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Thermal Simulation for Magnetic Coupler of Wireless Power Transfer Electric Vehicles by Using Heat Sink and Thermoelectric Cooler

Umar Farooq[1], Shahryar Shafique[2], Muhammad Asif[3], Muhammad Arslan[4], Poramed Wongjom[5], Rizwan Ullah[6], Anton Zhilenkov[7], Saleh Mobayen[8], and Wanchai Pijitrojana[1,*]

[1]*Electrical and Computer Engineering Department, Thammasat School of Engineering, Thammasat University Rangsit Campus Klong Luang, Pathum Thani 12120, Thailand*
[2]*Ministry of IT & Telecommunications, Islamabad, Pakistan*
[3]*Department of Electrical Engineering, Main Campus, University of Science and Technology, Bannu 23200, Pakistan*
[4]*Department of Mechanical Engineering, University of Engineering and Technology, Lahore, Pakistan*
[5]*Division of Physics, Faculty of Science and Technology Thammasat University Rangsit Campus Klongluang, Pathum Thani 12120, Thailand*
[6]*Department of Electrical Engineering, Chulalongkorn University, Bangkok 10330, Thailand*
[7]*Department of Cyber-Physical Systems, St. Petersburg State Marine Technical University, Saint-Petersburg 190121, Russia*
[8]*Graduate School of Intelligent Data Science, National Yunlin University of Science and Technology 123 University Road, Section 3, Douliou, Yunlin 640301, Taiwan*

ABSTRACT: In challenging operational environments such as underground buildings beneath roadways, reliability and performance of wireless power transfer (WPT) systems for electric vehicles (EVs) heavily hinge on the operating temperature of the magnetic couplers. Addressing this, this study introduces a novel approach employing heat sink and thermoelectric cooler technologies to mitigate temperature rise in magnetic couplers, which is particularly crucial for high-power applications. Utilizing ANSYS simulation, the study evaluates a WPT high-power application coil model with a total output power of 2 KW and an 18 cm air gap, with a 3.5 cm adjacent alignment to enhance thermal performance on both transmitter and receiver sides. Results demonstrate significant thermal enhancement, reducing the temperature of coils from 63°C to 54°C solely with the heat sink and further down to 48°C with the combined implementation of both heat sink and thermoelectric cooler. These measures effectively dissipate heat from the coils into the surrounding air, ensuring system efficiency and stability while facilitating functionality of system components.

1. INTRODUCTION

The inaccessibility of efficient electric vehicle charging infrastructure at equivalence for modern refueling stations of Internal combustion engine (ICE) vehicles remains a significant barrier to the rapid adoption of EVs. However, there is a need for quick and significant growth in adopting environment-friendly technologies as vehicles powered by electricity can help to overcome problems like air pollution and greenhouse gases associated with petroleum. These electric vehicles can be easily plugged into the grid, and the onboard energy storage system can be recharged using electricity [1–3]. Numerous technical issues and drawbacks of wired charging have been addressed by researchers in [4] and [5], and wireless charging of electric vehicles has been introduced as a solution. These drawbacks mainly include oxidation susceptibility and limited compatibility or universality. In severe weather like rain and snow, the living body will sustain injuries due to metal-to-metal contact during the charging [6]. In contrast to plug-in charging, wireless charging transfers power without the need for user interaction as the cable handling is eliminated, which results in more safety and comfort. The cost of the construction of wires is also reduced. In addition to offering electrical isolation, wireless power transfer (WPT) lowers the weight and volume of onboard charging [7]. The the Society of Automotive Engineers J2954 standardizes the primary electrical system specifications and boundary conditions for automotive wireless power transfer system (WPTS) [8]. It is considered a low maintenance charging technology for EVs that operate mainly on Faraday's law of electromagnetic interaction between the transmission coil buried under the ground and the receiving coil located under the vehicle. The transmission side also comprises a rectifier, an inverter, and a matching network. In contrast, the receiving side also consists of parallel resonant tanks, a rectifier, and a DC/DC converter [9]. Fig. 1 below shows a wireless electric vehicle system's components and architecture.

Magnetic coupler plays a crucial role in transferring power wirelessly from the transmitter to the receiver without the need for physical contact. The transmitter and receiver coil dimensions can be increased to increase magnetic coupling when a particular air gap is considered. When coil dimensions are expanded at a specific frequency, the quality factor rises while

* Corresponding author: Wanchai Pijitrojana (pwanchai@engr.tu.ac.th).

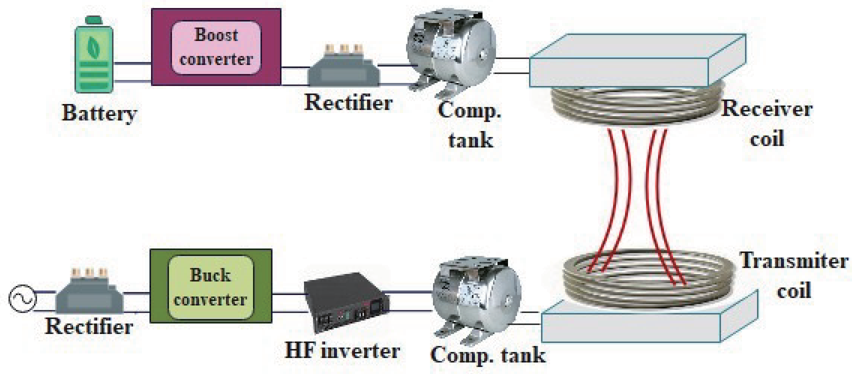

FIGURE 1. WPT system architecture.

ignoring AC losses. As a result, coil dimensions related to transmission frequency and air gap determine transmission efficiency primarily. Nevertheless, this efficiency is also affected by adding other parts, such as ferrites or shielding [10]. Therefore, parameters such as transmission frequency, air gap, and coil dimensions need to be specified while designing the magnetic couplers of WPT EVs. This calls for multi-objective optimization considering the mechanical, thermal, and electrical requirements [11]. Electromagnetic interference (EMI) and electromagnetic field (EMF) were mostly considered for safety in the electromagnetic environment where wireless power transmission is carried out. Even though wireless power transmission can reach high power levels measured in kilowatts, other factors still need to be considered. Additionally, WPT occurs in a frequency range higher than the commercial frequency, i.e., tens of kHz, and the induction heating phenomenon should be considered. It produces thermal energy in the conductive portion based on eddy current and skin effect, raising the temperature by causing liquid and gas molecules in the atmosphere to vibrate.

A robust induction phenomenon happens nearby, and a high current must be supplied to transmit high power. When a closed loop forms, the induction phenomenon causes the nearby conductive components to produce an induced current, forming the loop's concentrated charge to create a spike upon contact [12]. Every part of the WPT system results in losses [12, 13] that can affect and become dangerous to human health and electronic equipment if they depart from the expected range. The temperature variation of the magnetic coupler during operation is frequently disregarded in related studies. The power losses are also generated from the power electronic components, compensation networks, and magnetic pads on the transmission and receiver sides. The open-loop or closed-loop controller usually controls the heat dissipation in the electronic circuits. Magnetic couplers contribute a vast number of losses in the total losses produced by each component of the WPT system [12]. Copper losses, iron losses, and losses from the shielding plates due to which the temperature of pads rises, and if it is not optimized within a reasonable range, then it becomes a serious concern and challenge for the stability and efficiency of the whole system [14, 15]. This rise in the temperature will not impact the WPT system's power flow, voltage gain, and power gain. Still, it might risk the system's stability and affect the ferrite material's parameters [16]. Significant heat stresses in magnetic couplers can result in component failure, which is typically fatal and irreversible, just like in other electrical systems [17].

Consequently, it is imperative to examine the magnetic coupler's thermal properties. The precise impact of a temperature increase on the entire system still needs to be discovered, and there are currently few studies on the mechanism of magnetic coupler heating. Furthermore, there are a few ways to maximize magnetic coupler design regarding temperature rise. These magnetic pads are usually cooled by natural convection or forced air convection. Heat transfer can be carried out in three ways: radiation, convection, and conduction. Fourier's law, which measures how much heat moves through a particular area for a specific length, is the source of the fundamental law of heat conduction. The expression can be written as follows:

$$Q_1 = -\lambda A_1 \frac{dt}{dx} \tag{1}$$

where $\frac{dt}{dx}$ is the thermal gradient along the constant temperature surface average to the direction (°C/m); Q_1 is the heat transfer heat flow (W); λ is the thermal conductivity of the material (W/(m°C); and A_1 is the cross-sectional area in the vertical thermal conductivity direction. It is evident from Eq. (2) that raising the convective heat transfer area and the coefficient can both be considered to enhance convective heat transfer.

$$Q_2 = h_c A_2 \left(t_w - t_f\right) \tag{2}$$

Mutual thermal radiation occurs when there is a temperature differential between the items; otherwise, no thermal radiation will occur. The radiation heat exchange between two objects' surfaces can be calculated using Eq. (3) given below:

$$Q_3 = \delta_\circ A_3 \epsilon_{xt} F_{12} \left(T_1^4 - T_2^4\right) \tag{3}$$

Hence, a cooling assembly is needed to dissipate the warmness of the high-power Wireless Power Transfer configuration. Therefore, it is necessary to consider the magnetic coupler's

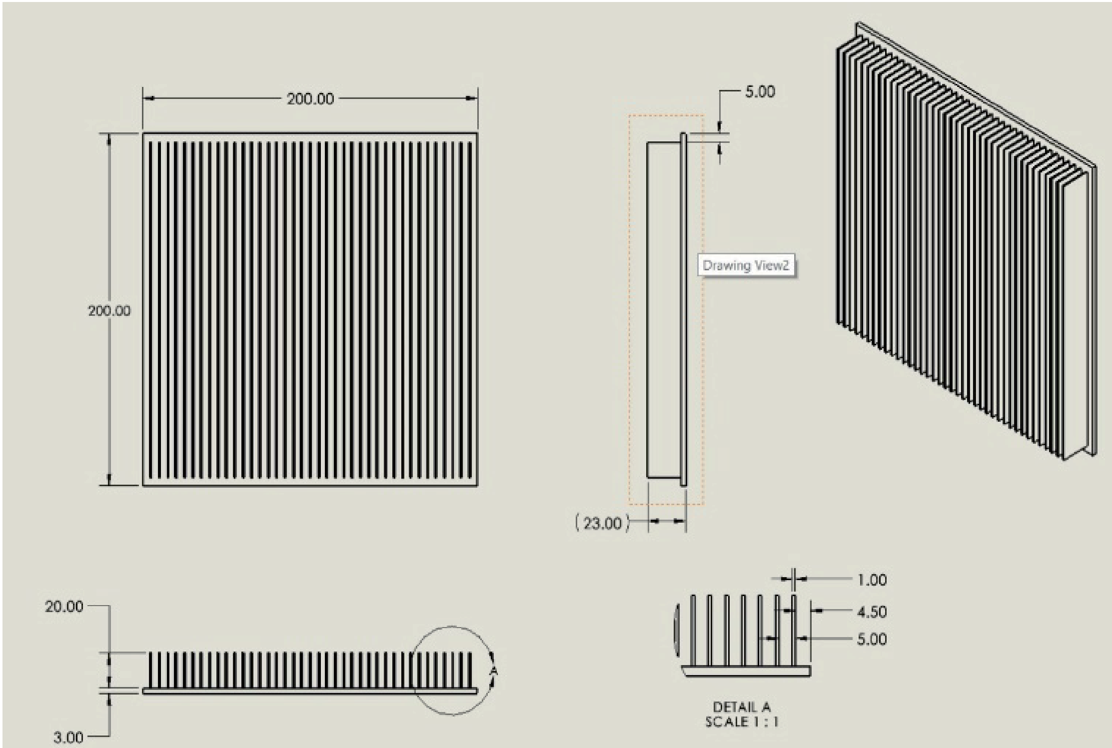

FIGURE 2. Skived Heat sink configuration.

thermal material design, which improves the thermal and heat dissipation issue out of the coil while implementing the natural charging system.

1. This study employs thermal simulation techniques to investigate the temperature behavior of a magnetic coupler under natural convection conditions, utilizing both a heat sink and thermoelectric cooler to mitigate coil temperature during operation.
2. The simulation model was constructed according to the SAE standard to ensure accuracy and reliability. The primary objective of this research is to reduce coil temperature by facilitating heat transfer from the coils to the surrounding air, thereby enhancing system stability.
3. To achieve this goal, heat exchangers and thermoelectric coolers are proposed for installation on the surface of the coils, enabling efficient heat transfer. By analyzing the results, the study aims to develop coil designs that effectively address thermal management concerns.

1.1. Heat Sink

A heat sink typically refers to a passive heat exchanger device responsible for transferring heat away from mechanical components into the air and dissipates it away from the device by keeping its temperature stable. Usually, it is made up of materials with a high heat capacity and thermal conductivity to absorb more heat energy without shifting towards a very high temperature and transmit it to the environment for efficient cooling. The performance can be improved by using thermal paste and filling the air gaps between the sink and heat spreader on the device, and the surface area is in contact with some cooling medium such as air [18]. Generally, there are two types of heat sinks: passive and active. The passive heat sink depends upon natural convection, which means that the resistance of warm air causes the airflow to be generated throughout the heat sink device. The structures are effective as they no longer require secondary power or control structures to remove heat from the configuration. However, such sinks are less potent at shifting heat from a device. On the other hand, active heat sinks use forced air to maximize the fluid flow throughout the hot region. Forced air is generated using a fan, blower, or sometimes movement of the whole component, like a motorcycle's engine, which is cooled by using the air passage alongside the heat sink fins. The skived heat sink is used in the analysis, which offers a highly optimized cooling system compared to bonded or brazed heat sinks [19, 20]. They are widely adaptable in industries as well as in power, medical, communication, industrial control, and server industries having large-scale applications because of their thermal density and power dissipation requirements; the heat sink utilized in this analysis is attached to the back of the aluminum plate composed of flat plates of 23 mm and a thickness of 1 mm covering a total area of 200 mm; The configuration/Labelling of Heat sink used in this analysis is shown in Fig. 2. An analysis was conducted to determine the impact of several parameters on natural convection heat transfer, including fin spacing, height, length, and temperature variation between the fin and its surroundings. According to the investigation, they improve the fin's height and length to enhance the overall heat transfer.

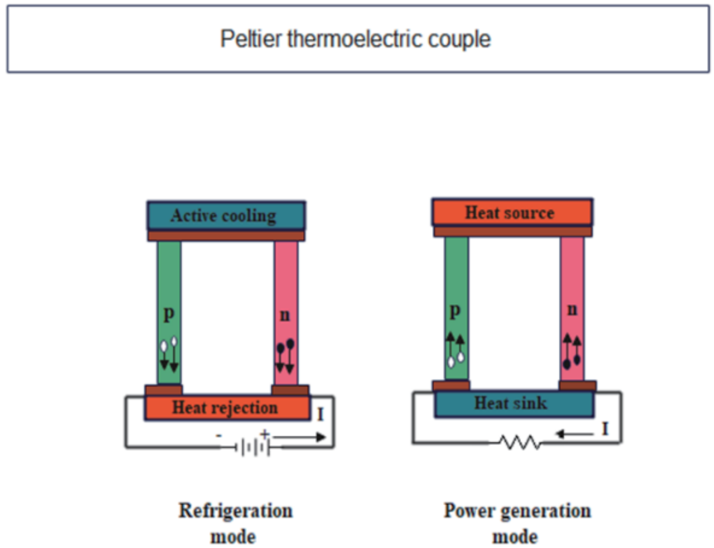

FIGURE 3. Principle of thermoelectric cooler using the Peltier effect.

According to the energy conservation law, at a steady state, the heat produced by the heat source Q and the heat absorbed by the heat sink must be equal. Newton's law of cooling is the source of the right-hand side of Eq. (4), which considers the heat sink's dissipation. Eq. (4) provides the heat sink's surface area A. Since these dimensions are assumed insignificant, the fins (t) and base (b) thickness are not included in the surface area calculation — the sum of Eqs. (4) and (5) yields the number of fins, N. Next, the heat sink's width, W, is determined using Eq. (6).

$$Q = h_{conv} A \left(T_s - T_{amb}\right) \quad (4)$$
$$A = N \times (H - b) \times L \quad (5)$$
$$W = (N - 1)\, S_{opt} + N_t \quad (6)$$

1.2. Thermoelectric Cooler

Thermoelectric coolers are commonly used as specialized cooling devices in military, aerospace, instrument, and industrial or commercial products [21, 22]. A thermocouple is composed of two distinct semiconducting thermos elements, which, applied in the proper direction through the connected junction, generate a thermoelectric cooling effect known as the Peltier-Seebeck effect [23]. It is essential to establish an efficient methodology in the design and development of the thermoelectric cooler apparatus to identify and maximize its performance within the constraints of the cooling system. The iterative method, as described in [24, 25], is the most used approach. Although this approach provides results based on the thermoelectric properties of TEC pellets, it is challenging and takes time for designers to carry out in practice. A few semi-analytical solutions for the junction temperature optimizations related to the operation current and pellet geometry are shown in [26]. It is observed that interdependent parameters like maximum temperature difference and cold side temperature (Tc) are present in these semi-analytical expressions, meaning that full closure necessitates an iterative process. Fig. 3 illustrates the idea behind thermoelectric coolers that use semiconductor Peltier effects. N and P type semiconductor thermoelements oppose heat to the surrounding environment by transferring heat from the cooled region to the hot-side heat sink. If the direction of the electric current is reversed, the direction of heat flow through the semiconductor materials will also be reversed [27].

2. MODELLING OF MAGNETIC COUPLER AND THERMAL ANALYSIS

2.1. Magnetic Coupler Model

Designing coil model of high-power application parameters used in this simulation is taken from [17], which demonstrates an impressive increase in the power transfer efficiency of a three-coil system compared to a conventional two-coil system, shown in Fig. 4. The coupler's electrical performance determines the required air gap between various components. Table 1 shows the parameters and materials used in designing the coil geometry, i.e., transmitter, receiver, and relay coils.

2.2. Simulation and Thermal Analysis

After designing the model in Solid Works, the geometry is imported into ANSYS and simulated using the steady-state thermal module shown in Fig. 4. After importing the geometry in ANSYS, a mesh model is created, and to achieve a mesh-independent solution, it is necessary to check the mesh quality before the simulation. In this case, the value of the mesh orthogonal quality is 0.35, which is less than 1, showing a good quality mesh represented in Fig. 5. Since we are using this analysis on the student version, the number of elements/nodes is kept less than 32000 to make sure that the study can be done smoothly. The utilization of the heat sink with the coil geometry is also shown in Fig. 6.

TABLE 1. Parameters for the designing of the system.

Parameters	Value	Parameter	Value
No. of turns for Tx coil (coil a) (greenish)	18	Core measurement [cm] (green)	$52 \times 52 \times 0.5$
No. of turns for Rx coil (coil b) (orange)	14	Shielding measurements dimension [cm] (grey and yellow)	$54 \times 54 \times 0.5$
No. of turns for relay coil (blue)	70	Core thickness (green)	0.5 cm
The inner radius of three coils	5 cm	Shield thickness (grey and yellow)	0.5 cm
Axial width of three coils	20 cm	Airgap	18 cm
Conductor depth	1 cm	Side misalignment	3.5 cm

TABLE 2. Load setting for simulation.

Object Name	**Convection**	**Radiation**	**Radiation 2**	**Internal Heat Generation**
State		Well-defined		
Scope				
Scoping Method		Geometry Selection		
Geometry	442 Surfaces	436 Faces	6 Faces	2 Bodies
Definition				
Type	Convection	Radiation	Radiation	Internal Heat Generation
Film-Coefficient	5 W/m^2·°C (step applied)	-	-	-
Ambient Temperature	22°C (ramped)	22°C (ramped)	22°C (ramped)	-
Convection Matrix	Program Controlled	-	-	-
Intimidated		No		
Correlation	-	To Ambient	Surface to Surface	-
Emissivity			0.5 (step applied)	

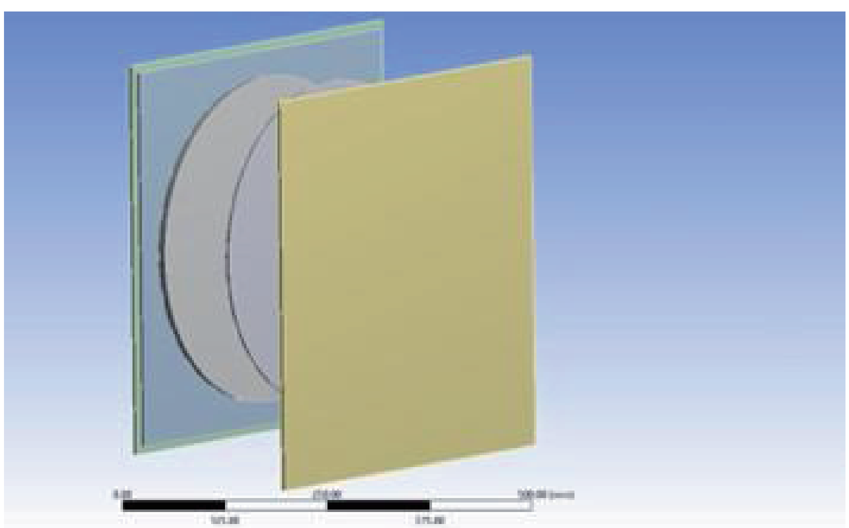

FIGURE 4. Designing magnetic coupler (TX and RX) having relay coil geometry for thermal analysis.

2.2.1. Setup and Solution

After getting the mesh, a setup is run to get the boundary conditions of the object in both geometries with and without the heat sink. The state at the inlet is fully defined, having a uniform temperature of 22°C. The loading setting for the simulation is shown in Table 2.

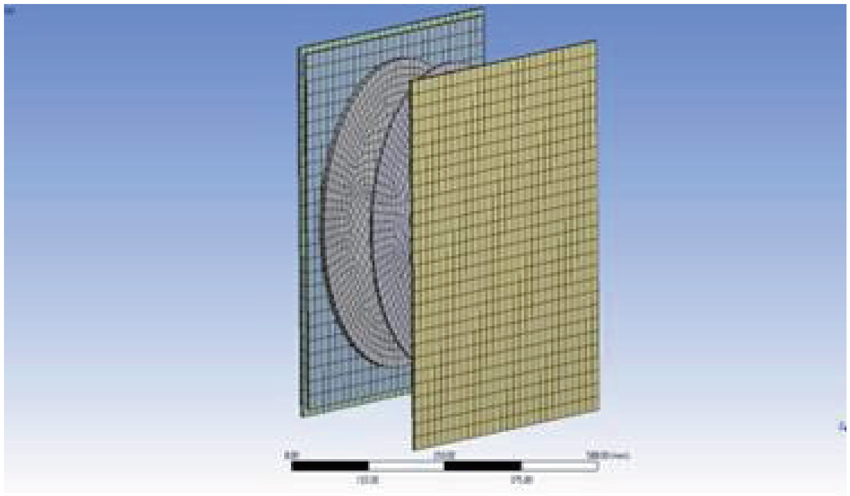

FIGURE 5. Meshing model of coil geometry.

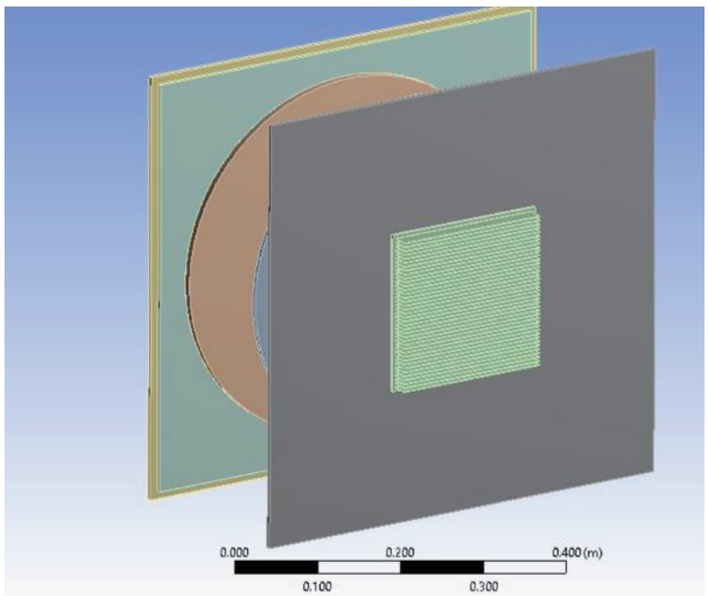

FIGURE 6. Designing magnetic coupler geometry with heat sink for thermal analysis.

TABLE 3. Properties of copper.

Parameters	Values
Isotropic thermal conductivity	$400\,\mathrm{W\,m^{-1}C^{-1}}$
Density	$8933\,\mathrm{kg\,m^{-3}}$
Specific heat Constant Pressure	$385\,\mathrm{kg^{-1}C^{-1}}$

2.2.2. Properties of Material

Different material properties used in designing the coil geometry are shown in Tables 3–5.

2.2.3. Simulation Analysis Results with and without Heat Sink

Figures 7(a) and (b) show the magnetic core and coil base temperature distributions before and after heat sink utilization with geometry. Analysis indicates that the maximum temperature of the coils in the operating condition is 63°C before using the heat sink and 54°C after using the heat sink. The maximum and minimum temperatures achieved after the simulation are 54°C and 25°C, respectively. This shows that the temperature is entirely reduced by utilizing the heat sink in the geometry of the coil as compared to the thermal results of the coil without a heat sink.

(a)

(b)

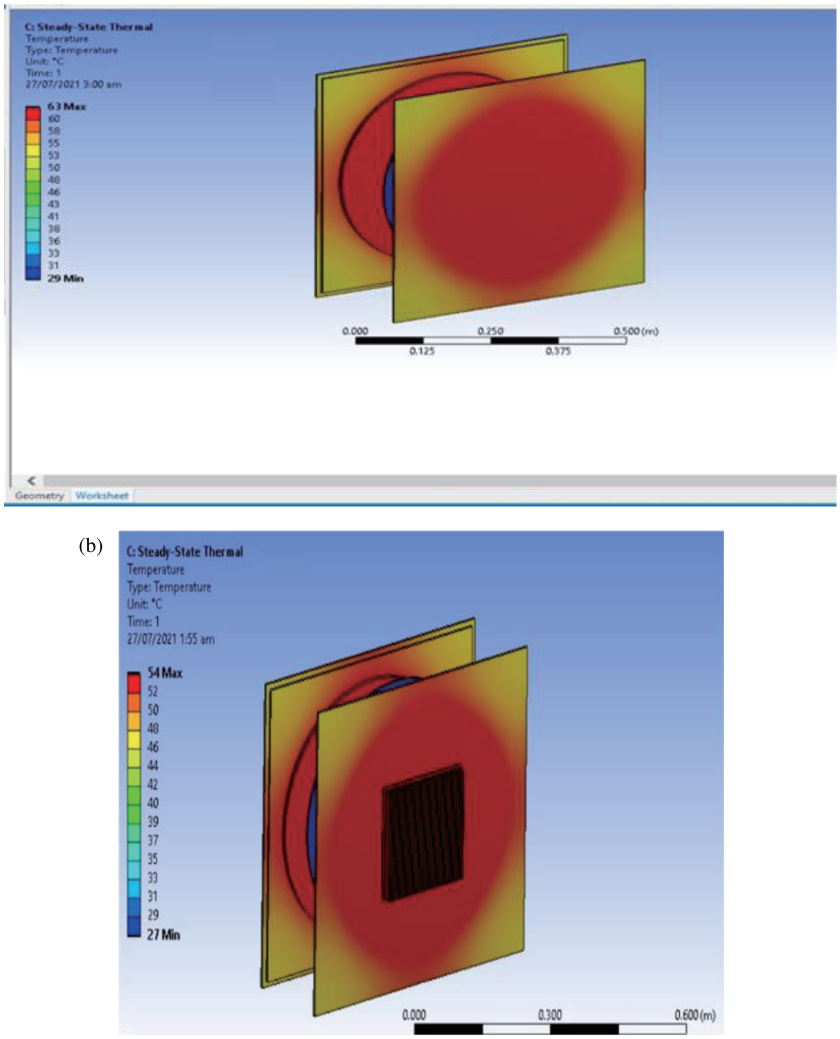

FIGURE 7. (a) Temperature distribution result of Geometry without Heat sink. (b) Temperature distribution result of Geometry with Heat sink.

TABLE 4. Stainless steel and ferrite properties.

Parameters	Values	Parameters	Values
Isotropic Resistivity	$237.5\,\mathrm{W\,m^{-1}C^{-1}}$	Tensile yield	$2.91e+008\,\mathrm{Pa}$
Density	$2689\,\mathrm{kg\,m^{-3}}$	Poisson's Ratio	0.28
Young's Modulus	$951\,\mathrm{J\,kg^{-1}C^{-1}}$	Bulk Modulus	$1.5152e+011\,\mathrm{Pa}$
Thermal Conductivity	$24.9\,\mathrm{W\,m^{-1}C^{-1}}$	Shear Modulus	7.8125e+010 Pa
Zero-Thermal-Reference Strain Temperature	22 C		

TABLE 5. Aluminum properties.

Parameters	Values
Isotropic Thermal Conductivity	$237.5\,\mathrm{W\,m^{-1}C^{-1}}$
Density	$2689\,\mathrm{kg\,m^{-3}}$
Specific Heat Constant Pressure	$951\,\mathrm{J\,kg^{-1}C^{-1}}$

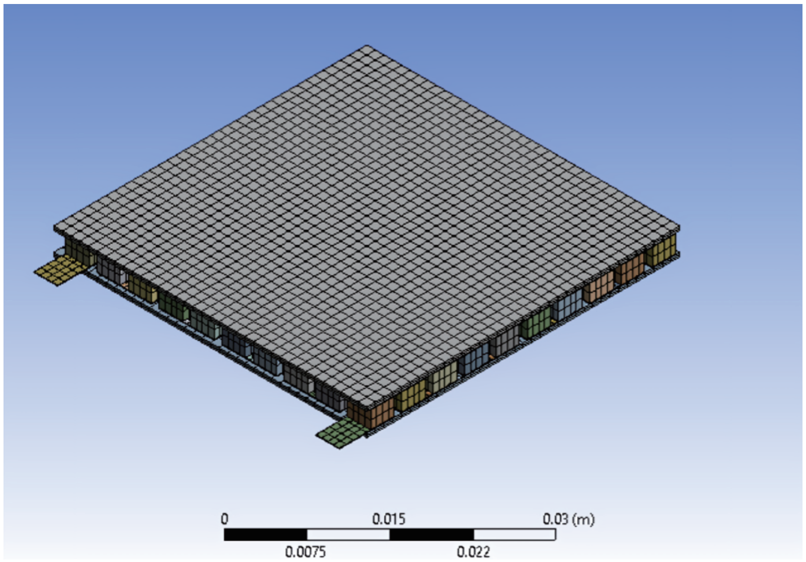

FIGURE 8. Meshing model Thermoelectric cooler design for Magnetic coupler model.

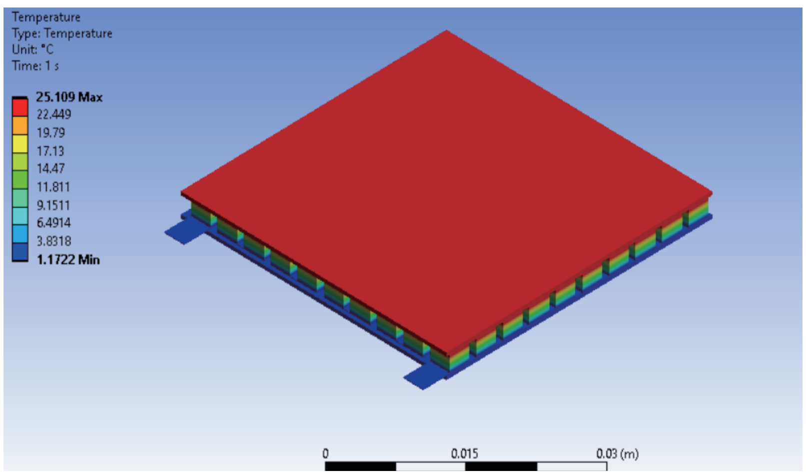

FIGURE 9. Temperature analysis of Thermoelectric cooler design for Magnetic coupler model.

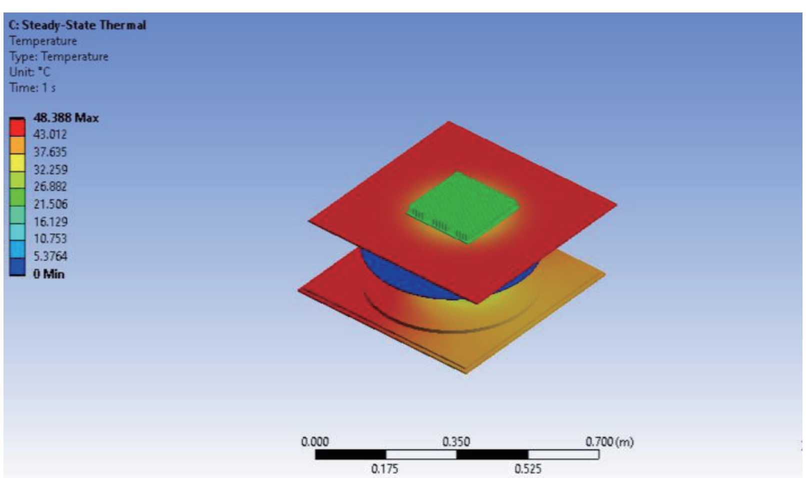

FIGURE 10. Magnetic coupler thermal distribution utilizing a Thermoelectric cooler and Heat sink.

3. SIMULATION ANALYSIS RESULTS BY UTILIZING THERMOELECTRIC COOLER

A thermoelectric cooler is also designed after analyzing the magnetic coupler with the heat sink. The mesh is analyzed in Fig. 8. At the same time, the temperature analysis of this model is shown in Fig. 9. By utilizing the TE cooler with the coil geometry and heat sink and analyzing its thermal effect, results show a considerably more significant reduction in the operating magnetic coupler's temperature from 54°C to 48°C, as shown in Fig. 10.

4. CONCLUSION

In this research work, the modeling of a magnetic coupler and its temperature distribution is shown by utilizing a heat sink and thermoelectric cooler on the surface of an aluminum plate. ANSYS steady-state thermal module and SOLIDWORKS were used to get the results for geometry and simulations. The amount of heat transfer and temperature is relatively high in high current and voltage applications because of the increased temperature in the system, which is why a proper heat transfer medium is required to avoid such issues. The simulation results show that the temperature of the magnetic coupler is reduced to 54°C from 63°C and then to 48°C with the utilization of a TE cooler along with a heat sink of WPT in high-power applications, so the temperature of the coil, which causes significant losses and affects the stability of the system can be improved. The simulation analysis proves that the heat sink and thermoelectric cooler can be applied to reduce the temperature of the WPT system's magnetic coupler while not affecting the magnetic flux from the transmitting coil to the receiving coil. In the future, several modifications can be made to design the geometry of the heat sink. This may include choosing different or effective materials for the heat sink and modifying the structure or shape, such as a round shape. System and design modifications can improve the magnetic coupler's weight, which can be adjustable and easily installed in the vehicle body.

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