

Determination of Significant Parameters and Their Contributions In Temperature Measurement using Analysis of Variance and Taguchi Method

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Abstract - This work is devoted to the optimization of temperature measurement procedure by determination of the effect of significant parameters throughout the temperature measurement. The experimental studies result in Negative Temperature Coefficient thermistors, which will shed light on a critical point during temperature measurement. The results of experimental temperature measurement are presented by applying different tools in Design of Experiments (DOE), namely Taguchi method and Analysis of Variance (ANOVA). In the experimental studies, the effects of four parameters are considered, including the operator, air velocity, immersion level and the diameter of the probe. These parameters are chosen because in most test cases they are repeatedly involved. The results demonstrate that the probe diameter of the thermistor is the most significant factor with the percentage of contribution of 41.87%. Hence, Design of Experiment is considered as reasonable tool in finding the critical parameters and their contributions in temperature measurement.

Keywords - Process Optimisation; Temperature Measurements; Analysis of Variance; Taguchi Method; Design of Experiment.

1. INTRODUCTION

Nowadays, temperature measurement plays a critical role in the industrial environment and comprise a wide variety of methods and applications. Many processes require either a monitoring or continuous control of the temperature. These applications may range from the simple measurement of water temperature to advanced applications like monitoring of combustion chamber surface temperatures [1], and the temperature of a weld in a laser welding application [2, 3]. A wide variety of sensors and devices has been developed to address this demand, ranging from simple thermometers to more advanced thermocouples and infrared temperature sensors [4]. While many types of sensors are available, five sensor types including Thermistors, Thermocouples, Resistance Temperature Detectors, Infrared Temperature Sensors, and Semiconductor or Integrated Circuit Temperature Sensors are used for actual measurement of temperature in the industry. The semiconductor sensors are mostly used in

printed circuit board applications and infrared sensors for non-contact measurements. For industrial applications, which require precise temperature measurements, thermocouples and thermistors are the most popular sensor types due to their accuracy [5].

Thermocouples are extremely robust temperature measurement sensors; therefore, they are used in both large-scale industrial applications and small-scale laboratory measurements. Most of the thermocouples today are manufactured from two dissimilar materials welded together. A wide variety of materials is suitable for thermocouple manufacturing, and each material pair has different characteristics of temperature range and voltage that classifies thermocouples in types [6]. Nowadays, thermocouples with a wide variety of size and accuracy have been produced. The super fine thermocouples were produced with a small outer diameter and a quick response time, which could be 0.08 (mm) and 0.05 (s), respectively [7]. The response time of a thermocouple is defined as the time it takes to reach 62.3% of an instantaneous temperature change. The application of K-type thermocouple with the 130 μ m diameter and 0.15s response time was presented by Mamedov and Lazoglu [8] for temperature measurement of the micro-milling process. Li et al. [9] used built-in thin film thermocouples for measuring temperature close to the tool-chip interface during machining of Ti6Al4V alloy.

Thermistors are temperature sensors with an electrical resistance that changes in response to temperature. Unlike Resistance Temperature Detectors or thermocouples, thermistors do not have standards associated with their resistance and temperature characteristics. Consequently, each thermistor material provides a different resistance – temperature relation. While thermistors are one of the most right types of temperature sensors with an accuracy of $\pm 0.1^{\circ}\text{C}$, they are limited in their temperature range. Therefore, thermistors are used in specific applications that

require precise temperature measurement in the limited temperature range. For instance, Kumar et al. [10] used thermistors instantaneous monitoring of the temperature of the prosthetic device while Tymchik et al. [11] used them for determination coefficient of thermal conductivity for biological materials.

Many statistical tools are applied to identify the significant parameters affecting the data collection in engineering for different applications. One of the statistical tools is the Design of Experiment (DOE) to determine the significant controllable factors affecting the quality of injected parts in injection molding industry. It was found that process parameters such as melting temperature, packing pressure and geometrical parameters such as gate and runner design are considered as significant parameters [12-14]. DOE, ANOVA and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) for analyzing the effect of manufacturing parameters on the final quality of injected parts were applied. The contribution of each parameter on the final result was evaluated. Many internal and external defects of the plastic parts were used to evaluate the weight of the experimental parameters. Finally, by using the DOE and its relevant tools, the optimum levels of individual parameters were determined to have fewer defects in injected parts [15].

Another application of mentioned statistical tools was presented by Moayyedean et al. [16] to evaluate different parameters affecting the strain measurement. The influence of the temperature, the length of wires and the set point of forces for strain measurement were experimentally investigated at different levels. By using the Taguchi method, better control over the right level of controllable factors was achieved. It was found that the most significant factor was temperature with a maximum contribution. The results revealed that the strain measurements were

influenced by temperature with 76.35%, followed by effects of length of wires and the point of application with 7.66% and 6.77%, respectively.

However, to the best of the authors' knowledge, there is not enough study to show the effect of different parameters affecting the temperature measurements. Also, there is no study to determine significant parameters and the percentage of contribution to temperature measurement using DOE.

In this paper, a series of experimental tests using thermistors were conducted to investigate the significant parameters and their percentage of contribution throughout the temperature measurement using DOE. The Data Acquisition system is used for data collection. After an accurate calibration of the sensor, the relative percentage of contribution of each parameter is evaluated by comparing their relative variance. The selected parameters in this study are the operator, air velocity, the immersion level, and probe diameter.

2. SELECTION OF PARAMETERS

The main goal of the paper is to improve the quality of temperature measurement for different applications by determining the best combination of parameters and levels affecting the measurement procedure as shown in Table 1. In this study, the significance of four parameters and their contributions are investigated. These parameters are the operator (P_1), air velocity (P_2), the immersion level (P_3), and probe diameter (P_4), which are considered at three different levels. These levels are chosen based on to a wide range of real applications. Taguchi orthogonal array method is applied to optimize the measuring process and to achieve the best configuration of controllable parameters.

Table 1. Selected parameters and their levels.

	P_1 :Operator	P_2 :Air Speed	P_3 :Immersion level	P_4 :Probe diameter
Level 1	1	Low	1/4	Small (1/8")
Level 2	2	Medium	1/2	Medium (3/16")
Level3	3	High	3/4	Large (1/4")

According to the number of selected parameters and their levels, L9 orthogonal array of Taguchi was selected as shown in Table 2. According to the selected orthogonal array, Taguchi technique decreases the number of experiments, which leads to a reduction in time and cost. This particular design of orthogonal array covers whole parameters with a small number of experiments, allocates control parameters, design variables to the columns of an array, and transfers the integers in the array columns into the real setting of parameters [17, 18].

Table 2: L9 orthogonal array of Taguchi for data collection

Experiment #	P ₁ :Operator	P ₂ : Air velocity	P ₃ :Immersion level	P ₄ :Probe diameter (inch)
1	1	Low	1/4	1/8
2	1	Medium	1/2	3/16
3	1	High	3/4	1/4
4	2	Low	1/2	1/4
5	2	Medium	3/4	1/8
6	2	High	1/4	3/16
7	3	Low	3/4	3/16
8	3	Medium	1/4	1/4
9	3	High	1/2	1/8

2.1. S/N (Signal to Noise) ratio

Taguchi proposes S/N ratio to determine the quality characteristics considered for any problems in engineering design. S/N ratio has three categories: the smaller the better, the nominal the best, and the higher the better [19]. The S/N ratio applies the average values to convert the experimental results into the value, which is feasible for the evaluation characteristic of an optimum parameter analysis [20]. Since, the objective of this study is to keep the measured value as close as possible to the target value via optimum parameters, the nominal the best quality characteristic has been selected for the calculation of S/N ratio, which is defined in Eq.1 [21].

$$S/N = 20 \text{ Log } \left(\frac{\bar{y}}{s} \right), \tag{1}$$

where, \bar{y} is the response power (based on the number of experiments) and s is the noise power. The calculation for \bar{y} and s are shown in equations 2 and 3, respectively [21].

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i, \tag{2}$$

$$s^2 = \frac{1}{n-1} \sum_{i=1}^n (y_i - \bar{y})^2, \tag{3}$$

3. Experimental Setup and Temperature Measurements

The experimental setup starts with the calibration of the temperature sensor. The negative temperature coefficient (NTC) thermistors with three different diameters were used for experiments. Initially, the temperature was measured in two different levels, namely; high temperature and low temperature. Table 3 shows the temperatures and Resistances for each sensor used to find the values of thermistors’ constants A, B, and C based on Eq.4. Finally, by using the DAQ system and Eq.4, the value of resistance and temperature are determined as follow:

$$\frac{1}{T} = A + B * \text{Ln}(R) + C * \text{Ln}(R)^3. \tag{4}$$

Where, T is the temperature, R is the resistance, and $A, B, \text{ and } C$ represent three different variables.

Table 3. Temperature and resistance for Thermistor.

Sensor diameter [inch]		1/8	3/16	1/4
Low Temperature	Temperature [°C]	12.5	13.5	12.5
	Resistance [Ω]	16680	15950	17570
High Temperature	Temperature [°C]	48	45	55

	Resistance [Ω]	4500	4650	3540
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For the calculation of thermistor’s constants (A , B , and C), the temperature was measured three times at two different conditions. The evaluated coefficients using Eq.4 are presented in Table 4. The accuracy of calculations and measurements was validated and maximum overall error for the temperature of 25°C was measured as 0.0007%, which is negligible.

Table 4. The thermistor coefficients and error calculation.

Probe Diameter	A	B	C	R [Ω]	T [$^{\circ}\text{C}$]
Small	1.883723	-0.328473	0.00151235	10000	25.00062757
Medium	1.854616	-0.322332	0.00147721	10000	25.00173041
Large	1.348893	-0.2395283	0.001148375	10000	24.99984050

L9 orthogonal array was selected to design the experiments. The selected array with process parameters is presented in Table 2 and experiments were performed as shown in Figure 1.

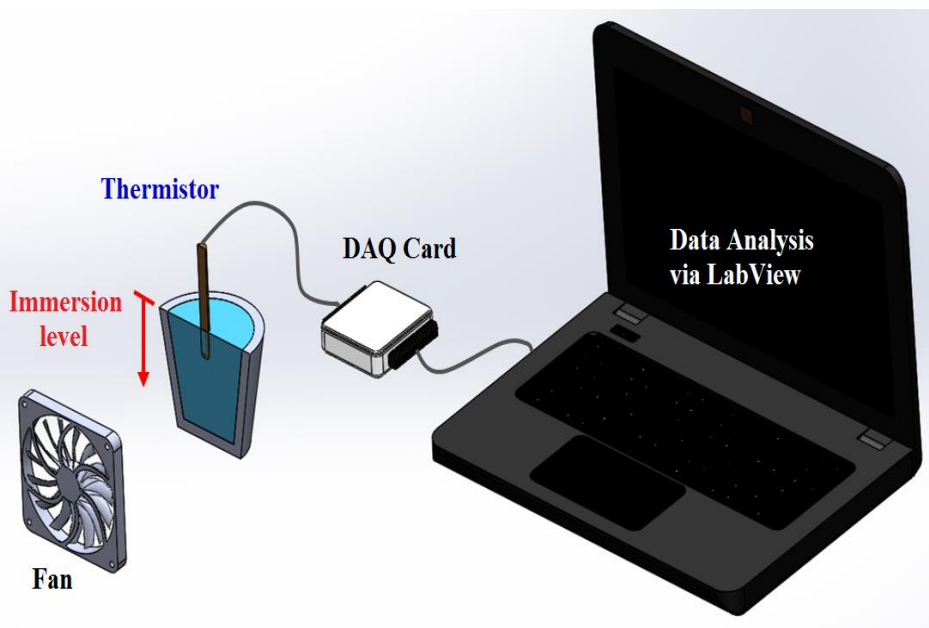


Figure 1: Schematic of the experimental setup, including a fan, thermistor and data acquisition system.

The evaluated results of measurements, comprising the resistance and temperature are presented in Table 5 for all test cases. To ensure consistency of temperature measurements they were repeated for 3 times.

Table 5: Temperature measurement of the test cases based on L9 orthogonal array, using three different resistances.

Experiment#	R_1 [Ω]	R_2 [Ω]	R_3 [Ω]	T_1 [$^{\circ}\text{C}$]	T_2 [$^{\circ}\text{C}$]	T_3 [$^{\circ}\text{C}$]
1	10960	10980	10990	21.967	21.911	21.883
2	10430	10420	10420	23.625	23.656	23.656
3	10970	11010	11020	22.146	22.042	22.016
4	10940	10990	11020	22.225	22.094	22.016
5	10960	11000	11030	21.967	21.855	21.771
6	10530	10520	10540	23.323	23.353	23.294
7	11140	11150	11150	21.616	21.589	21.589
8	10920	10980	11030	22.278	22.120	21.990
9	11070	11090	11120	21.660	21.605	21.523

After experimental measurements, S/N ratios were calculated using Eq.4. “The nominal the best” is the objective of this study. The calculated results for temperature measurement and S/N ratio have been determined in Table 6. The response power \bar{y} and the noise power s were calculated using equations 1 and 2, respectively. The value for the Signal to Noise ratio (S/N) was calculated based on Eq. 3 for each experiment.

Table 6: S/N ratio for all test cases.

Experiment #	$T_{ave}[^{\circ}C]$	S^2	S	S/N ratio
1	21.92	0.0018	0.042	54.15
2	23.64	0.0003	0.017	62.54
3	22.06	0.0047	0.068	50.10
4	22.11	0.0111	0.105	46.40
5	21.86	0.0096	0.098	46.93
6	23.32	0.0008	0.029	57.84
7	21.59	0.0002	0.015	63.10
8	22.12	0.0208	0.144	43.71
9	21.59	0.0047	0.068	49.92

From the collecting data in Table 6, the average S/N ratio for response table can be calculated, as shown in Table 7, to determine the optimal levels of the selected parameters.

Table 7: The response Table of S/N ratio.

	P_1 :Operator	P_2 : Air velocity	P_3 :Immersion level	P_4 :Probe diameter
Level 1	55.59	54.55	51.90	50.33
Level 2	50.39	51.06	52.95	61.16
Level 3	52.24	52.62	53.38	46.74
Difference $ \Delta T $	5.199	3.488	1.474	14.42

The larger value of $|\Delta T|$ shown in Table 7 demonstrates the significance of each parameter. It is clear that P_4 is the most significant parameter followed by P_1 , P_2 , and P_3 . The optimum set of parameters can be evaluated from Table 7 by selecting the highest level of S/N for each parameter. The best results are P_1 at level 1, P_2 at level 1, P_3 at level 3 and P_4 at level 2.

Once the optimum set of the parameters was defined, the relative percentage of contribution is calculated by comparing the relative variance of temperature averages of each parameter. ANOVA computes the quantities such as degrees of freedom, the sum of squares, the pure sum of a square and the percentage of contribution. The calculation of the sum of the square for each parameter and the total sum of squares can be written as [21]:

$$SS_{P_i} = \sum_{i=1}^{K_A} \left(\frac{A_i^2}{n_{A_i}} \right) - \frac{(\sum_{i=1}^N x_i)^2}{N} \tag{5}$$

$$SS_T = \sum_{i=1}^{K_A} x_i^2 - \frac{(\sum_{i=1}^N x_i)^2}{N} \tag{6}$$

$$SS_E = \left(SS_T - \sum_{i=1}^{K_A} SS_{P_i} \right), \tag{7}$$

where A_i is the average temperature for each level, n_{A_i} stands for the number of levels, x_i is the temperature value in each experiment, N is the number of experiments and k_A represents the number of parameters. For the calculation of the total degree of freedom (F) and the degree of freedom of each level (F_i) following equations were used, respectively [21]:

$$F_i = x_i - 1, \tag{8}$$

$$F_t = N - 1, \tag{9}$$

To determine the error of degree of freedom, Eq. 10 is applied as follow [21]:

$$F_e = F_t - \sum_{i=1}^{K_A} F_i \tag{10}$$

Finally, the percentage of contribution of each parameter (P_{P_i}) is calculated as [21]:

$$P_{P_i} = \frac{SS_{P_i}}{SS_T}, \tag{11}$$

By using Eq.5 – Eq.11 the weight or percentage of contribution of each parameter is calculated as shown in Table 8. The results indicate that the probe diameter with 41.87% has the highest contribution, followed by the operator with 24.28 %, immersion level with 17.45 %, and air velocity with 16.38 %.

Table 8: Analysis of Variance (ANOVA) of parameters, including the percentage of contribution of the parameters.

	F	S	P %
P₁:Operator	2	1.0387	24.2865
P₂: Air velocity	2	0.7006	16.3814
P₃:Immersion level	2	0.7466	17.4572
P₄:Probe diameter	2	1.7910	41.8747
Error	0	0.000	0.000
Total	8	4.2771	100.0

4. CONCLUSION

The effect of the operator, air velocity, immersion level and probe diameter have been investigated in this paper throughout the temperature measurement. Design of experiment (DOE) and related tools, namely Taguchi method, Signal to Noise (S/N) ratio and Analysis of Variance (ANOVA) were applied to reduce the noise from the controllable parameters. Hence, the optimal levels of selected parameters were identified including their percentage of contribution to improve the quality of the measurement process. The result demonstrates that P4 is the most significant parameter followed by P1, P2, and P3 and the optimum set of parameters are P1 at level 1, P2 at level 1, P3 at level 3 and P4 at level 2. Finally, based on the ANOVA, the probe diameter (P4) has the highest percentage of contribution (41.87%) followed by the operator (P1) with 24.28%, immersion level (P3) with 17.45% and air velocity (P2) with 16.38%.

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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