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Original Research Paper

Experimental investigation of nanofluid free convection over the vertical and horizontal flat plates with uniform heat flux by PIV

R. Parizad Laein, S. Rashidi, J. Abolfazli Esfahani *

Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad 91775-1111, Iran

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ABSTRACT

This paper applies the particle image velocimetry (PIV) to measure the laminar boundary layer thickness of TiO_2–water nanofluid free convection over the vertical and horizontal flat plates with constant heat flux. The results are presented for two values of heat flux strength equal to 3000 and 7000 w/m^2. The effects of nanoparticles and heat flux strength on the boundary layer thickness and velocity profiles are investigated in details. Finally, a comparison is performed between the experimental, theoretical and numerical results for different conditions. The obtained results revealed that the velocity boundary layer decreases by adding the nanoparticles to the base fluid. These reductions, at $\phi = 0.1\%$, are in the vicinity of 7.5% and 5.2% for $q'' = 3000$ and 7000 wm^{-2}, respectively. Also, the maximum reductions in the vertical velocity component by adding the nanoparticles at $\phi = 0.1\%$ are in the vicinity of 4% and 3.3% for $q'' = 3000$ and 7000 wm^{-2}, respectively.

1. Introduction

Particle image velocimetry (PIV) is an essential measurement technique to measure instantaneous velocity and related properties in fluids. This technique can provide detailed qualitative and quantitative information of flow structure. Progress in laser technologies and electronic imaging systems provided many contributions for this technique in fluid mechanics laboratories. Some of these contributions are swirling flows, spray dryers, burners, chemical processing plants, turbulence flows, etc. An application of PIV is in the field of nanofluids. The measurement of boundary layer in nanofluids has gained vast interest among researchers because which can help to realize the effects of nanoparticle on flow and heat transfer characteristics.

Some researchers used PIV for natural convection flows. For example, natural convection in a differentially heated cavity has been studied by Corvaro and Paroncini [7]. The cavity was heated by a hot strip and the effect of the position of this source on the natural convection heat transfer was investigated in details. The streamlines, the velocity maps and the velocity vector distributions at different Rayleigh numbers have been plotted by PIV techniques. They observed a movement of air developed inside the enclosure when the strip started to become warm. In another research, Corvaro et al. [8] investigated the natural convection within the enclosure with opposite heated and cooled walls. They applied PIV to obtain the details of the velocity field within the cavity. Also, the velocity was obtained by numerical method and the results were compared with the experimental results. They observed very good agreement between two results. Gandhi et al. [11] studied two-phase natural convection in rectangular tanks by CFD simulations and PIV measurements. They found that the total energy input rate decreases with decrease in the aspect ratio (ratio of length of heating tube to the liquid level in tank). Note that the velocity distribution of turbulent flow was calculated using discrete wavelet transform subjected to the PIV flow measurement. Butler et al. [6] analyzed the natural convection around a heated horizontal cylinder that was placed in a differentially heated square cavity. Also, PIV was applied to record the flow structures generated in this research. The computed results showed that the flow structures were greatly influenced by the temperature difference across the side walls. Natural convection flow in a differentially heated open channel has been studied by Sanvicente et al. [25]. They used PIV technique to investigate the mean velocity field and velocity fluctuations at different channel heights. They observed that the velocity profiles were partly superposed at mid-height in the channel but they were differed at the open boundaries. Biswas et al. [4] applied PIV technique during the natural convection with protruded heater on the non-heated lower wall of a rectangular enclosure. They obtained the effect of Rayleigh number on flow fields by PIV technique.

* Corresponding author.
E-mail address: abolfazl@um.ac.ir (J. Abolfazli Esfahani).

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Nomenclature

g	gravitational acceleration (m s^{-2})
Gr	Grashof number (–)
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
q''	heat flux (W m^{-2})
p	pressure (Pa)
Re	Reynolds number (–)
T	temperature (K)
x, y	rectangular coordinate components (m)
u, v	velocity components in x and y directions (m s^{-1})

Subscripts

f	base-fluid
p	particle

Greek symbols

ϕ	particle concentrations (–)
δ	boundary layer thickness (m)
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1}) $\nu = \mu/\rho$
ρ	density (kg m^{-3})

Some researchers studied the natural convection flow along a flat plate with different conditions [16,33]. For example, Siddiqa et al. [26] studied the natural convection flow over an inclined flat plate with internal heat generation and variable viscosity. They found that the rate of heat transfer decreases with increase in heat generation parameter for a high Prandtl number. Molla et al. [17] investigated the natural convection flow over an isothermal vertical flat plate with temperature-dependent viscosity and heat generation. This research indicated that the momentum and thermal boundary layers become thinner with increase in values of viscosity-variation parameter. Alzwayi and Paul [2] performed a numerical study on transition of free convection flow between two vertical plates with isothermal boundary conditions. They reported that the flow transition for the isothermal condition takes later than that in the adiabatic condition. In another research, the natural convection of non-Newtonian power-law fluids over an isothermal horizontal plate has been investigated by Guha and Pradhan [12]. They observed that the hydrodynamic boundary layer was influenced by the non-Newtonian nature of fluid.

Some researchers investigated the effects of nanofluid on free convection flow past a flat plate or other structures [10,1]. For example, Hamad et al. [13] discussed about magnetic field effects on free convection nanofluid flow over a vertical semi-infinite flat plate. They showed that the velocity profiles decrease with increase in magnetic parameter for a fixed value of the particle concentration. Aziz et al. [3] studied the free convection boundary layer nanofluid flow over a horizontal flat plate embedded in a porous medium. They reported that the local Nusselt number increases when the buoyancy forces become negligible. Dominguez et al. [9] studied the effects of nanofluids upon boiling by using particle image velocimetry. They reported that the magnitude of vorticity increases and the sign of it changes with increase in nanofluid concentration. Valipour et al. [29] discussed about Magnetohydrodynamics flow and convective heat transfer around a solid circular cylinder covered with a porous substrate. They applied the least square method to present two equations for the average Nusselt number [22,14,23,24].

The literature review showed that most of researches in PIV field are for internal flows such as natural flows in enclosure. Investigation of natural convection over a flat plate has many engineering and industrial applications include the semi-conductor wafers, storage of energy and electronic chips. In such applications, researchers try to develop a heating or cooling system. Utilizing the nanofluids could be a way for such development. As shown in this section, there are some researches about the effects of nanofluid on free convection flow past a flat plate but there is a lack of experimental data for such critical topic. Therefore, the present research focuses on the experimental investigation of free convection nanofluid flow over a flat plate by PIV.

2. Experiment part

2.1. Experimental setup

A design of free convection flow is needed to measure the velocities of nanofluids and the thickness of the boundary layer. The simplest way to create a laminar free convection flow on a flat plate is a surface with constant heat flux. A flat and thin electrical element is used as a heater to create a constant heat flux on the surface in this experiment. This element is placed on an opaque copper sheet with a thickness of 1 mm and dimensions of 10 × 15 cm. The space between the plate and heater is filled by silicone adhesive. Two cubes with dimensions of 10 × 30 cm and 30 × 10 cm (length × depth) are used for vertical and horizontal cases, respectively. Also, a dimmer has been used to provide different heat fluxes in heater. Glass particles with diameters of 50–100 μm are used as tracers for image velocimetry. Particles are stirred with a magnetic stirrer to better dispersion of particles within the fluid. The experiments are performed with a green laser with power of 200 mW. The schematics of different devices and setup of this experiment are shown in Fig. 1.

2.2. The basic principles of particle image velocimetry (PIV)

The basic principles of particle image velocimetry are very simple and consist of four general steps. These steps are shown at Fig. 2. First, the fluid should be seeded with particles to visualize flow for PIV purposes. These particles should be neutrally buoyant and small with respect to the flow phenomena for following the flow accurately. The cross section of experiment illuminates by a thin luminous plate with high resolution. Note that the illumination is usually provided by a laser light sheet in PIV. The illuminated plane in the particle-seeded flow is imaged by a camera with it's chip digital (charge coupled device (CCD)) in order to record the whole plane in focus. The final step is process analysis. This step consists of four sub-steps as following:

- Selection of interrogation areas or sub-images for analysis.
- Correlation analysis.
- Finding the displacement peak.
- Calculating the velocity vector and repeat for next set of sub-images.

2.3. Testing method

Experiments are performed for TiO_3–water nanofluid with two values of particle concentration ($\phi = 0$ and 0.1%) and heat flux strengths ($q'' = 3000$ and 7000 w/m^2). Here, $\phi = 0$ represents the