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TAGUCHI-BASED PARAMETER'S OPTIMIZATION IN ELECTROSPRAY COOLING WITH MIXED WORKING FLUIDS

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Abstract

The rapid increase in power density of modern electronic devices has made compact and effective cooling strategies indispensable. In this work, the Taguchi experimental design method was employed to optimize electrospray cooling performance. Experiments were conducted with a constant nozzle diameter and a fixed nozzle-to-heat sink distance, using three different working fluids (100% ethanol, 90% ethanol-10% water, and 80% ethanol-20% water), flow rates between 0.3-0.5 ml/min, and applied voltages ranging from 6-10 V. The temperature difference (ΔT) was used as the primary evaluation parameter. Analysis of variance indicated that fluid composition and flow rate significantly influence cooling efficiency, whereas voltage plays a relatively minor role. The most favorable operating condition was identified as 80% ethanol-20% water at 0.5 ml/min and 6 V.

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1. Introduction

The minimization of electronic components and the rapid increase in processing capacities have made the management of high thermal loads on surfaces a critical engineering problem [1, 2]. From this standpoint, electrospray cooling—also referred to as electrohydrodynamic (EHD) spraying—has attracted growing research interest, primarily because it combines high heat transfer capability with minimal fluid consumption and a compact system design [3].

Electrospray atomization is the process by which a conductive liquid is atomized under a high electric field as a result of the combined effects of evaporation and electrostatic forces overcoming surface tension [4]. In this process, heat transfer performance depends on numerous parameters, including applied voltage, spray flow rate, nozzle geometry, heat sink to nozzle distance, and the thermophysical properties of the fluid used [5]. With electrospray formation, heat transfer increases due to the high surface area of the droplets sprayed onto the surface [6].

Although a single coolant (e.g., water, ethanol, or HFE-7100) is typically used in electrospray cooling systems, experimental studies conducted in recent years using mixtures of fluids with different physicochemical properties (e.g., HFE-7100-ethanol, water-ethanol) have shown that thermal performance can be improved. Table 1 presents the results obtained by mixing fluids in electrospray cooling.

Fluid properties (such as surface tension, heat of vaporization, and dielectric constant in ethanol-water mixtures) can directly affect cooling performance. For instance, incorporating water into ethanol has been shown to enhance the effectiveness of electrospray cooling, particularly under elevated flow rate conditions [7].

The optimization of multi-parameter experimental systems is critical for improving efficiency and quality in engineering processes. In this context, statistical experimental design methods enable effective results to be obtained by minimizing the number of experiments. Among various

experimental design strategies, the Taguchi method emerges as a particularly efficient and widely adopted approach in this domain. Developed by Taguchi, this methodology seeks to enhance product and process quality by reducing the influence of uncontrollable environmental variations through the application of orthogonal arrays and signal-to-noise (S/N) ratio analysis. The Taguchi method concretely demonstrates the significant advantages that statistical experimental design approaches offer in terms of efficiency and resource savings when optimizing experimental systems [11, 12].

Table 1. Literature summary

Researcher	Coolant type	Parameters	Findings
Kabakuş et al. [4]	100% Water, 50% Ethanol - 50% Water, 100% Ethanol	Flow rate, fluid type	A 50% ethanol-water mixture reduced panel temperature by 59% compared to water and increased electrical efficiency by 6.8%.
Taheri et al. [7]	Water- Ethanol (0%, 35% ve 70%)	Applied voltage, flow rate, and fluid properties	The stability region formed by spraying water-ethanol mixtures with electrospray was determined. A high water volume ratio in the mixtures significantly increased the critical heat flux.
Wang et al. [8]	R141b and Ethanol	Effects of break-up modes, impingement characteristics	With improved spray characteristics, ethanol evaporation increased and cooling efficiency reached 92.6%.
Tian et al. [9]	R141b and Ethanol	The investigated parameters included the applied voltage, the coolant flow rate, and the ethanol mass concentration.	Elevating both the applied voltage and the volumetric flow rate resulted in a marked improvement in the cooling performance of the electrospray system.
Xu et al. [10]	HFE7100- Ethanol	Key operational parameters, including applied voltage, flow rate, spray height, degree of liquid subcooling, and ethanol concentration, were systematically investigated.	The incorporation of a minor fraction of ethanol into HFE 7100 markedly enhanced the charging efficiency of the cooling fluid, primarily by elevating its electrical conductivity.

This study aims to optimize cooling by electrospray on a $5 \times 5\,\text{cm}$ heat sink surface under conditions of fixed nozzle diameter and fixed heat sink to nozzle distance. The experimental design was systematically carried out based on the Taguchi approach, using three different flow rates, three different voltage levels, and three different fluid compositions: ethanol, 90% ethanol-10% water, and 80% ethanol-20% water. In this context, the study statistically analyzed the effect of parameters on thermal performance indicators (ΔT and heat transfer coefficient), defined optimal operating

conditions, and presented results regarding the applicability of electrospray cooling with binary fluid systems.

2. Material and Methods

In the present study, the Taguchi method was employed to optimize and identify the key parameters influencing electrospray cooling performance in the heat sink. A schematic representation of the experimental setup is presented in Figure 1.

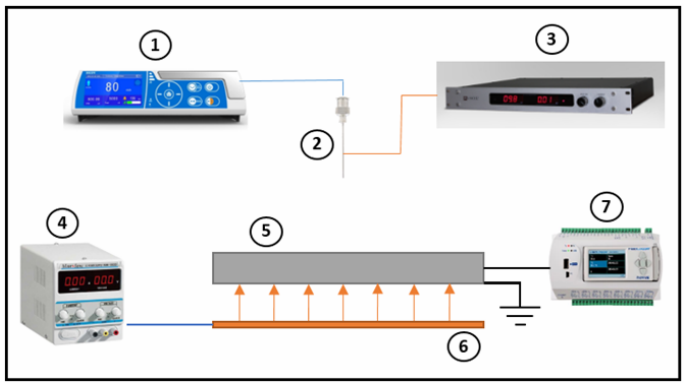

Figure 1. Experimental setup schematic (1. Infusion pump, 2. Stainless steel nozzle, 3. Static electricity charger, 4. DC power supply, 5. Heat sink, 6. Silicone heater, 7. Data logger).

The experiments were conducted at a constant heat flux (3.56 W/m^2) and a constant nozzle-heat sink distance (30 mm). An aluminum heat sink measuring $50 \times 50 \times 4$ mm was used in the experiments. The constant heat flux was provided by a silicon heater connected to a DC power supply. The heat flux was established to evaluate the cooling performance of the heat sink under conditions exceeding 100°C. A stainless steel nozzle with a diameter of 25G ($d_i = 0.26$ mm) was used in the study. Ethanol was used as the alcohol in the experiments due to its low vaporization temperature and surface tension. Water, which has a high vaporization enthalpy, was used as the additive. The coolant fluids were delivered to the stainless steel nozzle using a Hedy 15 infusion pump. A Nanoliz NL-K 25 high-voltage power

supply was used to create the electrospray between the nozzle and the heat sink. All surfaces of the heat sink, except for the surface in contact with the spray, were insulated with glass wool insulation. Temperature measurements were taken using five T-type thermocouples, four on the heat sink and one in the environment. The thermocouples were installed by drilling holes at the exact center of the four sides of the heat exchanger at 5, 10, 15, and 20 mm intervals. After the temperature values stabilized, they were read using the Novus Fieldlogger data logger and recorded on a computer.

2.1. Calculations

The heat transfer mechanisms taking place on the surface of the heat sink are represented by equation (1).

$$Q_{total} = Q_{con} + Q_{vap} + Q_{rad} + Q_{loss}. \quad (1)$$

Q_{con} represents the amount of convection occurring from the heat sink surface, Q_{vap} represents the amount of heat transfer occurring through evaporation, Q_{rad} represents the amount of heat transfer occurring through radiation, and Q_{loss} represents the amount of heat lost. Heat transfer by radiation from the surface accounts for approximately 1% of the total heat transfer. This is because the surface area through which heat transfer occurs is quite small. In addition, since all surfaces of the heat sink that are not in contact with the spray are insulated, the amount of loss accounts for approximately 3% of the total heat transfer. Therefore, Q_{rad} and Q_{loss} can be neglected. Furthermore, considering that the losses are quite low, it can be said that the entire amount of energy produced by the silicon heater is transferred to the heat sink. Thus, the heat transfer equation becomes equation (2).

$$Q_{total} = Q_{con} + Q_{vap} = VI. \quad (2)$$

V and I are the voltage and current values set by the DC power supply, respectively. The heat transfer coefficient is expressed by equation (3).

$$h = \frac{Q_{total}}{A(T_{sur} - T_{\infty})}. \quad (3)$$

The temperature difference between the heat sink surface and the ambient environment is denoted as ΔT. The uncertainty associated with the heat transfer coefficient was evaluated using equation (4) [13].

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{0.5}. \quad (4)$$

In equation (4), w_R denotes the overall system uncertainty, R corresponds to the function of independent variables, $(x_1, x_2, ..., x_n)$ represent the independent variables, and $(w_1, w_2, ..., w_n)$ indicate the uncertainties associated with these variables. The experimental uncertainty of the heat transfer coefficient was determined to be 1.02%.

2.2. Experimental design

In this study, where the optimum parameters and values were determined using electrospray cooling in the heat sink, experiments were conducted for three different fluids, flow rates, and voltages. The experimental parameter values determined for three levels and three parameters are given in Table 2. “Fluid” refers to the type of coolant used in electrospray cooling, “Flow rate” refers to the flow rate of the coolant, and “Voltage” refers to the voltage applied to the nozzle for atomization. The experimental design obtained using the Taguchi method based on the L9 (3^3) orthogonal array to determine the parameters with the lowest ΔT value in the cooling of the heat sink is presented in Table 3. Experimental design and data analysis were conducted using Minitab 18.

Table 2. Experiment design parameters and level values

Experimental parameters	Low	Levels middle	High
Fluid	100% Ethanol	90% ethanol + 10% water	80% ethanol + 20% water
Flow rate (ml/min)	0.3	0.4	0.5
Voltage (V)	6	8	10

Table 3. Experimental design performed using the Taguchi method according to the L9(3^3) orthogonal series

Exp. No	Fluid	Flow rate	Voltage	ΔT
1	100% Ethanol	0.3	6	52.64
2	100% Ethanol	0.4	8	41.97
3	100% Ethanol	0.5	10	33.23
4	90% Ethanol + 10% water	0.3	8	40.25
5	90% Ethanol + 10% water	0.4	10	34.47
6	90% Ethanol + 10% water	0.5	6	15.79
7	80% Ethanol + 20% water	0.3	10	31.05
8	80% Ethanol + 20% water	0.4	6	22.20
9	80% Ethanol + 20% water	0.5	8	11.17

3. Result and Discussion

In this study, the Taguchi method was employed to identify the optimal ΔT and heat transfer coefficient for a heat sink utilizing electrospray cooling. Based on an L9 (3^3) orthogonal array, nine experiments were conducted, leading to the determination of the corresponding ΔT values, as summarized in Table 3. A variance analysis was performed to identify the effective parameters. The model summary obtained from the variance analysis is presented in Table 4.

Table 4. Model summary

R-Sq	R-sq(adj)	R-sq(pred)
97.63%	96.2%	91.6%

The high statistical criteria of the model obtained as a result of the experimental studies are shown in Table 4. The model's coefficient of determination (R^2) is 97.63%, indicating that a large portion of the experimental data is explained by the regression model. The adjusted coefficient of determination $(R^2\text{adj} = 96.2\%)$ demonstrates that the model exhibits overfitting and maintains its reliability by accounting for the effect of the number of factors included in the model. Additionally, the predictive

coefficient of determination (R^2pred = 91.6%) shows that the model can make accurate predictions not only for the current data but also for new data. These results demonstrate that the model obtained using Taguchi experimental design is reliable and valid in terms of both explanatory power and predictive ability. The parameters affecting ΔT are shown in the variance analysis table (Table 5).

Table 5. Variance analysis table for ΔT

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	*F*-Value	*P*-Value
Regression	3	1358.47	97.63%	1358.47	452.823	68.58	0.000
Fluid	1	670.24	48.17%	670.24	670.244	101.51	0.000
Flow rate	1	677.24	48.67%	677.24	677.238	102.57	0.000
Voltage	1	10.99	0.79%	10.99	10.989	1.66	0.253
Error	5	33.01	2.37%	33.01	6.603		
Total	8	1391.48	100.00%				

The results of the variance analysis (ANOVA) show that the model is statistically significant (Table 5). A total of 97.63% of the variance is explained by the regression model, with only 2.37% attributable to the error term. This indicates that the model accurately represents the experimental data. When examining the factors, fluid type (48.17% contribution, *P*-value < 0.05) and flow rate (48.67% contribution, *P*-value) emerge as the most dominant parameters. The *F*-values of both factors (101.51 and 102.57) are quite high, confirming their strong effects on the output variable. In contrast, the contribution of the voltage factor was limited to 0.79% and was not found to be statistically significant (*P*-value = 0.253). In conclusion, the model established within the scope of the Taguchi experimental design reliably reflects system behavior; in particular, it has been demonstrated that fluid type and flow rate are decisive factors in performance. The regression analysis yielded the following equation (equation (5)).

$$\Delta T = 89.64 - 10.57\,\text{Fluid} - 106.2\,\text{Flowrate} + 0.677\,\text{Voltage}. \quad (5)$$

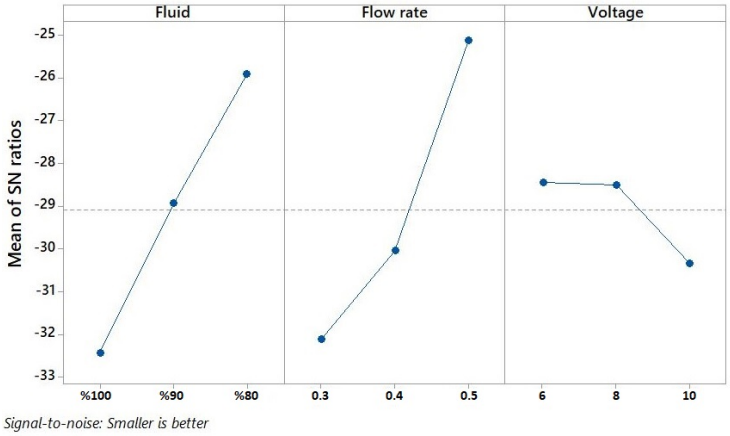

Figure 2. Main effect graph for ΔT.

The main effects plot of the signal-to-noise (S/N) ratios, presented in Figure 2, illustrates the influence of the experimental parameters on system performance. According to the 'smaller-is-better' criterion, lower S/N ratio values correspond to improved performance. Analysis of the plot indicates that fluid type is the most significant factor, with a pronounced reduction in the S/N ratio observed upon variation of this parameter. Similarly, an increase in flow rate also significantly affects the system output, with higher S/N values obtained at lower flow rates. In contrast, the voltage parameter has a relatively limited effect; while the S/N ratio remains similar at low and medium voltage levels, a relatively noticeable decrease is observed at the highest voltage value.

These results are consistent with the ANOVA findings, indicating that the most critical determinants of system performance are fluid type and flow rate, while voltage has a secondary effect.

When examining the interaction graph, it can be seen that the relationship between voltage and ΔT is not unidirectional and constant, but rather changes direction depending on both the type of fluid used and the flow rate (Figure 3). In particular, at low flow rates (0.3 ml/min), an increase in voltage reduces ΔT as expected, but at medium or high flow rates

(0.4–0.5 ml/min) and with different fluids, this effect is reversed, and an increase in voltage causes ΔT to increase. These findings indicate that thermal and fluid-dynamic processes in the system cause different limiting mechanisms to become dominant as the voltage increases.

The fact that the lines in the graph are not parallel to each other and even intersect at some points is evidence of a strong interaction effect. This situation reveals that the effect of voltage on ΔT cannot be interpreted independently but must be evaluated in conjunction with fluid type and flow rate. In other words, the primary effect of voltage is misleading when considered in isolation, as this effect strongly depends on the fluid type and flow rate.

Physically, while the system's thermal response is more linear in low-voltage*low-flow rate regions, ΔT can increase in high-voltage*high-flow rate combinations due to a decrease in the amount of fluid evaporating from the surface. Mixing water into ethanol creates a fluid layer on the heat-receiving surface at low temperatures and high flow rates, thereby reducing the amount of heat released from the surface and increasing ΔT. In this context, the expectation that an increase in voltage will reduce ΔT is only valid under specific experimental conditions and cannot be generalized.

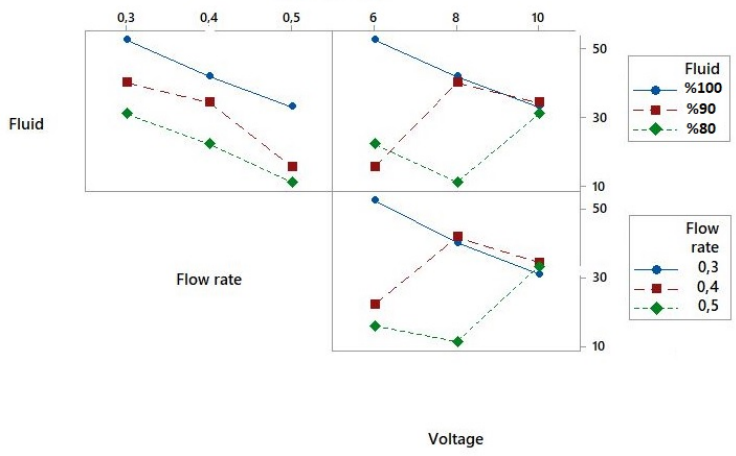

Figure 3. Interaction graph for ΔT.

As a result, when the main effect graph is examined, the factors affecting ΔT are as shown in Table 6. Experiments conducted at optimal parameter values determined $\Delta T = 11.3^{\circ}\mathrm{C}$, and the corresponding heat transfer coefficient value was calculated as $h = 315.04\ \mathrm{W/m^2K}$.

Table 6. Optimum values

Parameters	Optimum values
Fluid	80% ethanol + 20% water
Flow rate (ml/min)	0.5
Voltage (V)	6

4. Conclusion

In this study, the parameters affecting thermal performance in electrospray cooling systems were systematically investigated using the Taguchi experimental design approach. The findings revealed that the type of fluid and flow rate have a dominant effect on heat transfer, while voltage contributes to a more limited extent. In particular, the use of ethanol-water mixtures provided a higher heat transfer coefficient and lower temperature difference compared to pure ethanol. The optimal conditions were determined to be an 80% ethanol-20% water mixture, a flow rate of 0.5 ml/min, and a voltage of 6 V. The heat transfer coefficient of 315.04 $\mathrm{W/m^2K}$ obtained under these parameters demonstrates the high efficiency of electrospray cooling. However, the strong interaction between the relationship between voltage and ΔT and the fluid composition and flow rate indicates the complex fluid-dynamic mechanisms of the system. Therefore, future studies should investigate different fluid types, expanded flow rate-voltage ranges, and advanced modeling approaches.

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