Journal of Brilliant Engineering 1 (2026) 41095

Brilliant Engineering

journal home: www.acapublishing.com/journals/4/ben

Research Article

Optimization of Electrospray Cooling Performance Using Isopropyl Alcohol-Water Binary Mixtures: A Full Factorial Design Approach

Ahmet Öztürk*,[1]

[1]*Artvin Çoruh University, Department of Machinery and Metal Technologies, Artvin, Turkey*

Keywords

Heat transfer,
Cone-jet mode,
IPA–water mixtures,
Full factorial design,
Electrospray cooling.

Abstract

This study tested the performance of Electrospray (ES) cooling using binary mixtures of water and isopropyl alcohol (IPA). The main aim was to identify how combinations of fluid property, flow rate, and electrical potential interact under conditions of constant heat flux (3850 W/m²). A full 33 factorial experiment was performed for each of three values of mixture composition (10, 30, and 50% IPA) using three different flow rates (15, 30, and 45 ml/h) and three different levels of voltage (9, 10, and 11 kV). The analysis showed that flow rate has the greatest influence on cooling performance (57.02% impact). Fluid properties were found to produce the best cooling results with the 30% IPA/70% water mixture because of their ability to provide a balance of thermal capacity and low surface tension. Using the optimum condition of a high voltage (11 kV) allowed for a stable cone-jet mode that provided effective atomization and surface wetting. Lower levels of IPA were shown to hinder the formation of stable jets because of the increase in surface tension, while higher concentrations of IPA were limited by lack of thermal capacity. From the analysis of data, the optimum operating conditions were found to be flow rates of 45 ml/h, voltages of 11 kV, and 30% IPA, resulting in a minimum temperature difference of 14.12 K. These results were confirmed by the statistical regression analysis (R^2=0.974) model.

1. Introduction

Electronics are getting smaller every day. As all products become smaller we are also seeing an increase in thermal management challenges posed by the higher and higher heat outputs (heat fluxes) of microchip technology. Therefore, an appropriate thermal management strategy is essential to the reliability and operational longevity of a modern electronic device (new generation microchips). Traditional air-cooling and passive liquid-cooling systems are becoming less effective in dissipating the ultra-high heat flux levels that we are encountering today [1]. In this sense, electrostatic levitation may be a solution for providing the necessary means to manage the increased levels of heat output, as electrostatic levitation is able to achieve a high heat-transfer coefficient, even at low flow rates, and enables control of the fluid-flow dynamics through a controllable electric field.

Electrostatic levitation works by creating and accelerating microscopic, charged droplets of a conductive liquid onto a heated surface through the use of a controllable electrical charge to generate repulsive forces between the droplets (Coulomb repulsion). The charged droplets create thin-film turbulence and an increased rate of evaporation upon impact with the heated surface, resulting in a significant enhancement of the heat-transfer process. The thermal characteristics of electrostatic levitation can be affected by numerous parameters such as voltage and flow rate, as well as nozzle designs, environmental conditions, and the thermophysical properties of the working fluid [2], [3], [4].

The properties of the coolant are a major factor in the performance of different types of systems. Water would be an excellent coolant because it possesses high thermal conductivity and latent heat, but atomizing pure water requires extremely high voltage (due to its high viscosity) [5]. In contrast, a variety of alcohols such as ethanol, methanol, and isopropanol (IPA) are able to achieve lower surface tension and therefore easier to atomize than water; however, they possess less thermal energy capacity than water. In this regard, Sönmez performed a comparative study of various liquid and aqueous mixtures of ethanol, methanol and IPA [6]. His experiments were performed by atomizing methanol, ethanol and IPA and their 50% and 75% aqueous mixtures using a fixed voltage of 10 kV. Sönmez found that under certain environmental conditions, there were unique benefits from using methanol-water mixtures; that viscosity and surface tension were the primary physical properties responsible for determining atomization quality, and that latent heat was the dominant contributor to cooling capacity for all types of mixtures. Similarly, Wan et al. (2024) [7] sought to improve the heat capacity of aqueous fluids using microencapsulated PCM slurries, while Jiang et al. (2019) [8] found that adding ethanol in mixtures of biodiesel and ethanol facilitated faster evaporation of biodiesel oils by reducing the diameter of the droplets. These studies highlight how modifications to the properties of fluids can improve their performance.

Research is now looking into environmental factors as a part of studying fluid properties. For this reason, a new method has been developed that will provide more insight into how fluid properties affect other dynamic parameters of the system and the environmental conditions under which it operates. While conventional studies generally focus on very low flow rates, industrial cooling needs have brought high flow rate applications to the forefront. In their study examining ES morphology at high flow rates, Shao et al. (2024) [9] visualized that increasing the flow rate shifts the spray mode to the "multi-jet" regime and extends heat transfer limits. Similarly, Xu et al. (2021) [10] emphasized the effect of spray modes (dripping, cone-jet, multi-jet) on boiling regimes, while Liu et al. (2025) [11] analyzed the effects of ambient pressure and temperature on droplet velocity and spray angle, demonstrating the sensitivity of ES cooling to thermodynamic environmental conditions. Also, Tian et al. (2024) [12] increased the heat transfer area using macro-structured surfaces and reported the synergistic effect of surface modifications with the electric field.

*Corresponding Author: ahmetozturk@rtvin.edu.tr
Received 08 Dec 2025; Revised 22 Dec 2025; Accepted 22 Dec 2025

https://doi.org/10.36937/ben.2026.41095

Although the existing literature establishes the potential of ES cooling, the vast majority of studies focus either on single-parameter effects or the behavior of pure liquids. Studies involving the systematic optimization of binary mixtures, which combine the thermal capacity of water with the atomization ease of alcohol, particularly at high flow rate ranges and different voltage levels—are limited. In this study, the researchers evaluated both the individual effects of each mixing ratio, applied voltage and flow rate, as well as all of the possible complex interactions of those parameters using a statistically valid model of L3^3 full factorial design. In doing this, the researchers were able to gain a more accurate understanding of which parameters would be most dominant in impacting cooling performance in high heat flux applications, and to determine optimal operating conditions for those systems.

2. Materials and Methods

This study employs a current cooling system that consists of various components, shown in Figure 1: a high voltage power supply, a direct current (DC) power supply, a syringe pump, a data acquisition system, an aluminum heatsinks, a silicone heater, a nozzle of stainless steel, and thermocouples embedded into the heatsink. The heatsink is a flat plate (40×40×5 mm) of aluminum, which provides a flat surface for cooling by the ES. The back of the heatsink is attached to an electrically insulated silicone heater that has been powered with a variable DC supply to provide a uniformly distributed heat flux of 3850 W/m [6] (around 373.15 K). Both the heater and the heatsink were insulated thermally and electrically from the rest of the system using appropriate insulating materials to limit any electric leakage and provide accurate measurements.

Working fluids were introduced through a syringe pump, which provided accurate control over the rate of flow during testing. All distances between nozzle tips and heating plate surfaces were maintained at 30 mm during all tests. The positive terminal of the high-voltage power supply was connected to the nozzle, with the heating plate at ground potential, allowing the creation of a static electric field required to generate electric sprays. In this case, working fluids were delivered to the nozzle tip in the form of a cone-jet configuration, resulting in highly charged micrometer-sized droplets released from the nozzle into the heated surface of the heating plate.

Ambient and heated surface temperatures were measured using K-type thermocouples, connected to the data logger. This connection allowed for high-resolution tracking of the transient temperatures of both surfaces throughout the duration of the experiments.

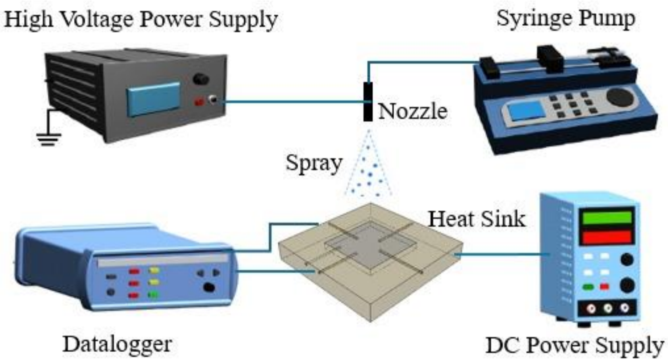

Figure 1. Schematic illustration of the experimental setup

A thorough statistical method used to investigate multiple variables at multiple levels, the full factorial design requires that an experiment be run at each of the possible combinations of these variables. The number of experiments necessary to accomplish this (Equation 1) is calculated by taking the number of combinations of all of the levels of all of the variables to be investigated.

$$N = n^k \quad (1)$$

N is the number of experiments performed while n is the number of possibilities (levels). k represents the number of factors in each experiment. The full factorial method allows for the comparison of the effects of an individual (parameter) as well as the interaction between two or more parameters on the system and the relationship between the parameters and how they behave in relation to each other (linearity). These capabilities of full factorial design create opportunities for improving performance and finding the best (optimal) operating conditions for a system. All experiments were run three times with each run being uniquely defined by the design matrix for the purpose of ensuring reproducibility and minimizing variation in the experimental results. The final values reported in the Results section of this article reflect the average values of all three repetitions of each experiment.

In this study, the authors applied a statistical methodology to investigate the cooling capabilities of the ES system. The authors chose three independent variables (Mixture Ratio (X_1), Flow Rate (X_2), and Applied Voltage (X_3)) and employed a three- level full-factorial design to capture any potential non-linearity and interactions that occur between the independent variables. The experimental domain and the corresponding levels for each parameter are summarized in Table 1.

Table 1. Experimental domain for each parameter with three levels

Parameters	Symbol	Unit	Level 1 (Low) (-1)	Level 2 (Medium) (0)	Level 3 (High) (+1)
Mixture Ratio (IPA:Water)	X_1	v/v (%)	10:90	30:70	50:50
		w/w (%)	8:92	25.2:74.8	44.1:55.9
Flow Rate	X_2	ml/h	15	30	45
Applied Voltage	X_3	kV	9	10	11

Based on this design, a total of 27 experiments were conducted, and the experimental matrix and results are presented in Table 2.

Table 2. Experimental Design and Results

Exp. No.	Coded Factors (X_1, X_2, X_3)	Mixture Ratio (%IPA/Water)	Flow Rate (ml/h)	Voltage (kV)	ΔT (K)
1	-1, -1, -1	10-90	15	9	22.85
2	-1, -1, 0	10-90	15	10	18.76
3	-1, -1, +1	10-90	15	11	17.34
4	-1, 0, -1	10-90	30	9	18.73
5	-1, 0, 0	10-90	30	10	17.43
6	-1, 0, +1	10-90	30	11	15.83
7	-1, +1, -1	10-90	45	9	17.16
8	-1, +1, 0	10-90	45	10	16.30
9	-1, +1, +1	10-90	45	11	15.21
10	0, -1, -1	30-70	15	9	17.89
11	0, -1, 0	30-70	15	10	17.33
12	0, -1, +1	30-70	15	11	16.94
13	0, 0, -1	30-70	30	9	16.64
14	0, 0, 0	30-70	30	10	15.92
15	0, 0, +1	30-70	30	11	15.38
16	0, +1, -1	30-70	45	9	15.87
17	0, +1, 0	30-70	45	10	14.97
18	0, +1, +1	30-70	45	11	14.12
19	+1, -1, -1	50-50	15	9	22.07
20	+1, -1, 0	50-50	15	10	22.77
21	+1, -1, +1	50-50	15	11	23.49
22	+1, 0, -1	50-50	30	9	18.27
23	+1, 0, 0	50-50	30	10	16.56
24	+1, 0, +1	50-50	30	11	15.89
25	+1, +1, -1	50-50	45	9	15.80
26	+1, +1, 0	50-50	45	10	14.82
27	+1, +1, +1	50-50	45	11	14.19

In this study, a three-level and three-factor full factorial experimental design, as presented in Table 2, was used. A total of 27 experimental design points were tested, and measurements were carried out for each operating condition. For every experiment, data acquisition commenced only after the system reached steady-state, and time-averaged values were used in the subsequent analyses. To investigate the ES cooling performance, mixtures of IPA and deionized water were used as the working fluids. The mixtures were prepared volumetrically prior to each experiment. Three volumetric mixture ratios were selected: 10% IPA–90% water, 30% IPA–70% water, and 50% IPA–50% water. Flow rates of 15, 30, and 45 ml/h and voltage levels of 9, 10, and 11 kV were evaluated.

For each experiment, the temperature of the heat sink surface is denoted as $T_{surface}$, and the ambient temperature is denoted as $T_{ambient}$(292.02 K). The response variable of the study was defined as the temperature difference between the heat sink and the ambient environment, expressed in Equation (2):

$$\Delta T = T_{\text{surface}} - T_{\text{ambient}} \tag{2}$$

Since improving ES cooling corresponds to reducing the surface temperature, the "smaller is better" quality criterion of the Taguchi method was adopted.

For the full factorial design, the signal-to-noise (S/N) ratio corresponding to the "smaller is better" performance index was calculated using Equation (3):

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{3}$$

where y_i represents the measured value of ΔT in each trial, and n denotes the number of repetitions. The calculated S/N ratios were used to generate main effects plots, enabling the determination of the optimal level for each parameter. Higher S/N ratios indicate increased stronger of the system against noise factors and a more effective reduction in ΔT.

A multivariate regression model for ΔT was developed using experimental data. The statistical significance of the model and the contribution of each parameter were evaluated through analysis of variance (ANOVA). This approach allowed the quantitative identification of the relative effects of IPA–water mixtures, flow rate, and voltage on ES cooling performance, and helped the determination of the optimal combination of fluid composition, flow rate, and voltage.

The thermophysical properties of the coolant mixtures used in the experiments were calculated at the reference temperature corresponding to the experimental conditions (298.15 K ambient temperature). High accuracy thermophysical property data were obtained using the NIST REFPROP 10 (Reference Fluid Thermodynamic and Transport Properties Database) software, and the results are presented in Table 3. Although mixture ratios were prepared volumetrically, REFPROP calculations were performed using mass-based compositions to ensure thermodynamic consistency. The software uses highly accurate empirical models, including the Helmholtz free energy formulation, validated over wide ranges of temperature and pressure for pure fluids and mixtures.

Table 3. Thermophysical Properties of the Fluids

Thermophysical Properties	100% Water	10% IPA 90% Water	30% IPA 70% Water	50% IPA 50% Water	100% IPA
Boiling Point (K)	373.15	368.68	358.45	354.95	355.75
Thermal Conductivity (W/mK)	0.607	0.520	0.385	0.290	0.135
Surface Tension (mN/m)	72	46.5	30.8	24.7	21.2
Specific Heat Capacity (kJ/kgK)	4.18	4.05	3.72	3.35	2.68
Latent Heat (kJ/kg)	2260	2150	1820	1450	664
Density (kg/m3)	997	984.1	956.3	919.2	785
Viscosity (mPas)	0.89	1.25	2.10	2.85	2.04
Electrical conductivity (µS/cm)	0.055	2.5-4.0	1.5-2.5	05-1.2	0.06

Experimental uncertainties have been determined according to the manufacturers' specifications, as summarized in Table 4. The standard uncertainty analysis method proposed by Kline and McClintock [15] has been applied to estimate the overall uncertainty of the calculated parameters. According to this method, the total uncertainty for the temperature difference has been calculated as ~0.7°C.

Table 4. Thermophysical Properties of the Fluids

Instrument	**Measured Parameter**	**Measurement Range**	**Accuracy**
Infusion Pump	Flow Rate(Q)	0.1–1200 ml/h	±5%
High Voltage Power Supply	Voltage(V)	0–30 kV	±1% (or ±0.1 kV)
K-Type Thermocouples	Temperature(T)	-200 to 1250 °C	±0.5 °C
Data Acquisition System	Voltage Signals	0–10 V	±0.05%
Digital Caliper	Distance(H)	0–150 mm	±0.02 mm
Precision Balance	Mass(m)	0–220 g	±0.001 g

3. Results and discussion

The results obtained from the experimental study conducted using the full factorial method are presented in Table 2. For the ΔT performance characteristic, the "smaller is better" quality criterion was adopted, and the main effects of the control factors on the S/N ratios were analyzed accordingly.

Table 5. ANOVA for the S/N ratio (smaller-the-better) including main effects and two-factor interactions

Source	DF	SS	MS	F-value	P-value	Contribution (%)
IPA content	2	4.56	2.28	12.14	0.0038	11.56
Flow rate	2	22.48	11.24	59.90	<0.0001	57.02
Voltage	2	4.23	2.11	11.27	0.0047	10.73
IPA × Flow rate	4	5.48	1.37	7.30	0.0088	13.91
IPA × Voltage	4	1.05	0.26	1.40	0.3180	2.66
Flow rate × Voltage	4	0.12	0.03	0.17	0.9496	0.32
Error	8	1.50	0.19	-	-	3.81
Total	26	39.42	-	-	-	100.00

The ANOVA results presented in Table 5 statistically reveal the influence of the key parameters investigated in the ES cooling process on the response variable. According to the analysis, the flow rate emerged as the most dominant factor, accounting for 57.02% of the total variance. With a big high F-value (59.90) and a highly significant p-value (<0.0001), the flow rate is identified as the most influential parameter. The finding suggests that in electrostatic ES systems, the flow rate significantly affects droplet size formation, the density of droplets covering the target surface, and the overall cooling performance of the system.

The second most important factor contributing to total variance in cooling effectiveness is the interaction of the IPA content and flow rate which contributes 13.91% to the total variance. This interaction's statistical significance (p = 0.0088) provides evidence that the combined effects of the mixture composition and the flow rate significantly alter the behavior of the ES system. Variations in flow rate together with variations in the IPA content also affect the size and charge distributions of the droplets, which can either enhance or decrease the cooling effectiveness.

IPA content (11.56% contribution) and applied voltage (10.73% contribution) were also statistically significant contributors to cooling effectiveness (p=0.0038, p=0.0047, respectively). Increasing the concentration of IPA in the mixture results in reduced surface tension, which enhances stable atomization. Higher voltages generate greater electrostatic forces controlling the atomization and droplet ejection processes.

The low p values for both the interaction, IPA×Voltage and Flow Rate×Voltage, indicate that neither of these interactions has much bearing on how the system behaves because both are overshadowed by their main effects. Using error analysis to identify an optimal level and the degree of correlation between parameters does not take into account any one parameter alone. Therefore, it is recommended that researchers utilize both this method and the very rigorous analysis via S/N ratios to provide clear indications as to which levels of the factors will lead to optimal performance with respect to the variables related to the thermal conductivity. The Equation will be useful to model what happens in other experimental designs as research progresses.

The regression equation generated from the data collected, which represents the temperature difference (ΔT):

$$\Delta T = 30.94 + (0.0118 \times X_1) - (0.152 \times X_2) - (0.938 \times X_3) + (0.00491 \times X_1 X_2) \quad (4)$$

According to the analysis, the regression model created has done an outstanding job of modeling the change in ΔT, in addition to fitting the experimental (empirical) data well; thus, it has been confirmed that the performance of determination is significantly high (R2=0.974 · and adjusted R2=0·921).

The relationship between mean S/N ratio and flow rate, applied voltage, and IPA content was shown in interaction Plots shown in Figure 2; The interaction plots illustrate how these 3 different parameters may interact to create different effects on performance and will thus differ in strength depending on how they interact with each other.

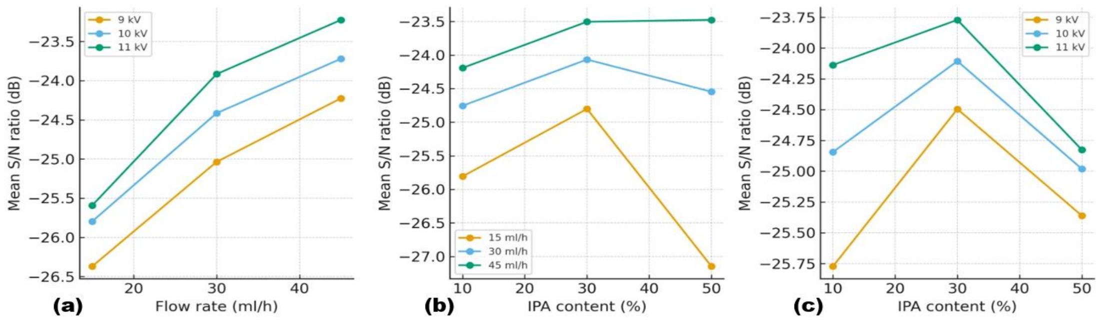

Figure 2. Interaction plots of the control factors on the S/N ratio

The interaction plot created using the S/N ratios reflects the differences in performance associated with IPA levels (IPA=30%, IPA=10% and IPA=50%) and voltage applied (at 9, 10 and 11 kV). As seen in interaction plot 2a, at all three voltage tends (9,10 and 11 kV), at an IPA level of 30%, performance is optimal, while the performance decreases when IPA levels are lower or higher than 30%. Excessive amounts of IPA disrupt the desired droplet distribution and thus cause the spray to be destabilized, while insufficient amounts of IPA do not maximize the surface tension or conductance characteristics of the surface of the work piece. The flatter trend in slope across the 2a 11 kV interaction Plot reflects decreased sensitivity of the spray system to IPA level changes at the higher voltage levels.

In figure 2b, the relationship between the flow rate and the IPA content shows an increase in S/N ratio with increasing flow rate, with maximum S/N ratios occurring at an IPA concentration of 30%. At lower flow rates (15 ml/h), variations in the IPA content have a more significant impact on the response variable as compared to higher flow rates (45 ml/h), where the curve becomes relatively stable, indicating that higher flow rates provide increased stability to the spray, consequently reducing IPA dependence. Higher flow rates also increase the droplet flux produced, thus positively affecting the performance of the cooling system.

Figure 2c indicates that for all voltage levels (11, 12, and 13 kV), the S/N ratio improves with increased flow rates. When the flow rate is increased from 15 ml/h to 45 ml/h, there is an increase in performance at every voltage level. This observation agrees with the ANOVA analysis, which indicated that flow rate had the greatest contribution to the response variable. Lastly, the effect of flow rate at 11 kV is more substantial than at 12 or 13 kV, suggesting that higher voltage helps to stabilize the spray and enhances the effect of increasing flow rate on cooling performance.

The non-linear relationship between the temperature difference (ΔT) and the percent of IPA content that was observed is due to the fact that the ability to atomize a fluid is dependent upon the ability to provide a sufficient amount of energy to overcome the molecular forces (i.e., surface tension) that exist within a fluid, while at the same time, the ability to effectively remove heat energy from the atomizing fluid is dependent upon the properties of the fluid (i.e., thermophysical properties).

When the percent of IPA was 10%, the high surface tension (~46.5 mN/m) of the fluid opposes the forces generated from the Coulomb repulsion between charged particles in the fluid and may, therefore, inhibit the formation of a stable Taylor cone, resulting in the atomization of the fluid in a coarse spray regime, limiting the total surface area available for evaporative cooling. Transitioning to the use of a 30% IPA mixture resulted in an abrupt change in behavior; at this concentration, the surface tension drops to approximately 30.8 mN/m, thus overcoming the effects of the capillary forces and allowing the formation of a stable cone-jet mode and finer atomization. Although there are still many water molecules in the mixture retaining their high specific heat and latent heat forms; it represents an optimal point in the middle (the optimal balance) where the fluid is beginning to become easily atomized while having the ability to absorb a large amount of heat flux, but the condition deteriorates at a 50% IPA concentration due to thermodynamic limitations, since the high alcohol content has dramatically reduced the specific heat and latent heat, limiting the fluid to a lower total heat capacity.

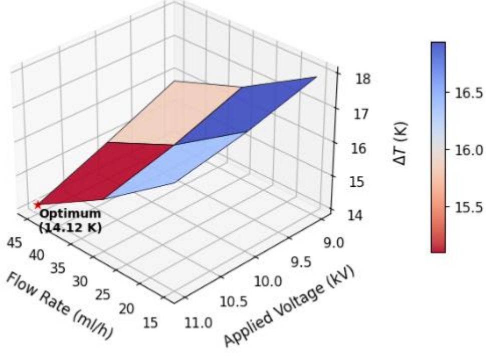

Figure 3. 3D Response surface plot

The evaluation of the trends identified in the parametric study has shown that increasing the flow rate improves significantly the cooling capability of this method. Increasing the flow rate from 15 ml/h to 45 ml/h significantly enhances the convective dissipation of heat from the heated surface, with a reduction in the mean temperature difference of 19.94 K to 15.38 K, respectively. On the other hand, the mixture composition's effect follows a non-linear pattern. Specifically, using an alcohol fraction of 10% (i.e. 10% IPA) is limited due to the high surface tension of the water, which limits the capability of atomization; conversely, at a 30% alcohol fraction, both atomization and surface wetting are maximized and produce the optimum heat transfer performance; while the use of 50% IPA is limited by the thermal capacity of the alcohol and thus prevents further increases in cooling effectiveness. An increase in the applied potential yields enhanced performance by decreasing droplet size and extending the effective evaporation surface area.

Based on the S/N ratio analysis and the mean response tables, the optimal operating conditions required to achieve minimum surface temperature and maximize heat transfer in the ES cooling system have been identified. The results that indicate that the combination of a 45 ml/h flow rate (High Level), an applied voltage of 11 KV (High Level), and a 30% IPA–70% water mixture ratio (Medium Level) provides the most favorable balance between hydrodynamic stability and thermodynamic capacity. The developed regression model further confirms that this parameter set yields the highest cooling performance within the tested experimental range.

4. Conclusions

In this study, the cooling performance of an ES system using IPA–water binary mixtures were systematically investigated by means of a three-factor, three-level full factorial design. Mixture ratio, flow rate and applied voltage were selected as control parameters, while the temperature difference between the heat sink surface and the ambient (ΔT) was taken as the response variable under the "smaller-the-better" performance criterion. The main findings of the work can be summarized as follows:

- Flow rate was identified as the most influential parameter, contributing 57.02% to the total variance in ΔT. Increasing the flow rate from 15 ml/h to 45 ml/h clearly enhanced convective heat removal and reduced the mean temperature difference from 19.94 K to 15.38 K, confirming that hydrodynamic conditions predominantly govern ES cooling performance in the investigated range.
- The composition of mixtures of liquid metals has a non-linearly proportional impact on their ability to cool down. Mixtures of isopropyl alcohol (IPA) and water that were tested showed that the lowest temperature differential and highest S/N ratios were reached at a composition of 30% IPA and 70% of water, and that compositions above (50% IPA) and below (10% IPA) this, had a poorer performance than this mixture in regards to droplet size and the ability to maximize the effective evaporation area on heated surfaces. This optimum is a result of a balance between thermodynamic capacity (i.e., high specific heat and high latent heat), and atomization tooling (e.g., atomization tooling was improved by lowering the surface tension).
- The increase of applied voltage (between 9kV to 11kV) also increased the performance of the IPA-water mixture. However, applied voltage was statistically significant but less important than the flow rate and the ratio of the mixtures. Increasing the applied voltage will directly lead to a reduction in droplet size and more stable cone-jet conditions, which in turn increases the effective evaporation area on heated surfaces.
- The major interaction contributing to the variability between the mixture ratio and flow rate (13.91% of the total variability) was greater than that for the IPA×voltage and flow rate×voltage interactions, which were statistically insignificant. Therefore, when optimizing the properties of a fluid using these parameters, it is more important to control the fluid properties and flow rate than to use applied voltage. The interactions involving voltage should play a smaller role in the optimization procedures in the range tested.
- By using S/N analysis as a method to analyze the operating conditions, the optimum conditions within this range are 30% IPA and 70% water, with a flow rate of 45 ml/h, with applied voltage of 11kV, allowing the maximum amount of thermal energy transfer through the droplet size.
- Based on S/N ratio analysis and the regression model, the optimum operating conditions within the tested range were determined as 30% IPA–70% water mixture ratio, 45 ml/h flow rate and 11 kV applied voltage, yielding a minimum surface temperature difference of 14.12 K. The developed second-order regression model, with a high performed of determination (R^2=0.974; adjusted R^2=0.921), successfully captured the experimental trends and can be used as a predictive tool for design and optimization purposes.

Overall, the results show that properly optimized IPA–water mixtures can offer a more performed and tunable cooling alternative compared with pure working fluids under the examined ES conditions. The proposed full factorial design framework provides a strong basis for parameter optimization and sensitivity analysis in electrospray-based thermal management systems. Future studies may extend this approach to different nozzle geometries, structured cooling surfaces and higher heat flux levels, as well as to alternative binary and ternary coolant formulations tailored for microelectronics and power electronics cooling applications.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no Known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1.] Chakraborty, S., Shukla, D., Panigrahi P. K., A review on coolant selection for thermal management of electronics and implementation of multiple-criteria decision-making approach. Appl. Therm. Eng. 245 (2024) 122807, doi: 10.1016/j.applthermaleng.2024.122807.

[2.] Xu, H., Wang, J., Wang, Z., Wang, H., Yu, K., Zhang, W., Zuo, L., Kim, H. B., Review of electrospray cooling and charged droplets heat transfer. Phys. Fluids 37(11) (2025), doi: 10.1063/5.0299519.

[3.] Kim, Y., Jung, S., Kim, S., Choi, S. T., Kim, M., Lee, H., Heat transfer performance of water-based electrospray cooling. Int. Commun. Heat Mass Transf 118 (2020) 104861, doi: 10.1016/j.icheatmasstransfer.2020.104861.

[4.] Jowkar, S., Jafari, M., Morad, M. R., Heat transfer characteristics of high flow rate electrospray and droplet cooling. Appl. Therm. Eng 162 (2019) 114239, doi: 10.1016/j.applthermaleng.2019.114239.

[5.] Yakut, R., Yakut, K., Sabolsky, E., Kuhlman, J., Determination of heat transfer and spray performances of isopropyl alcohol electrospray. Sensors Actuators A Phys 332 (2021) 113135, doi: 10.1016/j.sna.2021.113135.

[6.] Sönmez, F., Experimental study and comparative analysis of electrospray cooling with water-alcohol mixtures. Heat Transf. Res. 2025, doi: 10.1615/HeatTransRes.2025061208.

[7.] Wan, H., Liu, P. J., Qin, F., He, G. Q., Li, W. Q., Heat transfer enhancement of electrospray cooling with microencapsulated phase change material slurry (MPCMS): A comprehensive numerical model and experimental study. Int. J. Heat Mass Transf 224 (2024), doi: 10.1016/j.ijheatmasstransfer.2024.125293.

[8.] Jiang, Z., Gan, Y., Ju, Y., Liang, J., Zhou, Y., Experimental study on the electrospray and combustion characteristics of biodiesel-ethanol blends in a meso-scale combustor. Energy 179 (2019) 843–849, doi: 10.1016/j.energy.2019.05.024.

[9.] Shao, Y., Wang, J., Wang, H., Zhou, X., Xie, Z., Zhu, X., Ding, Y., Chen, R., Liao, Q., Characterization of dynamics and heat transfer in electrospray at elevated flow rates. Int. J. Heat Mass Transf 226 (2024) 125473, doi: 10.1016/j.ijheatmasstransfer.2024.125473.

[10.] Xu, H., Wang, J., Li, B., Yu, K., Tian, J., Wang, D., Zhang, W., Effect of spray modes on electrospray cooling heat transfer of ethanol. Appl. Therm. Eng. 189 (2021) 116757, doi: 10.1016/j.applthermaleng.2021.116757.

[11.] Liu, Y. Q., Wan, H., Song, Q. L., Li, W. Q., On the influences of ambient pressure and temperature on electrospray cooling. Appl. Therm. Eng. 278 (2025), doi: 10.1016/j.applthermaleng.2025.127285.

[12.] Tian, J., He, C., Chen, Y., Wang, Z., Zuo, Z., Wang, J., Chen, B., Xiong, J., Experimental study on combined heat transfer enhancement due to macro-structured surface and electric field during electrospray cooling. Int. J. Heat Mass Transf. 220 (2024) 125015, doi: 10.1016/j.ijheatmasstransfer.2023.125015.

[13.] Boulahdjel, S., Sali, S., Bouafia, S., Zougar, L., Kermadi, S., Mansouri, E., Tabet, N., Labeche, H., Ayachi, M., Comprehensive study of optical, structural, photoluminescence and electrical properties of CBD-CdS: A full factorial design approach. Mater. Sci. Eng. B. 321 (2025) 118485, doi: 10.1016/j.mseb.2025.118485.

[14.] Kabakuş, A., Yakut, K., Optimization of finned heat sin ks with electrospray cooling: Full factorial method. Heat Transf. Res. 55(6) (2024) 47–64, doi: 10.1615/HeatTransRes.2023049860.

[15.] Kline, S. J., McClintock, F. A., Describing uncertainties in single-sample experiments. Mechanical Engineering 75(1), (1953) 3-8.

How to Cite This Article

Öztürk, A., Optimization of Electrospray Cooling Performance Using Isopropyl Alcohol-Water Binary Mixtures: A Full Factorial Design Approach, Brilliant Engineering, 1(2026), 41095.
https://doi.org/10.36937/ben.2026.41095