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Experimental investigation on convective heat transfer enhancement by EHD in wire to plate configuration

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Abstract

The purpose of this study was to experimentally investigate the enhancement of forced convection heat transfer by corona wind in a channel scaled to potential future drying systems. An experimental rig was designed to investigate the thermal and dynamic effects of electro-hydrodynamic (EHD) induced air flow on the grounded bottom wall. The primary air flow, blown into the channel at controlled temperature and velocity, was disturbed by EHD secondary flow generated by a wire electrode. Using IR imaging, the heat transfer exchange at the wall was calculated in several configurations (i.e. electrodes location, wire-electrode to plate distance, applied voltage, primary air flow velocity), allowing the selection of optimal configurations according to the objective of minimum energy consumption or homogeneous transfer. Particle Image Velocimetry (PIV) characterization conducted on some configurations highlighted the vortices generated by the combination of the secondary and the primary air flows. Analysis of the flow patterns allowed to explain the enhancement of the local and average heat transfer coefficients. Higher enhancement could be obtained in the cross-wire configuration but led to heterogeneous treatment. For a more homogeneous one, the longitudinal wire configuration should be preferred thanks to the development of contra-rotating vortices moving in the channel.

27 Nomenclature

28	A	Surface area	$[m^2]$
29	b	Ion mobility	$[m^2.V^{-1}.s^{-1}]$
30	d	Inter –electrode spacing	$[cm]$
31	h	Heat transfer coefficient	$[W.m^{-2}.K^{-1}]$
32	I	Electric current	$[A]$
33	L	Length	$[m]$
34	Ne_{EHD}	EHD number	$[-]$
35	P	Electric power	$[W]$
36	Re	Reynolds number	$[-]$
37	ρ	Air density	$[kg.m^{-3}]$
38	T	Temperature	$[^{\circ}C]$
39	U	Velocity	$[m.s^{-1}]$
40	U_{∞}	Primary mean flow velocity	$[m.s^{-1}]$
41	V	Voltage	$[V]$

42 Subscripts

43	0	reference
44	amb	ambient
45	i	threshold
46	loc	local
47	m	mean
48	p	plate
49	s	secondary
50	sup	polystyrene support
51	top	top
52	$wire$	wire
53	x	refer to x axis
54	y	refer to y axis
55	z	refer to z axis

56

57 Abbreviations

58	EHD:	Electro Hydro Dynamic
59	PIV:	Particle Image Velocimetry

60 DBD: Dielectric barrier discharge

61 IR: Infrared

62 1. Introduction

63 One of the most promising techniques to enhance convective heat transfer in air is based on the
64 use of the Electrohydrodynamic (EHD) induced air flow. The basic principle of EHD is the
65 mechanism by which an electric field is used to influence the flow pattern. The effect can be carried
66 out by corona discharge to induce flow motion (ionic wind) using either AC or DC high voltages.

67 Since EHD induced flows do not use any mechanical moving parts, they are of great interest and
68 can be used in many thermal engineering applications. The advantages of using EHD technique
69 include the reduction in size of the facility, improved control of thermal characteristics by
70 monitoring the electrical field intensity, and simplicity in setting up due to the minimal
71 requirements [1]. Moreover, their fast response and simplicity make them more attractive as the
72 electric energy is converted simply into kinetic energy and many studies have demonstrated the
73 excellent potential of EHD as a technology for improving the energy efficiency of thermal systems.
74 [2–6].

75 Several studies have been carried out concerning the use of EHD in process engineering. Large
76 varieties of geometrical configurations, operating parameters and working fluid have been the
77 subject of numerical and experimental investigations. EHD flows have been much investigated
78 for their potential applications as flow actuators [7] or electrohydrodynamic thrust [8], in heat
79 exchangers [9] and cooling devices [10], for electrosprays [11], collecting particles [12] or
80 corona-enhanced chemical reactions [13]. Some studies such as [14] and [15] demonstrated the
81 ability of corona discharges to reduce drag by modifying the boundary layer.

82 The use of EHD in the presence of a bulk flow to alter an external boundary layer has been an
83 area of growing interest in the aerospace community while has received little attention for heat
84 transfer enhancement. However, studies on this subject have shown that the increase in the heat
85 transfer coefficient can be high depending on the configuration. For example the increase can
86 reach 250% for a heated plate in air [16], 270% in a wire / plate configuration [17] and up to
87 830% for HCFC-123 boiling application [5]. A list of relevant studies using EHD in process
88 engineering applications, dealing with heat transfer enhancement, is presented in Table 1.

89

Table I Some studies carried out on the use of EHD in processes specifically dedicated to heat transfer enhancement, with varying electrodes configurations and working fluids.

Reference	Type of research	Fluid	Electrode shape	Application
[17–19]	Experimental	Air	wire / plate	Convective heat transfer
[19,20]	Numerical	Air	wire / plate	
[16,21]	Experimental	Air	multi-wires / plate	
[21,22]	Numerical	Air	multi-wires /plate	
[3]	Experimental	Air	needle-array / plate	
[23–25]	Experimental	Air	wire / tube	
[26]	Experimental	Air	Multi-rod / plate	
[27,28]	Numerical	Air	wire / cylinder	
[29]	Experimental	Air	wire / tube and 2 wires / tube	
[30]	Experimental	Air	needle / meshed plate	
[10]	Experimental	Air	wire / semi-cylindrical contour	
[31]	Experimental	Air	wire / triangular tube	
[32]	Experimental	Fe ₃ O ₄ / ethylene glycol	wire / wire	
[19]	Experimental / Numerical	Oil	wire / plate	
[6,33–36]	Experimental	Air	wire / plate	Drying
[37]	Numerical	Air	wire / plate	
[4]	Numerical	Air	multi-wires / plate	
[38]	Numerical	Air	wire / mesh and periodic wire / mesh	
[39,40]	Experimental	Air	single-pin, needle / plate	
[41–43]	Experimental	Air	multi-pin, multi-needle / plate	
[44]	Experimental	Air	needle / wire	
[45]	Experimental	Air	multi-pin/wire	
[46]	Experimental	HFC-134a	wire / inner tube wall	Condensing systems
[47]	Experimental/Theoretical	HCFC-123	wire / inner tube wall	
[1]	Experimental	HFC-134a	wire / inner tube wall	
[48]	Experimental	HFC-134a	rod / inner tube wall	
[49]	Experimental	HFC-245fa	rod / inner wall	
[50]	Experimental	HCFC-123	concentric wire / cylinder	Boiling systems
[51]	Experimental	HFC-134a	concentric wire / cylinder	
[52]	Experimental	HFE 7000	rod / inner tube wall	
[5]	Experimental	HCFC-123 and CFC-11	rod / tube wall	
[53]	Experimental	N-pentane	rod / cylinder sheet	
[2]	Experimental	HCFC-123	wire mesh / tube wall	
[54]	Numerical	liquid CCl ₄	wire / wire	
[55]	Experimental	NaCl solutions	pin / plate	Evaporating systems
[56]	Experimental	HFC-134a	wire mesh / rectangular ribs	
[57,58]	Numerical	Water	wire / plate	
[59]	Experimental	HCFC-123 and HCFC-141b	plate multilayered /plate	

[9]	Experimental	HFE-7000	wire / inner tube wall	
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Many studies deal mainly with natural convection flow [19,21,31,32], and are rarely focused on the forced convection flow. Velkoff and Godfrey [16] reported the first experiments on heat transfer enhancement by ionic winds in the presence of external flows. They demonstrated that the heat transfer was enhanced in the low-velocity regime; however, the ionic wind was swamped by the bulk flow. Thus, it was ineffective as the bulk velocity increases. A wide range of studies either experimental [18,26,29,30], and numerical [4,20,22,28] have been conducted using EHD for heat transfer intensification in a channel. These studies have shown that the most effective EHD-induced flow can be achieved by lowering the bulk flow velocity.

Moreover, the EHD phenomenon in a channel depends on various parameters such as Reynolds number and applied voltage. The EHD is also a function of geometrical aspect such as the number of electrodes, the distance between electrodes, the wire radius, and the characteristics of the channel [60]. It can be noticed that many questions regarding the optimization of the operating parameters remain unanswered while the control of heat transfer remains a key factor for many industrial applications.

During the past decade, EHD has undergone a growing interest in aerodynamic induced secondary flow in drying process. The literature points out that the EHD-induced flow has widely attracted the researchers' attention and they developed assisted-drying processes [37,39,42–44]. Compared to conventional hot air forced convective drying systems and freeze-drying, EHD drying systems in a channel can improve the energy efficiency by reducing energy consumption. Increasing locally, the heat and mass transfer lead to the reduction of the high inlet velocity of the drying air. This contributes to a significant reduction of the energy consumption in the whole drying process.

As reported by Kudra and Martynenko [61], EHD drying was recognized as an energy efficient and environmentally friendly technique: the drying time was reduced by about 15-40% with a drying rate multiplied by 1.3 to 4.52, depending on the operating conditions, type of material and amount of humidity in the sample. Ould Ahmedou et al [60] have shown that the ionic wind generated by a corona discharge could lead to weight losses equivalent to those resulted from forced convection at 4.2 m.s^{-1} . They concluded that EHD drying process is a promising alternative to enhance heat and mass transfer. Lai [35] was one of the first to demonstrate that EHD technology could be scaled up from laboratory bench to industrial size. The results revealed that the drying enhancement by corona wind in real applications depends on many

factors such as corona polarity, electrode spacing and height, conveyor moving velocity, characteristics of material, etc. He concluded that an accurate tune of these factors is necessary to optimize the operating conditions of the system. Regarding the electrode configuration, one can notice from Table 1, that wire-plate and point-plate configuration are widely used. Lai and Wong [40] have found that the wire / electrode configuration was more suitable in EHD drying when compared to the needle at smaller values of supplied voltage. Defraeye and Martynenko [38], based on a numerical study, recommended the wire-to-mesh configuration for drying because the configuration provides a more uniform drying. It is however difficult to generalize these results as the electrodes configurations also depend on the drying process type (continuous or batch...) and the majority of studies have been conducted with small-size prototypes.

Given the simple design and reduced energy consumption, drying systems based on EHD enhanced heat transfer demonstrate a promising potential for bulk and industrial drying applications, especially for heat-sensitive products [62]. Nevertheless, as already raised [36,63], the main obstacle is the up-scaling and optimization of the EHD process and its associated system. For this reason, a parametric analysis is crucial to determine how the governing parameters affect the heat transfer rate in EHD drying applications.

Therefore, this paper focuses on both thermal and flow structure characterization for EHD induced secondary flow inside a semi-industrial scale channel using wire to plate configuration. Combining both Infrared (IR) thermal imaging and Particle Imaging Velocimetry (PIV) measurement technics, the influence of geometrical and operating parameters involved in the process were evaluated, with the aim to optimize the heat transfer intensification ratio to energy consumption.

Local and average convective heat transfer coefficients were calculated from the surface plate temperature measured by the IR system. Using air velocities resulting from PIV post-processing, the vortex structures generated by the interaction of secondary flow and primary flow were related to the heat transfer intensification. The effect of the inlet air velocity, the influence of geometrical parameters such as arrangement of wire-electrodes (parallel or perpendicular to primary air flow), wire-electrode to plate distance (d) and applied voltage (V) were investigated and discussed. From an analysis of energy consumption in each configuration, optimal configurations were selected. Since the final application of this study is dedicated to drying process, the analysis was extended by taking into consideration other criteria such as the homogeneity of the heat transfer coefficient.

To our knowledge, this work is one of the first where both PIV and IR imaging were used in a semi-industrial scale channel to analyze heat transfer enhancement due to EHD secondary air flow.

2. Material and methods

2.1. Experimental Set-up

The experimental set-up consisted of a rectangular channel section ($15\text{ cm} \times 19\text{ cm}$) as shown in **Fig.1**. Air flow was introduced into the channel at a controlled humidity using an Air Handling Unit (Munters ML 180, France). The inlet air temperature was adjusted by a cooling unit (Hitema, Italy) and the primary air flow velocity U_{∞} was controlled by valves. A honeycomb filter was placed at the entrance of the channel to stabilize the air flow. The investigation area, i.e. the plate, had dimensions of $15\text{ cm} \times 15\text{ cm}$ and was mounted flush to the bottom wall of the channel 100 cm downstream from the inlet. Electrically heated, the surface of the plate was considered to evaluate the heat transfer coefficient. The heat was supplied by Joule effect using a DC power supply (EL302, 30V 2A). A stainless-steel wire electrode ($\varnothing = 0.2\text{ mm}$) was placed in the flow channel over the plate. To induce the ionic wind, a positive corona discharge was applied to the wire using a high voltage supply (High voltage supplier, Spellman, USA). **Fig.1** also shows two configurations for wire electrode arrangement, parallel and cross-wire. For the parallel arrangement, the wire electrode was placed parallel to the primary flow direction, while the wire was oriented across the air flow in the cross-wire arrangement. For both arrangements, different values for inter-electrode gap, d , were considered.

Figure 1. Schematic diagram of the experimental setup and arrangement of electrodes

A humidity sensor (Vaisala HMT100, Finland), was placed right before the outlet to measure the humidity of the air flow in the channel. A velocity sensor (Velocicalc 9545, TSI, USA) was also introduced into the channel through an opening at the upper wall to measure the mean velocity of primary flow at the start of the investigation area. Moreover, temperature at different locations in the channel and the plate were recorded using several K type thermocouples. All the above-mentioned instruments were connected to a data logger (AOIP Datalog S20, France) where the measurements were acquired and recorded for further processing.

2.1.1. Thermal instrumentation

The heating plate, shown in **Fig. 1**, consisted of a heating foil (17.02Ω) insulated on both sides by a thin layer of Kapton ($50 \mu\text{m}$) and covered with a $30 \mu\text{m}$ aluminum layer on the upper face. The surface was used as both the ground electrode and the heat transfer surface. This surface was painted matt black (Electrotube, France) in order to achieve an emissivity close to 1. The assembly was placed on a 4 cm thick polystyrene insulating plate. The temperature field of the plate was measured with an infrared camera (Silver 450M Cedip, France) in the range of 3-5 μm . The camera had an accuracy of $\pm 0.01^\circ\text{C}$ with a spatial resolution of 0.428 mm/pixel. The acquisition frequency was chosen at 50 Hz with a maximum resolution of 1280 $\times$ 800. The control and data recording of the camera were provided by a specific software. The camera

was installed on a vertical support and adjusted vertically at the correct focal distance. A rectangular box, made with thick black matt paper, was placed between the camera and the channel to avoid reflections. Temperature measurement was conducted through a circular opening of 12 cm diameter at the top wall of the channel. To avoid air escaping from the channel, which could have affected the heat transfer on the surface plate, the hole was covered with a plastic foil, transparent at the working wavelength, and positioned at an angle $> 35^\circ$ to avoid any reflections. The circular opening did not provide access to the temperature of the heating plate corners. The cross section shown in **Fig.2** illustrates the thermal instrumentation in the cross-wire arrangement.

Figure 2. Cross-sectional view of the experimental set-up in cross wire-electrode configuration

Prior the beginning of the acquisition, about 15 minutes waiting time was required to allow the thermal equilibrium of the heating plate to be reached. By performing an energy balance under uniform heat flux, the local and mean steady-state heat transfer coefficients were evaluated from the local surface temperature and the mean temperature, respectively.

2.1.2. PIV Instrumentation

The experimental rig used above was adapted for 2D PIV measurements by making some technical modifications. Close to the investigation area, the upper and lateral walls were replaced by glass walls of 4 mm thickness. The main flow entered the viewing area and passed over the upper surface of the plate. The same reference point xyz defined in **Fig.1** was retained. Measurement in the xz plan was performed by positioning the laser sheet parallel to the primary flow and perpendicular to the plate. The camera (Flow-Sens, Dantec Dynamics, Denmark), focused in the direction of the y -axis and was placed perpendicularly to the laser sheet as shown in **Fig. 3-a**. For measurement in yz plan, the laser sheet was generated in the direction of the y -axis perpendicular to the primary flow while the camera was placed at the outlet channel in the direction of x -axis as shown in **Fig. 3-b**.

Figure 3. PIV measurement in the xz and yz configuration plans

The flow seeding was carried out by incense particles of diameter of $0.8 \mu\text{m}$ [64]. To generate seeding a combustion box was designed and placed at the air intake channel where several incense sticks were burned simultaneously. As reported in [64], seeding the flow with incense smoke particles is suitable for EHD flows. The particles concentration in the channel was measured by an optical particle counter (Grimm: model G1.10, Austria) and was of the order of $10^5 \text{ particles.L}^{-1}$, giving a particles density suitable for PIV measurement. The values of the measurement parameters are shown in **Table II**.

Table II. PIV acquisition parameters

Acquisition frequency	5 Hz
Number of snapshots	300
Size of the interrogation area	32×32
Time between two laser pulses	300 μs
Post-processing algorithm	Adaptive correlation

3. Results and discussions

For the purpose of heat transfer optimization in the channel, energy balance must be performed. The heat flux generated by Joule effect in the heating plate is mainly evacuated by convection with air through the upper face. The remaining heat is evacuated by irradiation with the channel walls and conduction through the downwardly polystyrene. The local and mean heat transfer coefficient respectively designated by h_{loc} and h_m were calculated for different configurations with the change in the electric power consumed P (W) for EHD generation. The power P was defined from the current and the voltage ($P = VI$).

The EHD number “ N_{EHD} ” introduced by [65] was defined by relation (1) which expresses the ratio of electrostatic forces to the inertial forces. This number is interesting to characterize the EHD flow configuration.

$$N_{EHD} = \frac{U_s}{U_\infty} = \frac{IL_{wire}}{\rho b A_p U_\infty^2} \quad (1)$$

The secondary flow velocity U_s was estimated from the experimentally measured electrical current value. Analytical relationship to calculate the velocity is given by equation (2). This relationship is described in the literature by [66] and [67].

$$U_s = \left[\sqrt{\frac{IL_{wire}}{\rho b A_p}} \right] \quad (2)$$

Experimental investigations for varying arrangement of wire-plate electrode under different values of the mean primary flow velocity U_∞ and the applied voltage V have been conducted. **Table III** shows either cross wire and longitudinal wire configurations under varying primary flow velocity, electrode gap and applied voltage.

Table III. Experimental configurations

Configuration	Primary air flow Velocity U_{∞} (m/s)	Electrode gap d (cm)	Voltage V (kV)
Cross wire	0.3	2	0 to 11
	0.6	4	0 to 18
	1.0	6	0 to 20
Longitudinal wire	0.3	2	0 to 11
	0.6	4	0 to 16
	1.0	6	0 to 18

From **Table III**, it can be noticed that the maximum applied voltage was limited due to the electrical arcing which mainly depends on the electrode gap. In the case of cross wire configuration and primary flow velocity of 0.3 m.s^{-1} ($Re = 3525$), **Fig.4** shows the corresponding current voltage characteristic curve for three different electrode gaps.

Figure 4. Current-Voltage characteristic curve in cross wire configuration for varying electrode gap ($U_{\infty} = 0.3 \text{ m.s}^{-1}$)

Increasing the electrode gap (from $d = 2 \text{ cm}$ to $d = 6 \text{ cm}$), led to the increase of the corresponding threshold voltage (from $V_i = 7.8 \text{ kV}$ to $V_i = 12 \text{ kV}$). As the electrode gap increased, the slope of the increase on current/voltage decreased and the value of the voltage limit increased. As a result, the corona discharge application range increased.

3.1. Temperatures and heat transfer enhancement

Fig.5 shows the temperature distribution on the plate given by infrared thermal camera images of both cross wire (**5a-c**) and longitudinal wire (**5e-g**) configurations for varying electrode gap and for a primary air flow velocity $U_\infty = 0.3 \text{ m/s}$. The blue vertical (**5a-c**) or horizontal (**5e-g**) lines in these figures correspond to the location of the wire electrode. It can be distinguished easily that the cooling of the plate mainly took place in portions just beneath the wire. When comparing between cross wire configuration and longitudinal wire, it can be noticed that in longitudinal wire the cooling effect was more homogeneous compared to the cross-wire case.

Figure 5. Temperature distribution mapping of: (a,b,c) cross-wire configuration and (e,f,g) longitudinal wire configuration for $U_\infty = 0.3 \text{ m/s}$.

Because the power supplied to the plate may be slightly different between each experiments, as well as air temperature, it was not possible to evaluate the heat transfer enhancement directly from the temperature distribution. Only the determination of the mean heat transfer coefficient makes it possible the comparison of the different configurations.

Fig.6 and Fig.7 displays the evolution of the mean heat transfer coefficient h_m as a function of the power consumption in cross wire and longitudinal wire configurations, respectively, for three primary air flow velocities.

Figure 6. Evolution of the mean heat transfer coefficient (h_m) as a function of power consumption in cross wire configuration

Figure 7. Evolution of the mean heat transfer coefficient (h_m) as a function of power consumption in longitudinal wire configuration

As the cases of forced convection without EHD correspond to $P = 0$ W, **Fig.6** and **Fig.7** confirm first of all the benefit of EHD to enhance the heat transfer coefficient in all the studied configurations. Moreover, the mean heat transfer enhancement due to EHD was, as expected, significant at low primary air flow velocity in most cases. Whatever the inter-electrode gap, the primary air flow velocity value of $U_\infty = 0.3$ m/s provided a greater value of the mean heat transfer coefficient h_m as compared to other velocities. At this low value of U_∞ , inertial forces are reduced and electrostatic forces take over.

The influence of the electrode gap also clearly appears on these figures. At the lowest value of d , the primary air flow velocity had no influence on the heat transfer coefficient. Electrostatic forces were so high that they generated an impinging jet that blocked the primary air flow. It can also be noticed that the power consumption in all cases was slightly higher when the electrode gap was set to 4 cm. In one hand, the maximum voltage was limited to 9 kV for $d = 2$ cm due to potential arcing. On the other hand, the ions collected by the plate for $d = 6$ cm were lower than for $d = 4$ cm due to the increased wire-electrode distance.

From **Fig.6**, the optimal configuration in the cross-wire configuration is selected for the primary air flow velocity of 0.3 m/s and an electrode gap set to 6 cm. It offered the largest heat transfer coefficient ($h_m = 34.6$ W.m².K⁻¹) corresponding to an intensification of the mean heat exchange of the order of 8 times greater than the case of forced convection without EHD. Moreover, this maximum of heat transfer enhancement was obtained with a low value of the electric power ($P = 1.68$ W).

From **Fig.7**, the optimal configuration in the longitudinal wire case is selected also for the primary air flow velocity of 0.3 m/s but for the electrode gap of 4 cm . This case allowed to reach a high heat transfer coefficient ($h_m = 30.9 \text{ W.m}^{-2}.\text{K}^{-1}$) which was 7 times greater than the case without EHD, with a low electric power ($P = 1.66 \text{ W}$). It can be noticed that at the larger electrode gap ($d = 6 \text{ cm}$), the heat transfer enhancement was relatively small and presented a peak value at the intermediate electric power. This is due to the fact that the origin of the jet generated by the ionic wind was far from the plate. The jet then expanded beyond this latter, was more spread out and had a lower cooling effect. All these results confirmed the need to investigate the modification of the flow pattern by the ionic wind.

3.2. Flow structure

In this section, the dynamic behavior of the flow structures involved in heat transfer intensification were investigated. Cross wire and longitudinal configurations with $d = 4 \text{ cm}$ and $U_\infty = 0.3 \text{ m/s}$ were firstly analyzed and compared. For both configurations at $V = 16 \text{ kV}$, the values of the heat transfer coefficients were similar: $h_m = 25 \text{ W.m}^{-2}.\text{K}^{-1}$.

3.2.1. Cross wire configuration

PIV measurement was performed in a plan positioned parallel to the primary air flow and perpendicular to the wire electrode located at distance $L_x = 1/2 L_p$. **Fig.8-a** displays the mean velocity field and **Fig.8-b** both the streamlines mapping and U_z velocity.

a) Mean velocity field U

b) Streamlines and velocity contour U_z

Figure 8. Mapping of mean velocity field U (a) and streamlines velocity contour of U_z component (b)

Fig.8 illustrates the mappings of the flow generated by EHD combined with primary air flow directed from right to left. In the investigation area, it is clearly shown that the bulk flow, strongly altered by electrostatic forces, has been modified. It has taken the shape of an air jet that impinges the plate on an area located underneath the wire and then expands in both sides. Furthermore, the IR images previously shown in **Fig.5** demonstrates that intense cooling took place specifically in the area underneath the wire. It is obvious from **Fig.8a** that the velocity component " U_z " had a major effect for cooling the plate. Consequently, the use of the velocity component " U_z " was considered as a relevant criterion of characterization that can be very appropriate to obtain a link with the heat transfer coefficient.

The effect of the primary flow velocity on the flow pattern neighboring the plate was investigated. **Fig.9** displays the contour maps showing the value of the " U_z " component and the streamlines for varying primary flow velocities.

a) $U_\infty = 0.3 \text{ m/s}$

b) $U_\infty = 0.6 \text{ m/s}$

c) $U_\infty = 1 \text{ m/s}$

Figure 9. U_z contour mapping and streamlines for varying primary flow velocities: **a)** $U_\infty = 0.3 \text{ m/s}$, **b)** $U_\infty = 0.6 \text{ m/s}$, **c)** $U_\infty = 1 \text{ m/s}$

When analyzing the velocity field mapping of the U_z component, it can be seen that the maximum values of $|U_z|$, about 1 m/s , was localized in the air jet zone underneath the wire and decreased with the increase of the primary flow velocity as described by many authors [50], [4]. For a primary flow velocity of 0.3 m/s , the air jet was clearly visible and directed from the wire to the plate. By increasing the primary flow velocity to 0.6 m/s , the air jet was driven downstream of the plate. A flow vortex could be clearly recognized at the leading edge of the plate in the investigation area (**Fig.9-b**). By increasing again the primary flow velocity to 1 m/s as shown in **Fig.9-c**, the primary flow became dominant making the air jet less relevant but still existing. As a result, the center of the vortex moved towards the jet location and blocked the upstream half-zone of the plate. A similar flow structure was obtained for the other electrode gaps set to $d = 2 \text{ cm}$ and $d = 6 \text{ cm}$. Therefore, the evolution of the flow structures when varying the primary velocity for these cases can be explained in the same way.

For a deeper analysis, the velocity profiles of the U_z component were plotted along the line **1** shown in **Fig.10**. This line parallel to the x -axis is located at distance $z = 1\text{ cm}$ above the plate in such a way to be as much as possible close to the plate while keeping a threshold distance away from the surface plate to avoid laser reflections.

Figure 10. Position of the line **1** on the xz plan (cross-wire configuration, $d = 4\text{ cm}$)

Fig.11 illustrates the variation of vertical component of primary flow velocity, U_z , lengthwise the **line 1** as a function of the non-dimensional distance of the plate length, L_p . Temperature profiles resulting from infrared thermography measurement were used to support the dynamic flow characterization as shown in **Fig.12**. Please note that the sharp peaks depicted in **Fig.12** are measurement artefacts as they correspond to the reflection of the wire observed by IR camera.

Figure 11. Velocity component U_z along the line **1**

Figure 12. Surface temperature profiles T_p

Results show that $|U_z|$ reached its maximum value in the area located just underneath the wire ($L_x = 1/2 L_p$). When increasing the primary flow velocity from 0.3 to 1 m/s, the magnitude of $|U_z|$ component decreased. Increasing the primary flow velocity disrupted and weakened the secondary flow that initially impinged the plate. The maximum $|U_z|$ for primary flow velocity of 0.3, 0.6 and 1 m/s were 1.2, 1 and 0.7 m/s, respectively. The location of maximum $|U_z|$ also experienced a shift to the left side of plate from the original position at $L_x = 1/2 L_p$.

For $U_\infty = 0.3$ m/s, U_z values remained negative in the whole range over the line 1. The Ne_{HD} number was equal to 7.56 in this case. It was also observed that the increase in the primary flow velocity for $U_\infty = 0.6$ m/s leads to the appearance of the positive values of the U_z component at the leading edge of the plate. Thus, the effect of the recirculation flow structures on the plate, shown in **Fig.9**, became less relevant. As a result, the Ne_{HD} number decreased due to the decrease of the electrostatic forces to the detriment of the inertial forces. The Ne_{HD} number was calculated to be 3.22. By increasing the primary flow velocity to $U_\infty = 1$ m/s, the area of positive U_z component shifted to the left illustrating the driving of the recirculation by the primary flow. This reduced the Ne_{HD} to a value of 2.10.

These profiles of the U_z component describe perfectly the surface temperatures distribution of the plate surface, as shown in **Fig. 12**. In this figure, the plate surface temperature profile, T_p , was measured on a line, which is projected from line 1 on xy plane ($L_x = 1/2 L_p$). The cooling of the plate was significant underneath the wire due to high values of $|U_z|$. Based on these results, it can be concluded that the higher $|U_z|$ the better heat transfer intensification. Therefore, the highest amount of heat transfer exchange could be expected to be achieved at $U_\infty = 0.3$ m/s.

Similar behaviors were obtained $d = 2$ cm and $d = 6$ cm concerning the evolutions of the U_z component and the temperature profiles. These results confirm those obtained on the convective heat transfer coefficient measurement by infrared thermography, where it has been shown that maximum heat transfer coefficient was achieved for the lowest primary flow velocity value.

To obtain the optimum electrode gap distance, the velocity profiles of U_z component were compared for the optimal primary flow velocity of $U_\infty = 0.3$ m/s. **Fig. 13** shows the velocity profiles of U_z component along line 1 for different electrode gaps.

Figure 13. U_z component profiles, along line 1 for primary flow velocity of $U_\infty = 0.3 \text{ m./s}$ at different electrode gaps.

From **Fig.13**, it appears that, compared to cases $d = 4 \text{ cm}$ and $d = 6 \text{ cm}$, the case of $d = 2 \text{ cm}$ had the lowest values of $|U_z|$, because in this case the voltage was limited to 9 kV to avoid arcing phenomenon.

At wire position of $L_x = 1/2 L_p$, and when $d = 4 \text{ cm}$, the U_z component profile was characterized by high values compared to the case when $d = 6 \text{ cm}$ which resulted in a greater heat transfer intensification. However, for $d = 6 \text{ cm}$ it can be noticed that in areas located upstream and downstream the wire, the U_z profile component was more spread out and exhibited greater values comparing to the case where $d = 4 \text{ cm}$. Therefore, if the local heat transfer underneath the wire was better for $d = 4 \text{ cm}$, the configuration with $d = 6 \text{ cm}$ gave rise to the highest average heat transfer coefficient (**Fig.6c**). These results show the necessity to take into account other aspects related to process application (homogeneous treatment vs local treatment) to conclude on both cases regarding the optimal heat transfer intensification case.

3.2.2. Longitudinal wire configuration

For the case of longitudinal wire configuration, PIV measurement was carried out basically in the two distinct planes, xz and yz at positions of $L_y = 1/2 L_p$ and $L_x = 1/2 L_p$, respectively.

The analysis focused on the optimal configuration ($d = 4 \text{ cm}$, $U_\infty = 0.3 \text{ m/s}$) giving rise to a maximum mean heat transfer coefficient $h_m = 25 \text{ W.m}^{-2}.\text{K}^{-1}$.

a) Mapping in xz plane

b) Mapping in yz plane

Figure. 14 Mean velocity vector and contour mapping for the optimal configuration in: a) in xz plane and b) yz plane

Fig.14 shows the mean velocity vector field in xz and yz plane. As shown in both planes, the EHD-generated flow combined with the primary air flow formed an air jet that impinged the plate. The air jet was located along the plate, underneath the wire (**Fig.14-a**) and formed two parietal jets developing on both sides of impinging zone (**Fig.14-b**). As a result, both velocity components U_z and U_y could be considered as the most relevant components influencing the cooling of the plate.

Therefore, in longitudinal wire configuration, one can consider the velocity component along y axis, U_y , as a relevant means of characterization in addition to U_z . For a better exploitation of U_y and U_z , the **line 2** displayed in **Fig.15** was used as reference for plotting the velocity profiles.

PIV measurement conducted in the yz plane, shown in **Fig.15**, reveals that the $|U_y|$ component presented relatively high values in an area very close to the plate on both sides the air jet. Therefore, the U_y component of the spreading air jet might have a major influence on cooling effect, say heat transfer intensification, on both sides of the plate.

Figure .15 Mapping of the U_y contours component and streamlines in xz plan

It was found previously in **Fig.5** that, for longitudinal wire configuration, the cooling of the plate along the wire was more homogeneous for $d = 4$ cm. This tendency might be explained by the change in the vortices shape structures of the secondary flow (swirl) along the plate.

To better understand the evolution of the flow structures, PIV measurements were carried out in the yz plane at different positions along the x axis: Position 1: $L_x = 1/4 L_p$, Position 2: $L_x = 1/2 L_p$, and Position 3: $L_x = 3/4 L_p$. The mapping of the streamlines and the velocity profiles of both U_y and U_z components lengthwise **line2** are shown in **Fig.16** and **Fig.17**, respectively.

$$L_x = 1/4 L_p$$

$$L_x = 1/2 L_p$$

$$L_x = 3/4 L_p$$

Figure. 16 Mapping of the U_y contours component and streamlines on the yz plan at positions:

(a) $L_x = 1/4 L_p$, (b) $L_x = 1/2 L_p$ and (c) $L_x = 3/4 L_p$

a) $L_x = 1/4 L_p$ b) $L_x = 1/2 L_p$ c) $L_x = 3/4 L_p$

Figure. 17 Velocity profiles component of U_z and U_y lengthwise line 2 on the yz plan at positions:

(a) $L_x = 1/4 L_p$, (b) $L_x = 1/2 L_p$ and (c) $L_x = 3/4 L_p$

According to the streamlines cartography displayed in **Fig.16**, it can be noticed that the vortices centers increased in height along the x axis. The velocity profile of U_y component plotted along **line 2** shows that the amplitude of U_y increased from 0.3 m/s at the first plane to 1.2 m/s at the last plane (**Fig.17c**). As the primary flow passed over the plate, it interacted with the EHD air jet to form two growing counter-rotating vortices. This growth resulted in the increase of transverse velocity, U_y in the direction of the primary flow (x axis). **Fig.17** also shows the profiles of U_z component plotted on **line 2**. This figure illustrates that the maximum absolute values decreased along the plate from 1.3 m/s at $L_x = 1/4 L_p$ to 0.6 m/s at $L_x = 3/4 L_p$. This tendency was confirmed with the results shown in **Fig.18**. The measurement performed on xz plane, at $z = 1 \text{ cm}$ shows that position $L_x = 1/4 L_p$ was characterized by the maximum velocity value of $|U_z|$. The results shown in **Fig.18**, explain clearly the concordance between the evolution of the U_z velocity component and the surface plate temperature profile presented in **Fig.19**: the minimum surface plate temperature, close to 30°C , occurred at $L_x = 0.4 L_p$ where vertical component of velocity reached its maximum, $|U_z| = 1.3 \text{ m/s}$. Similar behavior discussed in **Figs.18-19** was observed for other electrode gap values, $d = 2 \text{ cm}$ and $d = 6 \text{ cm}$, but with different magnitudes.

Figure 18. Velocity profiles of U_z component, along a line located at $z = 1$ cm in xz plane

Figure 19. Surface temperature profiles T_p , just beneath the wire

4. Conclusion

The present study is one of the first where both PIV and IR thermography were performed to investigate the heat transfer enhancement by ionic wind in a rectangular channel, which dimensions correspond to real size of potential future drying systems.

The experiments clearly demonstrated that such an approach is necessary to understand, in different wire-to plate electrode configurations, the results of heat transfer enhancement versus flow structure alteration.

Thermal characterization essentially made possible to identify and select optimal configurations according to different aspects like transfer enhancement, thermal homogeneity and energy consumption. The study of flow characterization by PIV figured out the relationship between the geometric and operating parameters with the heat transfer intensification distribution. It enabled the understanding of the mechanisms of secondary flows structures combined with the primary flow (air jet, vortex...). The following conclusions were derived:

In all cases, the highest heat transfer enhancement by EHD was obtained for the smaller primary air flow velocity (0.3 m/s). As expected, at low Reynolds number, primary air flow provided the most efficient use of the secondary air flow induced by EHD. This in fact corresponds to a large EHD number.

For the single wire-electrode arranged perpendicular to the primary air flow, the greatest increase in heat transfer occurred when the wire-electrode was set at the highest distance from the plate

($d = 6 \text{ cm}$) where it provided the best intensification ($h_m/h_0 = 8$). For the minimum value of wire to plate distance, the heat transfer enhancement was localized over a very limited area beneath the wire. In this case, the generated secondary flow was similar to an impinging jet that caused a strong intensification on an area located beneath the wire. Such a configuration should be selected when the objective consists in getting local heat/mass transfer enhancement without any necessity to get homogeneous treatment.

For the case of single wire-electrode arranged parallel to primary air flow, the highest increase in heat transfer enhancement was achieved for wire to plate distance of 4 cm which provided the most efficient combination of primary and secondary air flow where the intensification was improved 7 times ($h_m/h_0 = 7$). In this case, the air jet was generated along the wire where the maximum velocity was similar to that achieved with the cross wire. It was shown that contra-rotating vortices appeared and were developing as progressing in the channel. Such a configuration should be selected when the objective consists in getting an homogeneous treatment due the change in the vortices shape structures of the secondary flow along the plate.

Whatever the configuration, results indicated that such a deep analysis of heat transfer enhancement and flow structure is required for a correct design of future system (geometrical parameters and applied voltage) according to the objective. High local enhancement can be reached when decreasing the electrode gap but the enhancement is then limited by arcing phenomenon. A more homogeneous enhancement requires a larger inter-electrodes gap that lead to a larger jet with lower impacting velocities.

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Highlights

- Using EHD in thermal process leads to heat transfer enhancement and reduces energy consumption
- EHD induced secondary flow disturbs the thermal boundary layer and increases heat transfer
- Wire /plate electrode arrangement is efficient for combined secondary flow generation with primary flow in a channel
- Longitudinal wire configuration improves the homogeneity of heat transfer compared to cross wire configuration
- Combination of thermal and dynamic flow characterization is the main key for EHD process optimization