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Effect of process parameters on the EHD airflow

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ABSTRACT

This work deals with the assessment by numerical investigations of the electrohydrodynamic enhancement of heat transfer in a channel. In order to get a better understanding of the phenomena, we developed an original numerical approach. The model handles the couplings between a non-isothermal turbulent flow and corona discharges from multiple wires. The typical configuration consists in a channel where air enters at a given velocity. In the channel, the ionic wind is produced by multiple coronating wires. In this study, the model is used in order to analyse the effect of some process parameters (inter-electrode distance, wire radius, applied voltage) on the flow and on the convective heat transfer enhancement. We firstly confirm that the model operates well and permits selection of the best parameters in a specific configuration. The model reveals that similar flows could be obtained with different combinations between the inter-electrode distance and the applied voltage. In a second stage, the distance between adjacent wires is discussed. Synergetic effects are obtained for close wires; they locally lead to a tenfold increase of the heat transfer enhancement.

1. Introduction

Convection is still nowadays the main heat transfer mode that is applied in food processes. The thermal and refrigeration processes usually consist in blowing large air volume rates towards the food. If they are sometimes carried out in batch systems, like in an oven or in a cooling cabinet, they are more conveniently performed in a tunnel. In fact, continuous processes are more suitable for hygienic and process engineering considerations. Nevertheless, as air is a very bad heat transfer medium, it requires high velocities and it leads to high energy consumption.

As raised by Shoushtari [1], extensive research has been carried out for years on the development of novel and efficient techniques for the enhancement of heat transfer and mass transport of fluids. Indeed heat, momentum, or mass transport enhancement is a diverse and complex area. As mentioned by Allen and Karayiannis [2], the Electrohydrodynamic (EHD) enhancement technique offers great potential, especially the enhancement by flow of corona wind in the case of single phase convective heat transfer. The complex mechanisms of the corona discharge are well described in the literature [3,4]. 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, localized around the corona electrode, is the drift zone where momentum is transferred, by collision, from the ions to the neutral air molecules. The resulting corona wind flow has been well known for a long time [5] but it is still being investigated [6] because it is quite a major challenge to measure quantitatively the low flow speeds.

A recent literature review [7] confirmed that despite the past studies on the EHD enhancement of heat and mass transfer by corona discharge, they were restricted to some specific configurations. Past studies mainly dealt with the hydrodynamic process resulting from a corona discharge in external boundary layers, free convection systems or tube flows [8]. Even if the EHD enhancement of heat and mass transfer in natural convection was already highlighted [9,10], it is still a challenging research area [11].

In the present work, we are more interested in forced convection because the literature is more contradictory. Whereas a positive combined effect of inertia and electrical force was sometimes shown [12], it could happen that inertial effects were so predominant that no enhancement was given by the electrical effects [13,14]. Improvement of experimental techniques and of numerical tools permits us to deeply investigate these configurations and to get a better understanding of the mechanisms [15–17]. For example, in recent heat exchanger applications, experiments showed how the corona induced secondary flows that enhanced heat transfer in tubes [18,19].

The modelling approach to flows has already proved its ability to handle electrostatics [20–22] and more especially EHD flows [1,11,16,17,23,24]. In this latter case, Maxwell's equations of electrodynamics and Ohm's law are firstly solved and the electric body

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Nomenclature

b	ion mobility ($m^2\ V^{-1}\ s^{-1}$)
d	inter-electrode distance (m)
D	diffusivity coefficient of ions ($m^2\ s^{-1}$)
E	electric field strength ($V\ m^{-1}$)
E_c	electric field of ionization ($V\ m^{-1}$)
h	convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
H	channel height (m)
J	current density ($A\ m^{-2}$)
k	turbulent kinetic energy ($m^2\ s^{-2}$)
L	channel length (m)
p	pressure (Pa)
q	heat flux (W)
u	air velocity ($m\ s^{-1}$)
V	voltage (V)
R	wire radius (m)
R_c	radius of ionization zone (m)

Greek letters

α	thermal diffusivity ($m^2\ s^{-1}$)
ε	turbulent dissipation rate ($m^2\ s^{-3}$)
ε_0	dielectric permittivity of free space ($C\ m^{-1}\ V^{-1}$)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
θ	angle with respect to normal axis (°)
ρ	density of air ($kg\ m^{-3}$)
ρ_c	space charge density ($C\ m^{-3}$)
μ	dynamic viscosity ($Pa\ s^{-1}$)

Subscripts

0	wire
in	inlet
t	turbulent
x	abscissa
w	lower wall

force is introduced into the momentum equations. The numerical study performed by Huang and Lai [16] demonstrated that this assumption of one-way coupling was valid for a wide range of governing parameters.

In this paper, we present a general algorithm based on a two-way coupling model. It permits us to conduct parametric studies for a wide range of process parameters without neglecting any interactions. This algorithm is employed to study the EHD flow and the convective heat transfer in a channel. The case of a single wire is firstly investigated to fix the applied potential and some geometrical parameters. Then, some simulations are carried out on a configuration with two wires. The influence of the distance between wires on the flow and the heat transfer is then discussed.

2. Numerical procedure

The configuration under investigation in this paper consists in a channel where air enters at given temperature T_{in} and velocity U_{in}. The objective is to enhance the convective heat transfer on the down plate by ionic wind. The down plate is the ground electrode and the ionic wind is generated by a corona discharge from one or two wires supplied with a high positive DC voltage (Fig. 1).

As the channel airflow is altered by the Coulomb force acting on the space charge, the calculation of the electric field and space charge density is crucial. 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 ρ_c in the drift region. The electric problem is then governed by Maxwell's equations of electrodynamics (Eqs. (1)–(3)) and Ohm's law (Eq. (4)). The current density must satisfy this charge conservation equation where we neglect nor the convective component nor the ion diffusion.

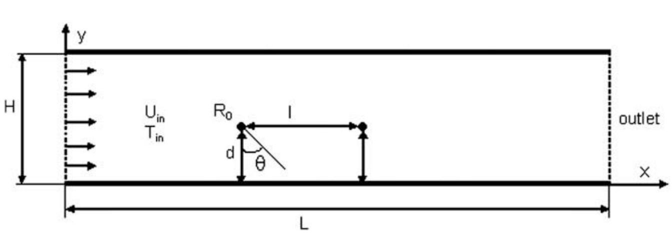

Fig. 1. Schematic of the wires–plate geometry.

$$E = -\nabla V \quad (1)$$

$$\nabla \cdot E = \frac{\rho_c}{\varepsilon_0} \quad (2)$$

$$\nabla \cdot J = 0 \quad (3)$$

$$J = \rho_c bE + \rho_c u - D\nabla\rho_c \quad (4)$$

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 ($\partial V/\partial n = 0$). The formulation of proper boundary conditions for the space charge density is not so easy. As well described by Feng [20] and successfully applied by Zhao and Adamiak [23], the Kaptsov hypothesis is adopted. It suggests that the electric field increases proportionally to the voltage below the corona onset, but will preserve its value after the corona is initiated (Eq. (5)). The threshold strength of electric field for the corona onset at the corona electrodes is reasonably described by Peek's semi-empirical expression (Eq. (6)). In normal conditions of pressure and temperature, we consider $\delta = 1$ and $E_c = 2.47 \cdot 10^6\ V\ m^{-1}$ at R_c. To deal with Kaptsov's condition and

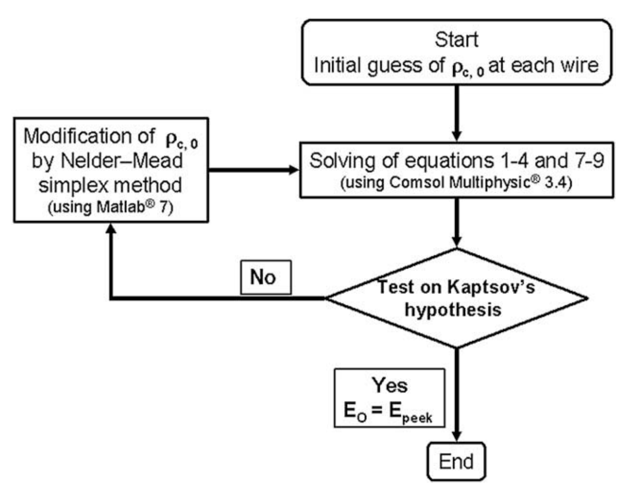

Fig. 2. Flowchart of the numerical procedure.