Electrohydrodynamic modelling and its application to heat transfer enhancement
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ABSTRACT

In food processes, convection is still the main heat transfer mode and air is the most common heat transfer medium. The heat transfer enhancement at fluid -solid interfaces remains one of the crucial issues of these processes. The electrohydrodynamic (EHD) enhancement by ‘ionic wind’ is a promising technique that consists in applying an electric field of very high voltage and low electric current. The main objective of this study is to evaluate the performance of EHD enhancement of heat transfer in a square channel. The ionic wind is generated to disturb the air flow and to increase the convective heat transfer coefficient. Numerical and experimental investigations are performed in order to analyse the influence of the key parameters (velocity, geometry, applied voltage) on the heat transfer coefficient. EHD equations are solved by combination between Matlab\textsuperscript{®} and Comsol\textsuperscript{®}. Experiments are conducted using infrared camera in order to measure the surface temperature and to calculate the local heat transfer coefficient. In the set-up, air is blown at a velocity up to 5 m/s and the ionic wind is generated by a wire electrode located across the channel. We obtain a good agreement between the model and the experiment (maximum discrepancy of 10\% on Nusselt number). At Re\textasciitilde5000 the enhancement of the heat transfer by the electric body force leads to a three-fold increase of the mean heat transfer coefficient. The numerical model permits to determine that multiple wires are required to obtain a significant enhancement over a wide surface. The distance between adjacent wires should be twice the distance between the wire and the ground plate. The modelling approach gives relevant information and basic rules could be derived to design EHD experiments.

Keywords: airflow; convection; infrared camera; electrohydrodynamic

INTRODUCTION

Forced convective heat transfer is the main heat transfer mode in bio and food processes. Air is widely used in heating or refrigerating processes despite its bad heat transfer properties. To ensure the desired treatments, high velocities are required and lead to high energy consumption. The boundary layers that form on the surfaces offer a significant resistance to the flow of heat. Enhancing techniques should therefore be performed in order to modify the air flow and to increase the convective heat transfer coefficient. The Electrohydrodynamic (EHD) enhancement technique offers a great potential, especially the "corona wind" for single phase convective heat transfer [1]. The corona wind is produced at the vicinity of a highly curved electrode surface where the local electric field strength is sufficiently large to ionize the gas molecules [2]. The ionization zone remains localized around the corona electrode. While the whole process is rather complex, the net effect is that ions of the same polarity as that of the corona electrode, are drifting to a collector electrode. Outside the ionization zone is the region called the drift zone where momentum is transferred, by collision, from the ions to the neutral air molecules. The resulting flow has been termed the corona wind [3]. The EHD enhancement of heat and mass transfer by corona wind, so-called corona discharge, has been extensively studied in external boundary layers or free convection systems [4]. Concerning the enhancement of heat transfer in the case of forced convection, contradictory results were observed for a laminar tangential flow over a surface. The combination between inertial and electrical forces could lead to a four-fold increase of the Nusselt number [5]. Other authors observed no enhancement of heat or mass transfer by EHD [6]. Literature is rather poor concerning the EHD enhancement of heat transfer in channel flows. Most of them concerned a wire electrode parallel to the main air flow for heat exchanger applications [7]. The case of a transversal electrode in a channel received less attention despite its great interest in bio and food processes [8, 9, 10]. This configuration could be the most interesting to continuously treat food product like in the electrostatic smoking process [11]. Drying of food has also been investigated but only in batch configuration [12-16]. The main objective of this study is to analyse the EHD enhancement of heat transfer in a channel. We combine modelling and experimental investigations to assess the influence
of the ionic wind on the local heat transfer coefficient at the surface of a heated plane in a square channel. 
The experimental set-up and the governing equations are firstly described. Experimental results are given and 
the validation of the model against experimental data is pointed out in the case of a single wire. The benefit 
of the modelling approach is raised in the case of two wires.

MATERIALS & METHODS

The experimental setup is shown in Figure 1. Air, at controlled temperature (20°C) and humidity (20 %), was 
blown at the desired velocity Uin [0 -5 m/s] in a square channel (15x15 cm). The channel, made of 
polyurethane material (thickness 2 cm) was 2 m long. The test section was located at 1.5 m from the inlet 
(x/Dh=10) where we verified that the flow was fully developed. A high-voltage DC power supply was used 
to charge the wire electrode (Rw=0.1 mm) at the desired voltage V0. This wire was located 3 cm above the 
heated plate. The temperature profile of the plate was measured with an infrared camera. The air temperature 
and the temperature of the walls close to the test section were measured using K-type thermocouples. A data 
acquisition system was used to record the different measurements. Another power supply was used for the 
heated plate shown in figure 2. It was constituted of very thin layers of conductive and dielectric materials. 
The upper copper layer was used as the ground electrode. The plate surface, which was lightly painted 
homogeneously to diminish the shining surface of the copper, had an emissivity equal to 0.99. The infrared 
camera was calibrated before every set of experiments. The sensitivity of the camera was ±0.1°C with a 
spatial resolution of 0.428 mm/pixel. The temperatures were measured at the centre line of the heated plate 
(along a line perpendicular to the wire) so that edge effects were not included in the subsequent calculations.

![Figure 1. Sketch of the experimental set-up.](image)

![Figure 2. Heated plate, (a) photo before painting (b) scheme of the layers](image)

The model takes into account the classical steady-state equations of fluid dynamics (Eq. 1 to 3) where 
turbulence is taken into account using the standard k-ε model. The ionization layer at the vicinity of the wire 
is not modelled, we consider that the electric charges are injected from the ionization zone and form a space 
charge \( \rho_c \) in the drift region. The resulting Coulomb force \( \rho_c E \) acts as a source term in the momentum 
equation (Eq 3). The electric problem is then governed by Maxwell’s equations of electrodynamics (Eq. 4 to 
6) and Ohm’s law (Eq. 7). The current density \( J \) must satisfy this charge conservation equation.

\[
\begin{align*}
\nabla \cdot u &= 0 \\
\rho(u \cdot \nabla) u &= -\nabla p + \left( \mu + \mu_t \right) \nabla^2 u + \rho_c E \\
u \cdot \nabla T &= \nabla \cdot \left( \kappa \nabla T \right) \\
E &= -\nabla \phi \\
\nabla \cdot E &= \frac{\partial \rho}{\partial t} \\
\end{align*}
\]
\[ \nabla \cdot J = 0 \]  
\[ J = \rho_c bE + \rho_c u - DV \rho_c \]  
\[ (6) \]  
\[ (7) \]  

The boundary conditions for the potential are very straightforward: a given potential \( V_0 \) at the corona electrodes, zero at the ground plate and Neumann conditions elsewhere (\( \partial V / \partial n = 0 \)). For the space charge density, we adopt Kaptsov’s hypothesis and apply Peek’s semi-empirical expression \([8, 11, 17]\). The charge density at the wire was determined using the Nelder–Mead simplex method implemented in Matlab®. A developed velocity profile is fixed at the inlet, a no-slip velocity is imposed at the walls and a neutral conditions is fixed at the outlet (\( \partial u / \partial n = 0 \)). Concerning energy, a Dirichlet condition is applied at the inlet; adiabatic conditions are applied elsewhere except at the grounded plate. In order to calculate the convective heat transfer (Eq. 8), Neumann condition is imposed (\( -\lambda \partial T / \partial n = \varphi_{\text{convection}} \)) at this plate. The heat flux at the plate \( \varphi_{\text{convection}} \) and the inlet temperature \( T_{in} \) are given by measurements. Equations 1-7 are solved using Comsol Multiphysics®, a Partial Differential Equations solver based on the Finite Elements Method. Details on this model and on the numerical procedure are available in the literature \([18]\).

**RESULTS & DISCUSSION**

During experiments, the positive applied voltage \( V_0 \) was incrementally increased from 4 to 20 kV and the corresponding corona current \( I \) was measured. The resulting Current-Voltage characteristic is shown in Figure 3. In this configuration, the onset voltage is close to 9 kV; ionization of air appears at this value and ions are drifted towards the ground plate. It is noticeable that the numerical model is able to predict this curve with a very good accuracy. It is confirmed that the procedure used to determine the boundary conditions for \( \rho_c \) is very well suited. For the following heat transfer experiments, the applied voltage was set at 15kV.

![Figure 3. Current-Voltage characteristic](image)

In the heated plate, we fixed the current at 0.4 A and the voltage was 6.8 V. The corresponding electric power was entirely dissipated by Joule effect (\( \varphi_{\text{heating}} = 121 \text{ W/m}^2 \)). Figure 4a illustrates the surface temperature measured by the IR camera through a sapphire window. This temperature results from the heat losses by conduction throughout the polyurethane, by radiation with the internal walls of the channel and by convection with the flowing air (figure 4b). In stationary regime, the local convective heat transfer coefficient \( h_x \) (eq. 8) is derived from the heat balance expression (eq. 9). The local Nusselt number \( Nu_x \) was obtained from the conventional definition (eq. 10) where the hydraulic diameter \( D_h \) is equal to the height of channel \( H \).

\[ h_x = \frac{\varphi_{\text{convection}}}{T_{w,x} - T_{\text{air}}} \]  
\[ \varphi_{\text{convection}} = \varphi_{\text{heating}} \times \varphi_{\text{conduction}} \times \varphi_{\text{radiation}} \]  
\[ Nu_x = \frac{h_x D_h}{\lambda_{\text{air}}} \]  
\[ (8) \]  
\[ (9) \]  
\[ (10) \]
Experiments were performed for inlet velocities $U_{in}$ ranging from 0 to 1.25 m/s. Figure 5 presents the temperature and Nusselt number along the plate for $U_{in}=0.56 \text{m.s}^{-1}$; it corresponds to a Reynolds number $Re$ equal to 4940. Two cases are considered: without EHD ($V_0=0$) and with EHD ($V_0=15 \text{kV}$). The cases without electric field correspond to pure force convection. Figure 5a indicates that the plate, initially at a uniform temperature (37.5°C ± 0.2°C), is more cooled when EHD is applied. In this case, the cooling effect is maximum below the wire ($x/L=0.5$). The model is able to predict the temperature profile, especially in the first part of the plate. The maximum discrepancy in the second part is 0.7°C. In term of Nusselt number, the prediction is also good because the maximum discrepancy is 20% (figure 5b). The enhancement factor, defined as the ratio between Nusselt numbers with and without EHD is locally tripled and the average enhancement factor is equal to 2.5. For a higher inlet velocity $U_{in}=1.25 \text{m.s}^{-1}$, figure 6 shows that the maximum discrepancy is of the same order but the phenomena at the leading edge are not so well predicted. It clearly appears that the enhancement ratio is not so important for this higher Reynolds number.

For the lower Reynolds number ($Re=4940$), figure 8 presents the flow pattern predicted by the model. It is shown that the ionic wind alters the flow field and is efficient to cool the plate. This figure also indicates that the flow is modified in the restricted area where the Coulomb force is predominant. At $x=0.15\text{m}$, the flow behaviour becomes a channel flow because the inertial force is predominant compared to the Coulomb force.
In order to enlarge the effect of the EHD enhancement, multiple wires should be placed in the channel. The model is able to handle these configurations by considering the Kaptsov’s hypothesis on each wire [18]. Figure 9 demonstrates this ability in the case of two wires separated by a large distance. When the distance between wires is sufficiently large, it can be considered that each wire acts independently.

CONCLUSION

The two-way coupling model that was developed to analyse the EHD enhancement in a square channel is relevant to predict the effect of the ionic wind on the heat transfer. Moreover, as the charge density at the corona electrode is determined using an optimization procedure, the model permits to predict the current-voltage characteristic. The experimental set-up based on infrared thermography permitted to quantify the EHD enhancement and to validate the numerical results for two Reynolds numbers. The efficiency of the ionic wind was pointed out at Re=4940 with an applied voltage equal to 15 kV. It could lead to a three-fold increase of the mean heat transfer coefficient. Further experiments should be conducted to investigate a larger range of process parameters and to confirm numerical results obtained with multiple wires. The modelling approach gives relevant information and basic rules could be derived to design EHD experiments. These latter will consists in applying corona wind during thermal processes (baking, drying). It is expected that the heat transfer enhancement would permit to reduce the energy consumption without modification of the food qualities.

REFERENCES


