Effect of Electric Force Direction on Fluid Flow and Heat Transfer in Channel Flow

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Abstract

This paper aims to numerically investigate fluid flow and heat transfer enhancement in channel flow perturbed by electric field. In this simulation, angle between electrode and ground point is varied in range of $\theta = 0 - 315$ degree. High electrical voltage is applied at 20 kV. Temperature and average velocity of inlet hot-air flow are controlled at 60^{o}C and 0.3 m/s, respectively. The results are shown that swirling flow is created in streamwise direction when voltage is applied. In addition, position and vortex strength depend on location of electrode respecting with ground position. However, when $\theta = 0$ degree, effect of shear flow is not strong enough to induce swirling flow. Furthermore, electric force affects the swirling flow characteristics in relation with the heat transfer enhancement in the sample.

Keyword: Electrohydrodynamic, Electric force, Heat transfer, Swirling flow, Numerical analysis.

1. Introduction

With increasing necessities for saving energy and environmental concerns, many researchers have paid much attention to develop strategies for improving heat transfer equipments to be more efficient. An effective method to enhance heat transfer in a channel flow is to utilize Electrohydrodynamic (EHD) [1-4]. The advantages of this method are that flow can be manipulated in various inlet flow conditions as well as no addition of moving part. Chaktranond and Rattanadecho [1] experimentally investigated the influences of electrical voltage on the heat and mass transfer in porous packed bed subjected to hot-air drying. The results showed that the convective heat transfer coefficient and drying rate were considerably enhanced with the increasing electrical voltage. Ahmedou and Havet [3] investigated the EHD enhancement on a drying process. The results showed that when cross flow air velocity was low and the distance between product and Corona wind was small, the drying rate was enhanced. Saneewong Na Ayuttaya et al. [4] numerically investigated influence of two ground arrangements, i.e. Wire-to-Wire (*WW*) and Wire-to-Plate (*WP*), on electric-driven swirling flow. The results showed that electric field distributions from both arrangements are quite different. These results caused the characteristics of swirling flows to appear differently. Strength of vorticity was inversely proportional to the distance between electrode and ground positions. Moreover, increase of inlet flow velocity suppressed effect of electric force on vortex strength, resulting in lower heat transfer enhancement.

In this study, interactions among electric force, heat transfer and fluid flow are considered. Moreover, the angle between electrode and ground points are varied in the range of $\theta = 0 - 315$ degree.

2. Computational domains

The computational domains are shown in Fig.1 and compose of main three parts: (1) electric field, (2) fluid flow and (3) heat transfer. The boundary condition of the problem is showed in Fig.2.

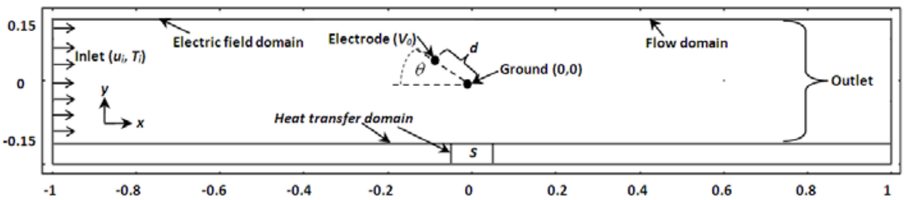

Fig.1 Computational domain.

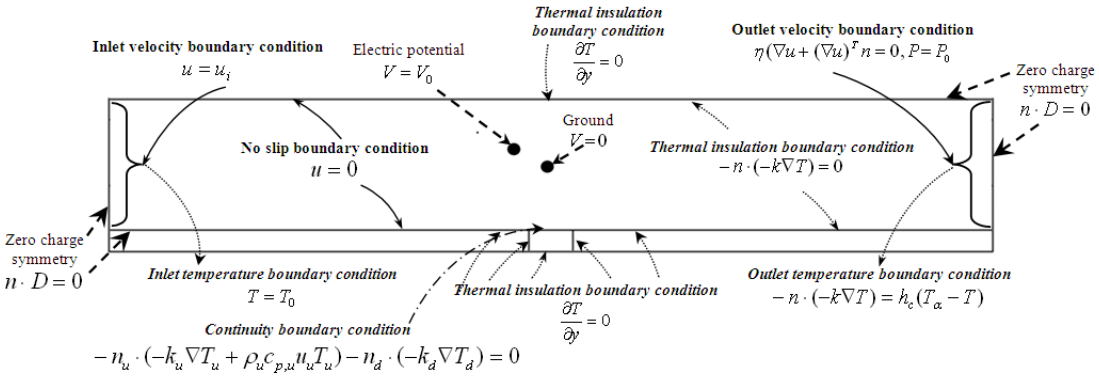

Fig.2 Boundary condition used in analysis.

Dimensions of channel are 2.0 m long × 0.3 m high. A sample (*S*) of 10 cm × 5 cm is placed at the lower wall and it is filled with water. Surfaces of sample are assumed to be adiabatic, except top surface is exposed to hot-air flow. Electrode and ground points are assumed to be a circle with a diameter of 0.5 mm. Space charge density (q_0) at the tip of electrode is considered from Griffiths [5]. Position of ground is fixed at the center of channel. The distance (*d*) between electrode and ground is 4 cm.

2.1 Electric force calculation

To simplify the problem, the dielectric property is constant and the effect of magnetic field is negligible. Electric field distribution is computed from Maxwell's equations listed as below:

$$\nabla \cdot \varepsilon \vec{E} = q, \quad (1) \qquad \vec{E} = -\nabla V, \quad (2)$$

$$\nabla \cdot J + \frac{\partial q}{\partial t} = 0, \quad (3) \qquad J = qb\vec{E} + q\vec{u}, \quad (4)$$

where E is electric field intensity, t is time, q is the space charge density in the fluid, ε is dielectric permittivity, ρ is density of fluid, V is electrical voltage, J is current density, b is ion mobility and u is airflow velocity. When electrical voltage of wire (V_0) is considered, it is fixed at $V_0 = 20kV$. Electric force is computed by Coulomb force,

$$\vec{F}_E = q\vec{E} \quad , \qquad (5)$$

2.2 Fluid flow calculation

In simulation, the inlet air velocity is uniform and $u_i = 0.3m/s$. Properties of fluids are assumed to be constant and evaporation effect is neglect. Fluid flow is computed through the continuity and Navier–Stokes equations, where electric body force is included,

$$\rho\left[\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u}\right] = -\nabla\vec{P} + \mu\nabla^2\vec{u} + \vec{F}_E, \qquad (6)$$

where P is pressure and μ is viscosity of fluids. The last term of Eq.(6) is electric force per unit volume. Enhancement of airflow velocity is presented by velocity ratio (u_r), which is defined as the maximum velocity perturbed by electric field to inlet airflow velocity,

$$u_r = \frac{u_{\max,EHD}}{u_i}, \qquad (7)$$

2.3 Heat transfer calculation

Effect of joule heating is neglected [1] and emission or absorption of radiant energy is not considered. Temperature distribution in a channel flow is calculated by energy equation,

$$\rho C_p\left[\frac{\partial T}{\partial t} + \vec{u}\nabla T\right] = k\left(\nabla^2 T\right), \qquad (8)$$

where C_p is the specific heat capacity and k is thermal conductivity and T is temperature. The initial temperature of hot-airflow in channel is be $T(t_0) = 60\ ^{\circ}C$. Convective heat transfer coefficient is defined by the thermal equilibrium,

$$h_c = -\frac{k_w}{\Delta T}\frac{\partial T}{\partial n}, \qquad (9)$$

where n is normal vector. The initial temperature of sample is $T_w(t_0) = 20\ ^{\circ}C$. Enhancement of heat transfer is presented by convective heat transfer ratio which is the ratio of average convective heat transfer coefficient perturbed by electric field to average convective heat transfer of free air,

$$h_{cr} = \frac{\bar{h}_{c,EHD}}{\bar{h}_{c,free\ air}}, \qquad (10)$$

The interface layer between air and sample is treated by

$$-n_u \cdot (-k_u \nabla T_u + \rho_u c_{p,u} \vec{u}_u T_u) - n_d \cdot (-k_d \nabla T_d) = 0 \qquad (11).$$

where η is kinematics viscosity, the upper and the lower interfaces are designated by subscript *u* and *d*, respectively.

The computational scheme is assembled in finite element model using a collocation method. This study provides a variable mesh method for solving the flow, temperature and electric field problem. The equations are solved by using COMSOL. Lagrange quadratic element is chosen as the basic functions with triangular shapes. This convergence test leads to the mesh with approximately 9,000 elements.

The properties of air flow and sample are shown in Table 1. Properties of sample are shown in Table 2.

Table 1 Properties of air

Modeling parameter	**Value**
Ion mobility, b	$1.80\times10^{-4}\ m^2/V.s$
Dielectric permittivity, ε	$8.85\times10^{-12}\ F/m$
Kinematics viscosity, η	$1.76\times10^{-5}\ m^2/s$
Density, ρ	$1.060\ kg/m^3$
Specific heat capacity, C_p	$1.008\ kJ/kg.K$
Thermal conductivity, k	$0.028\ W/m.K$

Table 2 Properties of sample

Modeling parameter	**Value**
Kinematics viscosity, η_w	$1.005\times10^{-5}\ m^2/s$
Density, ρ_w	$998\ kg/m^3$
Specific heat capacity, C_{pw}	$4.190\ kJ/kg.K$
Thermal conductivity, k_w	$0.588\ W/m.K$

3. Results and discussion

3.1 Effect of electrode position on swirling flow

Effect of electrode position on electric field is shown in Fig.3. With the effect of charged air moving from electrode to ground, the shear flow layer is created and induces occurrence of the swirling flow, as shown in Fig.4. Electric field from various angles causes pattern and location of swirling to be different. And also, it indicates that electrode position respecting ground affects swirling direction. However, when θ

= 0 and 180, electric force and fluid force perform in the same direction. Therefore, effect of shear flow is not strong enough to induce swirling flow. Moreover, it is noticed whether swirling occurs near upper or lower wall, fluid velocity is higher. It is because effective flow area becomes smaller.

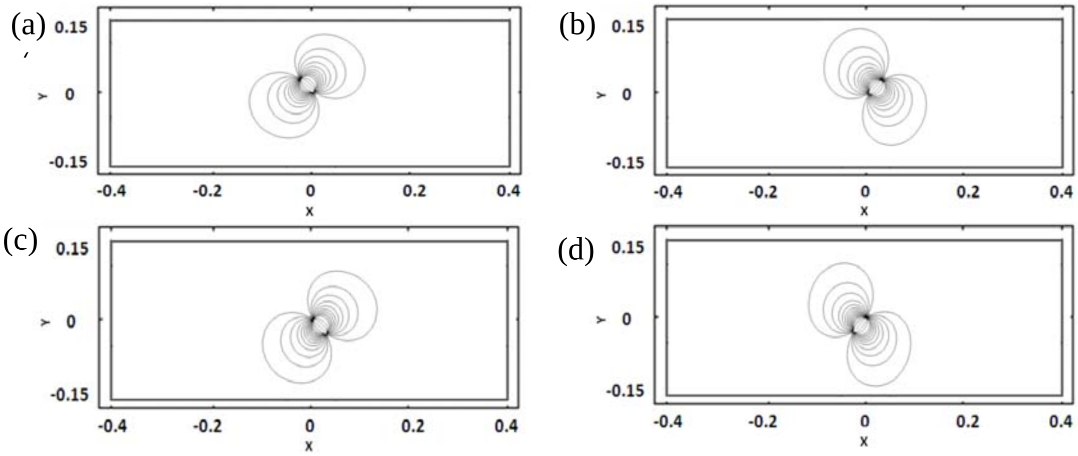

Fig.3 Electric field when d = 4 cm in various θ : (a) θ = 45 (b) θ = 135 (c) θ = 225 and (d) θ = 315.

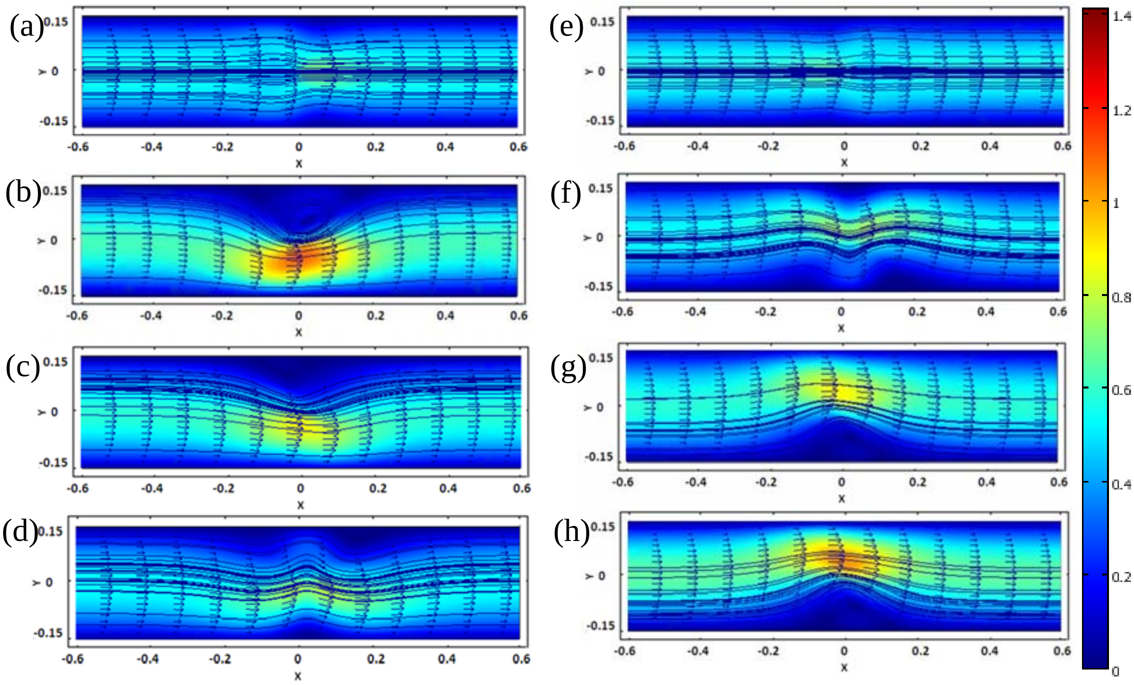

Fig.4 Swirling flow: when d = 4 cm in various θ: (a) θ = 0 (b) θ = 45 (c) θ = 90 (d) θ = 135 (e) θ = 180 (f) θ = 225 (g) θ = 270 and (h) θ = 315.

Figure 5 show effect of electric force in various angle (θ) on fluid velocity and swirling strength. As addressed above, when θ = 0, effect of electrically-driven shear flow does not induce the swirling flow but, in Fig.5, ω is not zero. This is because shear wall effect induces swirling flow. Due to the electric force direction performs in the same direction of fluid flow, u_r and ω are highest at $\theta = 45$. By $\theta = 315$, u_r is high but ω is lowest due to ω is considered both of magnitude and direction. Inversely, when electric force performs in the opposite direction ($\theta = 180$), u_r and ω are low.

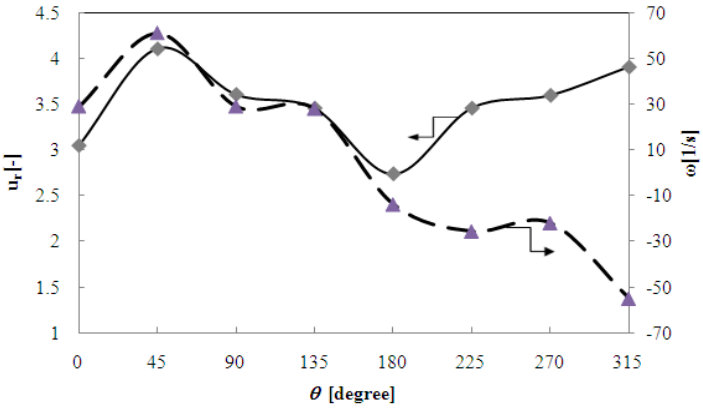

Fig.5 the maximum velocity ratio (u_r) and vorticity in various angle (θ).

3.2 Effect of swirling flow on heat transfer

Comparison of temperature contours between with and without EHD cases is shown in Fig.6. With effect of swirling flow near the upper wall, heat is much transferred from main flow into the lower wall. It causes temperature of sample to be increased faster, and temperature of air at downstream to be lower.

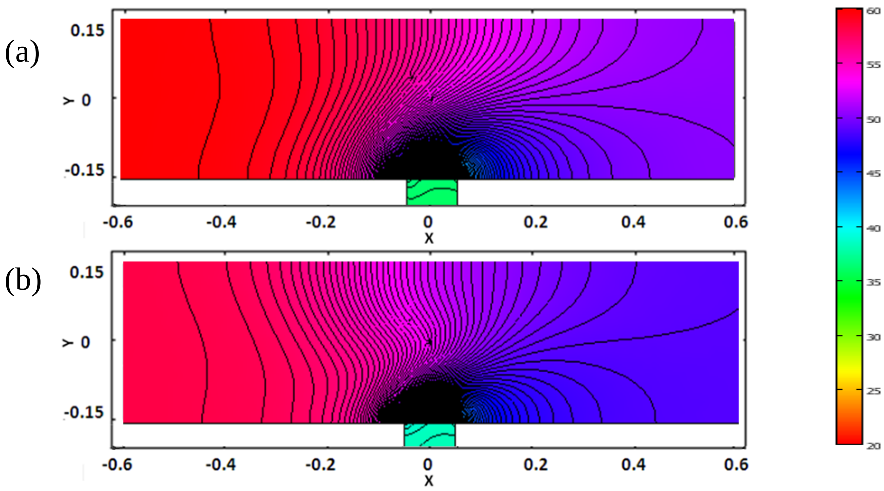

Fig.6 Temperature contour at t = 300s: (a) No EHD (b) With EHD at $\theta = 45$.

Figure 7 shows effect of swirling location on heat transfer. In Fig.7(a) and (b) where swirling flow appears near the upper wall, fluid flow near the sample surface moves faster and then leads the heat to more transfer towards the sample surface. In Fig.7 (c) and (d) where swirling flow appear near the lower wall. Swirling direction is supported with airflow direction so it can attract heat at sample surface, as a result, temperature within sample is rapidly increased. Fig.7(b) and (c), temperature within sample is slowly increased because electric force cannot induce swirling flow. In addition temperature within sample is so slowly increased even if electric force can induce swirling flow, as shown in Fig.7(d). Due to swirling flow can induce in opposite direction with airflow direction.

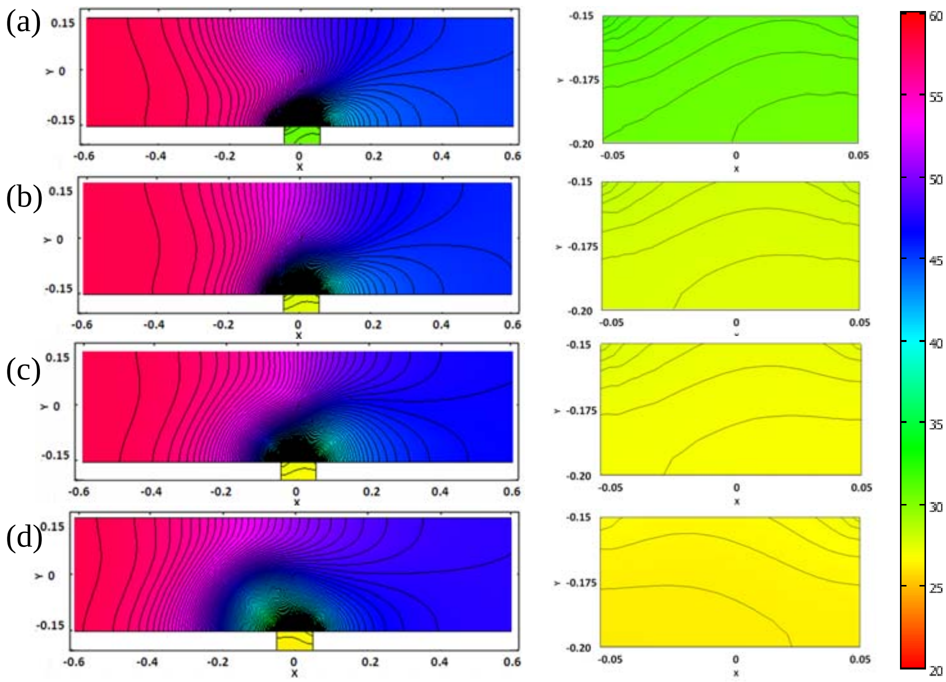

Fig.7 Temperature contour in various θ at t = 120 sec: (a) θ = 45 (b) θ = 135 (c) θ = 225 and (d) θ = 315. (Left in channel and right in sample)

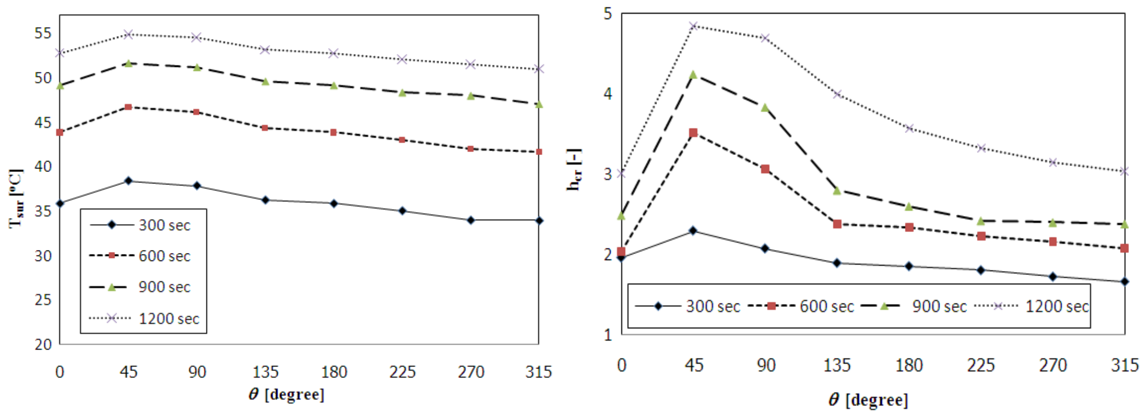

Fig.8 (Left Fig) Average surface temperature of sample in various θ and time.
Fig.9 (Right Fig) Average convective heat transfer ratio when various θ and time.

Fig.8 shows average surface temperature ratios (T_{sur}) in various times and θ. It can be seen that temperature ratios when θ = 45 is higher than the other. From Fig.9, average convective heat transfer ratio at θ = 45 is highest in every time, It can be seen that besides the shear flow effect, convective heat transfer is affected by location of electrode. So electric force affects the swirling flow characteristics in relation with the heat transfer enhancement.

4. Conclusion

Numerical analysis of fluid flow and heat transfer in a channel flow subjected to EHD effects is carried out. The conclusions are obtained as follows:

1. Angle between electrode and ground affects location and direction of swirling flow. This is because electric force induces shear flow in different directions.
2. Fluid flow above the sample surface moves faster and then leads to enhancement of convective heat transfer coefficient.

5. References

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