

A Study on the Effects of Various Parameters on the Thermal Performance of a 10 W Heater

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Abstract - This article examines the impact of various physical factors on the thermal performance of a 10 W electric heater, serving as a surrogate for integrated circuits (ICs) on printed circuit boards (PCBs). Using a 2^3 factorial experimental design, three factors were evaluated: shunt surface finish, thermal paste application, and enclosure surface treatment. Statistical analysis performed using JMP Pro revealed that thermal paste and enclosure surface treatment significantly influence the heater's surface temperature ($p < 0.05$), whereas the shunt surface finish was found to be non-significant. The results demonstrate that the combination of thermal paste and pure aluminum enclosure optimizes heat dissipation.

Index Terms—Thermal performance, Design of Experiments (DOE), PCB cooling, 10 W Heater, ANOVA, Heat dissipation.

I. INTRODUCTION

The escalating power density in modern microelectronics has made thermal management a primary constraint in the design and reliability of electronic systems. As integrated circuits (ICs) become smaller and faster, the heat flux generated per unit area increases, leading to elevated junction temperatures. It is widely recognized in the industry that for every $10\text{ }^\circ\text{C}$ increase above the optimal operating temperature, the reliability of a silicon-based component is reduced by approximately 50%. Consequently, understanding the pathways through which heat dissipates from a Printed Circuit Board (PCB) assembly to its environment is critical for preventing thermal-induced failures such as solder joint fatigue, delamination, and accelerated aging.

In this research, a 10 W resistive heater is employed as a controlled surrogate for a high-performance IC. While a 10 W load may seem modest, in the context of a compact PCB environment, it represents a significant thermal source that requires efficient conduction paths. The study focuses on the "thermal stack" between the heat source and the ambient air. This stack includes the thermal interface material (TIM), the intermediate shunt (heat spreader),

and the external mechanical enclosure.

The complexity of heat transfer in such a system is governed by Fourier's Law of Heat Conduction, where the rate of heat transfer is directly proportional to the material's thermal conductivity and the temperature gradient.

However, real-world surfaces are never perfectly flat; microscopic asperities create air pockets that act as thermal insulators. By utilizing a 2^3 factorial Design of Experiments (DOE) frame study systematically quantifies how varying the surface chemistry of the aluminium components and the introduction of a high-conductivity thermal paste influences the steady-state temperature of the heater. This introduction of statistical rigor allows for the separation of significant physical drivers from experimental noise, providing a data-driven foundation for thermal design choices in electronic packaging. framework, this study systematically quantifies.

II. LITERATURE REVIEW

The field of thermal management in electronic packaging has evolved rapidly as component miniaturization pushes the limits of heat flux density. Current literature focuses on two primary areas: the physical mechanisms of heat transfer at the interface level and the application of statistical methodologies to optimize these variables.

1. Printed Circuit Boards (PCBs) are no longer merely structural components; they are integral to the thermal path of a system. As noted by Korf et al. (2019), the multi-element chemical and physical composition of modern boards creates complex thermal gradients. Research indicates that approximately 55% of electronic device failures are directly attributed to excessive operating temperatures (Fayyaz et al., 2022). In high-performance systems like CubeSats, a continuous heat dissipation of 10W from a single component can create critical "local thermal hotspots" that require passive or active cooling to prevent system failure (Brouwer, 2017).

2. A significant portion of thermal resistance occurs

at the interface between the heat source and the heat spreader (shunt). Even when surfaces appear flat, microscopic asperities create air gaps. Since air has an extremely low thermal conductivity (approximately 0.026 W/mK), these gaps act as thermal insulators. Improvements in Thermal Interface Materials (TIMs) enhance heat transfer by filling these voids with a higher-conductivity medium (Fabris et al., 2011). While bulk TIM conductivities typically range from 1 to 10 W/mK, their performance is highly dependent on surface wetting and the ability to form a uniform thickness under pressure (Fabris et al., 2011).

3. The external surfaces of the mechanical enclosure contribute to heat dissipation through both conduction and radiation. While pure aluminium is a superior conductor, surface treatments like chromating or powder coating are often applied for corrosion resistance. However, these treatments can significantly alter the contact resistance and emissivity of the surface. For instance, oxidation and surface roughness can increase contact resistance by up to six orders of magnitude, making the removal of oxide layers critical for achieving high thermal conductance (NASA, 1986). Furthermore, the enclosure can act as either a barrier or a conduit for heat; in compact designs, heat spreading and direct conduction to the casing are often as vital as convective airflow (EDA Direct, 2019).

4. Historically, thermal testing followed the "one-factor-at-a-time" (OFAT) approach. However, modern research favours the 7-step DOE framework proposed by Montgomery (2017). The advantage of a 2³ factorial design, as utilized in this study, is its ability to identify not only the primary drivers of temperature but also the interaction effects between factors—such as whether the benefit of thermal paste changes based on the shunt's surface finish. By utilizing JMP Pro for statistical validation, this study aligns with current engineering standards for robust experimental design.

III. PROPOSED SYSTEM

The proposed system is designed to evaluate the thermal resistance of a component-to-ambient path in a controlled environment. The setup utilizes a 10W electric heater as a consistent thermal load, simulating the heat flux of a high-performance Integrated Circuit (IC) on a Printed Circuit Board (PCB).

A. Physical Architecture

The system consists of three primary physical layers, referred to as the "thermal stack." Each layer is strategically chosen to facilitate or resist heat transfer from the source to the external environment.

Thermal Source (10W Heater): A resistive heating element providing a constant 10W power input. This serves as the heat-generating "junction" of the surrogate system.

Heat Spreader (Aluminium Shunt): An intermediate conduction block attached directly to the heater. The shunt's primary function is to increase the surface area available for heat transfer.

Mechanical Enclosure: A secondary housing containing both the heater and the shunt. It acts as the final boundary before heat is dissipated into the surrounding air through convection and radiation.

B. Controlled Factors and Levels

The system was tested using a 2³ factorial design, involving three independent variables, each at two levels. This allows for the observation of how specific material treatments and interface qualities affect the system's ability to maintain a low operating temperature.

Factor A: Shunt Surface Finish.

Pure Aluminium: High thermal conductivity, untreated surface.

Chromated: A chemical conversion coating used primarily for corrosion resistance.

Factor B: Thermal Interface Material (TIM).

With Paste: Application of thermal paste with thermal conductivity of 5 W/m·K. This ensures, between the heater and shunt to displace microscopic air gaps.

Without Paste: Direct mechanical contact between the two metal surfaces.

Factor C: Enclosure Surface Treatment.

Pure Aluminium: Standard conductive casing.

Black Powder Coated: A protective finish that potentially increases emissivity but may add a layer of thermal resistance.

Experimental Environment and Controls

To ensure that the measured response (temperature) is exclusively a result of the proposed factors, the system is placed within a Heat Chamber.

Ambient Control: The chamber is set to a constant 40°C with 20% relative humidity to isolate the design factors from atmospheric variations.

Mechanical Integrity: The heater and shunt are secured within the enclosure using steel screws tightened to a constant torque of 1.2 N·m. This ensures uniform contact pressure across all experimental runs, minimizing variations in contact resistance.

Timing: Data is collected exactly after 60 minutes of power-on time. This duration was selected based on pre-test observations where the system reached a stable steady-state thermal equilibrium within approximately 26 minutes.

Measurement System

The primary sensor for data acquisition is a J-type thermocouple adhered to the surface of the heater. This sensor provides the "response variable" (temperature in °C). To mitigate experimental noise and human error, a digital stopwatch is used for timing, and the 24 total runs (3 replications per combination) are performed in a randomized

sequence generated by JMP Pro software to prevent systematic bias.

IV. OBJECTIVE

The primary goal of this experiment is to systematically determine the impact of physical material properties and interface treatments on the thermal management of a 10W power-dense component. By applying a structured statistical approach, the study seeks to isolate drivers of heat dissipation from the baseline noise of the experimental environment

V. METHODOLOGY

This section will explain the main procedure of conducting the experiment. The experiment will be conducted in a way to minimize all types of errors and nuisance factors that could lead to faulty interpretation. The experiment will be time-consuming since each replication will require approximately one hour:

1. Put the 10W heater inside the mechanical enclosure (Pure aluminum or Aluminum with black powder coating)
2. Place the shunt material (Pure aluminum or chromated) inside the mechanical enclosure and connect it with constant steel screws (1.2 N-m torque) to the heater.
3. Apply a controlled quantity of thermal paste between the heater and shunt to ensure surface-to-surface contact attachment (if the replication includes thermal paste).
4. Install a thermocouple directly to the heater.
5. Place the mechanical enclosure inside the heating chamber.
6. Set the temperature of the heating chamber to 40 °C 20% humidity.
7. Wait until all parts inside the heating chamber reach 40 °C, and then power-up the heater.
8. Measure the temperature of the heater using a thermocouple after one hour.

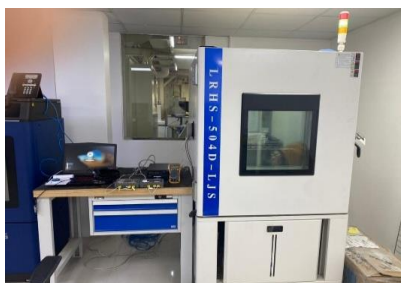


Figure 1. Heat Chamber

The factors in this experiment are classified into four types: design factors, held-constant factors, allowed-to-vary factors, and nuisance factors. The design factors are to be studied in this experiment by changing them and measuring the results. There are

three design factors to be analysed in this experiment, the shunt surface treatment, adding thermal paste and the surface treatment of the aluminum enclosure.

The allowed-to-vary factors in this experiment are those of no major effect on the interpretation of the results. An example of those factors would be the ambient temperature and humidity of the lab since the experiment is running inside a controlled chamber with specified temperatures.

The nuisance factors in this experiment could vary. The fluctuations in the power supply ($\pm 0.2\%$) to the heater can cause different temperatures in the heater. The thermocouple has a tolerance of 1 Degree Celsius. These factors can cause variations in the results; however, this small error should be allowed in this experiment.

Randomization would be implemented to minimize the effect of nuisance factors. Assigning random treatment numbers to the sequence of experiments would let us avoid as many nuisance factors as possible.

Choice of Experimental Design

The choice of experimental design depends on the number of factors and what the experimenter is seeking to observe and obtain the results. The objective of experiments is usually: 1) Comparative 2) Screening and 3) Response surface objective. The objective of comparative experiments is to compare several factors and draw conclusions on one factor. In screening experiments, the objective is to find the most influential factors from a large group of factors. In response, the experimenter wants to draw an estimation of the interaction effect between factors or optimize a process.

For this experiment, the main objective is to find the effect of several factors on the surface temperature of the heater. Since the goal of the experiment is to find the factor with the highest impact on the surface temperature of the heater, a factorial design will be selected. The number of factors and levels are as mentioned in table 1 above, three factors, and two levels in each.

Since there will be three factors and two levels for each factor, the general factorial design of 2^3 can be used to calculate the results. The three-factor analysis of variance model to be used is found below, where $i, j, k = 2$, and $n=3$:

$$y_{ijkl} = \mu + \tau_i + \beta_j + \gamma_k + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\beta\gamma)_{jk} + (\tau\beta\gamma)_{ijk} + \varepsilon_{ijkl} \begin{cases} i = 1, 2, \dots, a \\ j = 1, 2, \dots, b \\ k = 1, 2, \dots, c \\ l = 1, 2, \dots, n \end{cases}$$

Experiment Execution

On Friday 11/26/2021, the experiment to study the thermal performance was conducted at Jeddah – Saudi Arabia – KAU Private Lab. The experiment was performed according to the randomization method generated by JMP Pro software in figure 2. The run order is also listed in the JMP randomized sheet. The results of the experiment are shown in table 3 below. It was observed that the temperature readings would stabilize after 26 minutes; therefore, each run consumed around half an hour, and all runs were conducted throughout one day at the laboratory.

Statistical Analysis of the Data

The data were analyzed using JMP Pro. The results are discussed in terms of the main factors and their interactions for each of the main factors and the interactions between them are shown in figure 2. The main model has a P-value of less than 0.0001, which illustrates the significance of the model.

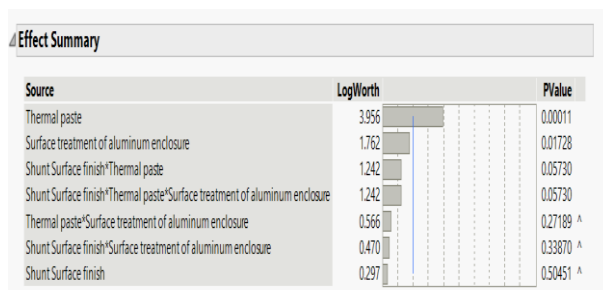


Figure 2. Effect summary of the model on JMP Pro

Hypothesis I is to test whether the material of the shunt surface finish has a significant effect on the surface temperature of the heater or not. According to the values obtained from JMP Pro in figure 6, the shunt surface finish has a P-value of 0.50451. Therefore, the null hypothesis H_0 is accepted, which concludes that the surface finish of the shunt has no significant effect on the response temperature of the heater, assuming a 95% confidence level ($\alpha=0.05$). Hypothesis II is to test whether having thermal paste has a significant effect on the response temperature of the heater or not. From the values obtained in JMP Pro, the p-value for the thermal paste is 0.0001. Therefore, we can reject the null hypothesis H_0 and conclude that the thermal paste has a significant effect on the response temperature of the heater. Hypothesis III is to test whether the surface finish of the aluminum enclosure has a significant effect on the response. From the values obtained in JMP Pro, the P-value for the surface treatment is 0.017, which is less than the 95% confidence level (0.05); therefore, we can reject the null hypothesis and conclude that the material of the enclosure surface finish has a significant effect on the temperature of the heater.

Hypothesis IV is to test whether the interactions between the shunt surface finish and thermal paste has an effect. The P-value of this interaction is 0.057; therefore, we can accept the null hypothesis and conclude that the interaction between these two factors has no significant effect on the temperature of the heater.

the factors and interactions are listed in order of significance on the temperature of the heater. Assuming a 95% confidence level, only the first two factors would have a significant effect.

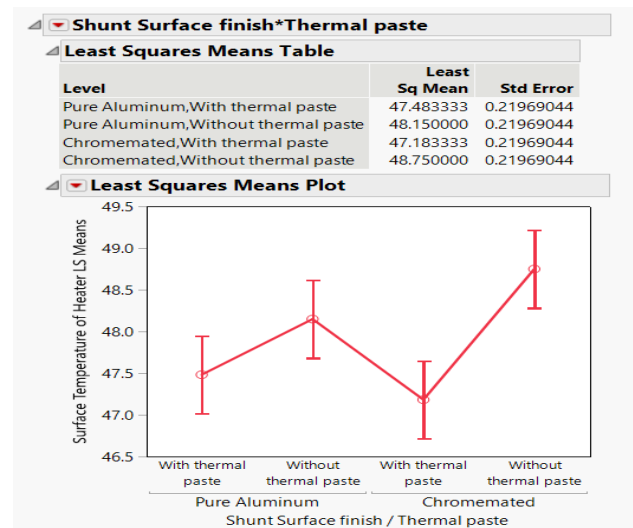


Figure 3. Effect of the interactions (two-way interactions) of Shunt surface finish, thermal paste, surface of aluminum enclosure.

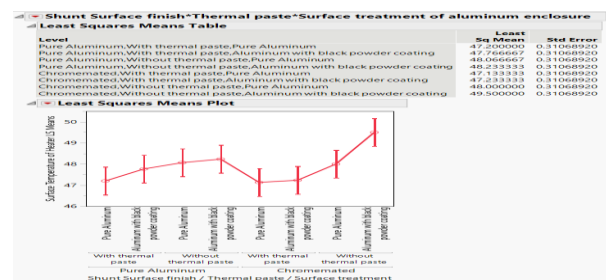


Figure 4. Effect of the interaction of shunt surface finish, thermal paste, and surface treatment of enclosure.

It can be concluded from figure 4 above, that the 3-level interaction has no significant effect on the temperature; however, the combination that resulted with the lowest heater temperature is, with thermal paste and pure aluminum surface enclosure.

Verification of Normality

As illustrated in figure 5 below, the normal probability plot was obtained from the JMP Pro

analyzer. The assumption of normality is almost satisfied for this experiment. The data do not fully follow the predicted line, but it is almost satisfactory with only a few points deviating from the line. The R^2 value shown in Figure 6 is approximately 73%, which indicates moderate explanatory power. This indicates that the data do not fully follow a straight line, and that there are obvious deviations in the data results.

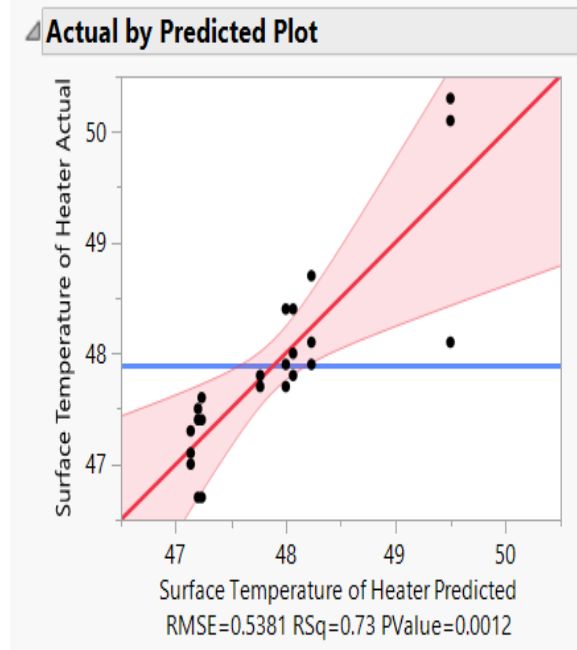


Figure 5. Normal probability plot on JMP Pro

Analysis of Variance (ANOVA)

As shown in figure 6 below, the overall model has a p-value of 0.0012, which indicates that the experiment has significant factors that affect the response factor: the surface temperature of the heater. The degrees of freedom obtained are also indicated in the figure below.

Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	12.745000	1.82071	6.2874
Error	16	4.633333	0.28958	Prob > F
C. Total	23	17.378333		0.0012*

Figure 6. Analysis of Variance data on JMP Pro

Analysis of Residuals

The residual normal plot is demonstrated in figure 7 below. The plot shows that the residuals fit along the straight line, proving that the residuals are normally distributed. Moreover, figure 8 below shows the residual vs predicted plot, the distribution of the points is not ideal, this can be due to the small

number of readings.

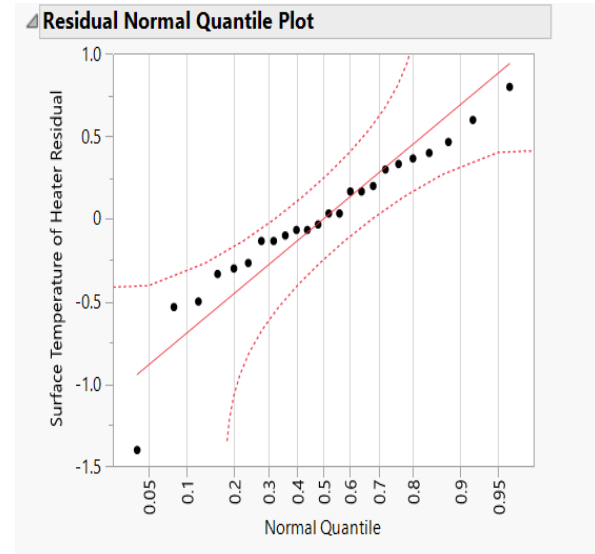


Figure 7. Residuals versus predicted plot from JMP Pro

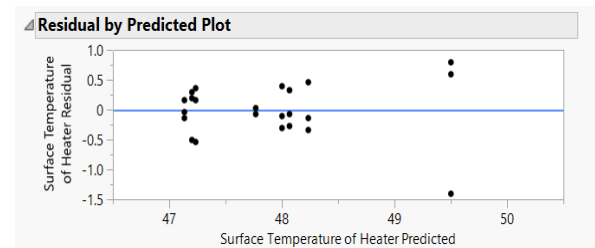


Figure 8. Residual vs Predicted Plot on JMP Pro

VI. RESULTS AND FINDINGS

The data from the 24 experimental runs were analysed using Analysis of Variance (ANOVA) at a 95% confidence level ($\alpha=0.05$). The model evaluated the primary effects of shunt finish, thermal paste, and enclosure treatment, as well as their high-order interactions.

A. Statistical Significance (ANOVA)

The overall model demonstrated high statistical significance with a p-value of **0.0012**, indicating that the variations in temperature were not due to random chance.

Factor B (Thermal Paste): This was the most influential factor in the study ($p < 0.0001$). The results confirmed that replacing air gaps with a 5 W/m·K thermal interface material significantly reduced the heater's surface temperature by facilitating superior conduction.

Factor C (Enclosure Surface): This factor was also statistically significant ($p = 0.017$). The pure aluminium enclosure outperformed the black powder-coated version, suggesting that the added

thickness of the coating acted more as an insulator than a radiative aid in this specific setup.

Factor A (Shunt Finish): With a p-value of **0.5045**, the shunt finish (pure vs. chromated) was found to be statistically non-significant. This implies that at a 10W load, the internal finish of the heat spreader does not meaningfully impact the final temperature compared to the interface quality.

B. Interaction Effects

A key finding of the 2^3 factorial design was the lack of significant interaction effects. All two-way interactions (e.g., Shunt Finish \times Thermal Paste) and the three-way interaction yielded p-values greater than 0.05. This indicates that the benefits of thermal paste and pure aluminium enclosures are independent of each other and can be applied universally to improve thermal performance.

C. Model Adequacy and Residuals

The model achieved a Coefficient of Determination (R^2) of **0.73**, meaning that the three design factors account for 73% of the observed temperature variability. The remaining 27% is attributed to experimental noise, such as the $\pm 1^\circ\text{C}$ tolerance of the thermocouple and $\pm 0.2\%$ power supply fluctuations.

The **Normal Probability Plot** of the residuals showed a linear distribution, confirming that the errors are normally distributed and that the ANOVA results are valid. There was no evidence of non-constant variance or systematic bias in the data.

D. Optimal Configuration Findings

To achieve the lowest operating temperature for the 10W heater, the experimental data identifies the following optimal combination:

1. **Thermal Interface:** Use 5 W/m·K thermal paste.
2. **Enclosure:** Use a pure aluminium surface treatment.
3. **Shunt:** The surface finish (Pure or Chromated) may be chosen based on cost or corrosion needs, as it does not affect thermal performance at this power level.

VII. CONCLUSION

The thermal performance experiment was conducted using three main factors. Each factor was tested at two levels. The effects of the interactions between these factors were also provided. A full factorial experiment was conducted using JMP Pro. There was no need for blocking in the experiment since all the results were obtained with constant conditions. The objective was to confirm the factors and

interactions of factors that have significant effects on the temperature of the electric heater.

After conducting the 24 runs, the data was used to analyze the significance of each factor in order to accept or reject the null hypothesis. The null hypothesis is to assume that the factor or interaction has no significant effect on the temperature. The null hypothesis was rejected for two factors only, the thermal paste and the surface treatment of the aluminum enclosure. These two factors proved to have a significant effect with a confidence level of 95%. Therefore, the P-value needs to be less than 0.05 to reject the null. The data obtained proved that the rest of the factors and interactions have no significant effect.

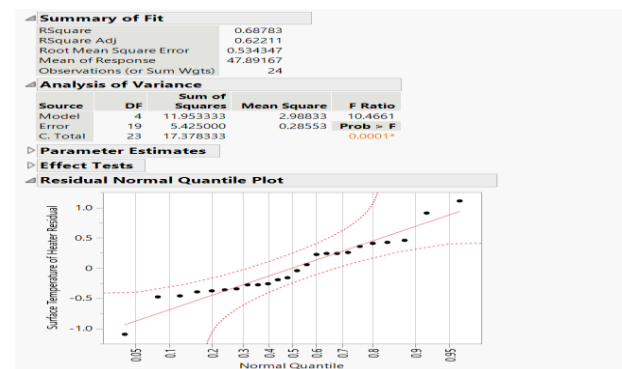


Figure 9. Results after removing the insignificant factors.

The results after removing the completely non-significant factors/interactions can be shown in the figure below. As expected, the P-value and R^2 values were reduced, and the modified residual is also demonstrated.

To reflect the experiment on real life, the main goal would be to dissipate heat from the electric heater, which mimics an IC on a PCB. Decreasing the temperature of the heater as much as possible is desired. Therefore, adding thermal paste and having a pure aluminum enclosure would increase the dissipation of heat from the electric heater to the surrounding by increasing conduction.

The R^2 model obtained before removing the non-significant terms was 0.73, and the R^2 adjusted is 0.61, which indicates that only 73% of the temperature readings are from the demonstrated model.

Conducting the experiment according to the randomized runs provided by JMP Pro was necessary to minimize any errors that can lead to misleading results. Moreover, conducting more iterations would have resulted in a higher confidence level. But due to the limited time available, only three replications were performed for each condition. The analysis showed that the only two factors are significant; however, the thermocouple used to measure the temperature has a noise level that can lead to inaccuracies in the data. The results

can be improved by utilizing an upgraded thermocouple with a lower tolerance level.

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