ENHANCING MICROWAVE OVEN PERFORMANCE AND TRANSFORMER QUALITY THROUGH EFFICIENT HIGH VOLTAGE TRANSFORMER COOLING

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This paper describes a method and device for effectively cooling a high voltage transformer inside a microwave oven, with the aim of swiftly removing heat generated during operation, hence improving both the microwave oven's and the transformer's performance and quality. The device incorporates corrugated tank surfaces, electrical connection lines with protrusions, and epoxy to prevent cooling oil leakage. The transformer is inserted into a designated tank and sealed to separate the coil and core from the outside environment, allowing for better cooling and protection against electrical shock. Additionally, an oil is injected to absorb heat generated by the high temperature of the core and coil. The effectiveness of this method is validated through the finite element method and computational fluid dynamics techniques. Numerical analysis revealed a significant decrease in the maximum temperature rise of the transformer by around 44.2°C. This finding suggests that transformer oil cooling is a more effective method for controlling temperature rise in microwave ovens compared to traditional cooling methods.

Key words*: High voltage transformer, microwave, oil, cooling, heat, temperature*

1. Introduction

Microwave ovens are household appliances that cook or reheat food using a magnetron-type microwave tube with a high-voltage and filament-voltage power supply. They use a conventional transformer to increase the voltage of the power supply. The transformer consists of a core, primary, filament and secondary windings that are wound around the core. The transformer is installed in an electrical component area that is partitioned from the cooking chamber. A high-voltage capacitor and a cooling fan are also located in the same area as the electrical components. In this context, high-voltage transformers are crucial in microwave ovens for generating microwave radiation, but their efficiency depends on effective thermal management.

The thermal performance of high-voltage transformers is crucial for their operational lifespan, safety, and effectiveness. They operate under varying load conditions, and overheating can lead to performance degradation, reduced lifespan, increased maintenance costs, and safety hazards in extreme cases. Transformers generate heat due to coil resistance and eddy currents from magnetic flux density variations. To dissipate this thermal energy, a cooling apparatus is used. Conventional high-voltage transformers use insulation paper to conduct heat from the coil to the core, but this method does not provide sufficient cooling. Natural and forced convection cooling methods, which use fans for enhanced cooling, struggle with efficient heat management during transformer operation. The sealed portion of the transformer also weakens the cooling effect. Mounting a high-voltage transformer on an external device exposes users to dangers like electrical shocks. Traditional cooling methods in microwave ovens rely on empirical approaches, which often fail to manage heat efficiently. As power requirements evolve, there is a pressing need for innovative cooling techniques that offer precise temperature control and enhanced performance.

Traditional transformer structure designs use complex empirical formulas for calculating parameters, loss, and temperature rise, which limit accuracy. The processes of design, machining, testing, and optimization can lead to low accuracy. Transformer structures are often complex due to their special functions, making independent testing difficult. Recently, computational fluid dynamics (CFD) and finite element method (FEM) simulations have been applied to study transformer cooling, addressing heat transfer and electromagnetic problems[1-8]. These techniques accurately predict transformer behavior without costly prototypes, identify potential issues, and improve transformer installation safety. Numerical simulations can save time and cost in research and enhance development efficiency.

This research aims to enhance transformer thermal performance prediction formulas for heat generation and distribution within coils, and to develop more efficient calculation methods based on experimental results. The presentation of reviewed research publications can be easily examined in their major context. Researchers such as Pierce [9] developed a mathematical model to predict the rise in hottest spot temperature in transformers by analyzing heat transfer constants. teNyenhuis et al [10] presented a 2-D FEM thermal calculation of core hot-spot temperature in power and distribution transformer and discusses two calculation methods for accurately determining core hot-spot temperature. Hwang et al [11] developed a three-dimensional thermal model of a high-frequency transformer, utilizing FEM and electromagnetic field analysis to estimate local losses and validate its accuracy. Lefevre [12] described a mixed analytical and numerical method for studying the electromagnetic and thermal behavior of a dry type transformer under nonlinear loads, accounting for skin and proximity effects in the windings. Tsili [13] introduced a hybrid thermal modeling technique for transformers, combining numerical and analytical calculations to accurately predict temperature distribution characteristics and improve design calculations. Rosas [14] proposed a system for enhancing oil-immersed electrical transformer cooling using heat pipes, based on theoretical analysis and experimental results. Nakata and Takahashi [15] explored the use of numerical field calculations to analyze flux distributions in transformer cores, considering factors like core constructions, joint configurations, and magnetizing characteristics. Enokizono et al [16] introduced a new model for vector magnetic properties, incorporating hysteresis, and applied it to transformer core models, calculating iron loss and addressing anisotropic problems. Most transformer research has been focused on electric transformers, with high-voltage transformer research for microwave ovens being relatively rare.

A recent study focused on the computation of temperature distribution by Ding et al [17] presents a novel iron core configuration for leakage inductance transformers used in microwave ovens. The proposed approach involves using diverse silicon steel sheet models to mitigate loss and heat, as well as altering the iron core arrangement from E-I to E-E type. As a consequence, a substantial reduction in temperature increase is achieved. However, those proposed approaches could be found to increase the cost and complexity of implementing diverse silicon steel sheet models. Additionally, the alteration of the iron core arrangement may lead to difficulties in maintaining structural integrity and stable performance over time.

Hence, the current investigation has been carried out in light of the previous problems. This study aims to propose a method for cooling a high voltage transformer to quickly remove heat during operation. It involves implementing a sealed design, isolating the coil and core from external elements, and improving cooling efficiency. The study also addresses the treatment of electric connection lines from the transformer and enhances tank stability. These improvements are intended to protect the transformer from potential dangers, such as electrical shocks during microwave oven assessments. The goal is to develop a practical, efficient, and cost-effective cooling solution that can be integrated into existing systems, enhancing the overall performance and quality of both systems. Hence, in this study, an electromagnetic model of the proposed transformer was made with Ansys-Maxwell 3D and co-simulated with Ansys-Simplorer programme. Afterwards, the thermal effects of the transformer losses were carried out with the ANSYS-Mechanical Workbench module, and thus the thermal behavior of the transformers according to the load conditions was revealed. The number of finite elements in the model is about 400,000 and the number of degrees of freedom is about 1,200,000. The typical error of the solution of the system of linear equations is about 1×10^{-6}.

The rest of the paper is organized as follows. In Section 2, calculation of loss and heat dissipation is described. In Section 3, model description and loss measurementare presented. In Section 4, numerical methodology is described. In Section 5, discussion of the results is carried out.

2. Calculation of loss and heat dissipation

The transformer has two main components, the core and the winding, which are responsible for generating heat due to electromagnetic losses. The heat source in a transformer comes from the loss of core and winding, including iron core and copper losses. All these losses contribute to the overall heat generation in the transformer, which can lead to overheating and insulation aging.

2.1.1 Sources of heat generation

The winding loss, also known as copper loss, is caused by the resistance of the copper wire used in the transformer winding. When current passing generates load loss through the windings, causing flux leakage and generating the most heat during operation. Therefore, load loss may be accurately defined by eq. (1).

$$P_{Load} = P_{cu} + P_w + P_s \tag{1}$$

where, P_{Load} [W] – the total power loss in the transformer, P_{Cu} [W] – the power loss due to resistance in the transformer's windings, P_w [W] – the winding eddy current loss, and P_s [W] – the stray loss of winding.

The No-load loss can be divided into two components: hysteresis loss, which quantifies the loss of material due to the primary flux density in both the rolling and transverse directions, and eddy loss, which takes into consideration the loss caused by eddy currents resulting from the leakage magnetic flux flowing perpendicular to the direction of lamination. The no load loss can be expressed by eq. (2).

$$P_{NL} = P_h + P_e + P_c \tag{2}$$

where P_{NL} [W] – the No-load loss of transformer, P_h [W] – the hysteresis loss, P_e [W] – the eddy current loss and P_c [W] – the stray loss of core.

Eddy current and hysteresis losses account for nearly 99% of iron losses. Therefore, the No-load loss is usually approximated as an iron loss, which is calculated using Steinmetz equation (eq. (3))[18].

$$P_{NL} = K_h f \left(B_m^2\right) + K_e \left(fB_m\right)^{1.5} + K_c \left(fB_m\right)^2 \tag{3}$$

Where P_{NL} [W] – the total core losses (usually called as iron losses), f [Hz]– frequency, B_m [T]– the magnetic flux density, K_h – the static hysteresis coefficient , K_e – the eddy-current coefficient, and K_c –excess eddy loss.

The main internal heat sources of transformers are winding load loss and iron core no-load loss. The magnetic field and thermal field indirect coupling calculation scheme converts these values into heat production rate per unit volume, solving the temperature field of oil-immersed transformers.

2.1.2 Modeling and analysis of heat transfer processes

This section explains the use of CFD-based thermal-fluid modeling, which incorporates losses from electromagnetic analysis. The dissipation heat of internal heat is a comprehensive process that identifies three methods: conduction, convection, and radiation. The transformer utilizes a Q_{Cu} winding and a Q_{Fe} iron core as its heat source. Heat is transmitted to each surface through heat conduction and then dissipated from the surface to the transformer oil through heat convection. Finally, the heat of transformer oil is transferred to the oil tank wall through heat convection and radiation, which then dissipates to the surrounding environment. Fig. 1 illustrates a schematic diagram of the heat transfer process of an oil-immersed transformer, where Q represents the heat dissipating from the oil tank wall to the surrounding environment.

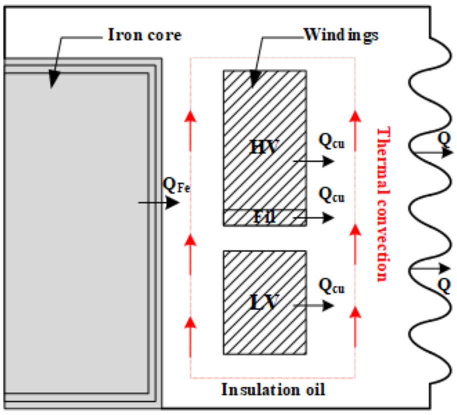


Figure 1. Transformer heat transfer diagram

Fourier's law (eq. (4)) , Newton's law(eq. (5)), and Stefan-Boltzmann's law (eq. (6)) are used to describe heat conduction, convection, and radiation. The equations are:

$$Q_{cd} = -kA_{cd}\nabla T \tag{4}$$

$$Q_{cv} = hA_{cv}\Delta T \tag{5}$$

$$Q_r = \varepsilon A_r \delta \left(T_w^4 - T_a^4\right) = A_r h_r \left(T_w - T_a\right) \tag{6}$$

where Q[Wm^{-2}]– the heat generation rate, k [Wm^{-1}K^{-1}]– the thermal conductivity, *h* [Wm^{-2}·K^{-1}]– the convection coefficient, A [m^{-2}]– the wetted area of heat transfer, ε– the thermal radiation coefficient, δ – the Stefan–Boltzmann's constant, h_r – the equivalent radiation coefficient, T_w [K] – the temperature of transformer tank, and T_a [K]– the ambient temperature.

Transformer oil is assumed to have an ideal incompressible Newtonian fluid characteristics[19, 20]. The mathematical model consists of simplified equations for mass eq. (7), momentum eq. (8), and energy conservation eq. (9), as follows:

$$\nabla \cdot \rho U = 0 \tag{7}$$

$$(\rho \mathrm{U} \cdot \nabla)\mathrm{U} + \nabla p - \mu \nabla^2 \mathrm{U} = F \tag{8}$$

$$Q + \nabla \cdot (\lambda \nabla T) = \nabla \cdot \left(\rho C_p U T\right) \tag{9}$$

where ρ [kgm^{-3}]– the density, μ[Pas] – the dynamic viscosity of transformer oil, U[ms^{-1}] – the velocity vector of the oil, V [m^{3}] – the volume of insulation oil, p[Pa] – the pressure of fluid, F[Nm^{-3}] the density vector of external force, C_p [Wm^{-1}K^{-1}] – the specific heat capacity of insulation oil, T[K] – the temperature, λ [Wm^{-1}K^{-1}] – the heat conductivity, and Q [Wm^{-3}] – the heat source.

The external heat, Q dissipation of a transformer is primarily determined by heat convection along its outer surfaces, as described by the third thermal boundary condition. Following Newton's law for cooling. Convection heat transfer occurs when fluid moves along a solid surface, and the coefficient can be calculated using eq. (10).

$$h = \frac{k_f}{l}\mathrm{Nu} \tag{10}$$

where *h* [Wm^{-2}·K^{-1}] – the convective heat transfer coefficient, *l*[m] – the characteristic length, k_f[Wm^{-1}K^{-1}] – the thermal conductivity of fluid, and Nu – the Nusselt number.

The Nusselt number of vertical plane Nu_v and horizontal plane Nu_h can be analyzed using heat-transfer theory can be calculated using respectively eq. (11), and eq. (12).

$$\mathrm{Nu}_v = \left\{0.825 + \frac{0.387\mathrm{Ra}^{1/6}}{\left[1 + (0.492/\,\mathrm{Pr})^{9/16}\right]^{8/27}}\right\}^2 \tag{11}$$

$$\mathrm{Nu}_h = 0.27\mathrm{Ra}^{1/4} \tag{12}$$

$$\mathrm{Pr} = \frac{\mu C_p}{k} \tag{13}$$

$$\mathrm{Ra} = \frac{g\beta\Delta T\, l^3 \rho}{\mu\alpha} \tag{14}$$

where R_a – the Rayleigh number, P_r – the Prandtl number, $\alpha[\mathrm{m^2s^{-1}}]$ – the thermal diffusion coefficient, C_p $[\mathrm{Wm^{-1}K^{-1}}]$ – the specific heat, k $[\mathrm{Wm^{-1}K^{-1}}]$ – the thermal conductivity, g $[\mathrm{ms^{-2}}]$ – the gravity acceleration, β $[\mathrm{K^{-1}}]$ – the volume expansion coefficient, ΔT [K] – the temperature difference between fluid and the solid surface, and μ[Pas] – the dynamic viscosity of the external fluid.

3. Model description and loss measurement

Fig. 2 depicts the schematic of the high voltage transformer, which typically consists of two secondary windings, one producing a low voltage output of 3.1 to 3.2 volts, primarily used to illuminate the magnetron filament. The second winding generates a high voltage AC output of 1800 to 2800 volts, with an average value of 2200 volts, which is required to operate the magnetron and generate microwaves for heating. A voltage doubling circuit is used to convert the high voltage AC output of the transformer into a form the magnetron can use, consisting of a diode and a high-voltage capacitor. This configuration converts AC voltage to DC, effectively doubling its magnitude, ensuring the magnetron obtains the necessary high voltage for its operation. The dimensions and specifications of the chosen transformer are depicted in fig.3.

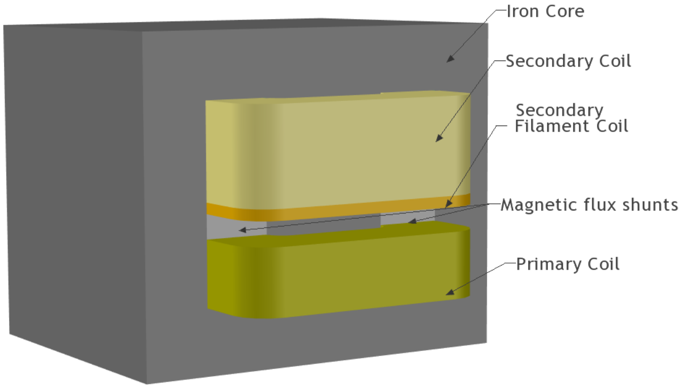


Figure 2. 3D model of transformer shape and its core elements

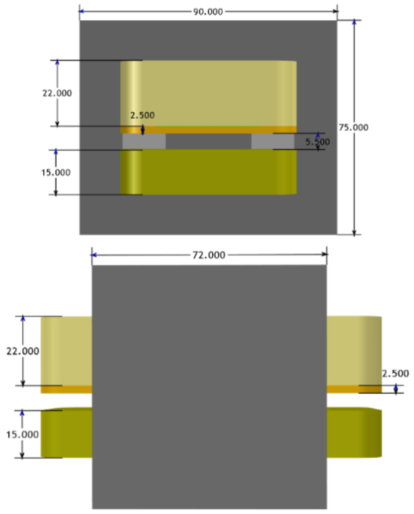


Figure 3. Simplified transformer size overview

The transformer has technical specifications of 700VA rated power, 50 Hz operating frequency, and 230/220 V [21,22]. It uses M125-027 type core material and copper conductor windings in modeling studies. Electric parameters are provided in tab. 1.

Table 1. Technical details of the transformer

Transformer Data	Value
Rated power	700VA
Turn of primary / secondary coil	230/2200
Primary voltage	AC 190- 240V
Secondary voltage	AC 2100V
No-load current	2.5A
Frequency	50Hz

The transformer operates in deep saturation, causing significant losses in iron core and copper coils. A quarter model was chosen due to transformer symmetry. Power losses were determined using MAXWELL and ANSYS Workbench software for coupled steady-state thermal analysis, while transformer geometry was imported from FEA electromagnetic software. Fig. 4 depicts an integrated circuit schematic for joint simulation of Maxwell and simplorer.

The electromagnetic FEA of a transformer reveals iron core and winding losses at a 220 V input voltage. Fig. 5(a) shows instantaneous curves, revealing an average iron loss of 8.4 watts. Fig. 5(b) shows instantaneous copper loss curves, indicating an average copper loss of 70.30 watts.

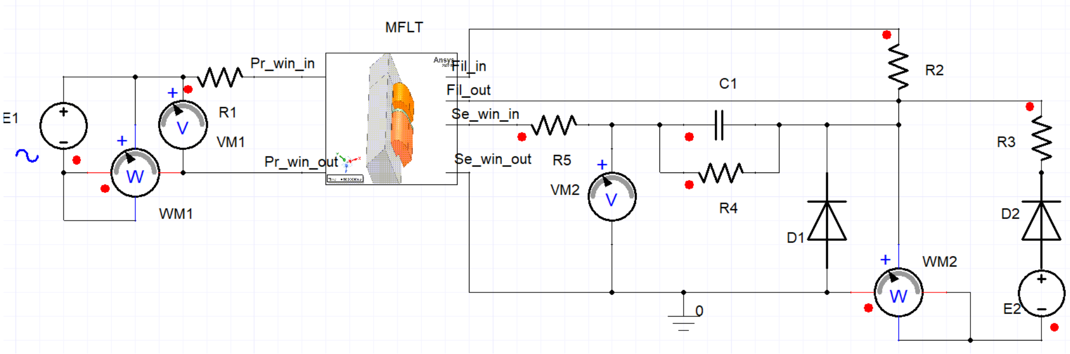
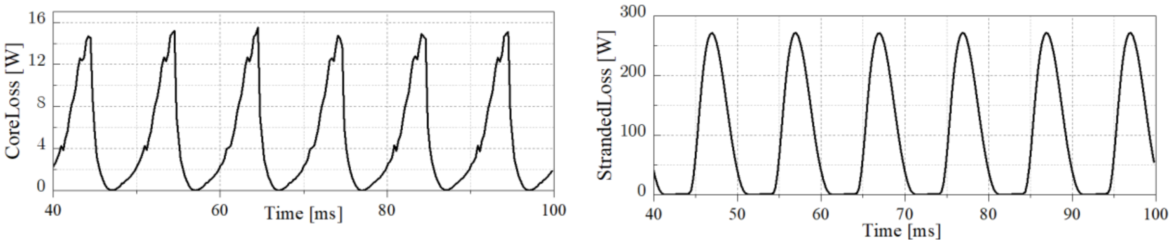


Figure 4. The integrated circuit schematic for the joint simulation of maxwell and simplorer



(a)

(b)

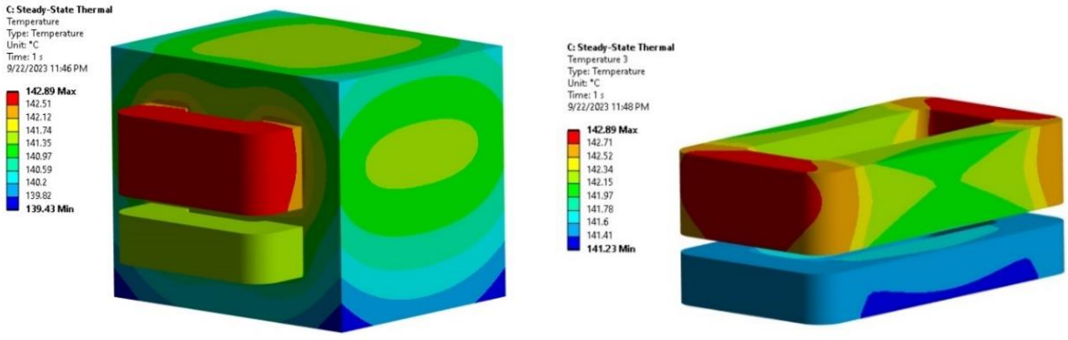
Figure 5. Transformer losses, (a) iron core loss, (b) copper winding loss

The thermal analysis of the core and winding losses is based on electromagnetic analysis data. The core and windings heat sources were determined and are given in tab. 2. It can be seen that the majority of heat source generators are powered by HV voltage, accounting for 59% of the total, followed by primary windings at 35% and the core at 6%, indicating that HV voltage is the primary contributor to heat generation.

Table 2. Measured value for heat generation

Part	Heat generation(W/m^3)
Core EI	103360.675
Magetics Shunts	25840.16875
H.V Windings	1000325.034
H.V Filament Windings	113672.8023
L.V Windings	682036.8138

The study uses a convective heat transfer coefficient of 20W/(m2·K) and a room temperature of 22°C for analyzing heat generated by iron and copper losses. Core and winding losses are imported into ANSYS Mechanical, with a maximum loading case considered and a 10 mm core meshing size maintained at unity. The temperature distributions of the core and winding from coupled thermal FEA are shown in fig. 6, with a difference due to the heat generated by the resistance of the winding material and the heat dissipation capability of the core. The iron core shows a gradual rise in temperature, while the high-voltage side winding experiences higher temperatures due to increased electrical stress and current. Fig. 6(a) illustrates the temperature distribution across the entire model ranging between 139.43°C and 141.35°C. Fig. 6 (b) identified the highest recorded temperature within the HV windings, reaching 142.89°C.



(a) **(b)**

Figure 6. Temperature distribution of 3-D model with traditional cooling methods, (a) full model, (b) HV, LV, and H.V filament windings

Overall, this temperature distribution within the transformer highlights the importance of efficient cooling mechanisms to maintain optimal performance and prevent overheating. To achieve this, various cooling techniques are implemented, such as oil cooling, which helps dissipate the excess heat generated during operation.

4. Numerical methodology

4.1. Proposed cooling device geometry

The geometrical model of the cooling device is depicted in fig. 7. The cooling tank is a crucial part of a cooling system, designed to optimize heat dissipation. It is proposed to be used in microwave ovens, where the transformer is submerged in a tank of transformer oil. The tank consists of a base, case, and cover, with terminals connected to electrical connections from the transformer. Corrugated portions form on the side surfaces for faster cooling. The transformer is fixed to the base via argon welding and mounted on the base via weld holes. The cooling tank is designed for

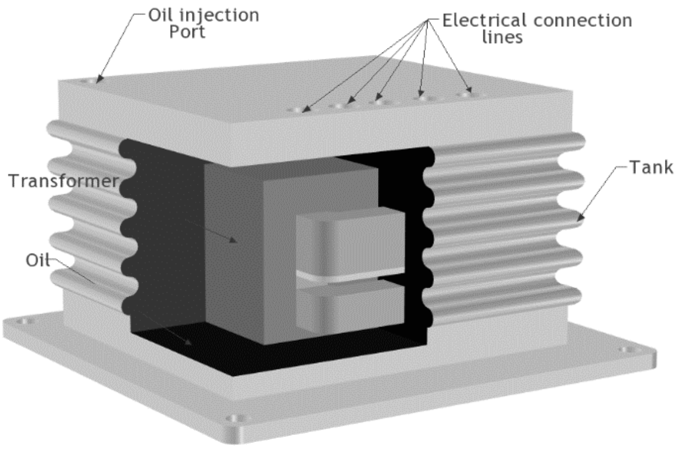


Figure 7. 3D geometric model of tank and cooling system

safety with high-quality, high-temperature-resistant lines and protrusions to prevent electrical shock and accidental contact with live components. It is coated with specialized epoxy material for insulation and resistance to cooling oil, while a custom-fitted steel casing with rubber gaskets enhances cooling efficiency and reduces oil contamination risks.

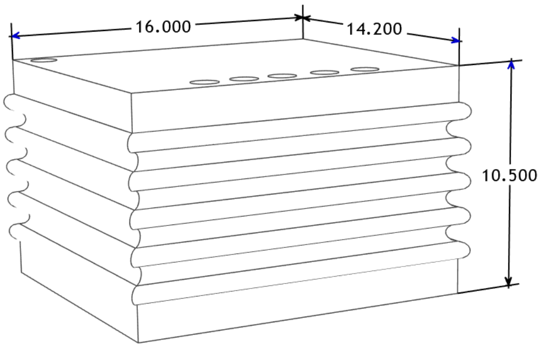


Figure 8. Main dimenion of tank

Fig. 8 provides the main dimensions (16cm ×14.2cm×10.5cm) of the tank, which was chosen to accommodate a high-voltage transformer while maintaining compactness and efficiency. The tank's dimensions were carefully chosen to securely house a transformer within a limited space while also being compact for easy transportation and installation, making it ideal for various industrial settings. The tank's design balances functionality and practicality, ensuring it fulfills its purpose without compromising on space or performance. The dimensions of the stainless steel cooling system were determined using transformer size and computational fluid dynamics simulations to optimize cooling performance.

4.2. Cooling process

The study proposes a method for cooling a high voltage transformer. The process involves inserting the transformer into a tank, sealed with locking mechanisms and threaded closures, and using a high-quality, thermally stable cooling oil. The oil is injected into the tank using a controlled-rate pump system, monitored and adjusted for optimal performance. The tank is made of thermally rolled steel plate, and the cooling oil is nonconductive and incombustible. Fixing means are provided to secure the transformer and electrical connection lines.

4.3. Numerical analysis

The present investigation included the use of ANSYS Fluent software for the purpose of conducting thermal analysis. Fig. 9 shows the flowchart outlining the thermal analysis that was conducted. The determination of transformer losses is conducted at the first step of thermal analysis, focusing on transformer losses and core and winding losses using FEA. The Maxwell 3D program's transient solver allowed for modeling and simulation studies that closely resemble actual operating conditions. Simplorer and Maxwell software were used concurrently for performance testing on a transformer under electronic circuits. The next step involved integrating loss data from the Maxwell program with ANSYS Mechanical Workbench to compute steady-state thermal effects. The core and winding temperatures were assessed before selecting an appropriate cooling technique to effectively dissipate heat.

The cooling efficiency of the chosen cooling method was tested using fluid dynamic software before prototype production. Maxwell 3D data was used to analyze losses in the core and windings, and if insufficient, the method was revised. The design process was completed after FEM validation, allowing for transformer prototype production. The coupling simulation model of the fluid-thermal field was established based on structural characteristics and heat dissipation conditions. The study simplified winding structure and oil flow conditions inside transformers, focusing on temperature distribution and hot spot temperature. Thermal conductivity, constant pressure heat capacity, density, and other transformer parameters were considered constants independent of temperature.

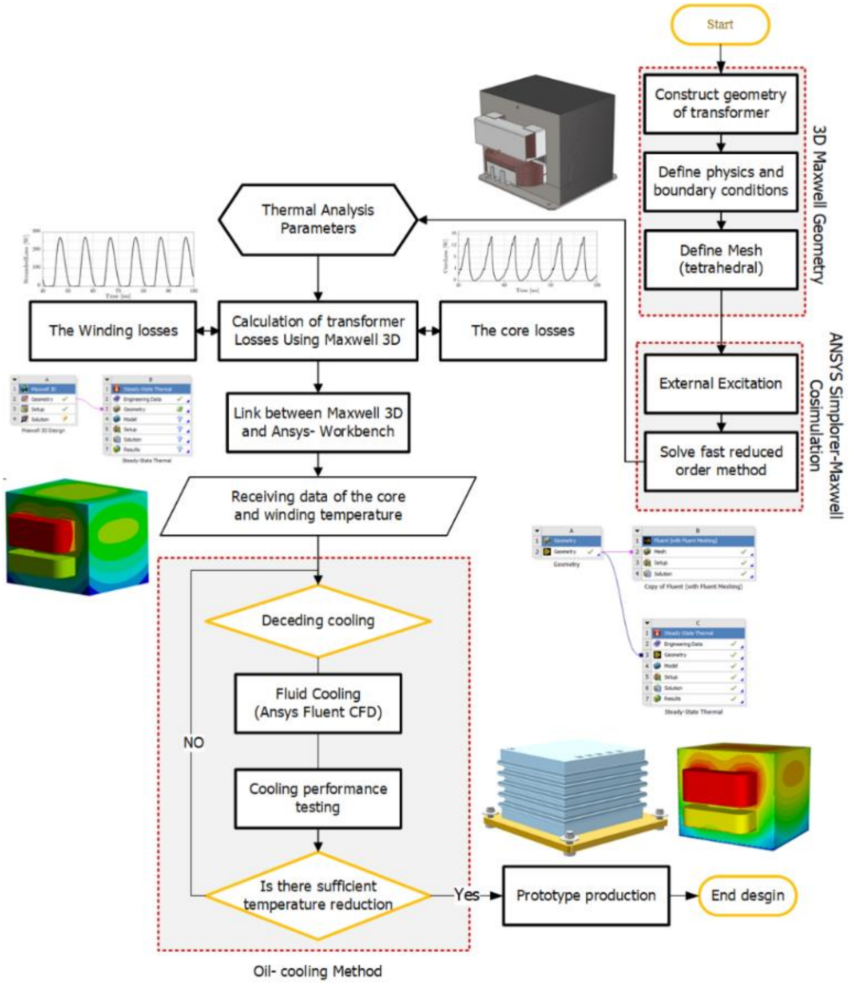


Figure 9. Flowchart illustrates the software implementation for the investigation of a novel tank geometrie

The simulation of transformer temperature field requires setting parameters for winding metal conductor, core material, and flow. These parameters are based on copper, silicon steel, and transformer oil parameters, with their respective material properties illustrated in tab. 3.

Table 3. Physical proprites of transformer

Features	Iron Core (silicon steel)	Windings (Copper)	Transformer oil
Density [kgm^{-3}]	7650	8933	850
Specific heat volume (jkg^{-1}K^{-1})	486	400	1600
Thermal conductivity (Wm^{-1}K^{-1}))	23.3	385	0.15
Viscosity (kgm^{-1}s^{-1})	-	-	0.0026

5. Results and disscusion

This section presents the temperature field distribution results of the transformer under the same operating conditions with a cooling system. Fig. 10 illustrates the temperature distribution of a transformer, highlighting the thermal effects of insulation oil. The LV winding recorded a maximum temperature of 94.86°C, while the HV winding reached 98.67°C. The full model temperature ranged between 80.00°C and 98.69°C, with the highest point in the central region of the HV winding. The core contributed to a smaller proportion of overall losses due to its larger surface area exposed to cooling oil. The results show a significant enhancement in cooling efficiency with the immersed oil cooling method, reducing the temperature from 142.89°C to 98.69°C.

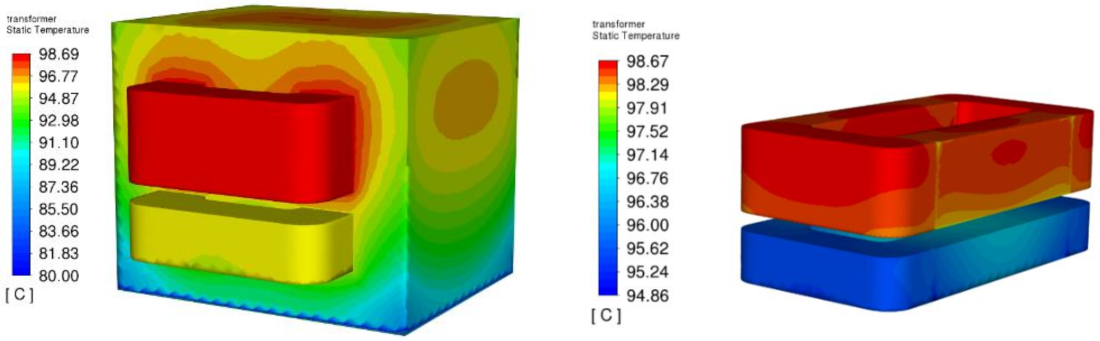


Figure 10. Temperature distribution of 3-D model with oil-cooling, (a) full model,(b) HV, LV, and H.V filament windings

Fig. 11 shows temperature oil contours for tank geometries, with a maximum surface temperature of around 80°C. The lowest temperature points are on the outer surface. The temperature decreases in the middle of the top surface of a transformer due to air exposure, high heat transfer, file location, and heat dispersal methods. Heat dissipates towards the sides, increasing the oil temperature. Oil density varies, with less dense oil rising to the top. Therefore, the oil temperature on the upper surface should be high.

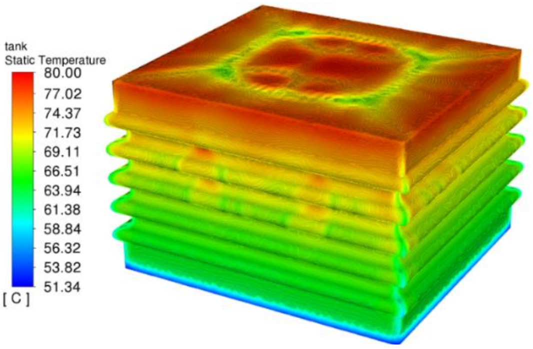


Figure 11. Heat map depicts the surface temperature of the oil tank

Fig. 12 shows that insulation oil has the fastest flow rate within the winding gap due to elevated temperatures and rapid convective heat transfer, with the upper tank section experiencing an accelerated flow rate of 0.02 m/s. Fig. 13 illustrates the simulation of temperature distribution gradient along the vertical direction of transformer oil, the hot oil continues to rise in the upper section of the tank due to buoyancy force, and the coldest points at outer tank edges.

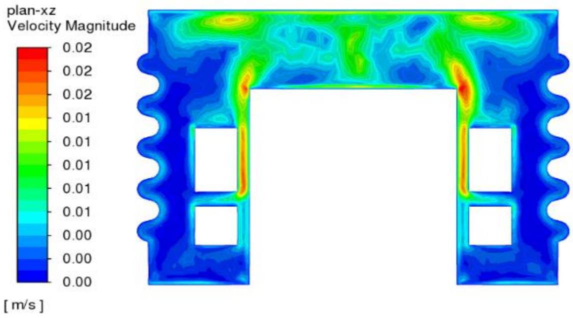


Figure 12. A sectional flow rate of insulation oil a cross (xz)

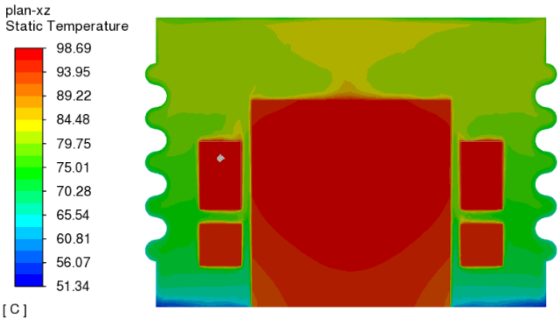


Figure 13. Temperature distribution in transformer oil

The numerical simulation results reveals that immersed oil cooling significantly reduces transformer temperature compared to conventional methods under the same operating conditions. The proposed cooling method improved the performance of microwave ovens and transformers, prolonging their lifespan, ensuring safety, and surpassing conventional methods in efficiency. This superior efficiency and safety feature has set a new standard for microwave oven cooling technology.

6. Conclusion

This study presents a method to improve the cooling efficiency of high voltage transformers in microwave ovens. The device aims to remove heat generated during operation, enhancing the performance and quality of the oven. The high voltage transformer was cooled using a tank filled with oil to absorb heat from the core and coil. Significantly, a numerical analysis revealed a decrease in the transformer's maximum temperature rise of around 44.2°C. According to these findings, transformer oil cooling is preferable to conventional cooling techniques, and is a better way to control temperature rise in microwave ovens. The research confirms the hypothesis that a significant temperature difference exists between the cooling fan and transformer oil-cooling system, emphasizing the need for effective cooling methods to optimize transformer performance and extend its lifespan. Future research might focus further on refining cooling strategies, looking into new uses, and examining the durability and long-term effectiveness of these approaches in real-world situations.

Nomenclature

c_p – specific heat
B_m – magnetic flux density
f – frequency
V – volume
T – temperature
q – heat source
P_{Load} – transformer total power loss
P_{Cu} – transformer winding resistance loss
P_w – winding eddy current loss
P_s – winding stray loss
P_{NL} – transformer no load loss

k – thermal conductivity
h – convective heat transfer
A – wetted area of heat transfer
T_a – ambient temperature
T_w – transformer tank temperature
Q_{Cu} – windings heat source
Q_{Fe} – iron core heat source
Q – oil tank wall heat dissipation
U – oil velocity vector
p – fluid pressure
F – external force density

P_h – hysteresis loss
P_e – eddy current loss
P_c – core stray loss
P_{NL} – core loss
K_h – hysteresis coefficient
K_e – abnormal coefficient
K_c – eddy-current coefficient

Greek symbols

ρ – density
σ – heat conductivity
μ – viscosity
α – thermal diffusion coefficient
g – gravity acceleration
β – volume expansion coefficient
ε – thermal radiation coefficient
δ – Stefan–Boltzmann’s constant

l – characteristic length
Nu – Nusselt number, [-]

Nu_v – Nusselt number of vertical plane , [-]
Nu_h – Nusselt number of horizontal plane , [-]
Ra – Rayleigh number, [-]
Pr – Prandtl number, [-]
h_r – equivalent radiation coefficient

Abbreviations

CFD – computational fluid dynamics
FEM – finite element method
HV – high voltage
LV – low voltage

Subscripts

a – ambiant
s – surface
w – wall

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