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Numerical Simulation of Air Flow Driven by Electric Field in a Rectangular Duct

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Abstract

This study numerically investigates the characteristics of air flow driven by electric field in a 3-D rectangular duct. Electrode wires are suspended from the upper wall of the duct and a ground wire is placed across the flow direction. High electrical voltage is applied at 20 kV. In addition, average velocity of the inlet air is controlled at 0.1 m/s. The results show that when electrical voltage is applied, electric field is highly dense in the region between electrode and ground wires. Moreover, swirling flow is created in the direction parallel to fluid flow. Adjusting the electrode location affects the flow pattern. Furthermore, vortex strength depends on location of electrode. Finally, increasing the electrode numbers increases the electric force, causing more violent flow.

Keywords: Electrode arrangement, Electric field, Electrohydrodynamics;

1. Introduction

The modification of flow patterns with electric fields, so-called electrohydrodynamics (EHD), is an attractive method to enhance convective heat transfer with low energy consumption. The idea is that when electrical voltage is introduced to air flow, ions from a sharp electrode move towards to the ground electrode. As a result, the momentum of air flow 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.

So far, many researchers have studied the EHD for heat transfer enhancement. Kasayapanand [1] numerically investigated the electric field effect on natural convection in the partially open square cavities. The results showed that the flow and heat transfer enhancements were the decreasing function of Rayleigh number. Moreover, the volume flow rate and heat transfer coefficient were substantially improved by the electric field effect. Chaktranond and Rattanadecho [2] 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 heat and mass transfer rates in the porous packed bed were

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considerably enhanced with the strength of electric fields. Saneewong Na Ayuttaya et al. [3] numerically investigated the effect of ground arrangements on swirling flow in a 2-D rectangular duct. The result showed that flow was widely swirled and extended with ground plate more than with ground wire. Using ground wire, however, could be induced the swirling towards to a local place. Moreover, Saneewong Na Ayuttaya et al. [4] also found that when the gap between electrode and ground wires in the vertical direction (*h*) was not zero, swirling flow was occurred and its direction depended on location of *h*. In addition, the gap in the horizontal direction (*l*) became closer, size of swirling became smaller but vorticity was stronger. This was because of higher and denser electric field intensity. Furthermore, Saneewong Na Ayuttaya et al. [5] also reported that with multiple ground wires, it could spread the swirling wider over the surface of sample. This causes temperature inside the sample to be rapidly increased.

In this current study, the effects of electrode wire arrangement and electrode number on air flow in 3-D rectangular duct flow are investigated in order to consider completely flow characteristic with an EHD effect.

2. Computational model

The computational simulation domain is 0.2 m high × 0.2 m wide × 2 m long as shown in Fig.1. It is composed of main two parts: the first and second parts are air flow and electric field domain.

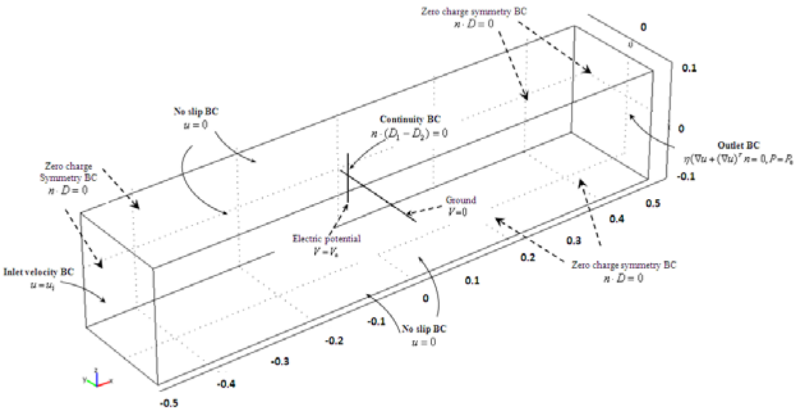

Fig.1. Computational model

Electrode wire is suspended from the upper wall of the duct and a ground wire is placed across the flow direction. In simulations, diameter of electrode and ground wires is 0.5 mm. Space charge densities (q_0) at the tip of electrode is considered from Griffiths [6], of which most of the corona current is collected at the wires. Position of ground wire is always fixed at x = 0 m and z = 0 m. While distance between electrode and ground wires are varied in the horizontal (*l*) directions and distance between electrode and ground in the vertical (*h*) direction is fixed at 1 cm. When focus of electrode number (*n*), n = 1 to 5 is installed across the flow direction.

2.1 Analysis of electric field in a channel flow

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:

$$\nabla \cdot \varepsilon \vec{E} = q \,, \tag{1}$$

$$\vec{E} = -\nabla V \,, \tag{2}$$

$$\nabla \cdot J + \frac{\partial q}{\partial t} = 0 \,, \tag{3}$$

$$J = qb\vec{E} + q\vec{u} \,, \tag{4}$$

where $\vec{E}$ is electric field intensity, q is the space charge density in the fluid, ε is dielectric permittivity (8.85×10^{-12} F/m), V is electrical voltage, J is current density, b is ion mobility (1.80×10^{-4} m^2/Vs), t is time and $\vec{u}$ is air flow velocity. The governing equation for computing the electric force per unit volume performing on fluid flow can be expressed as:

$$\vec{f}_E = q\vec{E} \,, \tag{5}$$

In Eq.(5), the electrophoretic force or Coulomb force results from the net uncharged within the fluid or ions injected from the electrodes.

2.2 Analysis of flow field in a 3-D rectangular duct

In simulations, the air is a single phase, the fluid physical properties are assumed to be constant and flow is incompressible. The continuity and Navier–Stokes equations which coupled with Coulomb force equation are expressed as:

$$\nabla \cdot \vec{u} = 0 \,, \tag{6}$$

$$\rho\left[\frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u}\right] = -\nabla\vec{P} + \mu\nabla^2\vec{u} + \vec{f}_E \,, \tag{7}$$

where P is pressure, μ is viscosity of air, and ρ is density of air (1.06 kg/m^3)

Pressure at the outlet boundary condition is considered with no viscous stress. This boundary condition specifies vanishing viscous stress along with a Dirichlet condition on the pressure,

$$\eta(\nabla\vec{u} + (\nabla\vec{u})^T \cdot n = 0 \ \text{ and } \ \vec{P} = \vec{P}_0 \,, \tag{8}$$

where η is dynamic viscosity (1.76×10^{-5} m^2/s), P_0 is atmospheric pressure and T is transpose of matrix.

The computational scheme is assembled in finite element model using a collocation method. The idea is to choose a finite-dimensional space of candidate solutions and a number of points in the domain and to select that solution which satisfies the given equation at the collocation points. In order to obtain a good approximation, a fine mesh is specified in the sensitive areas. This study provides a variable mesh method for solving the flow and electric field problem. The equations are solved by using COMSOL. Lagrange quadratic element is chosen as the basic functions with triangular shapes. The system of governing equations is solved with the unsymmetrical multi-frontal method. This convergence test leads to the mesh with approximately 40,000 elements.

3. Results and discussion

In simulations, the uniform inlet air velocity, u_i is 0.10 m/s and the electrical voltage at electrode tip, V_0 is applied at 20 kV

3.1 Analysis of single electrode in a 3-D rectangular duct

Fig.2 shows electric field from single electrode, the gap (l) in the horizontal direction is varied while the elevation (h) in the vertical direction is fixed at 1 cm. For the boundary condition of electric field, space charge density at duct wall is equal to zero. Figure 2 (a) - (d) shows the electric field. It can be seen that the electric fields move outwardly from electrode wire to ground wire and concentrate at both electrode tip and ground wire. When the gap is closer, electric field is more concentrated. On the other hand, when the gap is longer, electric field intensity decreasingly concentrates.

Fig.3 shows the sizes of swirling flow in various gaps. When the gap (l) becomes larger, the bigger swirling flow presents. This is because the electric force performs on fluid with longer distance. In Fig.3 (d), swirling flow is not presented due to low shear flow. As shown in Fig.4, adjusting the electrode location affects the flow velocity which is represented as the maximum velocity field ratio ($u_r = u_{max}/u_i$) and vorticity (ω). It can be seen that u_r and ω are inversely proportional to square of gap, i.e. $u_r \propto l^{-2}$ and $\omega \propto l^{-2}$, respectively. It means when the gap (l) becomes closer, the maximum velocity field and vorticity become higher.

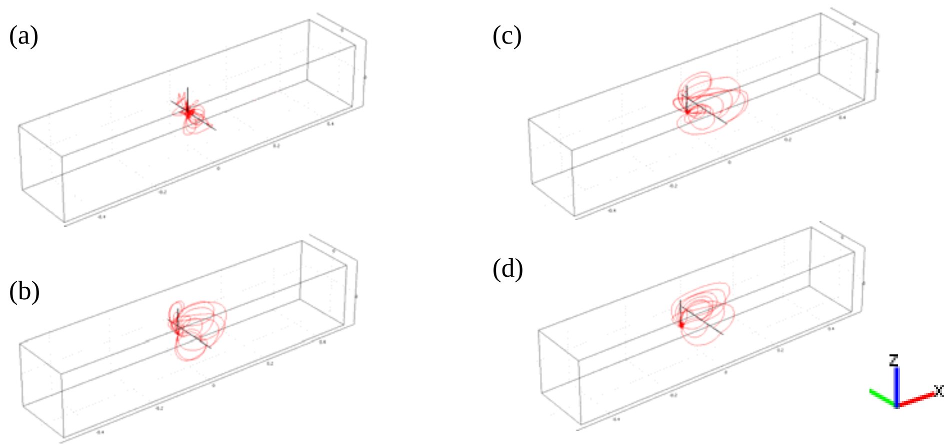

Fig.2 Electric field in various l when h = 1 cm (a) l = 2 cm; (b) l = 4 cm; (c) l = 6 cm; (d) l = 8 cm

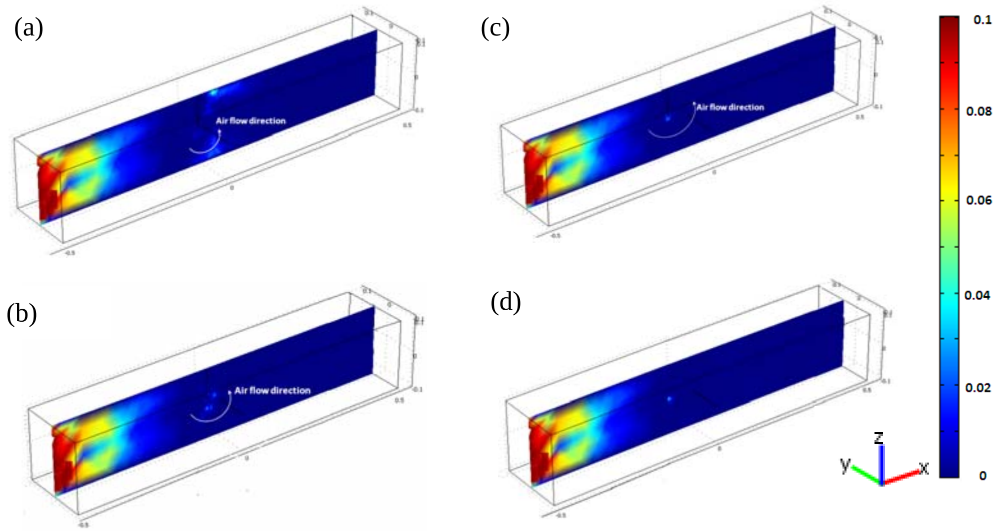

Fig.3 Swirling flow in various *l* when *h* = 1 cm (a) *l* = 2 cm; (b) *l* = 4 cm; (c) *l* = 6 cm; (d) *l* = 8 cm

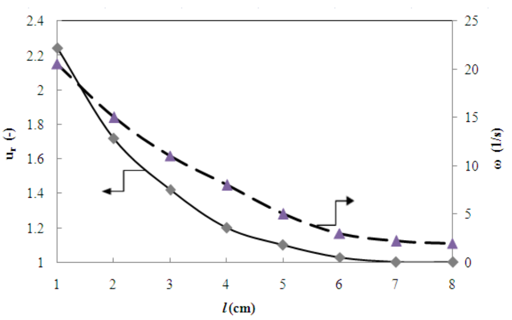

Fig.4 The maximum velocity ratio (u_r) and vorticity (ω) in various *l*

3.2 Analysis of multiple electrodes in a 3-D rectangular duct

In order to investigate the effect of multiple electrodes on electric field and fluid flow, the elevation (*h*) and gap (*l*) are fixed at *h* = 1 cm and *l* = 4 cm, respectively.

The pattern of electric fields created by multiple electrodes is shown in Fig.5. Increase of the electrode number (*n*) increases the magnitude of the electric field intensity. Due to high gradient of electrical voltage, the maximum magnitude of electric field intensity takes place between electrode and ground wires.

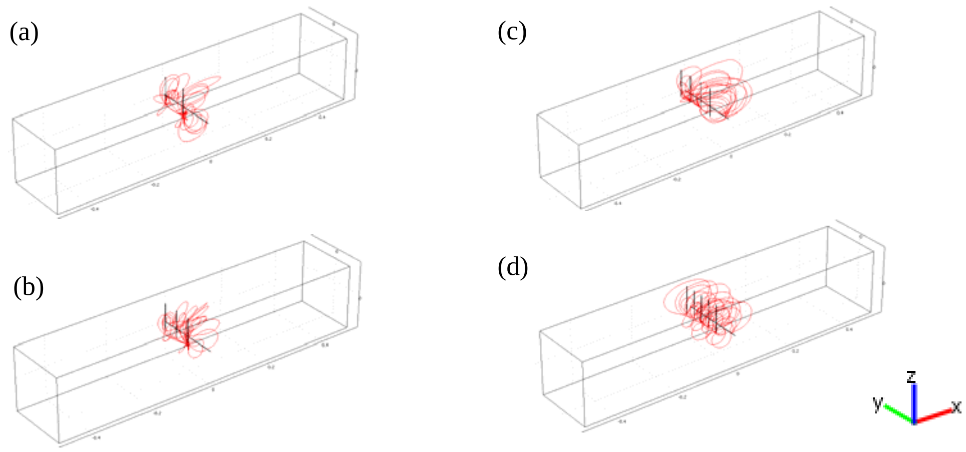

Fig.5 Electric field in various n when h = 1 cm and l = 4 cm (a) n = 2; (b) n = 3; (c) n = 4; (d) n = 5

Swirling flow with various electrode numbers is presented in Fig.6. The swirling flow becomes stronger when the electrode number (n) is increased. Fig.6 (a) shows swirling flow on y-z plane when n = 2. Three swirling flows are appeared between electrode and ground zone. Two big swirling flows and a small swirling are appeared near electrode wires. Fig.6 (b) shows swirling on x-z plane when n = 5. It can be indicating that swirling flow disturbs the region behind the ground wire and it causes flow to be more violent. In addition, when the electrode number is increased, swirling is wider, resulting in enhancement of momentum transfer in fluid flow.

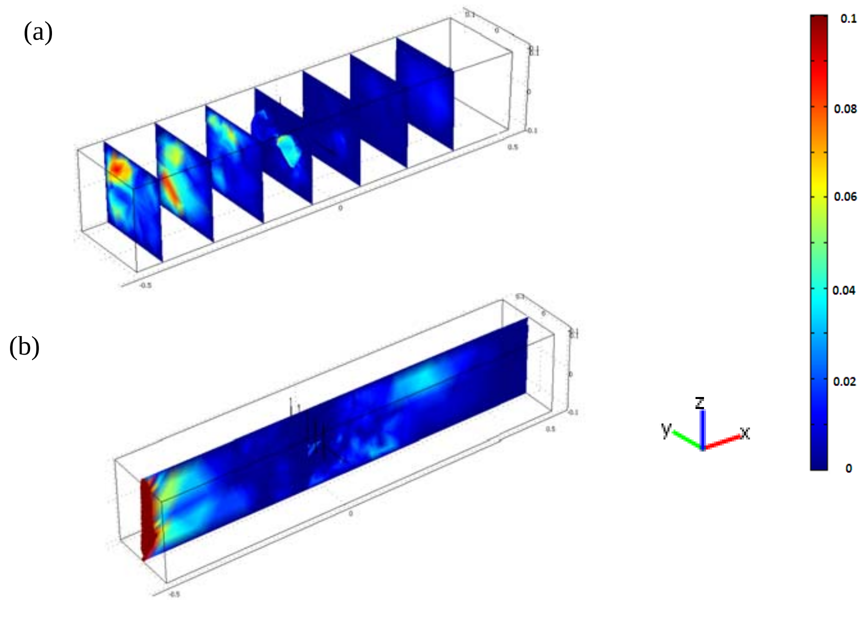

Fig.6 Swirling flow in various n when h = 1 cm and l = 4 cm (a) n = 2; (b) n = 5

Fig.7 shows effect of gap (l) on fluid velocity, Similar to single electrode case, it can be seen that u_r is inversely proportional to square of gap, i.e. $u_r \propto l^{-2}$. And also, the u_r, is varied with the electrode number (n). Fig.8 shows that the vorticity gradually increases when the electrode number increases. But when increasing the gap, swirling is weaker.

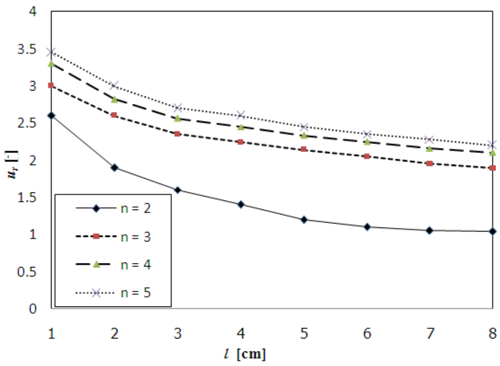

Fig.7 The maximum velocity ratio (u_r) in various l and n

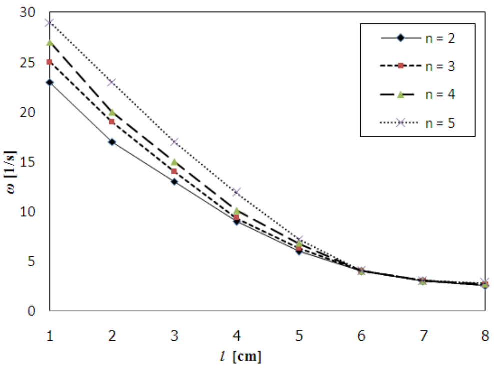

Fig.8 Vorticity (ω) in various l and n

4. Conclusion

Numerical simulation is carried out to investigate the influences of the electrode arrangements and the electrode number on fluid flow in the 3-D rectangular duct. The conclusions are obtained as follow:

(1) With smaller distance between electrode wire and ground wire, Coulomb force becomes stronger, resulting in higher strength of vorticity. Inversely, when the gap (l) is larger, swirling flow is wider but weaker.

(2) When the electrode number increases, electric field intensity increases. This causes the gradient of electrical voltage to be more increased. Consequently, swirling flow becomes stronger.

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