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Thermal and structural analysis of oil-based type transformer

Yağlı tip transformatörde termal ve yapısal analiz

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Abstract

In this paper, a hermetically sealed transformer with a power of 1600 kVA is used to make the mechanical calculations and analysed according to the heat generated by energy transmission. The heat generated on the transformer causes the insulation oil to heat up and increase in volume. Accordingly, the increasing insulation oil volume in the transformer tank causes a pressure increase on the tank. In our study, mechanical stresses created by the temperature and pressure increase due to the heat generated are calculated. These calculations are investigated according to strength, cooling, and construction approaches of tank with the corrugated wall and analysed its effect in design using ANSYS@FLUENT and ANSYS@MECHANICAL combination simulation software based on Finite Element Method. Temperature distribution and thermal limitations are critical to correct design. Temperatures exceeding the permissible thermal limits can cause serious damage to transformer components. On the other hand, a tested prototype tank is provided to compare the numerical, analytical, and experimental values. However according to the results, the stress concentrations are observed at the critical connection points, indicating the possibility of failure if an extra unexpected load is real.

Keywords: Winding, Design, Transformer, Structural and thermal analysis, Flow

Öz

Bu çalışmada, 1600 kVA gücünde hermetik olarak kapatılmış bir transformatör kullanılarak mekanik hesaplamalar yapılmış ve enerji iletiminden kaynaklanan ısıya göre analizleri yapılmıştır. Transformatörde oluşan ısı izolasyon yağının ısınmasına ve hacminin artmasına neden olur. Buna bağlı olarak trafo tankında artan izolasyon yağı hacmi tank üzerinde basınç artışına neden olur. Çalışmamızda sıcaklığın oluşturduğu mekanik gerilmeler ve oluşan ısıya bağlı olarak basınç artışı hesaplanmıştır. Bu hesaplamalar, oluklu duvarlı tankın mukavemet, soğutma ve yapım yaklaşımlarına göre incelenmiş ve sonlu elemanlar yöntemine dayalı ANSYS@FLUENT ve ANSYS@MECHANICAL kombinasyon simülasyon yazılımı kullanılarak tasarımdaki etkisi analiz edilmiştir. Sıcaklık dağılımı ve termal sınırlamalar doğru tasarım için kritik öneme sahiptir. İzin verilen termal sınırları aşan sıcaklıklar, transformatör bileşenlerinde ciddi hasara neden olabilir. Öte yandan sayısal, analitik ve deneysel değerlerin karşılaştırılması için test edilmiş bir prototip tank sağlanmıştır. Ancak sonuçlara göre, kritik bağlantı noktalarında gerilme yoğunlaşmaları gözleniyor, bu da ekstra beklenmedik bir yükün gerçek olması durumunda sorun olasılığını gösteriyor.

Anahtar kelimeler: Sargı, Dizayn, Trafo, Yapısal ve termal analiz, Akış

1 Introduction

A transformer is a device which transfers electrical energy (power) from one voltage level to another one with AC. [1] The history of the transformers is based on to the Faraday's Law of induction. After the induction coil found by Nicholas Callan in 1836, the transformer is developed in 1885. The design of transformer was succeeded in a few years.

The classifications of transformers can be done in different ways. But the most preferred classifications are based on the cooling types (distribution oil immersed or power oil immersed, cast resin), the primary and secondary voltages (step-up, step-down) and intended purpose (generator, power, network, special).

In general, the most commonly used transformer types are dry or oil types. When dry type transformers (cast resin) are used then cooling is supported by air which is not good option in terms of safety because of absence of extension tank. In addition to, air insulation is not efficient as oil insulation. Therefore, the requirements for the protection quality of the windings of a dry transformer are consequently much higher due to this weakness. Channels with special geometries are designed in order to remove heat by means of convection. Optimization of the total surface area of channels designed is a problem that must be solved.

Another problem must be considered is that the surfaces of transformer which is in contact with environment create risks when the transformer is mounted on a base. Fixation points of transformer may affect the performance of transformer.

Oil immersed type transformer has many advantages when compared with air cooled dry types. First of all, oil transformers can be used at high power and voltages levels, Secondly, it has higher impact resistance on outer surfaces because of more smooth external surfaces. Finally, the

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regional climate may be relatively humid and hot at which oil transformer's performance is better.

Oil immersed type transformer structures use either radiator or corrugated wall for cooling the oil tank.

Corrugated wall type is generally used up to 4000 kVA. If the power requirements exceed 4000 kVA, then transformer with radiators are better solutions. The only difference between structure of radiator and corrugated wall types is that corrugated wall is capable of absorbing volume expansion due to temperature increase because of elastic structure behaviour of corrugated wall whereas this is not valid for radiator type [2]. The tank with corrugated wall oil immersed transformer is also called as hermetically sealed oil transformer. The working principle of a sealed oil transformer is based on the expansion action of the tank due to the volume change of the insulating oil with increasing temperature [3]. When the insulating oil expands, the volume of the corrugated wall fins increases, preventing pressure rise inside the transformer [4], as shown in Figure 1.

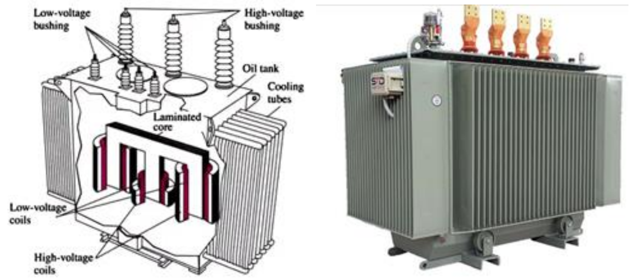

Figure 1. Hermetically sealed oil transformer

There are core and winding which are the heat source inside of the transformer tanks and there is a negative oil pressure between the tank and winding as shown in Figure 2. The heat generated from the heat source (winding) during current flow is dissipated through the cooling systems. Winding has 3 LV and 3 HV coils. The heat transfer is obtained as convection and conduction between heat source, oil, corrugated wall, and the air.

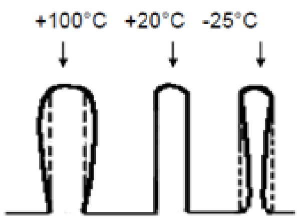

Figure 2. Corrugated wall fin volume change

The heat transfer of conduction is very small with respect to the convection according to the small thickness of the corrugated wall.

When the current flowed over the winding conductor, transformer losses some part of energy transformed as heat generation. The resistance to current flow in wiring produce heat and this causes temperature rise. The lifetime of a transformer is determined by the aging of the cellulose-based insulation within the windings. Therefore, excess temperature must be kept within the specified temperature limits.

When the transformer has excess (high) temperature, it can cause serious damage on the components. Temperature rise must be kept between 55ºC and 65ºC for standard oil-based transformers. These values are calculated assuming a maximum ambient temperature of 40ºC. F the transformer is sussed in an environment at which temperature is higher than this value then high temperature may cause a decrease in transformer life due to fatigue of the transformer. There will be a certain amount of wear on insulation paper for each excess temperature rise. It will consequently cause electrical discharge and mechanical stress and material deformation the tank.

On the other hand, viscosity of oil depends on the temperature. Increasing temperature changes viscosity and repeating cycles will cause to deterioration in the characteristics of oil. Additionally, the relative moisture within the oil is reduced with increasing temperature. The decrease in relative moisture content is due to the fact that solubility of water in the oil increases as the temperature of the oil increases. If the temperature rise is not controlled, then it can completely damage the transformer and even cause to fire. For this reason, the temperature rising must be well controlled so as not to cause damage on important and expensive power distribution devices or not to cause poor performance [5-8].

As a result of discussion above the transformer design must meet both thermal and structural integrity requirements under operating conditions.

In many studies, we can see some analysis and calculations to obtain the optimum design for the transformer. An expansion function is applied into the oil immersed transformer with corrugated wall regarding to the change of volume of the insulating oil with the increase in temperature [4]. Therefore, the thermal and structural stability of the transformer to cope with the pressure change due to temperature change is analysed. Also, there is a study related to a simulation using thermal analysis in finite element method model for the power distribution transformer. The study showed the maximum temperature is occurred in the region where the windings are located by [9].

In this study, the temperature limits are calculated analytically, analysed by using FEM method, and measured experimentally to compare results so as to develop a reliable numerical model for providing optimum life aging of the transformer to be reference to the designers. The proof of the reliability of FEM model showing results close to experimental and analytical values will help to use it for further design purposes especially for cost reduction.

2 Material and methods

Ansys program with two different features (CFD-Mechanical) were used to analyse the mechanical deformation on transformer when the oil temperature rises. In order to perform this analysis Fluid-Solid-Interaction approach is used.

CFD (Computational Fluid Dynamics) is a branch of fluid mechanics. The heat generated in the winding directly accelerates the aging of the insulation material. The CFD model uses temperature as input to find the stresses or pressures on the walls due to thermal expansion of oil. ANSYS Fluent has two main solvers based on Finite Volume Method that offer solutions that reduce memory usage and solution speed, especially for large problems, high Reynolds number turbulence, and source term-dominated flows. There are advantages in this respect. In Finite Volume Method, the domain is discretized into a finite set of control volumes, and the general transport equations are solved for this set of control volumes. These are Continuity, Momentum and Energy Equations.

Mechanical feature represents to examine the interaction of a fluid flow with a solid structure by using Static Structural Module. In our system, the fluid is a cooling oil, and the solid structure is the tank. There is a pressure occurred by expansion of oil due to heating on the tank. When the pressure is so high, there can be a damage on the tank walls due to the stress. Moreover, these negative mechanical effects are not wanted in the parts. So, in our study, the stress on the tank is analysed to avoid these circumstances and be reference for future designs.

There are some studies on different boundary cooling conditions of oil and oil with water for FEM and CFD analyses. In [10], it is seen that the hybrid cooling system consisting of oil and water is more effective in the case of insulating oil than full oil. However, the power of the transformer is 5 kVA and there is no corrugated wall/radiator in the structure. The hybrid cooling system is very effective with these small features, but the insulation oil for our system consists of anhydrous oil since we have high power and winding dimensions.

Before starting the analysis, the tank design is obtained numerically due to electrical and mechanical parameters regarding to winding which made of copper. Then, the oil to be used in the tank and the temperature and the pressure factors resulting from the use of this oil are calculated. In the end, relevant boundary conditions are implemented to the analysis and then the mesh is applied, and the system is run.

The specifications for the worked transformer are determined as in Table 1.

Table 1. Specifications of worked transformer

Specifications	
Power of transformer	1600 kVA
Heat generated from windings (W_{55})	11,06-kW
Height of HV-LV winding	824 mm
Diameter of LV winding	293 / 392 mm
Diameter of HV winding	408 / 524 mm
Tank LxBxH	1700 x 590 x 1550 mm

Then, the construction of the transformer was designed by a 3D CAD software. Here, outer dimensions of the tank (made of S235JR) are used to absorb the heat generated by active part (coils/windings). The used corrugated wall dimensions are as:

38 pieces (N_1), on top and bottom horizontal side in Figure 3.

200 mm fin depth (T_{w1}),
1.2 mm fin thickness (s),
1200 mm fin height (H_w),
The dimension between two fins (T_k) is 45 mm.
13 pieces (N_2), on left and right vertical side in Figure 3
50 mm fin depth (T_{w2}),
1.2 mm fin thickness (s),
1200 mm fin height (H_w),
the dimension between two fins (T_k) is 45 mm.

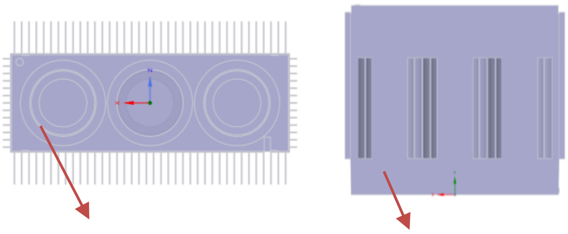

Figure 3. Oil volume

After drawn 3D of transformer, the geometry was imported into ANSYS software and fluent feature was connected to the geometry. Then, the oil volume of the transformer (Figure 3) was generated by Space-Claim interface.

2.1 *Heat dissipation capacity*

According to the construction of transformer, tank has a heat dissipation capacity depending on the oil temperature. We can perform calculation by making summation of its parts dissipation capacity. We can calculate the heat dissipation capacity of cover first, capacity of a fin of corrugated Wall secondly, then capacity of whole corrugated wall, and capacity of whole tank finally.

Heat dissipation capacity for cover seen as below Equation (1). Here, W_{55D} is a specific heat dissipation capacity for cover which is 0,6 kW/m^2. Bp is tank upper side bracket size which is 65 mm. The equation is multiplied with 2 due to the symmetry.

$$P_{55D} = 2W_{55D}\left(B + 2B_p\right) * 10^{-6} kW \quad (1)$$

$$P_{55D} = 2 * 0.6 * (590 + 2 * 65) * 10^{-6} = 8{,}64 * 10^{-4} kW$$

Heat dissipation capacity for a fin seen as below Equation (2). Here, W_k is characteristic heat dissipation for corrugated wall fins as seen Figure 4 due to fin depth. L_p is open form length for corrugated walls. K_2 is height effectivity factor for corrugated wall fin height as seen Figure 5. W_s is specific radiated heat which is 0.305 kW/m^2.

$$P_{55W} = H_w\left(W_k * L_p * K_2 + W_s * T_k\right) * 10^{-6} kW \quad (2)$$

L_{p1} = 404.2 mm for 200 mm fin side
L_{p2} = 104.8 mm for 50 mm fin side

$$P_{55W1} = 1200(0.283 * 404.2 * 0.97 + 0.305 * 45) * 10^{-6} = 0.15\ kW$$

$$P_{55W2} = 1200(0.342 * 104.8 * 0.97 + 0.305 * 45) * 10^{-6} = 0.06\ kW$$

Heat dissipation capacity for corrugated wall seen as below Equation (3). Here, E_w is fin extension length for sides as Equations (4) and (5). The equation is multiplied with 2 due to the symmetry.

$$P_{55WW} = (N_1 P_{55W1} + N_2 P_{55W2}) + \{2{,}24 * H_w * (E_{w1} + E_{w2}) + 0.86(T_{w1} + T_{w2} - 90)\} * 10^{-6} kW \quad (3)$$

$$E_{w1} = (L + 2s - (N_1 - 1) * T_k) * 0.5 = 18.7\ mm \quad (4)$$

$$E_{w2} = (B + 2s - (N_2 - 1) * T_k) * 0.5 = 26.2\ mm \quad (5)$$

$$P_{55WW} = 2 * (38 * 0.15 + 13 * 0.06) + \{2{,}24 * 1200 * (18.7 + 26.2\,) + 0.86(200 + 50 - 90)\} * 10^{-6} = 12.96\ kW$$

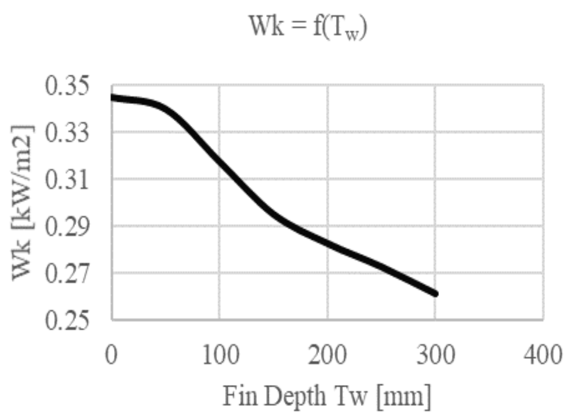

Figure 4. Characteristic heat dissipation for corrugated wall fins (W_k)

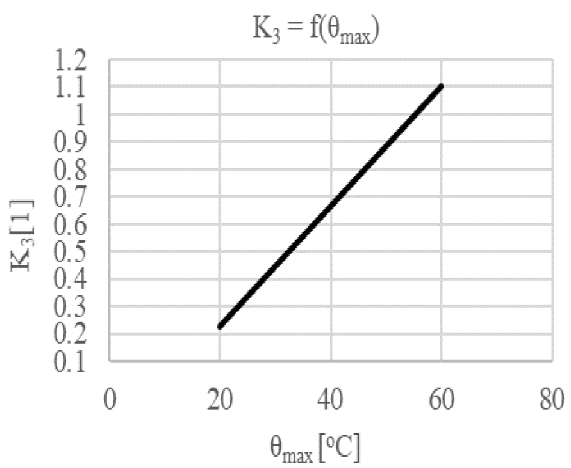

Figure 5. Height effectivity factor for corrugated wall height (K_2)

Heat dissipation capacity for tank seen as below Equation (6). [11,12,13] Here, K_3 is the heat dissipation capacity for max oil temperature which is 60°C as seen Figure 6.

$$P_{55} = (P_{55D} + P_{55WW}) * K_3\ kW \quad (6)$$

$$P_{55} = (8{,}64 * 10^{-4} + 12{,}96) * 1{,}1 = 14{,}25\ kW$$

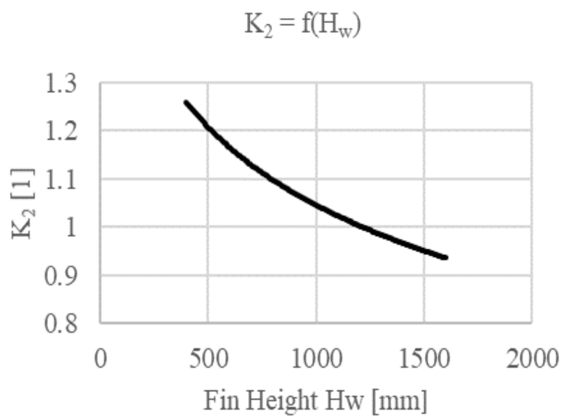

Figure 6. Heat dissipation capacity K_3 for oil temperature θ_{max}

2.2 *Pressure*

After calculated the heat dissipation occurred on tank due to transformer design, the pressure is obtained according to the temperature rise with Equations (7) and (8). Firstly, we need oil mas, density of oil, volume of oil at the related temperatures. The oil is filling at 25°C and the maximum ambient temperature is 40°C. As mentioned, Heat Dissipation Capacity chapter, the maximum oil temperature is 60°C. The oil mass for related tank is 1130 kg to fill the volume. The technical properties of used cooling oil which is mineral oil is shown as Table 2. [14-16]

Table 2. Properties of transformer oil

Property	Limits for transformer oil due to temperature			
	25°C	40°C	60°C	80°C
Density (kg/m^3)	890	880	869	856
Kinematic Viscosity (mm^2/sn)	17.08	9.59	5.37	3.43
Dynamic Viscosity (kg/m-sn)	0.015	0.008	0.005	0.003
Thermal Conductivity (W/m-K)	0.133	0.130	0.128	0.126
Specific Heat (J/kg-K)	1902	1974	2077	2187

$$T_{av,max} = T_{amb,max} + \left(T_{oil,rise} * \frac{\left(\frac{W_{55}}{P_{55}}\right)^{0.8}}{1{,}2} \right) °C \quad (7)$$

$$T_{av,max} = 40 + \left(60 * \frac{\left(\frac{11{,}06}{14{,}25}\right)^{0.8}}{1{,}2} \right) = 80{,}82\ °C$$

$$T_{max,rise} = T_{av,max} - T_{filling} = 55{,}82\ °C \quad (8)$$

After obtaining the temperature conditions, the pressure of tank was calculated in Equations (12) and (13). [17,18] Firstly, we need to oil volume of tank as Equation (9).

$$V = \frac{m}{\rho} = \frac{1130}{0.895} = 1262.57\ lt \quad (9)$$

The maximum density of the oil in Equation (11) is related to the maximum of volume for oil in Equation (10) and volume coefficient of expansion which is 0,000755774.

$$V_{max} = V * av * (T_{max,rise} + T_{filling} - 20) + V \quad (10)$$

$$V_{max} = 1262{,}57 * 0{,}000755774 * (55{,}82 + 25 - 20) + 1262{,}57 = 1320{,}6\ lt$$

$$\rho_{max} = 1130 / 1320.6 = 0{,}855\ kg/lt \quad (11)$$

$$P_{static,corrugated\ wall} = H_w * \rho_{max} * 0{,}0981\ Bar = (1{,}2 * 0{,}855) * 0{,}0981 = 0{,}1\ bar \quad (12)$$

$$P_{static,bottom} = H_k * \rho_{max} * 0{,}0981\ Bar = (1{,}55 * 0{,}855) * 0{,}0981 = 0{,}13\ bar \quad (13)$$

Now, we have the static pressures for corrugated wall and bottom.

2.3 CFD base

After the calculations are done and obtaining a good mesh, the setup for solution is generated. We must add boundary conditions for using sections which are cooling oil, winding and the corrugated wall in transformer to get results in CFD. When see the Table 3, the Taurus mineral datasheet consists of properties as density, volume, etc.

Table 3. Taurus mineral oil datasheet

Property 1-Function	Unit	Test Method	Specification Limits Min	 Max
Viscosity, 40ºC	mm^2/s	ISO 3104		12.0
Viscosity, -30ºC	mm^2/s	ISO 3104		1800
Pour point	ºC	ISO 3016		-40
Water content	mg/kg	IEC 60814		30
Breakdown voltage				
-Before treatment	kV	IEC 60156	30	
-After treatment	kV	IEC 60296	70	
Density, 20ºC	kg/dm^3	ISO 12185		0.895
DDF at 90ºC		IEC 60247		0.005

Secondly, the heat flux is calculated for the winding according to 11,06-kW heat generated with 3 HV and LV coils. The heat generated is divided to heat dissipating surfaces to obtain heat flux in Equation (14). There are 4 areas as shown Figure 7 to dissipate the heat in a coil. In above equation, the heat flux was calculated according to the areas.

$$A_1 = 2\pi rh = 2 * \pi * 0{,}262 * 0{,}824 = 1.35\ m^2$$

$$A_2 = 2\pi rh = 2 * \pi * 0{,}204 * 0{,}824 = 1.05\ m^2$$

$$A_3 = 2\pi rh = 2 * \pi * 0{,}147 * 0{,}824 = 0.76\ m^2$$

$$A_4 = 2\pi rh = 2 * \pi * 0{,}196 * 0{,}824 = 1.01\ m^2$$

$$A = 3A_1 + 3A_2 + 3A_3 + 3A_4 = 12{,}52\ m^2$$

$$\dot{q} = Q/A = 11060/12{,}52 = 883{,}1 \quad (14)$$

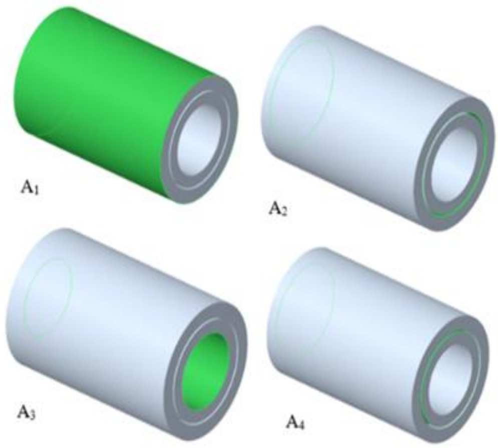

Figure 7. Heat dissipating surfaces (green areas)

Latest, the convective heat transfer coefficient of air for heat transfer between corrugated wall fin surface and the air is calculated with Equation (15). For this calculation, we need a heat dissipation capacity to examine. 0.06 kW fin side heat dissipation (P_{55W2}) capacity was considered. This 0.06 kW energy consists of one fin area with whole surfaces The heat transfer from internal fin to external fin is equal to the heat transfer from external fin to air on same plane. The fin physical properties are shown below Figure 8.

The 0.06 kW (60 W) heat dissipation capacity is valid for all surfaces as $4A_1$, $2A_2$ and $2A_3$. The thermal conductivity (k) of used material (S235JR) is 45 W/m℃.

$$Q = k * A_{all} * \Delta T \quad (15)$$

$$A_{all} = 4A_1 + 2A_2 + 2A_3$$

$$A_1 = 0{,}05 * 1{,}2 = 0{,}06\ mm^2$$

$$A_2 = 0{,}0084 * 1{,}2 = 0{,}01\ mm^2$$

$$A_3 = 0{,}05 * 0{,}0012 = 0{,}00006\ mm^2$$

We can neglect the heat transfer obtained from A3 side as the area is so small.

$$A_{all} = 4A_1 + 2A_2 = 0,24 + 0,02 = 0,26\ mm^2$$

$$60 = 45 * 0,26 * \Delta T$$

$$\Delta T = 5,13\ ℃$$

So, now we can calculate the heat transfer obtain an external one surface from A_1 side.

$$Q = k * A * \Delta T = 45 * 0,06 * 5,13 = 13,85\ W$$

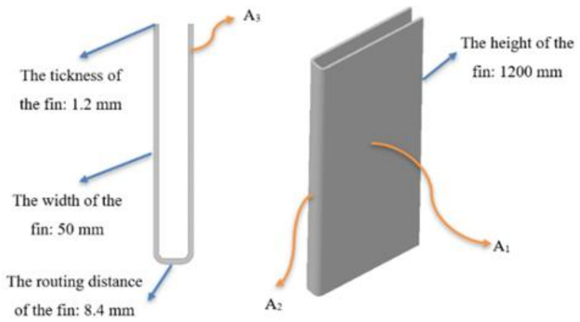

Figure 8. Corrugated wall fin physical properties

This 13.85 Watt is a heat transfer from internal fin to external fin based on the A_1 surface. We have also another heat transfer from external fin to air based on the A_1 surface. So, these are in same plane and have same heat transfer too. We have infinitely long fin according to the a/b ratio that is going to infinity as 1.2/1200=0.001. It can be determined from Fourier's law of heat conduction as $Q = \sqrt{hpkA}\Delta T$ (Equation (16)). The thermal conductivity of air at 26ºC is $0.2632\ W/mK$. [19] The temperature of the wall is approximately equal to $T_{max,rise}$. $T_{max,rise}$ is 55,82℃ so we can progress with 55℃.

$$\Delta T = T_{wall} - T_{air} = 55 - 26 = 29℃$$

$$p = 2(0.05 + 1.2) = 2.5\ m$$

$$A = 0.05 * 1.2 = 0.06\ m^2$$

$$Q = \sqrt{hpkA}\Delta T \quad (16)$$

$$Q = \sqrt{h * 0.06 * 0.2632 * 2.5} * 29$$

$$\sqrt{h * 0.06 * 0.2632 * 2.5} * 29.82 = 13.85$$

$$h = 5.2\ W/m℃$$

After the boundary conditions of the tank and windings are entered, some justifications must be entered for the system calculation.

2.3.1 *Circulation type*

The system has natural circulation because the density of the transformer oil changes caused by temperature differences.

2.3.2 *State of the system*

The state of the overall system that contains balanced flows and does not change over time is called the steady state, and this is described for our mentioned system.

2.3.3 *Model of the system*

In our system there are viscous and energy that are obtained according to the heat transfer between the winding, tank wall and the air. For the viscous model of the system is defined as Spalart-Allmaras Equation for some advantages (simple one equation, eddy viscosity transport equation consists, gives good results for pressure solutions with quality mesh) [20].

2.3.4 *Solution of the system*

Pressure-velocity coupling algorithms are used because of the small Mach number. Moreover, Couple method is preferred for be robust and efficient single-phase implementation for steady-state flows which our system has [21,22].

3 Mechanical base

After the CFD solution is done, static structural module is applied to examine the obtained stress and strain on the tank. In this study, there is an interaction of a fluid flow with a solid structure when fluid flow exerts the pressure or thermal loads on the structure. The loads may cause structural deformation.

We can transfer the geometry and the solution to result the structural response. Here, we have a fixed support on the wheelbase connection to the wheel, imported earth gravity and body temperature.

4 Result and discussion

Ansys FSI simulations give following results. It can be seen that the maximum temperature of the corrugated wall oil volume is occurred under the cover due to the rise of the oil flow with increasing temperature. The maximum temperature of the whole transformer oil is occurred on the winding section specially the middle of the oil channels because of the heat source as seen Figure 9.

The maximum pressure which is sum of static and working (dynamic) pressure is occurred on the bottom of the tank according to the hydrostatic pressure of oil. Analytical calculations made in this study show the total pressure is sum of the working and static pressures as seen Figure 10.

We have the temperature rise test result by Schneider Electric Laboratory as seen Table 4.

Table 4. Experimental results

Max oil temperature	Max temperature on LV winding	Max temperature on HV winding
43.3 ºC	59.6 ºC	58.3 ºC

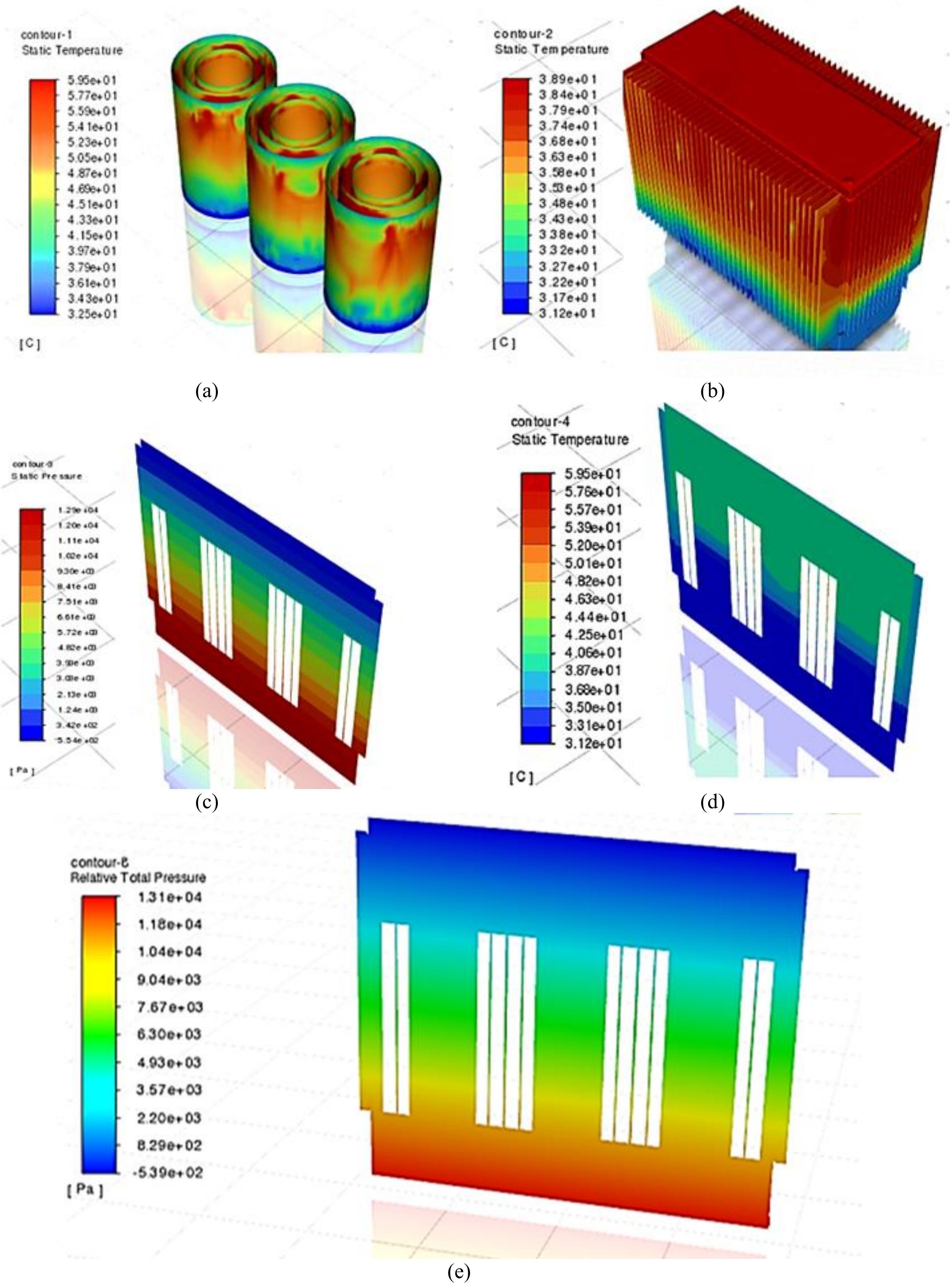

Figure 9. CFD results (a) Temperature distribution on windings oil volume (b) Temperature distribution on transformer oil volume (c) Pressure distribution on transformer oil volume with middle section (d) Temperature distribution on transformer oil volume with middle section (e) Working pressure on middle section of transformer oil volume

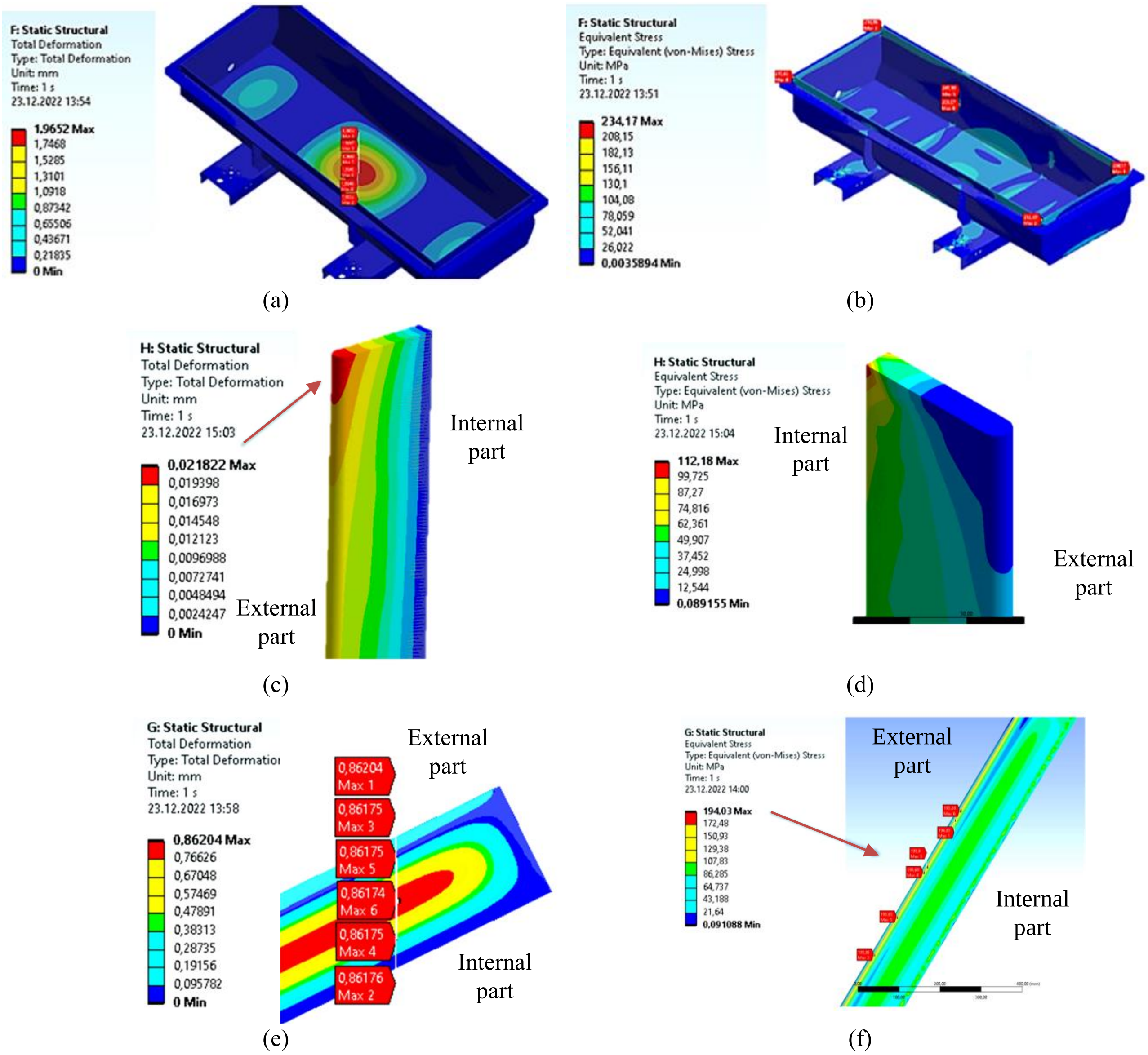

Figure 10. Mechanical results (a) Deformation on the tank bottom (b) von-Misses stress on the tank bottom (c) Deformation on the corrugated wall (short side) (d) von-Misses stress on the corrugated wall (short side) (e) Deformation on the corrugated wall (long side) (f) von-Misses stress on the corrugated wall (long side)

5 Conclusion

In this study, it was aimed to examine both the mechanical and thermal coupling effects on the stress,strain and temperature distribution of transformer when it is in operation.

Now, we can see the summary table of conclusion in Table 5. According to the results and evaluations, it has been determined that the worked tank design has enough stability and strength in case of compared to numerical, analysis and experimental results. The maximum temperature in the tank oil is 38.9°C which is occurred on the under the transformer cover plate in the analysis but when checking the experimental result, that is 43.3°C.

The maximum temperature on the windings is about 59.5°C in analysis, the numerical calculations are applied according to the 60°C (because of the capacity of insulation products to withstand temperature), and the numerical result is about 59°C in experimental result. The reason of these differences can be related to the production processes. The bending, welding or connection details could not be same quality with numerical and analysis results. When we examine at the pressure arising from the fluid expansion due to this temperature increase and decrease, we can see that the maximum working pressure (0.131 bar) is almost equal to the max static pressure (0.129 bar) and is consistent with the numerical results.

In addition, the mechanical effect of the applied pressure due to thermal expansion of oil on the product is more important on the bottom of tank and wheelbase. According to the distribution of stress, the internal tank bottom surfaces might not be highly effected. There are some locations that effected more with rest to other parts of the structure. As an example, if welding digs of fins will have radius (not sharp corners), then stresses at that edges could be decreased. On the other hand, the short side corrugated wall has small fin depth (50 mm), so the deformation and stress are occurred with small values in these edges as expected whereas, for the long side corrugated wall, the stress and deformation have greater value related to the fin extension geometry. The maximum deformation is obtained in the middle of the fin depth.

Table 5. Analysis result

Figure Number	Static Temperature (ºC)		Pressure (Pa)		Stress (Mpa)	Deformation (mm)
	Min	Max	Min	Max	Max	Max
9/a	32.5	59.5	-	-		
9/b	31.2	38.9	-	-		
9/c	-	-	$1.29*10^4$	$5.54*10^2$		
9/d	31.2	59.5	-	-		
9/e	-	-	$1.31*10^4$	$5.39*10^2$		
10/a						1.9652
10/b					234.17	
10/c						0.021822
10/d					112.18	
10/e						0.86204
10/f					194,03	

As a conclusion, considering the unit price of the steel parts, the overall thickness of the parts can be reduced if the design of critical regions of the stress distribution can be improved.

There are some possible future works can include:

- The tank bottom thicknesses could be decreased according to the pressure level.

- The structure of the wheelbase could be modified so as to get minimum stress.

- The connection point between the wheelbase and the wheel could be improved.

- The support profiles could be reconsidered due to the critical points.

Conflict of interest

The authors declare that there is no conflict of interest.

Similarity rate (iThenticate): %18

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