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Numerical investigation of electro hydrodynamics (EHD) enhanced water evaporation using Large Eddy Simulation turbulent model

Ghassem Heidarinejad*, Reza Babaei

Faculty of Mechanical Engineering, Tarbiat Modares University, PO Box 14115-143, Tehran, Iran

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ABSTRACT

In this paper, the electric field effect on enhancement of the water evaporation rate in a channel is numerically investigated. The coupled equations of electrical field, flow field, temperature field and species concentration fields are discretized using Finite Volume Method (FVM) and the implicit/hybrid difference form. This equations are solved via SIMPLE algorithm and the Kaptsov hypothesis. The turbulent flow is modelled by Large Eddy Simulation (LES). The numerical results show that the water evaporation rate is increased with the presence of electric field, but the effect of electric field is diminished at high Reynolds number.

1. Introduction

Applying electric field is a novel drying technique for enhancement of water evaporation rate. Electro-hydrodynamic enhanced (or EHD-enhanced) drying is a non-thermal drying technique which leads to low energy consumption as well as savings of costs [1,2]. To practice this, a high DC voltage is applied between two electrodes by a fine wire. It induces a secondary air flow (corona wind) between wetted surface and its ambient air. The secondary flow can enhance level of heat and mass transfer with producing turbulent flow [2,3].

Due to the complexity of the interactions among electric field, turbulent flow field, temperature field, and moisture concentration fields, previous studies concerned with the enhancement of heat and mass transfer using electric field were mostly investigated by experiments [4,5]. The food drying as one of the applications of EHD-enhanced mass transfer has been the subject of many studies, for example potato [6], apple [7], biomass [8] and mushroom [9].

Kasayapanand and Kiatsiriroat [10] investigated a numerical study of the effect of electrode arrangements on the characteristics of heat transfer enhancement in a wavy channel. They showed that local heat transfer coefficient decreases with increasing in Reynolds number or increasing in the distance between the wire electrodes and the wall surface. Lakeh and Molki [11] experimentally and numerically investigated the effect of EHD enhancement heat transfer on natural convection in a circular tube. They revealed that increasing of applied voltage causes significant augmentation of the heat transfer enhancement up to 8.7 times in comparison with the cases without electric field. Ahmedou and Havet [12] reported a numerical study of EHD-enhanced forced convection based on the couplings between a non-isothermal turbulent flow and electric field. They also studied the effect of some parameters such as the distance between electrodes and grounded plate, wire radius, arrangement of wires and applied voltage on the flow pattern and the convective heat transfer enhancement in a channel. They showed that the variation of wires distance away from the grounded plate causes different formation of secondary flows and has an important role in the heat transfer enhancement. Alamgholilou and Esmaeilzadeh [13] presented an experimental study on the cooling of the rectangular ribs established on the floor of a rectangular duct. They observed that the corona wind can enhance the heat transfer up to four times by increasing the applied voltage. Deylami et al. [14] investigated a numerical analysis of EHD-enhanced heat transfer for a fully developed turbulent flow using k–ε turbulence model. Their results indicated that different electrode and wire arrangements has a significant effect on the number of induced vortices and the size of the recirculating zones. They also showed

* Corresponding author.
E-mail addresses: gheidari@alum.mit.edu, gheidari@modares.ac.ir (G. Heidarinejad).

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the corona wind in low Reynolds number is more effective to enhance heat transfer. Lai et al. [15] presented an experimental study on enhancement of evaporation from a water surface using corona wind in a rectangular wind tunnel. According to their results, corona wind has a great enhancement effect on the water evaporation rate, but its effectiveness diminishes by increasing air flow velocity. Huang and Lai [16] conducted a two-dimensional numerical simulation of EHD-enhanced water evaporation based on the stream function and vorticity transport equation. They also showed the variation of Sherwood number as a function of the EHD Reynolds number and reported a good agreement between numerical simulation and experimental data.

Many experimental studies were conducted on EHD enhanced heat transfer. Although some numerical studies have recently been conducted on EHD-enhanced heat transfer (natural and forced convection), but a few numerical studies have been investigated on EHD enhanced mass transfer (water evaporation). The main objective of this study is the modeling of the effect of the corona wind on Water evaporation enhancement and the solving of governing equations by the computational fluid dynamics (CFD). Afterwards, the numerical results are validated using experimental measurements. Finally, we discuss on the flow pattern induced by the electrical force and the enhancement of the mass transfer.

2. Governing equations

To obtain governing equations, the following assumptions are used.

1. It is assumed that the fluid thermo-physical properties are constant, and are considered at the average temperature between the inlet air temperature and the water temperature.
2. The system is isolated and no heat transfer through walls.
3. It was assumed that the air is an incompressible gas.

2.1. Electric field equations

The governing equations for the electric body force per unit volume are expressed as [17]:

$$\vec{F}_e = \rho_c \vec{E} - \frac{1}{2}\vec{E}^2 \nabla\varepsilon + \frac{1}{2}\nabla\left[\vec{E}^2 \rho\left(\frac{\partial\varepsilon}{\partial\rho}\right)\right] \quad (1)$$

The first term on the right of Eq. (1), is the electrophoretic force (Coulomb force) that produces corona wind and it is dominant in heat and mass transfer applications. The second and third terms represent the dielectrophoretic force and electrostriction force. For incompressible fluids, the third term in this equation (electrostriction force) becomes negligible. In this work, the air and the water are incompressible fluids. Thus, electrostriction force is omitted from the calculations. The second term (dielectrophoretic force) depends on the permittivity gradient. The permittivity gradient is produced by variations in temperature of fluid and also inhomogeneity of the fluid (two-phase). The effect of variations in temperature is negligible at room temperature. Thus the effect of inhomogeneity of the fluid becomes important. The water in the zone water is homogeneous. Because the water vapor has no significant effect on the air properties, the air in the zone air is almost homogeneous (spatially constant properties). Thus, the density and permittivity are assumed constant for the air [17]. But Phase change in water-air interface is not negligible. Phase change in water-air interface produces a surface charge density (ρ_s). The surface charge density produced by phase change in water-air interface is incorporated into the Coulomb force and produces a surface force in water-air interface. Hence, the electric body force is simplified to the Coulomb force. The EHD governing equations are calculated by the following relations.

Maxwell equation (Poisson's equation) is given by:

$$\nabla^2 V = -\frac{\rho_c}{\varepsilon} \quad (2)$$

The electric field strength is defined by:

$$\vec{E} = -\nabla V \quad (3)$$

Current continuity equation is calculated as following:

$$\frac{\partial\rho_c}{\partial t} + \nabla\cdot\vec{j} = 0 \quad (4)$$

Ohm's law is given by:

$$\vec{j} = \rho_c b\vec{E} + \rho_c\vec{u} - D_e\nabla\rho_c \quad (5)$$

The three terms in Eq. (5) are drift, convection and diffusion currents, respectively. The ratio of the diffusion to the electric drift is proportional with the Debye length (λ_D), which is of the order of several nanometers. Thus the diffusion term is omitted from the calculations [17].

Moreover, by Combining in Eqs. (2)–(5), the following equation is obtained:

$$\nabla\rho_c\cdot(b\vec{E} + \vec{u}) + b\frac{\rho_c^2}{\varepsilon} = 0 \quad (6)$$

In above equation, $\vec{E}$ is the electric field strength, ε is electric the permittivity of the fluid, ρ is the flow density, ρ_c is the electric charge density, V is Electric potential, b is the mobility of ions in an electric field, and $\vec{u}$ is air velocity vector. The two terms of the Eq. (5) are drift (ion motion by electric field) and convection (ion motion by air flow), respectively. The air velocity vector in the Eq. (5) provides the coupling between the flow field and electric field. To determine the Coulomb force, the Eqs. (2), (3) and (6) are solved simultaneously.

2.2. Flow field and energy equations

The governing equations for the flow field are the continuity equation and the momentum equations (Navier–Stokes equations) in x, y and z directions.

Continuity:

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (7)$$

Momentum:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\bar{S}_{ij}\right] + F_{ei} \quad (8)$$

$$F_{ei} = \rho_c E_i \quad (9)$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho c_p T) + \frac{\partial}{\partial x_j}(\rho c_p u_i T) = \frac{\partial}{\partial x_j}\left[\left(K + \frac{\mu_t c_p}{Pr_t}\right)\frac{\partial T}{\partial x_j}\right] + F_{ev} \quad (10)$$

$$F_{ev} = \frac{\partial}{\partial x_j}\left[\rho D_v\left(c p_g T\right)\frac{\partial m_v}{\partial x_j}\right] \quad (11)$$

In Eq. (8), F_{ei} represents the electric body force (Coulomb force),