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Comparative analysis of heat transfer enhancement using direct current and alternating current corona discharge in pin fin arrays

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ABSTRACT

Corona discharge-produced ionic wind has emerged as a promising area of research for enhancing heat transfer. In contrast to conventional cooling methods, which often require complex geometrical designs and inefficient energy consumption, corona wind induction offers a cost-effective solution with lower energy requirements. This study focuses on investigating the effectiveness of direct and alternating corona discharge in enhancing heat transfer from pin fin arrays of heat sources. Using numerical simulations performed with COMSOL Multiphysics (6.0) and the finite element method (FEM), both DC and AC-sourced corona ionic winds were evaluated at electric field strengths ranging from $V = 15$ kV to $V = 25$ kV. Key parameters examined included the distance arrangement of high voltage electrodes to the pin surface (A), pin fin diameter (D_f), induced voltage (V), depth of corona wind penetration, and the differences between DC and AC corona. The findings revealed a direct relationship between the amount of induced voltage and the diffusion of corona discharge, resulting in significant heat transfer enhancement of up to 66.83 % in turbulent flow at $V = 25$ kV. Furthermore, direct corona induction exhibited a greater capability to enhance the heat transfer rate in comparison to AC induction. This discrepancy was notably more pronounced under turbulent conditions, registering at 10.02%, whereas in the laminar flow regime, the difference amounted to 4.73%. In addition, the results show that the implementation of corona wind leads to a significant increase in the Nusselt number, especially within the turbulent flow range, with the use of direct corona wind at a 25 kV voltage elevating the local Nusselt number value from 29.37 to 52.18. The results highlight the effectiveness and advantages of corona wind induction as an energy-efficient solution for tackling heat dissipation challenges in complex geometries.

1. Introduction

The development of advanced propulsion and energy systems such as magnet motors, energy storage systems, etc., which generate heat flux issues, requires very efficient thermal management systems to be capable to regulate excessive heat. Therefore, it is imperative to seek more effective and less complicated cooling methods to meet such demands [1]. The recent years witnessed new developments in the heat transfer enhancement methods such as microchannel cooling, phase changing cooling and other refrigerant-free solid state cooling methods. On the other hand, some conventional techniques are no longer capable of handling more challenging temperature control of high energy

density applications [2]. In recent years, the application of corona wind as an active method has captured the attention of scientists. Its outstanding features, including remarkably low power consumption and the generation of an air jet in proximity to the hot spot, have garnered significant interest. [3]. Corona wind discharge, also known as electrohydrodynamic (EHD) flow, is a phenomenon that occurs when a high voltage is applied to a pointed electrode or wire [4]. The strong electric field at the tip of the electrode ionizes the surrounding air molecules, which then collide with neutral air molecules, creating a flow of ions and air [5]. The flow of ions and air, or corona wind, moves from the pointed electrode to a flat or curved electrode with a lower voltage. The strength and direction of the corona wind can be controlled by varying the

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voltage, polarity, and geometry of the electrodes [6]. This phenomenon has many practical applications, including air filtration, printing, and cooling in electronic devices [7].

Corona wind proves highly efficient and feasible for cooling enclosed channels and mitigating hot spots within them. This approach is particularly advantageous compared to less efficient and more costly active cooling methods, often restricted by accessibility challenges. Fig. 1 visually displays the vortex removal around heat sources in a controlled experimental setup. In fact, analysing and investigating the effects of corona wind induction on the cooling of hot spots and increasing heat transfer requires interdisciplinary knowledge between electronics, fluid mechanics, and heat transfer [8]. Corona discharge is widely used in industrial applications such as ozone gas production [9], air purification [10], food drying [11], and surface cleaning [12], but heat transfer enhancement is one of the cases where the practicality of corona discharge has attracted the attention of many scientists.

Wang et al. [13] in an experimental and numerical study placed a high-voltage wire electrode between two blades connected together. The results of their experiment indicated that the heat transfer coefficient grows dramatically with the increase of the induction voltage and their numerical research also proved this issue clearly. In experimental research by Feng et al. [14], an investigation was conducted to examine the performance of two different types of corona injectors, namely needle-mesh and needle-fin. The study aimed to identify the primary factors that contribute to the enhancement of heat transfer and ion injection speed. The findings revealed that the distance between the electrodes and the number of needles emerged as the most influential parameters in achieving higher levels of heat transfer and ion injection speed. Electrical induction capabilities in different geometries led to its use in mini channels. The results showed that the rate of heat transfer is directly related to the voltage, while its relationship with the Reynolds number of the flow is inverse [15]. Zabetiyan et al. [16] examined forced convection inside a pipe under the influence of corona discharge and concluded that at a certain length of the pipe and an optimal voltage, an increase in heat transfer up to 100 % can be achieved.

Selecting the appropriate type of corona wind as an active cooling system presents a significant challenge. Researchers must carefully consider the problem conditions, geometry, and several other factors to determine whether a direct or alternating corona wind is more suitable for the application. This decision plays a vital role in optimizing the cooling performance of the system. Magnier et al. [17] investigated the air movement on a flat disk by employing DC corona discharge. Their experiments showed that at high Reynolds ($Re = 187,000$) the use of

direct electrical induction can lead to a reduction in the separation of the airflow from the disk and the continuous movement of air on the disk will clearly raise the heat transfer. Brendet et al. [18] investigated the effect of direct corona wind on reverse flow and coaxial flow with a needle electrode. A comprehensive study investigated the utilization of needle electrodes, and its results indicated a correlation between the intensity of the corona wind and the size of the air gap between the two electrodes for both positive and negative corona discharge [19]. Also, different items such as temperature, pressure, humidity, and the placement of the electrodes were examined into a review paper [20]. Recently, in experimental research by Kim et al. [21], the way of directing the airflow through the vertical fins and by corona wind was done in a controlled manner. The test results also confirmed that corona wind can increase heat transfer through obstacles that are placed vertically against each other.

The investigation of alternating corona wind poses a significant challenge due to the scarcity of research background and comparative results available on this topic. However, this scarcity could present an opportunity for researchers to explore into this field. One factor that may discourage researchers from exploring the capabilities of alternating corona is the self-quenching effect inherent in the phenomenon [22]. This effect momentarily interrupts the voltage field between two corona peak and it causes the corona wind to oscillate alternately between two minimum and maximum values [23]. Interestingly, this issue could potentially be leveraged to achieve a more uniform distribution of corona and generate a controllable vortex through the corona wind. Some scientists have already taken advantage of this phenomenon to control flames, yielding intriguing outcomes in their research endeavours. For example, Carsimamovic et al. [24] performed a numerical study on ionizing air molecules using alternating corona wind, with a specific focus on the non-uniform electric field. Their results clearly demonstrated that an increase in voltage leads to a corresponding increase in the energy loss caused by the corona wind. Also, Ma et al. [25] in an experimental project analysed the enhancement of heat transfer through the use of a point electrode and a plate-receiving electrode. Their results showed that corona induction leads to a 200 % increase in heat transfer coefficient, and the effect of the positive corona discharge is far more significant than electrical induction through the negative corona discharge.

Despite the existing body of research on corona wind's recognition and performance, there remains a strong need for further investigation into the AC corona phenomenon. This gap is highlighted by the scarcity of relevant research in the field of heat transfer concerning AC corona

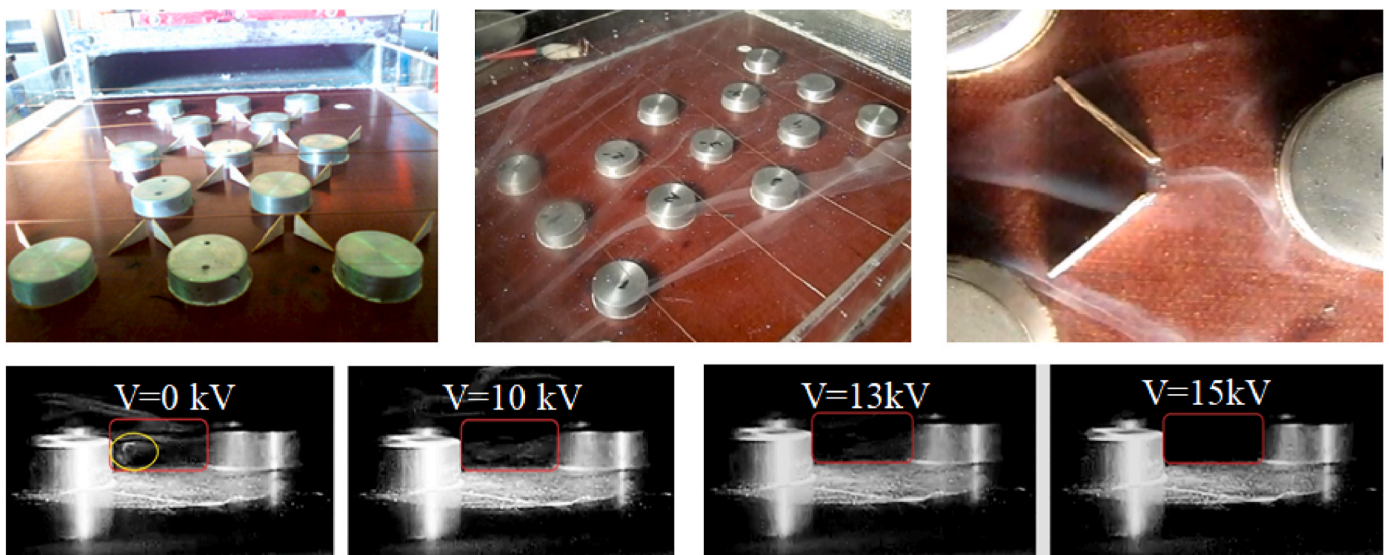


Fig. 1. Experimental design of removing thermal traps behind heat sources using corona wind [33].

wind performance. While this study has partially examined alternating corona wind operations, its primary focus lies in comparing the effectiveness of two distinct corona types in facilitating heat transfer within enclosed channels. The current article aims to clarify the capabilities of these two corona wind types by examining their impact on heat transfer on a common heat sink structure - pin fin arrays, to conduct comparative study without loss of generality, specifically focusing on direct and alternating induction methods. To assess the usefulness of these active heat transfer approaches, we measure temperature variations at different points within the tested channel, alongside changes in Nusselt number and velocity. Through this comprehensive analysis, we determine the most suitable corona discharge type for different fluid flow conditions, containing both laminar and turbulent regimes. Furthermore, we numerically present the extent of heat transfer enhancement compared to systems where an electric field is absent.

2. Methodology

2.1. Geometric model

The test chamber is a three-dimensional rectangular domain with dimensions $W = 1000$ mm, $D = 400$ mm, and $H = 100$ mm, as illustrated in the isometric view. Inside the chamber, five rows of three columns of cylindrical heat sources are arranged to simulate heat generation. These cylindrical heat sources have a diameter (D_f) of 50 mm, a height (H_f) of 15 mm, and generate a heat flux of $h = 300$ W/m². Additionally, these heat sources serve as ground electrodes, representing the zero-potential region in the simulation. The walls of the test section are modelled adiabatically with no-slip boundary conditions.

High-voltage electrodes are cylindrical wires placed perpendicular to the flow direction above the heat sources. These wires have a diameter of 1 mm, and their arrangement is detailed in Fig. 2. A two-dimensional numerical model has been developed to study airflow behavior under the influence of corona discharge. The investigation of alternating current (AC) corona discharge requires transient and time-dependent simulations due to its dynamic behavior and frequency sensitivity. Unlike steady-state models, transient simulations provide a more accurate representation of the oscillating corona wind, which fluctuates between maximum and minimum values based on the applied voltage and frequency. The unsteady nature of corona discharge phenomena, including ionization waves and charge accumulation, necessitates a time-

dependent modeling approach to capture the full range of system dynamics. To confirm the numerical findings, experimental investigations were performed under controlled environmental conditions, with an ambient pressure of 1 atm (101.3 kPa), an ambient temperature of 20 ± 2 °C, and a relative humidity range of 20 %–35 %. The experimental test section comprised a rectangular duct (400 mm $\times$ 40 mm $\times$ 200 mm) containing cylindrical heat sources arranged in the same configuration as the numerical model. High-voltage copper wires (diameter = 0.3 mm) served as the corona electrodes, while the aluminium surfaces of the cylindrical barriers functioned as the ground electrodes. The distance between consecutive high-voltage electrodes was 60 mm, and the gap between a high-voltage electrode and its corresponding ground electrode was 15 mm. Temperature changes were monitored using T-type thermocouples strategically placed on the heat sources and along the channel walls, while a manometer tracked pressure variations to accurately assess the corona wind effect. A high-voltage generator (input: 100–240 V AC, power: 35 W) provided the electric field. The applied voltage was continuously recorded using a data logger system connected to a dedicated monitoring software provided by the manufacturer. This setup ensured precise voltage control and real-time system stability during the experiments. The numerical model was validated by comparing the airflow patterns, temperature distributions, and pressure drop measurements obtained from the experimental study.

2.2. Assumptions

The numerical solution of the problem is based on a set of assumptions that will create a suitable framework for numerical simulation. These assumptions will guide the modelling and analysis process as the basic prerequisites for solving the problem. These assumptions include various aspects of solving the problem, including describing the airflow as a single-phase, incompressible fluid, which includes laminar, transient, and turbulent states [26]. Also, the time-dependent flow assumption for the air flow inside the duct, the heat transfer, and the high-voltage electric field ensure a simple yet representative depiction of the system's behaviour [27]. The assumptions are:

- The airflow is considered a single-phase and incompressible fluid flow, which is simulated in three different states: laminar, transient, and turbulent.

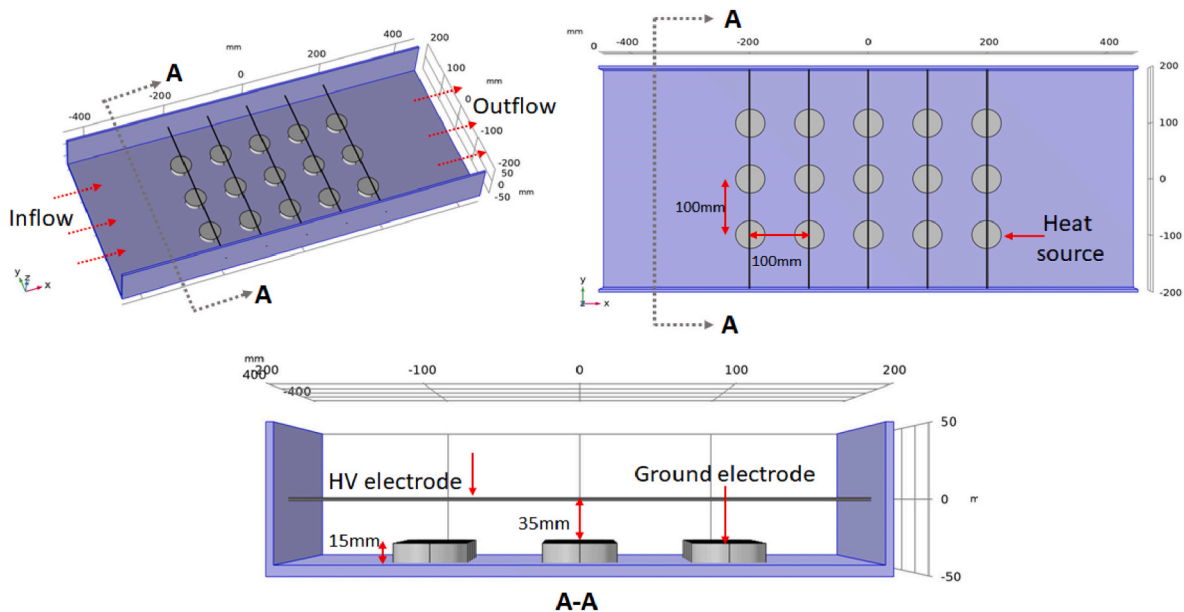


Fig. 2. Schematic design of the test section.

- Airflow and electric charge flow are simulated as time-dependent flow.
- The characteristics used for air are ideal gas characteristics, and the temperature and pressure characteristics for the initial moment of the test are assumed to be the same as the standard temperature and pressure (STP) conditions.
- Due to the small height of the channel and the characteristics of the fluid flow, the force of gravity is omitted.
- The numerical value of the frequency in the simulation is constant, and no fluctuation is considered for it.

2.3. Governing equations

The equations governing the fluid flow that should be used to solve the problem include the following equations:

Continuity equation:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

Navier-Stokes momentum equation:

$$\frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \frac{\partial}{\partial x_j} (-\rho \overline{u_i u_j}) + \rho g_i + F_{ef} \quad (2)$$

And:

$$F_{ef} = \rho_c \vec{E} - \frac{1}{2} \vec{E}^2 \nabla \varepsilon + \frac{1}{2} \nabla \left(\vec{E}^2 \left(\frac{\partial \varepsilon}{\partial \rho} \right) \right) \quad (3)$$

The presence of ionized air molecules in a corona discharge significantly affects the properties of the fluid, particularly viscosity and density. The momentum transfer between charged and neutral molecules modifies the fluid's effective viscosity by creating additional resistance to flow. This viscosity modification affects shear stress and velocity gradients, particularly near boundary layers where ion concentrations are highest. Similarly, ionization affects air density due to localized heating caused by charge recombination. This process slightly reduces air density in regions of high ionization, which may affect buoyancy currents and alter convective currents near heat sources [28]. In our numerical model, standard assumptions for fluid viscosity and density were applied, with the dominant effect of ionization via the electrohydrodynamic force (Eq. (3)).

And for the electric field intensity in both AC and DC electric field we have:

$$E(t) = E_{max} \cdot \sin(2\pi f t) \quad (4)$$

That:

$$E(t) = \frac{V(t)}{d} \quad (5)$$

In the above equations, ρ represents the fluid density, while u_i and u_j denote the velocity components in the i and j directions, respectively. Additionally, p is the pressure, μ is the viscosity, and ρg_i represents the gravitational force component in the i direction. Equation (3) appears as a body force in the Navier-Stokes momentum equation, inducing the electrohydrodynamic (EHD) force F_{ef} on the fluid. In Eq. (3), ρ_c is the charge density, E is the electric field vector, ε is the electric permittivity, and f represents the frequency. The second and third terms on the right-hand side of Eq. (3) become significant when multiple fluid phases are present in the test section; these terms are generally neglected in single-phase environments [29]. In such cases, the first term representing the Coulomb force acting on free electric charge constitutes the primary component of the electrohydrodynamic force. We selected the $k-\omega$ turbulence model for our study due to its robust capability in analyzing near-boundary layer patterns and their influence on heat transfer efficiency. This model effectively handles disturbances near the channel boundaries and the impacts of corona discharge on turbulent flow.

Compared to methods such as the $k-\varepsilon$ model [30], the $k-\omega$ model better addresses challenges like reverse pressure gradients, potential flow separation near walls, and backflow occurrences within channels. Given the likelihood of these scenarios in channel flows influenced by corona wind, adopting the $k-\omega$ model enhances the precision of our analysis [31]. This, in turn, provides a more accurate understanding of heat transfer under the demanding conditions posed by corona-induced disturbances and backflows. The equations related to the discretization of the turbulent flow inside the channel are presented in the following form [32]:

Energy equation:

$$\frac{\partial}{\partial x_i} [u_i (\rho e + p)] = \frac{\partial}{\partial x_j} \left((K + C_p \vartheta_T) \frac{\partial T}{\partial x_j} \right) \quad (6)$$

Turbulent kinetic energy equation:

$$\frac{\partial k}{\partial t} + u_i \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[(\vartheta + \sigma^* \vartheta_T) \frac{\partial k}{\partial x_j} \right] \quad (7)$$

Turbulent dissipation rate equation:

$$\frac{\partial \omega}{\partial t} + u_i \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{k} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(\vartheta + \sigma \vartheta_T) \frac{\partial \omega}{\partial x_j} \right] \quad (8)$$

In energy equation, K stands for the turbulent thermal conductivity, C_p is the specific heat at constant pressure, ϑ_T is the kinematic eddy viscosity. In Eq. (5), τ_{ij} represents the Reynolds stress tensor component k represents the turbulent kinetic energy dissipation and ω is a constant that represents the specific dissipation rate and ϑ is the kinematic viscosity. The constants used to discretize the equations governing the turbulence flow are presented in Table 1.

Accurate estimation of these constants is essential for obtaining precise predictions of turbulent flows in scientific simulations.

2.4. Boundary conditions

Fig. 3 shows that different boundary conditions are related to various regions and components in the designed geometry.

On the left side of Fig. 3, we encounter the boundary condition for the inlet flow. This condition outlines key attributes of the incoming air flow, like velocity or mass flow rate, along with other essential descriptors. Conversely, the right side presents the outlet flow condition. These conditions dictate how the outlet flow behaves, encompassing factors such as pressure, prevention of reverse flow, or unimpeded outlet discharge. The upper condition corresponds to the upper wall of the test section, where the no-slip condition prevails, signifying zero fluid velocity at the wall. This highlights the assumption of fluid adhesion to the solid surface. Likewise, heat source-related conditions are captured by the wall condition, which may include constants like heat transfer coefficient and heat flow rate, delegation on the nature of the heat transfer process. In systems involving voltage electrodes, applied boundary conditions must ensure their voltage aligns with the input voltage defined in the simulation.

2.5. Dimensionless evaluation

The local Nusselt number without applying an electric field is calculated using equation (9):

Table 1

Constant values to discretize turbulent regime.

Coefficient	α	β	β^*	σ^*	σ
Value	$\frac{5}{9}$	$\frac{3}{40}$	$\frac{9}{100}$	$\frac{1}{2}$	$\frac{1}{2}$

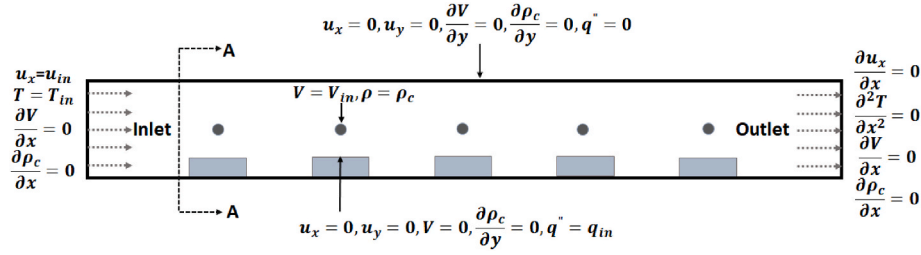


Fig. 3. Boundary conditions.

$$Nu_0 = \frac{h_0 l}{k} \quad (9)$$

In equation (9), Nu_0 represents the local Nusselt number, h_0 is the convective heat transfer coefficient, l represents the characteristic length and is equal to the distance from the upper surface of the heat source to the channel ceiling, and k represents the thermal conductivity of the fluid. The effective surface chosen to calculate the Nusselt number is part of the heat source body that is exposed to the fluid flow. Similarly, for the Nusselt number, after applying the electric field, the corresponding equation is as follows:

$$Nu = \frac{hl}{k} \quad (10)$$

In equation (10), Nu represents the local Nusselt number after applying the electric field, while h , l , and k retain their respective values as previously explained. By comparing the two Nusselt numbers obtained before and after applying the electric field, the coefficient of heat transfer can be determined using the following method:

$$E = \frac{Nu}{Nu_0} = \frac{T_V - T_0}{T - T_0} \quad (11)$$

In equation (11), E signifies the ratio of enhanced heat transfer attributed to corona wind discharge. T_V denotes the temperature after voltage application, T_0 represents the reference temperature of the surrounding atmosphere, and T stands for the temperature in the absence of an electric field. The calculation equations presented above provide the possibility to evaluate the quality of heat transfer before and after applying the electric field. Nusselt numbers are known as the best index of convective heat transfer performance, and by analysing the E ratio, the amount of heat transfer enhancement caused by corona wind discharge is investigated.

2.6. Grid independence

An essential aspect of numerical simulation is the solution's independence from the gridding method and the number of grids employed to represent the desired geometry accurately. Fig. 4 illustrates the meshing scheme adopted for the simulated channel, utilizing quadrilateral meshes to ensure the precision of the obtained results.

For the simulated channel, grid independence was performed by calculating the airflow temperature in the centre of the channel, which

was calculated in four different meshing samples. Meshing was done using free quad meshes, and the final number of meshes based on which the final solution was equal to 65535 meshes. The specifications of different meshes are shown in Fig. 5.

The value related to temperature for the middle point between the second and third thermal elements have been measured at $(x = -100\text{mm}, y = -35\text{mm})$ position. As it is clear from Fig. 5, the desired geometry was solved with five different meshing samples, and due to the slight difference in temperature and electric displacement obtained between the fifth and fourth sample meshing, the fourth mode meshing was selected as the optimal mesh. This choice avoids doubling calculations due to increased meshing.

3. Result and discussion

3.1. Numerical validation

The validation of the numerical study is a crucial step that precedes the discussion of results. The current numerical investigation aims to validate the experimental work conducted by Abdi lanbaran [33], with

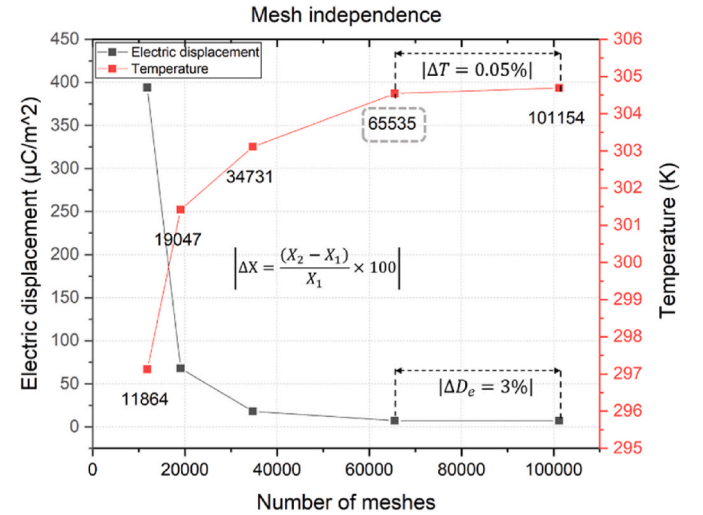


Fig. 5. Mesh independence check.

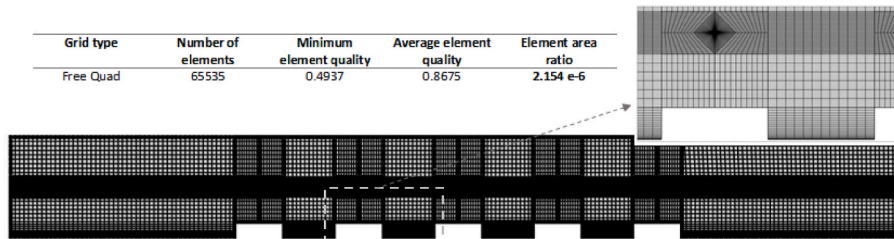


Fig. 4. Mesh structure of the designed channel.

the distinction that the present simulation explores the effectiveness of the corona wind in a larger geometry and at higher voltages. To ensure the accuracy and reliability of the numerical simulation data, a comparison will be made between the results obtained from the present study and the model derived from the earlier experimental work. Fig. 6 is the graph selected for validation and depicts the variations of $E = \frac{Nu}{Nu_0}$ and temperature variables against dimensionless variable $S = \frac{W}{H}$, representing the ratio of the width to the height of the channel. Fig. 6 is presented for a voltage of 15 kV, which is used in Reynolds 1100 & 3500.

The numerical simulation results for the E factor and the flow can also show a strong correlation with the experimental data with a deviation value of 4.6 %, which remains within the acceptable margin of 5 %. This is very accurate in terms of the reliability and accuracy of the method at this level of accuracy. The observed difference shows that the simulation model, for example, makes the underlying assumptions and strengthens the confidence in the predictive capabilities of the model. Consequently, these findings can be considered as a result of the experimental experience, which can be used to show that the computational analysis is very accurate.

3.2. Changing flow dynamics with corona wind

An essential aspect of heat transfer analysis is evaluating the effectiveness of active cooling methods in enhancing heat dissipation. This research investigates how corona wind induction alters the fluid flow regime, thereby influencing the heat transfer coefficient. Modifying the flow pattern around heat sources plays a crucial role in improving cooling efficiency. Fig. 7 illustrates the electric charge distribution generated by corona wind in the test section, offering insights into its influence on fluid flow behaviour. Understanding this interaction is key to optimizing corona wind for enhanced cooling performance.

The ion ejection process induced by corona discharge significantly alters airflow, leading to improved heat dissipation from heat sources. Applying high voltage to the electrodes initiates corona discharge, ionizing nearby air molecules. These ions interact with surrounding air molecules, creating an electric field that drives momentum transfer,

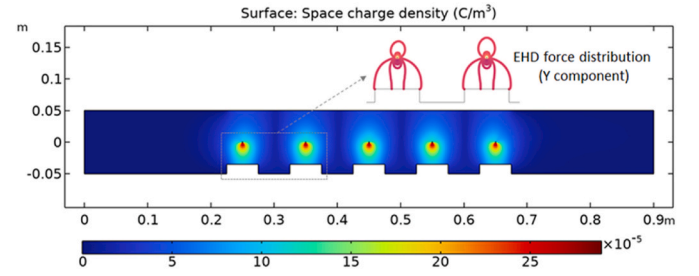


Fig. 7. Space charge distribution in the test section.

generating ionic wind [34]. This wind induces a hydrodynamic force, which is distributed perpendicularly to the main flow direction (as shown in the upper part of Fig. 7). Corona wind enhances convective heat transfer by disrupting airflow patterns, reducing thermal boundary layers, and promoting localized mixing. The ions travel from the high-voltage electrode to the grounded electrode, colliding with the airflow and redirecting its path into the spaces between electrodes. This disturbance induces vortex formation, further intensifying heat transfer by enhancing turbulence in the flow region.

Fig. 8 illustrates the channel velocity profiles, comparing flow behavior with and without an applied voltage. Without voltage (Fig. 8 (a)), the flow velocity between the heat sources is minimal, leading to the formation of heat traps. The airflow follows a nearly linear path from one electrode to the other. In contrast, applying voltage alters the flow direction and creates a triangular flow pattern between the electrodes; the size of this triangular region increases with voltage, indicating a stronger thrust of the main airflow toward the heat sources. At 15 kV, the corona wind interacts with the airflow, resulting in a penetration depth of approximately 10.43 mm. Increasing the voltage to 20 kV extends the penetration depth to 13.57 mm, while at 25 kV, the depth reaches 22.71 mm. This enhanced interaction improves convective cooling efficiency by allowing a greater portion of the airflow to reach the heat sources. The triangular region exhibits distinct characteristics, including a low-velocity, high-pressure zone along the channel.

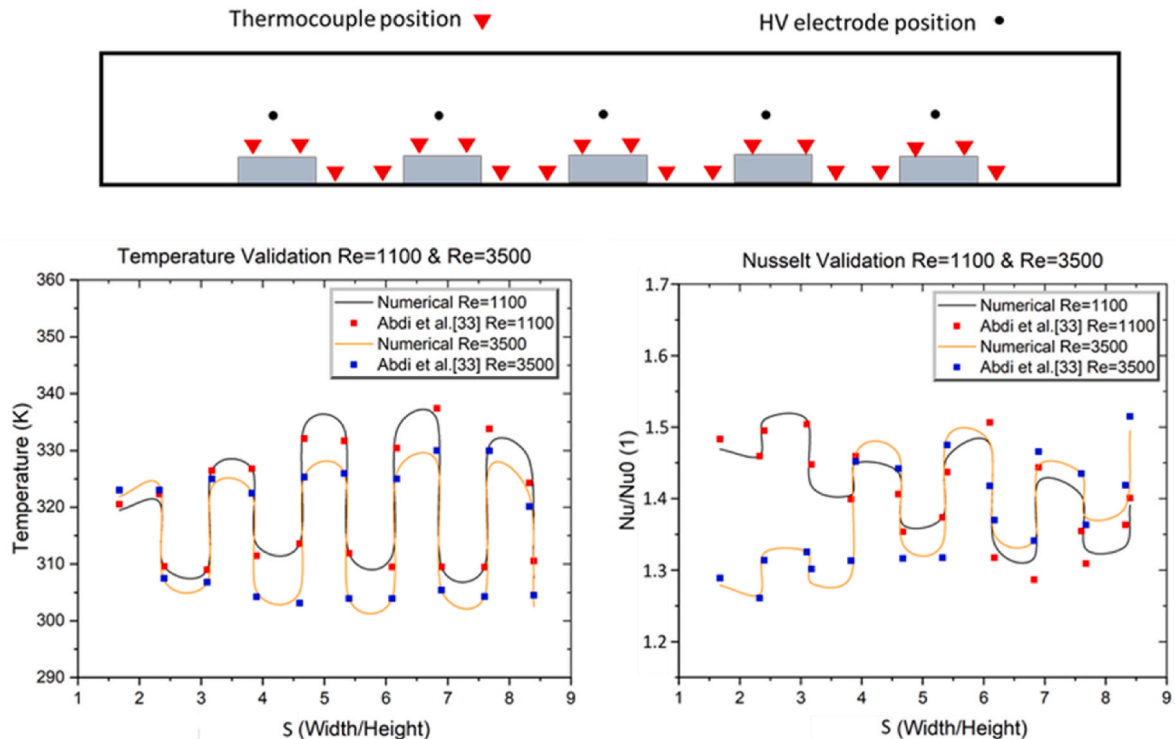


Fig. 6. Validation of numerical analysis for Re = 1100 & 3500 and V = 15 kV.

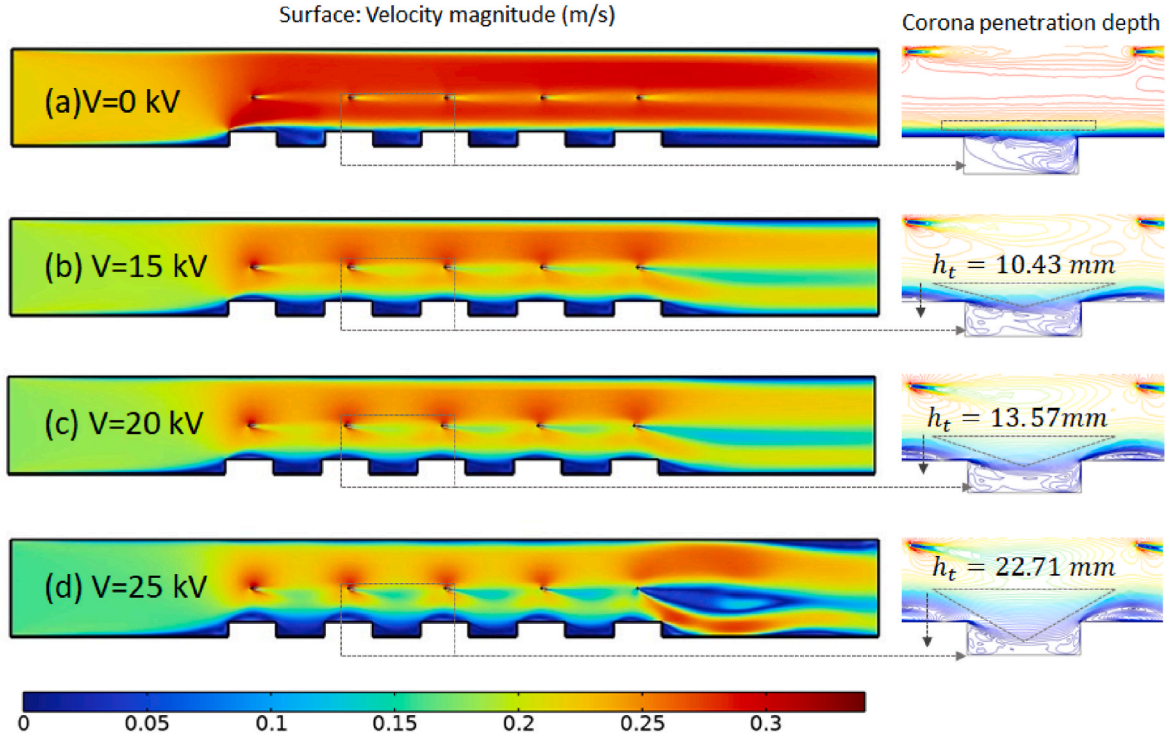


Fig. 8. Velocity contour for $Re = 1000$ (a) $V = 0$ kV (b) $V = 15$ kV (c) $V = 20$ kV (d) $V = 25$ kV.

Although this pressure is lower than that of the main airflow, it exceeds that of the vortices trapped between the heat sources, directing the fluid downward and disrupting vortex formation. As the applied voltage increases, the corona wind more effectively disrupts these trapped vortices, promoting better mixing and deeper penetration. Considerably, Fig. 8(d) shows a shield-like airflow structure at the fifth electrode that directs the main flow further downward, enhancing heat dissipation from the heat sources. Overall, these observations demonstrate a direct relationship between electric field strength and corona wind penetration depth. Higher voltages enhance convective cooling efficiency by modifying airflow structures and increasing the interaction between the corona-induced wind and the heat sources. This emphasizes the effectiveness of corona wind in improving heat transfer in confined geometries and its potential for advanced thermal management applications.

Fig. 9 illustrates the velocity vector variations in the region following the first heat source within the channel. The main figure and Fig. 9(a) depict airflow behavior without voltage application, while Fig. 9(b), (c), and 9(d) correspond to applied voltages of 15 kV, 20 kV, and 25 kV, respectively. This analysis examines how velocity vectors evolve between two heat sources and how voltage application induces airflow in

this region, contributing to cooling. In Fig. 9(a), the primary flow moves over the heat sources with minimal impact on the trapped vortex between them. This vortex circulates continuously in the low-velocity zone, where the main airflow lacks sufficient force to penetrate and disturb it. Due to this stagnant flow, the temperature in this region gradually rises, leading to the formation of a hot spot. Further details on this phenomenon will be explored in the thermal analysis section. Additionally, the left side of the first hole in Fig. 9(a) reveals an isolated area, nearly devoid of airflow vectors, indicating a region of thermal stagnation.

In contrast, Fig. 9(b) demonstrates a clear concavity in the velocity vectors, directing airflow toward the bottom of the channel upon voltage application. The electric field exerts a volumetric force on the main flow, propelling it from the high-voltage electrode toward the ground electrode. Ion release from the high-voltage electrode collides with air molecules, redirecting airflow downward. As a result, some trapped air integrates into the main flow, improving cooling efficiency. Unlike Fig. 9(a), which showed no velocity effects on the left side, Fig. 9(b) exhibits the formation of a small vortex near the heat source, inducing localized air circulation and enhancing cooling. As voltage increases to 20 kV

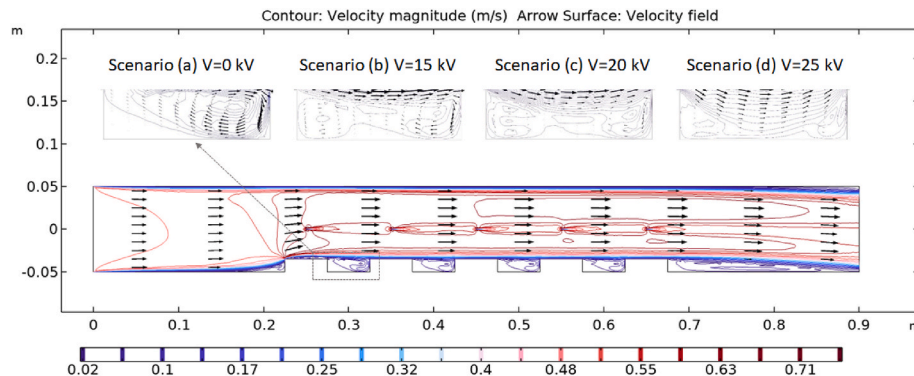


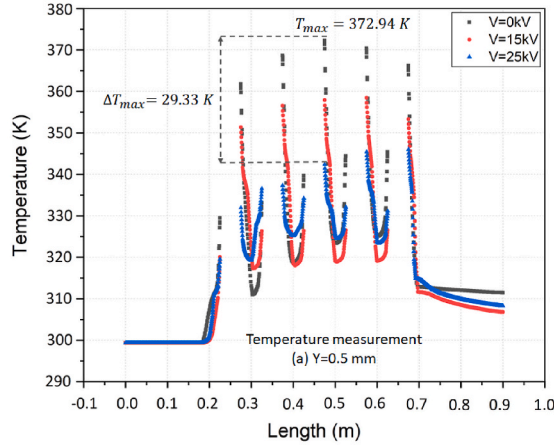
Fig. 9. Velocity vectors along the test chamber for $Re = 3000$ with different voltages scenario (a) $V = 0$ kV; (b) $V = 15$ kV; (c) $V = 20$ kV; (d) $V = 25$ kV.

(Fig. 9(c)), the main flow undergoes a more pronounced downward deflection, further reducing the trapped air volume between the heat sources and enhancing heat transfer efficiency. However, vortex patterns remain mostly unchanged, except for a small vortex on the left side, which remains detached from the main flow and circulates near the heat source. Fig. 9(d) presents the most significant transformation in the flow pattern. At 25 kV, the main flow is strongly redirected downward, actively penetrating the space between the heat sources. Small velocity vectors emerge along the left and right corners, indicating airflow drifting toward the vertical walls of the heat sources. However, these vectors return to the main flow direction, preventing thermal vortex formation and mitigating hot spot development over time. This analysis confirms that voltage application and corona wind induction

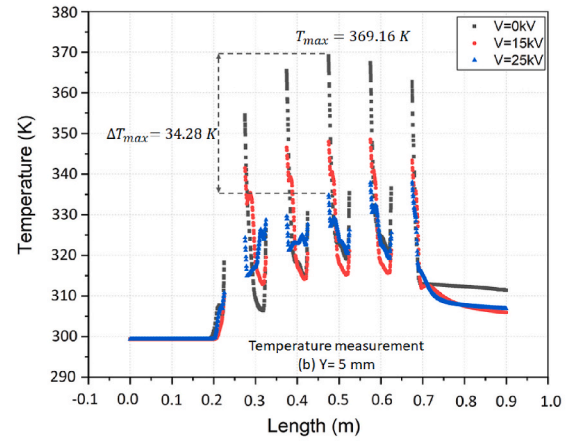
significantly alter airflow behaviour inside the channel. Increasing electric field intensity enhances corona wind strength, allowing greater control over airflow direction and distribution. Consequently, this phenomenon proves highly effective in eliminating hot spots and optimizing heat transfer across the system.

3.3. Leveraging corona wind for improved cooling

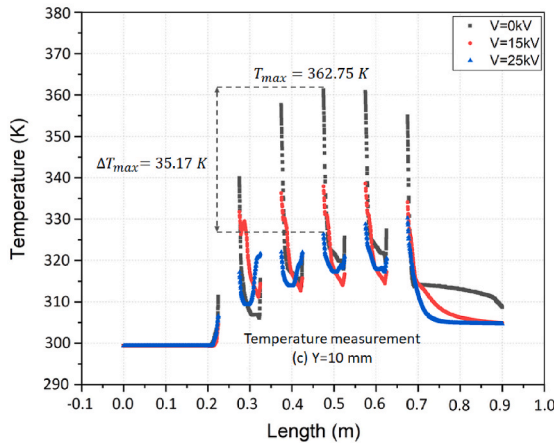
Fig. 10 illustrates temperature variations within the channel along four distinct vertical paths, spanning from the channel's base to the heat source surface. These measurements correspond to a Reynolds number of 3000 in the turbulent flow regime. To identify hotspots, a detailed temperature analysis was conducted along these four paths, as outlined



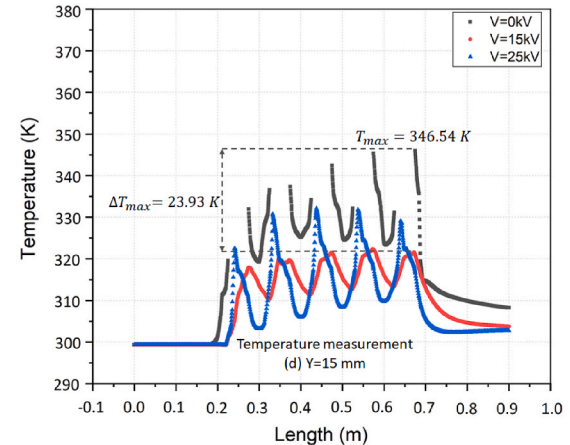
(a) Line position $y=0.5$ mm



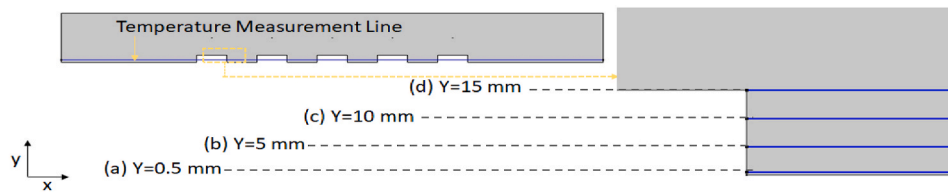
(b) Line position $y=5$ mm



(c) Line position $y=10$ mm



(d) Line position $y=15$ mm



Position of temperature measurement lines

Fig. 10. Temperature measurement to find hot spots for $Re = 3000$ on different positions (a) $y = 0.5$ mm (b) $y = 5$ mm (c) $y = 10$ mm (d) $y = 15$ mm.

in Fig. 10. The data in Fig. 10(a) reveals a significant temperature peak of 372.94 K at a position 0.5 mm above the test section's bottom surface, following the third heat source. This trend is consistent across all sub-figures in Fig. 10, showing that temperatures without voltage are consistently higher than those with applied voltage. The introduction of voltage leads to notable cooling effects, reducing hotspot formation in critical regions. With the exception of Fig. 10(d), a clear cooling trend is observed across Fig. 10(a)–10(c), indicating that higher voltages (25 kV) result in more effective cooling compared to lower voltages (15 kV). For example, in Fig. 10(a):

- Applying 15 kV reduced the highest temperature by 14.93 K.
- Applying 25 kV further reduced it by 29.33 K.

A significant reduction in channel outlet temperature is observed across all paths when voltage is applied. Voltage alters heat distribution, spreading thermal energy perpendicular to the main airflow direction, leading to enhanced cooling. The most effective cooling is observed at the path located 10 mm above the channel's bottom, where a 25 kV voltage results in a maximum temperature reduction of 35.17 K.

However, Fig. 10(d) reveals an unexpected phenomenon air temperature increases when voltage rises from 15 kV to 25 kV above the heat sources. This aligns with the airflow patterns in Fig. 8, where higher pressure and reduced airflow velocity are observed in certain areas. These conditions contribute to localized temperature increases, demonstrating that merely increasing voltage does not always lead to proportional cooling efficiency.

Fig. 11 presents the temperature contour for turbulent flow at a Reynolds number of 3000, illustrating four states with varying applied voltages: 0 kV, 15 kV, 20 kV, and 25 kV. This graphical representation allows for a detailed examination of temperature variations within the test chamber. Without voltage application, the only cooling mechanism is the airflow circulating inside the channel. As seen in Fig. 11(a), high temperatures ($T = 369.76$ K) develop between the heat sources due to a sharp velocity drop, resulting in limited convective cooling. The left side of the hole is particularly susceptible to excessive heating, leading to hot spot formation, which is most pronounced in the absence of voltage. Furthermore, temperature increases progressively along the channel, as hot air from one region further heats subsequent areas. This compounding effect leads to the highest temperature in the fourth hole, marking the most thermally critical region. Applying 15 kV initiates a clear shift in the cooling pattern. The heat source surfaces directly beneath the high-voltage electrodes experience notable cooling

compared to the no-voltage case. This effect is due to the increased density of free ions and intensified corona wind near the high-voltage electrode. As indicated by Equation (5), the electric field intensity is inversely related to distance from the HV electrode. Because the upper surfaces of the heat sources are closer to the high-voltage electrode, they experience a stronger electric field, reducing hot spot formation. At 15 kV, the right region inside the hole between the heat sources undergoes significant cooling, as seen in the comparison between Figs. 11(b) and 10(a). However, while the corona wind partially redirects trapped air from the left corner toward the mainstream, it fails to generate a stable airflow sufficient for cooling that area.

Fig. 11(c) follows a similar trend to Fig. 11(b), with the higher voltage (20 kV) enhancing cooling intensity and partially improving vortex release on the left side. The most substantial transformation occurs at 25 kV (Fig. 11(d)), where a complete change in flow pattern and cooling mechanism is observed. The corona wind deeply penetrates the hole between the two heat sources, drawing trapped air into the mainstream and effectively eliminating hot spots. Notably, the left side of the first hole, previously a high-temperature region, is completely cleared, reducing its temperature to 333.17 K. This cooling trend continues along the channel, ensuring efficient temperature reduction in the regions between heat sources. Another important observation is the formation of hot zones on the surface of the heat sources. These hot air masses, previously trapped in the holes, are lifted by the corona wind into the mainstream and carried toward the channel exit. In summary, voltage application and corona wind significantly alter temperature distribution and airflow behavior inside the channel. Different voltage levels result in varying degrees of cooling, demonstrating the effectiveness of corona wind in mitigating hot spots and improving heat transfer between the heat sources and airflow.

3.4. Corona discharge performance at different Reynolds

This study evaluates the effectiveness of corona discharge in altering fluid flow patterns and enhancing heat transfer performance across different Reynolds numbers (1000, 2000, and 3000). The simulation results highlight that the interaction between corona wind and the main airflow strongly depends on flow regime (laminar vs. turbulent). At low Reynolds numbers ($Re = 1000$), the fluid flow is highly sensitive to external forces, making corona wind highly effective in disrupting the thermal boundary layer and generating additional vortices. This secondary flow enhances local mixing, leading to a significant increase in the Nusselt number (Fig. 12).

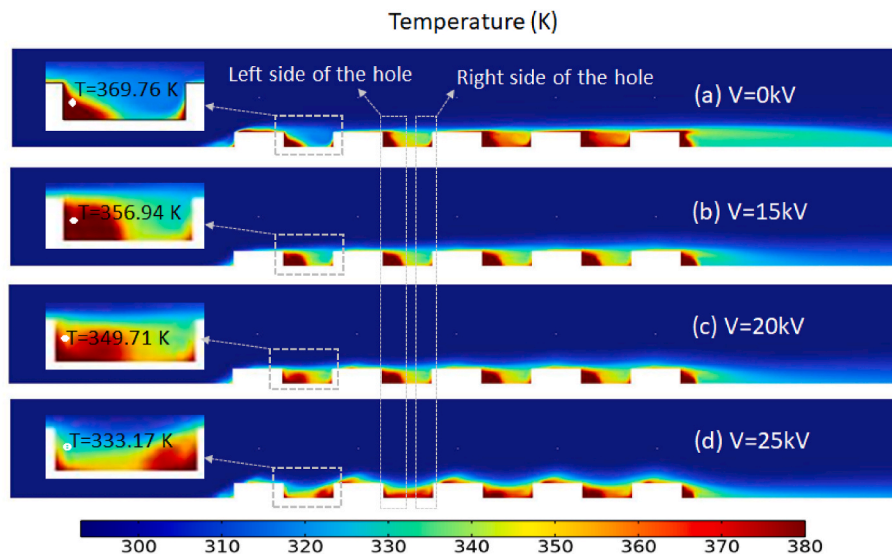


Fig. 11. Temperature contour along the test section for $Re = 3000$ with different voltages (a) free voltage (b) $V = 15$ kV (c) $V = 20$ kV (d) $V = 25$ kV.

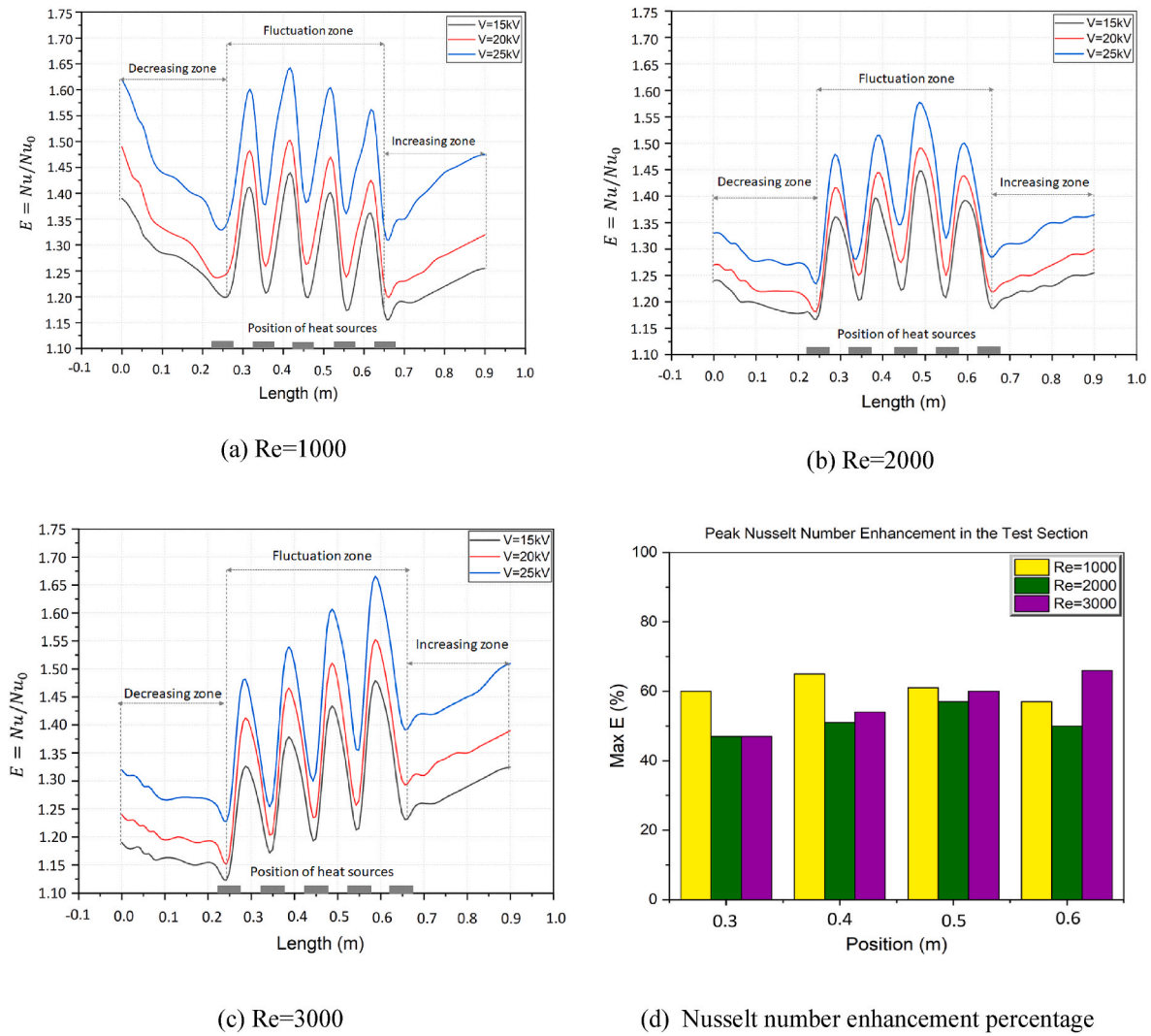


Fig. 12. The change process of Nusselt number by applying electric field for different Reynolds number.

In laminar flow, the thermal boundary layer is particularly vulnerable to disruption by corona-induced forces, and ionization-induced viscosity variations can further trigger instabilities that improve convective transport. Due to the absence of strong inertial forces, the cooling efficiency at low Reynolds numbers primarily depends on the magnitude of corona wind forces.

As the Reynolds number increases to 2000, the balance between inertial forces and corona-induced forces shifts. While corona wind continues to enhance heat transfer, its ability to generate new vortices is reduced. Instead of drastically altering the flow structure, corona wind now acts primarily to modify existing velocity gradients, improving heat transfer efficiency but with slightly lower sensitivity compared to laminar conditions. Ionization-induced viscosity variations in this regime influence flow stability, but their effect is less dominant compared to low Reynolds number cases.

In the turbulent regime ($Re = 3000$), fluid inertia dominates the flow field, significantly limiting the ability of corona wind to introduce new disturbances. Unlike in the laminar regime, where corona wind readily generates secondary flow structures, in turbulence, its role shifts to reinforcing existing turbulent fluctuations. Although heat transfer continues to improve, the relative enhancement is less pronounced, as turbulent flows naturally exhibit high convective transport efficiency. At this stage, corona wind primarily influences the near-wall region, disrupting boundary layer stability and improving heat transfer rates. Additionally, density changes caused by recombination heating

introduce minor buoyancy-driven variations, which may influence localized cooling near high-voltage electrodes.

At the highest applied voltage of 25 kV, the Nusselt number exhibits distinct variations along different positions within the channel, as shown in Fig. 12. The bar chart illustrates that the maximum percentage increase in heat transfer occurs at different locations depending on the Reynolds number. For $Re = 1000$, the peak enhancement reaches 65 % at 0.4 m, while for $Re = 2000$, the highest improvement of 57 % is observed at 0.5 m. In the case of $Re = 3000$, the largest increase, 66 %, occurs at 0.6 m. This trend suggests that as the Reynolds number increases, the location of maximum heat transfer shifts downstream, likely due to the greater influence of inertial forces in redistributing the airflow. At lower Reynolds numbers, the corona wind has a more immediate effect on heat transfer, resulting in earlier enhancement peaks, whereas at higher Reynolds numbers, the increased fluid momentum extends the region of maximum enhancement further downstream. As shown in Fig. 12(d), the bar graph visually confirms this trend, illustrating how peak heat transfer locations shift with increasing Reynolds number. These results indicate that the interplay between corona-induced flow acceleration and inertial effects governs the spatial distribution of convective heat transfer improvements, with the most significant enhancements occurring where these effects are optimally balanced.

3.5. The difference between DC and AC corona discharge

This study analyzes the impact of direct and alternating electric fields on fluid flow dynamics, highlighting the distinct effects of DC and AC corona wind. In DC corona, a constant voltage induces a steady charge transfer, producing a continuous corona wind. In contrast, AC corona operates under a sinusoidal voltage variation (50 Hz), leading to oscillatory airflow patterns. The oscillatory motion of AC corona wind induces periodic boundary layer disturbances, enhancing convective heat transfer efficiency in systems with time-dependent thermal loads. This effect is particularly beneficial for applications such as electronics cooling, pulsed laser systems, and phase-change heat exchangers, where localized heating occurs intermittently [24]. Unlike DC corona wind, which provides steady-state cooling, AC corona wind dynamically adjusts cooling intensity in response to temperature fluctuations [24]. The periodic fluctuations in airflow velocity modulate boundary layer thickness, promoting turbulent fluctuations, vortex shedding, and enhanced mixing, which redistributes thermal energy more effectively and reduces thermal resistance. This study investigates the extent to which corona wind enhances heat transfer, maintaining all other system parameters constant. A standard approach for evaluating heat transfer enhancement is analyzing the Nusselt number (Nu) as a function of Reynolds number (Re). Fig. 13 presents the Re - Nu relationship for both AC and DC corona discharge at a fixed point ($x = 485$ mm, $y = 10$ mm). To validate the numerical results, the simulation data is compared against experimental findings from Sparrow et al. [35]. The strong agreement between the no-voltage state ($V = 0$ kV) in this study and Sparrow's experimental data confirms the accuracy of the numerical model. Minor deviations at lower Reynolds numbers are attributed to geometric differences, as Sparrow's experiment used cubic heat sources, while cylindrical heat sources were applied in the present study. As the Reynolds number increases, the inhibitory effect of obstacle geometry on airflow decreases, which becomes especially prominent at $Re = 3000$. The graphs for both DC and AC corona wind clearly demonstrate the effectiveness of corona wind in enhancing heat transfer.

Notably, applying corona wind shifts the data on the Re - Nu diagram from the no-voltage region to the dashed region, indicating a significant increase in the Nusselt number at the same Reynolds number. A detailed examination of the graphical data reveals that higher voltage levels (e.g., 25 kV) lead to a more pronounced enhancement in the Nusselt number than lower voltages (e.g., 20 kV or 15 kV). Furthermore, a comparison between the AC and DC corona wind graphs along with an

analysis of the dashed region confirms that DC corona discharge outperforms AC corona discharge in heat transfer enhancement. DC corona generates a greater increase in the Nusselt number, making it the more effective method for improving convective cooling performance.

To further clarify the effectiveness of AC and DC corona discharge, Fig. 14 illustrates their impact on heat source cooling at $Re = 1000$ (laminar flow) and $Re = 3000$ (turbulent flow). The figure also presents the variation in the Nusselt number under both methods. An analysis of Fig. 14 reveals a key finding across both flow regimes: DC corona discharge consistently demonstrates higher cooling efficiency than AC corona discharge. This conclusion is quantitatively supported by the maximum Nusselt number values for each Reynolds number. In laminar flow ($Re = 1000$), the numerical coefficient E reaches $E_{DC} = 1.638$ for DC corona wind, whereas $E_{AC} = 1.564$ for AC corona wind in the best case. A similar trend is observed in turbulent flow, with higher E values for DC corona discharge at its peak state.

Fig. 14(a) highlights two key observations:

- The difference between maximum and minimum Nusselt numbers is smaller for AC corona wind than for DC corona wind. This sinusoidal characteristic allows regions near the electrodes to experience better cooling due to oscillations between zero and maximum values.
- In DC corona wind, coefficient E continuously decreases after the second heat source, while in AC corona wind, this effect is less pronounced. This occurs because DC corona wind forms an air shield (as shown in Fig. 8(d)), restricting the main fluid flow inside the channel and reducing flow velocity.

Using AC corona wind partially mitigates this issue, achieving effective cooling while minimizing fluid velocity reduction, particularly in longer channels. Fig. 14(b) further reinforces the higher cooling efficiency of DC corona wind over AC corona wind. Throughout the entire channel, DC corona wind maintains a stronger cooling impact, with its effect intensifying as the flow progresses. In turbulent flow, the higher inertia limits the manoeuvrability of AC corona wind, leading to a more uniform, constant trend. In contrast, DC corona wind actively enhances cooling as it moves along the channel. This distinction suggests that AC corona wind is less sensitive to Reynolds number variations than DC corona wind. The consistent behaviour of AC corona wind makes it a more practical option for longer channels in laminar flow conditions. While adjusting the frequency of AC corona wind can modify its behaviour, its self-dissipating nature is an inherent characteristic,

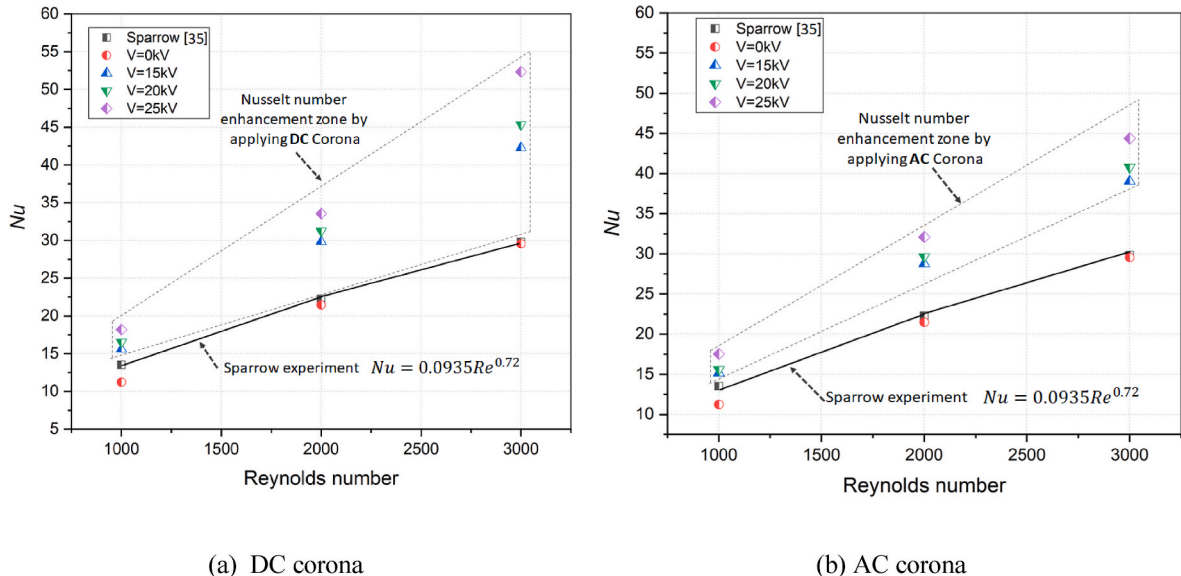


Fig. 13. Analysis of the Re - Nu diagram for AC and DC corona discharge.

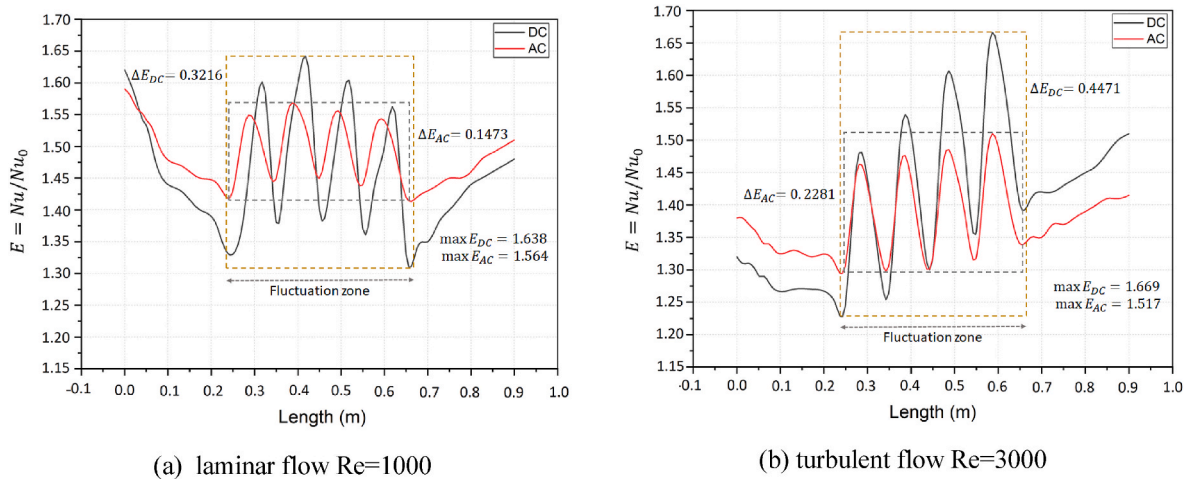


Fig. 14. Nusselt number ratio under DC and AC corona discharge (t = 60 min).

potentially explaining why DC corona wind is favoured in many studies for enhanced heat transfer.

3.6. Limitations and practical considerations

To provide a clearer comparison of the effects of DC and AC corona discharges on heat transfer and flow dynamics, Table 2 summarizes the key differences observed in this study.

As shown in Table 2, DC corona discharge produces a continuous, directional ionic wind that significantly enhances local heat transfer, while AC corona discharge generates an oscillatory flow that delivers more uniform cooling with slightly lower peak efficiency. Therefore, the selection between DC and AC corona cooling should be based on specific thermal management requirements DC being ideal for concentrated, high-intensity cooling, and AC being more suited for dynamic or spatially uniform applications. A comprehensive evaluation of corona discharge for heat transfer enhancement must consider both simulation outcomes and practical feasibility for industrial applications. Although numerical analyses confirm that corona discharge effectively modifies fluid flow and improves cooling efficiency, real-world implementation introduces several challenges:

- **Electrical Safety and Power Consumption:** High-voltage corona systems require strict electrical insulation to prevent hazards such as dielectric breakdown and arcing. Moreover, scaling these systems for industrial use demands a careful analysis of energy consumption relative to heat dissipation efficiency, as increased voltage may impose significant power demands.
- **Environmental Impacts:** Ion generation and charge transfer efficiency are highly sensitive to atmospheric conditions. Variations in humidity, ambient temperature, or air composition can alter ionization rates and, consequently, heat transfer performance.

Table 2
Comparing DC and AC corona effects on heat transfer.

Parameter	DC Corona Discharge	AC Corona Discharge
Nature of Wind	Steady, continuous ionic wind	Pulsating, oscillatory ionic wind
Peak Heat Transfer Enhancement	Higher peak enhancement	Pulsating, oscillatory ionic wind
Effect on Airflow	Strong directional jet, penetrates deep	Less directional, spreads evenly
Reynolds Number Sensitivity	More sensitive to changes in Re	More stable across different Re
Potential Applications	Localized cooling, focused heat removal	Dynamic cooling, oscillating thermal loads

- **Electrode Design and Durability:** Extended exposure to corona discharge can cause gradual electrode degradation due to surface erosion and oxidation. This degradation may diminish ionization efficiency and alter the corona wind distribution, ultimately affecting long-term heat transfer performance. Consequently, regular maintenance including cleaning or replacing electrodes is essential to maintain stable discharge behavior.
- **Scaling Challenges:** Transitioning from laboratory-scale experiments to industrial applications presents engineering challenges, such as maintaining uniform ion distribution and consistent system performance under varying conditions. In larger systems, ensuring even ion distribution across extensive heat exchange surfaces is difficult especially in turbulent flows and may affect the stability and effectiveness of corona-induced airflow patterns.

Addressing these practical aspects bridges the gap between theoretical performance and real-world feasibility, providing a balanced assessment of corona discharge technology for advanced thermal management. Furthermore, investigating the frequency-dependent behavior of AC corona winds and their interaction with variable thermal loads may offer deeper insights into their potential for dynamic thermal regulation applications.

4. Conclusion

This study conducted a numerical analysis of the effectiveness of direct current (DC) and alternating current (AC) corona discharge in enhancing heat transfer within pin-fin arrays. The results indicate that corona wind significantly influences airflow patterns and improves convective cooling, with DC corona demonstrating a stronger effect compared to AC corona. DC corona wind produces a stable and directional ionic flow that deeply penetrates the airflow, leading to superior heat dissipation, particularly in turbulent regimes, where it enhances heat transfer by 66.83 %. Conversely, AC corona wind, due to its oscillatory nature, offers a more uniform but less intense cooling effect. This characteristic makes it better suited for adaptive thermal regulation rather than applications requiring peak cooling efficiency. Additionally, the study highlights the relationship between corona discharge performance and the Reynolds number, showing that its effect is more pronounced in laminar flow conditions and gradually stabilizes as turbulence increases. Across different voltage levels, DC corona wind consistently achieves greater improvements in the Nusselt number and overall heat transfer rates. Despite the promising potential of corona discharge for heat transfer enhancement, practical challenges such as electrical safety, electrode longevity, and environmental influences

must be addressed. Future research should focus on optimizing electrode configurations, investigating the impact of frequency on AC corona wind, and exploring hybrid cooling strategies to expand its industrial applicability. In conclusion, DC corona discharge proves to be the more effective cooling solution for turbulent flow conditions, whereas AC corona wind is better suited for adaptive thermal management.

CRediT authorship contribution statement

Davoud Abdi Lanbaran: Writing – original draft, Validation, Software, Project administration, Methodology, Investigation, Formal

analysis, Conceptualization, Supervision. **Pouria Farokhi Kojour:** Software. **Chao Wang:** Writing – review & editing, Supervision. **Chuang Wen:** Writing – review & editing. **Zhen Wu:** Writing – review & editing. **Bo Li:** Writing – review & editing, Visualization, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare no conflicts of interest regarding this work. This research was conducted independently, without financial support, sponsorship, or affiliations that could have influenced the results.

NOMENCLATURE

c_p	[J/kg.K]	Specific heat capacity
D	[mm]	Depth of channel
D_e	[C/m ²]	Electric displacement
D_h	[mm]	Hydraulic diameter
D_f	[mm]	Fin diameter
E_e	[V/m]	Electric field intensity
F_{ef}	[N/m ³]	Electric field force
H	[mm]	Height of channel
H_f	[mm]	Fin height
h_t	[mm]	Triangle height
K	[W/m.K]	Turbulent thermal conductivity
k	[m ² /s]	turbulent kinetic energy dissipation
L	[mm]	Distance between electrode and pin
Nu	[-]	Nusselt number
P	[Pa]	Pressure
Re	[-]	Reynolds number
S	[-]	Dimensionless width of channel
T	[K]	Temperature without voltage
T_0	[K]	Atmosphere temperature
T_V	[K]	Temperature after applied voltage
u	[m/s]	Velocity
W	[mm]	Width of channel
ϵ	[-]	Electric permittivity coefficient
ρ_c	[C/m ³]	Electric charge density
ρ	[kg/m ³]	Density
μ	[Pa.s]	Viscosity
τ_{ij}	[N/m ²]	Reynolds stress tensor component
ω	[1/s]	specific dissipation rate
θ	[m ² /s]	kinematic viscosity
∂_T	[m ² /s]	kinematic eddy viscosity
Subscripts		
x		X direction
y		Y direction
t		Turbulent regime
out		External: Towards external heat sink
in		Internal: Between cooling and heat-generating layers
0		Ambient condition and no voltage

Data availability

Data will be made available on request.

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