Energy Conversion and Management 50 (2009) 287–296

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Enhanced heat transfer in partially open square cavities with thin fin by using electric field

N. Kasayapanand [a,*], T. Kiatsiriroat [b]

[a] School of Energy, Environment, and Materials, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand
[b] Department of Mechanical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand

ARTICLE INFO

Article history:
Received 25 December 2006
Accepted 20 September 2008
Available online 1 November 2008

Keywords:
Heat transfer enhancement
Cavity
Natural convection
Electrohydrodynamic
Fin

ABSTRACT

Numerical modeling of the electric field effect on the natural convection in the partially open square cavities with thin fin attached is investigated. The interactions among electric, flow, and temperature fields are analyzed by using a computational fluid dynamics technique. It is found that the flow and heat transfer enhancements are a decreasing function of the Rayleigh number. Moreover, the volume flow rate and heat transfer coefficient are substantially improved by electrohydrodynamic especially at low aperture size, high aperture position, and high inclined angle. Surprisingly, the maximum convective heat transfer is obtained at the minimum electrical energy consumption by placing electrodes at a suitable position. The optimum electrode arrangements for both single fin and multiple fins are also achieved.

1. Introduction

The open cavities are encountered in various engineering systems, such as solar thermal receivers, solar collectors, etc. Laminar natural convection heat transfer in the open cavities has received a sustained attention by various researchers that we will briefly review [1–5]. Le Quere et al. [1] presented thermally driven natural convection in the open cavities. Penot [2] conducted a similar problem using vorticity-stream function technique. Chan and Tien [3] studied the open square cavities, which had an isothermal vertical heated side facing the opening and two adjoining adiabatic horizontal sides. Abib and Jaluria [4] investigated the partially open enclosures having all sides insulated with a heat source at the bottom of the left wall and a partially open at the right wall. Bilgen and Oztop [5] presented the partially open square cavities in which the side facing the opening was heated by constant temperature and two adjoining walls were insulated. There are many applications in the finned cavities, such as ventilating in building, uncovered solar collectors having vertical strips, heat exchangers, electronic cooling devices, etc. Relating studies of the natural convection in the cavities with fin attached on the wall are conducted in the heat transfer literatures [6–9]. However, the heat transfer limit of this passive technique is depended on the fin efficiency, moreover, the heat trap may be occurred at a gap between the fins.

The technique of convective heat transfer utilizing electric field or electrostatic force from the polarization of a dielectric fluid is one of the more promising methods for enhancing heat transfer because of its many advantages. The method is easily implemented, for example, using only a transformer and electrodes, it consumes only a small amount of electric power. This technique is frequently called electrohydrodynamic (EHD) heat transfer, and it refers broadly to an interdisciplinary field dealing with the interactions between electric, flow, and temperature fields. In a typical gaseous medium, energy is transferred from free electrons to the gas molecules, and the latter move toward a grounded surface to increase the heat transfer coefficient. There exist some prior studies related to this use of EHD. Yabe et al. [10] investigated the phenomenon of a corona wind between wire and plate electrodes and found that the interaction between ionic wind and primary flow increased the heat transfer from a wall surface. Velkoff and Godfrey [11] studied heat transfer over a horizontal flat plate using parallel wire electrodes. The ionic wind promoted mixing of the primary flow, resulting in an increase of the heat transfer coefficient. A computational method applied to an electrostatic precipitator was reported by Yamamoto and Velkoff [12]. Tada et al. [13] presented the fundamental mechanism of heat transfer augmentation in a two-dimensional rectangular duct. Shu and Lai [14] investigated the buoyancy-induced flows in an enclosure under effect of electric field. The oscillatory flow generated by electric field was revealed by Lai et al. [15]. Lai [16] also presented the buoyancy effect on EHD augmented forced convection in horizontal channel. The effect of non-symmetric electric field on the EHD enhanced natural convection in an enclosure was involved by Tan and Lai [17]. Kasayapanand [18] conducted the corona wind augmented heat transfer inside the enclosure with the optimum electrode arrange-

---

* Corresponding author. Tel.: +66 0 2470 8699; fax: +66 0 2427 9062.
E-mail address: nat.kas@kmutt.ac.th (N. Kasayapanand).

0196-8904/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2008.09.031

Nomenclature

AR	aperture size (a/H)
AH	aperture position (b/H)
c_p	specific heat, J/kg K
D_e	charge diffusion coefficient, m^2/V s
$\boldsymbol{E}$	electric field strength, V/m
f	roughness factor, V/m
$\boldsymbol{F}_E$	electrohydrodynamic body force, N/m^3
$\boldsymbol{g}$	acceleration due to gravity, m/s^2
Gr	Grashof number
h	heat transfer coefficient, W/m^2 K
H	cavity height, m
$\boldsymbol{J}$	current density, A/m^2
k	thermal conductivity, W/m K
l_w	length of wire electrode, m
n	normal direction, m
N	number of electrodes
Nu	Nusselt number
P	pressure, N/m^2
Pe	Peclet number
Pr	Prandtl number
q	electric charge density, C/m^3
Q	volume flow rate
r	corona wire radius, m
Ra	Rayleigh number
Re	Reynolds number
t	time, s
T	temperature, K
$\boldsymbol{v}$	fluid velocity, m/s
$\boldsymbol{u}_e$	electric characteristic velocity, m/s
V	voltage, V
W	cavity width, m

Greek symbols

α	thermal diffusivity, m^2/s
β	volume expansion coefficient, 1/K
ε	fluid permittivity, F/m
μ	dynamic viscosity, kg/m s
ν	kinematics viscosity, m^2/s
θ	inclined angle, degree
ρ	density, kg/m^3
σ_e	electrical conductivity, 1/ohm m
τ	period
$\boldsymbol{\omega}$	vorticity, 1/s
ψ	stream function, m^2/s

Subscripts

0	without the electric field
P	at the grounded plate
m	mean value
w	wall surface

ment by computational fluid dynamics technique. All previous literatures of EHD are focused on the heat transfer enhancement on a flat surface just enclosure or channel. It can be found that there is no literature relating with the EHD effect on the open cavity or the finned attached, which is useful for many engineering applications. Thus, it intends to take an advantage if the heat transfer is doubly enhanced by coupling between passive (fin attached) and active (EHD) techniques, which has been investigated in this present study.

This numerical work conducts the electrostatic forces exerted on natural convection inside the open square cavities with thin fin attached. The governing equations of EHD phenomenon are formulated and the mathematical modeling has been carried out to analyze the EHD-enhanced secondary flow and heat transfer coefficient in two dimensions via a computational fluid dynamics technique. The wire electrodes are installed across the computational domain. The characteristics of flow and heat transfer are discussed as the parameters of Rayleigh number, supplied voltage, electrode arrangement, aperture size, aperture position, and inclined angle.

2. Theoretical analysis

The governing equations for the EHD force per unit volume $\boldsymbol{F}_E$ generated by an electric field of strength $\boldsymbol{E}$ in a fluid having electric charge density q, dielectric permittivity ε, density ρ, and uniform temperature T can be expressed as [19]

$$\boldsymbol{F}_E = q\boldsymbol{E} - \frac{1}{2}\boldsymbol{E}^2\nabla\varepsilon + \frac{1}{2}\nabla\left[\boldsymbol{E}^2\left[\frac{\partial\varepsilon}{\partial\rho}\right]_T\rho\right]. \quad (1)$$

In the symbolic notation, vectors are designated by bold-faced letters, while scalars are denoted by italic letters. The first term on the right $q\boldsymbol{E}$ is the Coulomb force exerted by the electric field upon the free charge or electrophoretic component, while the second and the third terms correspond to the dielectrophoretic and electrostrictive forces on and within the fluid. Eq. (1) is then included in the Navier–Stokes equation. By assuming an incompressible fluid, the conservation of momentum is given by

$$\rho\frac{d\boldsymbol{v}}{dt} = \rho\boldsymbol{g}_i + \boldsymbol{F}_E - \nabla P + \mu\nabla^2\boldsymbol{v}. \quad (2)$$

The vector $\rho\boldsymbol{g}_i$ is the gravitational force per unit volume, P is the local fluid pressure and the last term on the right hand side of the equation represents the viscous terms. Introducing the vorticity $\boldsymbol{\omega}$ as

$$\boldsymbol{\omega} = \nabla \times v, \quad (3)$$

to get the vorticity transport equation in two dimensional flow, the momentum equation can be rewritten in terms of the vorticity defined above, such that

$$\frac{\partial\boldsymbol{\omega}}{\partial t} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{\omega} = \nu\nabla^2\boldsymbol{\omega} - (\boldsymbol{E}\times\nabla)q - \beta(\boldsymbol{g}_i\times\nabla)T. \quad (4)$$

Defining the stream function (ψ) as

$$v = \nabla \times (\psi\boldsymbol{e}_z), \quad (5)$$

the vorticity transport equation can be obtained from Eqs. (4) and (5), which further gives

$$\nabla^2\psi = -\boldsymbol{\omega}. \quad (6)$$

Without any viscous dissipation effect, the energy equation can be written as

$$\frac{dT}{dt} = \alpha\nabla^2 T + \frac{\sigma_e\boldsymbol{E}^2}{\rho c_p}. \quad (7)$$

Gauss's law for the electric field is as follows

$$\nabla\cdot\varepsilon\boldsymbol{E} = q, \quad (8)$$

where the field $\boldsymbol{E}$ is given by

$$\boldsymbol{E} = -\nabla V. \quad (9)$$