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Numerical analysis of electric force influence on heat transfer in a channel flow (theory based on saturated porous medium approach)

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ABSTRACT

The present paper reports the influence of electrode and ground arrangement on electrically-driven airflow and heat transfer enhancement in a saturated porous medium placed in a channel flow. In simulations, the inlet velocity and temperature of air entering a test section are controlled at 0.35 m/s and 60 °C, respectively. High electrical voltage is tested in the range of 0–30 kV. The numerical results show+ that when electric field is applied, swirling flow caused by shear flow effect is observed. When electrode is placed near ground, swirling flow is small but it has a high strength. In addition, the strength of swirling flow is increased by increasing electrical voltage. With occurrence of swirling flow, the heat transfer is totally higher than the case of conventional hot-airflow. By comparing with a single ground, swirling flow created by multiple ground effect spreads wider over the surface of sample. This causes temperature of the sample to increase faster. It is found from flow visualization that behaviors of swirling flow obtained by smoke incense technique and simulation have a good agreement. Furthermore, enhancement of heat transfer in the sample depended on the arrangement of electrode and ground, as well as, the position of the sample.

1. Introduction

The increasing necessities for saving energy and environmental concerns have prompted the development of more effective heat transfer equipment with enhanced heat transfer rates. The flow in channel occupies an important place among the several heating systems [1–7]. One way to achieve considerable improvement in thermal efficiency is to extend heat transfer area and increase the flow velocity [8–10]. The convective heat transfer enhancement technique utilizing electrostatic force generated from the polarization of dielectric fluid or Electrohydrodynamic (EHD) can be one of the most promising methods among various active techniques because of its several advantages, for examples, a quick response to the flow control, a significant increase in the convection heat transfer, simplified implementation using only a small transformer and electrodes and a small consumption of electric power.

Mechanism of Electrohydrodynamic method is explained by Fig. 1. When electrical voltage is introduced to airflow, ions from a sharp electrode move forwards to the ground electrode, i.e. Corona wind [11]. As a result, the momentum of airflow is enhanced. Meanwhile, shear flow effect which is occurred by velocity difference between charged and uncharged air, induces the uncharged air to become swirling flow. This technique deals to the interdisciplinary field with subjects concerning the interactions between electric, flow, and temperature fields. In order to improve convective heat transfer, some researchers studied seriously in Electrohydrodynamic process [12–16]. Kasayapanand [12] studied heat transfer enhancement using Electrohydrodynamic technique for channel installing multi-electrode bank arrangements. The results showed that the electrode bank arrangement which obtained the best heat transfer performance was expressed incorporating with the optimum electrode distance ratio (transverse and longitude pitches). Moreover, the heat transfer enhancement was also depended on the number of electrodes per length and the channel dimensions. Huang and Lai [15] investigated the water evaporation enhanced by Corona wind. The Corona wind was generated by a wire electrode charged at a high dc voltage. The numerical results showed that water evaporation was able to be greatly enhanced by Corona wind. However, a cross-flow with a high velocity may diminish the effect of Corona wind. When the results were compared to experiments, the agreement was found to be reasonable, which indicated that the model had correctly represented the physical system. The discrepancy between numerical and experimental results was attributed to the variation of ambient conditions and the uncertainty in the electric properties of the media used in the numerical simulations. Chaktranond and

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Nomenclature

b	ion mobility (m^2/Vs)
C_p	specific heat capacity (J/K)
D	electric flux density (C/m^2)
E	electric field (V/m)
EHD	electrohydrodynamic
f_E	electric force (C/m^2 s)
H	height of channel (m)
h	distance between electrode and ground in the vertical direction (cm)
J	current density (A/m^2)
k	thermal conductivity (W/m K)
L	length of channel (m)
l	distance between electrode and ground in the horizontal direction (cm)
n	outward normal from medium and coordinate in x and y axis
P	pressure (N/m^2)
q	space charge density (C/m^3)
S	sample
T	uniform temperature (K)
T_α	ambient temperature (K)
t	time (hr)
u	airflow velocity (m/s)
V	electrical voltage (V)
x, y	axis

Greek letters

ε	dielectric permittivity (F/m)
η	kinematics viscosity (m^2/s)
μ	viscosity (kg/m s)
ρ	density (kg/m^3)
ϕ	porosity (–)
κ	permeability (m^2)

Subscripts

d	lower interface
eff	effective value
i	inlet
l	liquid phase
s	sample
s	solid phase
u	upper interface
0	atmospheric, initial and wire

Superscript

T	transpose of matrix

Rattanadecho [16] experimentally investigated the influences of electrical voltage on the heat and mass transfer in porous packed bed subjected to Electrohydrodynamic drying. The four wire electrodes and a wire ground were installed in the normal flow direction and cross flow direction, respectively. Electrical voltage was applied in the range of 0–15 kV. Average velocity and temperature of hot-airflow were controlled at 0.33 m/s and 60 °C, respectively. The results showed that the heat and mass transfer rates in the packed bed were increased. The convective heat transfer coefficient and drying rate were considerably enhanced with the strength of electric fields influencing Corona wind.

In order to consider flow phenomena or flow characteristic, measurements were performed to visualize the flow pattern. For the past decade, incense smoke techniques for investigating flow visualization of the EHD have been applied, in order to analyze the modifications of flow when it perturbed with an EHD effect. It is studied by some researchers, but very short time exposure pictures of Corona wind were captured. Recently, our research group has tried to numerically investigate Corona wind subjected to EHD effect, such as Saneewong Na Ayuttaya et al. [17] carried out on the numerical simulation for the effect of ground arrangements on swirling flow in a rectangular duct subjected to Electrohydrodynamic. The result shows that, airflow of plate ground was widely swirled and extended more than with wire ground but wire ground can strongly induced the swirling flow to the local place. In case of wire ground, the strength of local fields seemed to be very interesting in the way that the technique might be used in some applications that required the local strength of Corona wind and velocity field, etc. Saneewong Na Ayuttaya et al. [18] numerically explored the influences of electrode arrangements and the number of electrodes on the fluid flow under electric field. When the distance between electrode and ground in the vertical direction (h) $\neq$ 0 cm, swirling flow is occurred and its direction depended on location of h. The distance between electrode and ground in the horizontal direction (l) becomed closer, size of swirling becomes smaller but vorticity is stronger. This is because of higher and denser electric field intensity. With increasing the number of electrodes, electric field increased. This causes swirling to be larger and more violent.

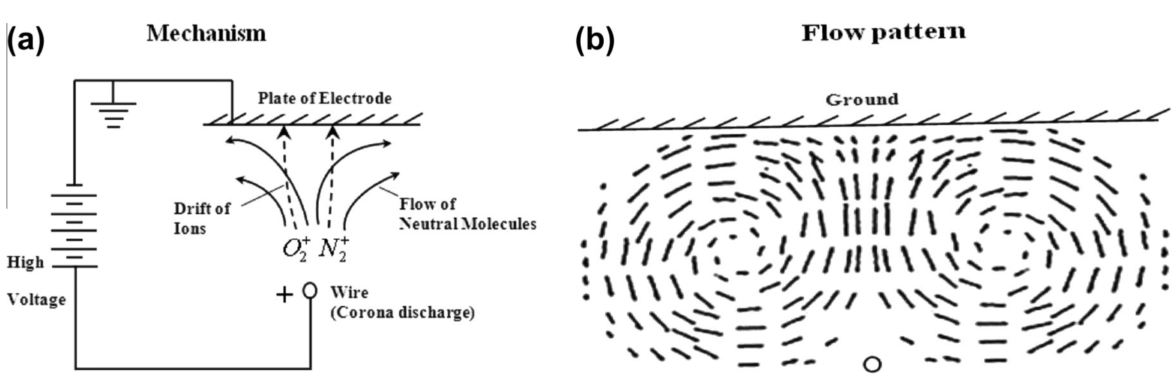

Fig. 1. Mechanism of Corona wind: (a) Mechanism of high electrical voltage (b) Corona wind pattern [11].