International Journal of Heat and Mass Transfer 102 (2016) 544–554

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Optimization of mixed convection heat transfer with entropy generation in a wavy surface square lid-driven cavity by means of Taguchi approach

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ARTICLE INFO

Article history:
Received 8 May 2016
Received in revised form 11 June 2016
Accepted 20 June 2016

Keywords:
Mixed convection
Nanofluid
Richardson number
Taguchi method
Lid-driven cavity

ABSTRACT

The optimum conditions of the mixed convection heat transfer in a wavy surface square cavity filled with Cu–water nanofluid by utilizing the Taguchi method is presented. The governing equations are first discretized by applying a finite volume method and then solved using SIMPLE algorithm. In the Taguchi method, the performance parameter is assumed to be the Nusselt number on the wavy surface. An L_{16} (4^3) orthogonal array is considered as an experimental plan for the design parameters. Also, the entropy generation on the wavy surface is examined. The effects of sundry parameter such as the volume fraction of Cu particles, the Nusselt number and the wavelength of the wavy surface on the flow and temperature fields are investigated. It is found that, in a given Richardson number, increasing of the wavelength of the wavy surface decreases the mean Nusselt number and the entropy generation. It is also observed that the case with $\Phi = 2\%$ and $\lambda = 0.25$ at the Richardson number of 0.01 is the optimum design for the heat transfer. The analysis of the Taguchi method leads the optimization process to achieve the maximum Nusselt number (maximum heat transfer) for the designed wavy surface square cavity.

1. Introduction

Mixed convection heat transfer in cavities has important applications in engineering systems, such as heat exchangers, solar collectors, cooling of electronic devices, chemical processing equipment, double pane windows, cooling of nuclear reactors, and food industries [1,2]. Some fluids are used for industrial purposes, have a low thermal conductivity. In order to increase the thermal conductivity of such kinds of fluids, some nanoparticles like AL_2O_3, Cu and TiO_2 are considered [3]. As a result the final combination of the base fluid and nanoparticles become nanofluid [4–6]. In recent years, many studies on the mixed convection flow and heat transfer in cavities with different shapes are investigated. The effects of the physical parameters on convective heat transfer have been investigated by many researchers. For example, Selimefendigil and Oztop [7] have performed a numerical study on mixed convection in a multiple ventilated cavity. Results showed that the heat transfer rate is affected by the deviations of Reynolds, Grashof and Strouhal numbers. A numerical investigation analyzing the mixed convection heat transfer in a lid-driven cavity with a sinusoidal wavy bottom surface has done by Al-Al-Amiri et al. [8]. They found that the mean Nusselt number increases with an enhancement in both the amplitude of the wavy surface and the Reynolds number. A steady-state free convection within a cavity, which was composed of two horizontal walls and two vertically bent-wavy walls, has numerically studied by Misirlioglu et al. [9]. In their study, the cavity was filled with a fluid-saturated porous medium. Anupindi et al. [10] have carried out lattice Boltzmann method to simulating flow in a lid driven cubic. Cheng and Liu [11] have done a numerical study to investigate the effects of effective parameters on the flow characteristics and heat transfer within a cavity with motion of the cooled upper lid. They found that heat transfer does not effect by enhance of inclination angle when the flow is in a forced convection dominated regime. Mehrez et al. [12] have performed a numerical study on mixed convection and entropy generation of nanofluids flow in an open cavity heated from below with uniform temperature. They concluded that by increasing of Reynolds number, Richardson number and volume fraction of nanoparticles, the heat transfer and the entropy generation increase. Rahman et al. [13] have done a numerical study on combined convection in an open channel with a square cavity. Results showed that flow field does not affect by length of heater for higher values of Hartmann number. Sivasankaran et al. [14] carried out a numerical study on the mixed convection in an inclined

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.056
0017-9310/

Nomenclature

C_p	specific heat (J kg^{-1} K^{-1})
Ec	Eckert number
g	gravitational acceleration (m s^{-2})
H	height of the cavity (m)
k	thermal conductivity (W m^{-1} K^{-1})
Nu_W	local Nusselt number, $Nu_W = \frac{hW}{k_{bf}}$
p	pressure (N m^{-2})
P^*	dimensionless pressure
Pr	Prandtl number
q''_0	heat flux (W m^{-2})
Ri	Richardson number
Re_W	Reynolds number, $Re_W = \frac{\rho_{bf} U_0 W}{\mu_{bf}}$
S	entropy generation (W m^{-3} K^{-1})
T	temperature (K)
T_L	low temperature (K)
u, v	velocity components along x-axis and y-axis, respectively (m s^{-1})
u^*, v^*	dimensionless of velocity component
W	width of the cavity (m)
x, y	x-axis and y-axis coordinates, respectively
x^*, y^*	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity, k ρ^{-1} cp^{-1} (m^2 s^{-1})
α_w	amplitude of the wavy surface
β	thermal expansion coefficient (K^{-1})
Φ	nano-particle volume fraction (%)
θ	dimensionless temperature
λ	wavelength of the wavy surface
μ	dynamic viscosity (Pa s)
υ	kinematics viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Subscripts

bf	base fluid
p	particle
nf	nano-fluid
s	surface

lid-driven cavity with discrete heating. Their results showed that the maximum heat transfer occurs at the inclination angle of 30° when the heater is located at the middle of the cavity. Purusothaman et al. [15] have done a 3-D numerical investigation on natural convection heat transfer in a cubical cavity caused by a thermally active plate under the presence of external magnetic field. They concluded that the heat transfer rate is powerfully repressed by the X and Y directional magnetic fields. Marchi et al. [16] investigated the problem of the heat transfer and flow inside a square cavity whose lid was movable and had a constant velocity. Their results were presented for 42 different Φ and their estimated discretization errors (U) were provided for a grid of 1024×1024 nodes and the Reynolds numbers (Re) of 0.01, 10, 100, 400 and 1000. Khorasanizadeh et al. [17] investigated the mixed convection and entropy generation of Cu–water nanofluid and pure water in a square lid-driven cavity. They found that for both the pure fluid and the nanofluid, increasing of the Reynolds number increases the mean Nusselt number, linearly. Alipanah et al. [18] studied the entropy generation due to irreversible heat transfer and fluid friction in a square cavity under different side wall temperatures and for compressible and incompressible natural convection flows. Their results showed that the entropy generation for the compressible flow is more than the incompressible flow. A 3-D investigation on the heat and mass transfer for the flow of a nanofluid between two parallel rotating plates with considering of magnetic effects has been performed by Mohyud-Din et al. [19]. The results revealed that the thermophoresis and Brownian motion parameters are directly related to heat transfer; however, they are inversely related to concentration profile. A numerical study on the flow and heat transfer of nanofluid in an asymmetric channel with expanding and contracting walls suspended by carbon nanotubes has been performed by Ahmed et al. [20]. They found that the nanoparticle volume fraction ϕ affects the velocity and temperature profiles and the heat transfer rate at walls considerably. An analysis on the heat transfer of nanofluids in stretchable convergent/divergent channels has been performed by Mohyud-Din et al. [21]. The results revealed that increasing the nanoparticle volume fraction reduces the temperature profile. Also, in the case of diverging channels, they found that using a magnetic field can control the possible separation caused by the backflows. An investigation on the heat and mass transfer of a viscous incompressible fluid in converging and diverging channel with chemical reaction has been done by Khan et al. [22]. The results showed that the fluid temperature enhances for the diverging channel case but reduces for converging channel due to increasing the opening angle. Also, some most relevant investigations can be seen in [23–27] and several therein.

According to the literature review and to the best knowledge of the authors, a numerical investigation on optimization of effective parameters on the mixed convection heat transfer in a wavy square cavity filled with nanofluid has not yet been reported. So the innovation in the study is to investigate the mixed convection heat transfer in a square cavity with a wavy wall under a constant heat flux (hot wall) along with entropy generation. The Taguchi method is used to investigate three effective parameters that affect the heat transfer rate, and finally the optimum geometry is obtained which maximizes this quantity. The effects of the Cu nano-particles volume fraction, the various wavelengths of the wavy wall and the Richardson number (0.01 to 100) on the flow streamlines, isotherm distribution and the mean Nusselt number are investigated by using L_{16} (4^3) orthogonal Taguchi array.

2. Formulation of the problem

The schematic of the geometry in which a square cavity with a hot wavy wall under a constant heat flux and a cold flat wall with a constant temperature is investigated as shown in Fig. 1. The flat walls are insulated, while the upper wall is considered to be movable and with a constant velocity of U_0.

The wavy wall is simulated using the following non-dimensional cosine function [28]:

$$x^* = \alpha_w \left[1 - \cos\left(\frac{2\pi y^*}{\lambda^*} \right) \right], \tag{1}$$

where, x^* and y^* are the non-dimensional coordinates in x- and y-axis directions, α_w is the amplitude of the wavy wall and λ^* is the non-dimensional wavelength. The fluid in the cavity is assumed to be Cu–water nanofluid. To obtain the flow and temperature fields