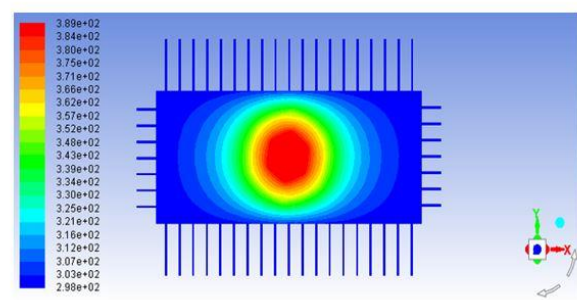


Fig.6 Temperature contour on the x-y plan at middle height of transformer

Figure (7) show the variation of transformer average temperature with shield for deferent types of PCMs (wax, P116, RT44) with oil of transformer. Constant heat generation (1850W) from the heater and mixed (convection and radiation) boundary conditions are applied.. The boundary condition of ambient temperatures used at four values which are (298, 310, 318, 328) K for this case of using shield of transformer oil and PCMs instead of pure transformer oil in this figure (0) represent the case of pure transformer oil . From these figures, it can be seen that, the average temperature decreased with used the amount of PCMs. Also from these figure it can be seen that, the better PCMs, which gives lowest average temperature, is different at each materials with different ambient temperature. This is due to difference in melting temperature range for PCMs studied which lead to variation in melting process and melted amount of PCMs at different values of ambient temperature. This indicate that, the suitability of certain PCMs depends on the working ambient temperature since the reduction in transformer temperature with selected PCMs depend on ambient temperature

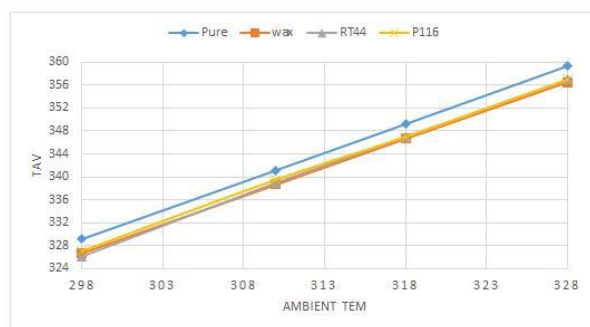


Fig. 7 variation of the average temperature of the transformer with the shield of PCMs used at different ambient temperature

Figure (8) represents the Variation of transformer maximum temperature with outside air temperature for pure oil, shield PCM. From this figure, it can be observed that, the maximum temperature increased with increasing air temperature for all cases. Also the maximum temperature in case of using PCM with oil is smaller than that of pure oil in same conditions due to extra latent heat absorbed as a result of melting PCM.

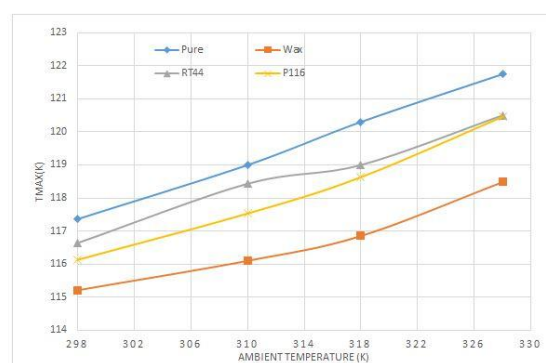


Fig. 8 variation of the maximum temperature of the transformer with the shield of PCMs used at different ambient temperature

Figure (9) show the variation of the sensible heat at the transformer for three types of PCMs (wax, RT44 and P116) at outside temperature of (298,310,318 and 328) K. This sensible heat gives an indication about the amount of the sensible heat that can be dissipated to the surrounding air. From this figure, one can observe that, the amount of heat transferred when using PCMs are larger than that of the case with pure oil due to the thermal conductivity for the PCMs lead to enhancement in the heat dissipation process. Also the results of figure reveals that, over the selected range of the paraffin wax give higher heat transfer due to its higher thermal properties.

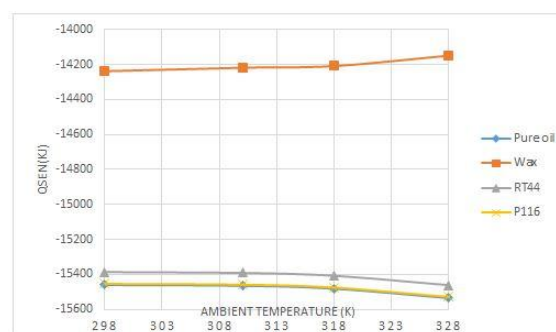


Fig. 9 variation of the sensible heat of the transformer with the shield of PCMs used at different ambient temperature

Figure (10) expression the variation of total heat (sensible heat and latent heat) when the PCMs placed inside transformer and at different ambient temperature. From these figures it can be confined that, the latent heat very useful in the transformers where at high temperature the mass fraction it will increasing as result the latent heat increasing and the total heat equal summation of latent heat and sensible heat as mention in above figures the sensible increasing by added PCMs so the heat transfer from coils and cores it's increase also if increasing PCMs that's mean increasing the heat storages it will enhancement heat transformer from electrical transformer.

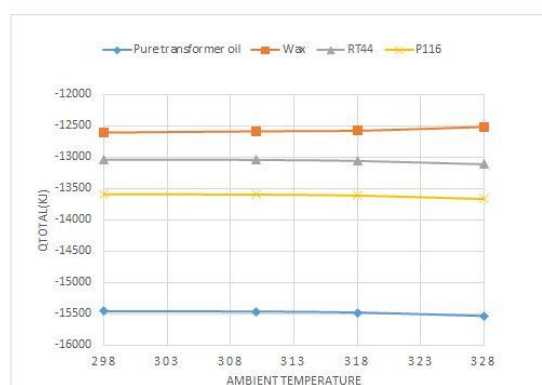


Fig. 10 variation of the total heat of the transformer with the shield of PCMs used at different ambient temperature

8- Conclusions:

In this paper, using of the phase change materials have been numerically studied with closed containers and mixed with oil for cooling of the electrical transformer. Different types of PCMs are selected (P116, RT44 and Paraffin wax) at different ambient temperatures with different mixed ratio and masses. From the obtained results, the following conclusions can be made:

1. Using of PCMs leads to reduce temperature of transformer compared with the case of pure oil.
2. The average temperature decreased with increased the mass of PCM due to increase in quantity of PCMs added.
3. Using PCM depending on the weather conditions.
4. Using the PCM as shield lead to reduce the maximum temperature compared with pure oil.

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