Experimental Thermal and Fluid Science 92 (2018) 326–345

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Whole field measurements to understand the effect of nanoparticle concentration on heat transfer rates in a differentially-heated fluid layer

S. Srinivas Rao, Atul Srivastava*

Department of Mechanical Engineering, Indian Institute of Technology Bombay, Powai 400076, Mumbai, India

ARTICLE INFO

Keywords:
Nanofluids
Natural convection
Differentially-heated fluid layer
Heat transfer rates
Interferometry

ABSTRACT

Experimental study on natural convection in a nanofluid-filled differentially heated cavity has been presented. Experiments have been conducted in an octagonal cavity with water and Al_2O_3/water-based dilute nanofluids of varying concentrations. A Mach Zehnder interferometer has been employed to record the projection data of convective field from four view angles (0, 45, 90 and 135°). The two-dimensional temperature fields determined through the quantitative analysis of the interferometric images have been employed to reconstruct the local field information using the principles of tomography. Results of the three-dimensional reconstructions clearly brought out the mechanisms of possible fluid movement in the differentially-heated cavity and its dependence on nanoparticle concentration. Near wall surface distributions of temperature fields as well as local Nusselt numbers indicated towards possible breakdown of large scale fluid structures into small length scale multiple roll-like circulatory loops at higher volumetric concentrations of dilute nanofluids. Local disturbances thus induced in the fluid layer due to the addition of nanoparticles resulted into better fluid mixing, which in turn led to an enhancement in the heat transfer rates with increasing concentration of nanofluids. Surface plots of Nusselt numbers obtained in the vicinity of the two thermally active walls of the cavity established an overall energy balance in the fluid layer.

1. Introduction

Ever since the inception of the concept of nano-meter sized metallic particles as the potential agent for achieving higher heat transfer rates was proposed by Choi et al. [1–3], the literature has seen an exponential growth in the number of studies reported. These studies include the ones that follow the numerical approach [4–7] as well as those based on experimental methods [8–12]. Irrespective of the approach followed, the primary interest has been to develop a fundamental understanding of the plausible reasons and/or mechanisms that play an important role in enhancing the heat transfer rates with nanofluids as the coolant medium. Of all the plausible mechanisms, phenomena such as Brownian motion, particle migration, alteration/disruption of thermal boundary have been believed to be the most prominent ones [13,14]. Considerable efforts have also been made to quantify the degree of enhancement in the heat transfer rates that can be achieved by varying parameters such as concentration, type and/or size of nanoparticles, choice of the basefluid, etc. These studies are particularly relevant in areas such as industrial sectors, power engineering, transportation, etc. [4–15].

The literature available in the field of nanofluids-assisted heat transfer processes reveals that the studies conducted under forced convection regime have reported a clear trend of enhancement in the heat transfer rates with increasing concentration of nanoparticles. For instance, Hwang et al. reported an enhancement of close to 8% in the heat transfer coefficient for a volume fraction of 3% of Al_2O_3 nanoparticles. The authors discussed the plausible roles of mechanisms such as particle migration, Brownian diffusion of heat through the dispersed nanoparticles, high energy transfer by nanoparticles etc. in enhancing the heat transfer rates [16]. Experimental works of Xuan and Li [17] quantified the level of enhancement in heat transfer coefficient in the context of compact heat exchanger with copper-based nanofluids. Experimental work of Wen and Ding [18] documented a substantial enhancement in heat transfer rates with γ-Al_2O_3 nanoparticles. Similar observations have also been reported in the works of Zhang et al. [19], Singh et al. [20], Sinha et al. [21], Sinha and Srivastava [22], Haridas et al. [23], Rajput and Srivastava [24].

In contrast to a wide range of studies reported under forced convection regime, literature on the usage of nanoparticles in natural convection-based heat transfer processes has been relatively limited. Moreover, a large scatter and contradiction with regard to the possible role of nanoparticles in affecting the heat transfer phenomenon is to be

* Corresponding author.
E-mail address: atulsr@iitb.ac.in (A. Srivastava).

https://doi.org/10.1016/j.expthermflusci.2017.12.001
Received 30 August 2017; Received in revised form 9 November 2017; Accepted 3 December 2017
Available online 07 December 2017

Nomenclature

a, b, c	constants
C	specific heat (J/kg K)
d	diameter
E	error
f	field parameter
g	gravitational acceleration (m^2/s)
H	height of test cavity (m)
k	thermal conductivity (W/m K)
K	number of iterations
L	length of the test cavity (m)
M	No. of view angles
n	refractive index
N	number of points
Nu	Nusselt number
O	convergence criteria
p	projection field
Ra	Rayleigh number
T	temperature (°C)
ΔT	temperature difference (K)
w	weighted function
x, y, z	coordinate axes

Greek symbols

β	thermal expansion coefficient (K^{-1})
μ	dynamic viscosity (N s/m^2)
ρ	density (kg/m^3)
α	thermal diffusivity (m^2/s)
η	relaxation factor
ε	fringe shift
ϕ	volumetric concentration
λ	wavelength (nm)

Subscripts

bf	basefluid
c	cold
corr	correlation
exp	experimental values
i	i^{th} ray
j	j^{th} column
h	hot
nf	nanofluid
np	nanoparticles
orig	simulated data
recons	reconstructed field

observed from the literature. While a select group of researchers have reported an enhancement in Nusselt number with increasing volumetric concentrations of nanoparticles, a few others have demonstrated the possibility of contradictory trends of heat transfer rates as the nanoparticle concentration is increased. Some of the notable studies highlighting such observations include the works of Ho et al. [25] who reported an enhancement in heat transfer rates at relatively lower ranges of concentration of nanoparticles, however, an opposite trend was reported at higher levels of nanoparticles concentration. Studies reporting a deterioration in the natural convection-based heat transfer rates with increasing concentrations of nanofluids can also be found in the works of Wen and Ding [26], Putra et al. [27] and Ding et al. [28]. On other hand, Nanna et al. [29] experimentally demonstrated a clear enhancement in heat transfer coefficients achieved under natural convection regime. Nanna and Routhu [30] also reported an enhancement in heat transfer rates with increasing concentration of alumina nanoparticles suspended in water. Authors of the present study have also reported an enhancement in heat transfer phenomenon as a function of increasing concentration of nanoparticles [31,32]. Quite recently, studies conducted for investigating the possible effects of magnetic field on the natural convection heat transfer characteristics of copper/water-based nanofluids in rectangular and trapezoidal shaped enclosures have been reported by Rashad et al. [33–36]. The authors reported an enhancement in heat transfer rates with varying inclination angle of the magnetic field in the trapezoidal enclosure. Astanina et al. [37] have also explored the influence of magnetic field applied over different inclination angles to study the process of heat transfer in square cavity filled with Al_2O_3/water-based nanofluids. Numerical work pertaining to natural convection in an inclined cavity that is subjected to time-periodic boundary conditions and filled with Al_2O_3/water-based nanofluids has recently been reported by Sheremet [38].

The above-presented discussion shows that the performance evaluation of nanofluids under natural convection regime has been a subject of considerable interest. In addition, it is to be noted that this mode of heat transfer finds significant importance in areas such as cooling of electronic equipments [39], geophysical flows [6,40], aqueous solution-based crystal growth processes [41] etc. In the context of nanofluid-based natural convection studies, the experimental configurations, as employed by a range of researchers, include heated flat plate immersed in the coolant medium (nanofluid/water), differentially-heated enclosures [31,32,42], etc. Of all the experimental configurations, natural convection associated with differentially heated fluid layer has gained considerable attention. The configuration wherein the two horizontal walls of the enclosure are differentially heated in such a way that the lower wall is maintained at a temperature that is relatively higher than that of the top wall is termed as the Raleigh-Benard configuration [43–50].

While a large body of literature pertaining to the theoretical/numerical and/or experimental studies on Rayleigh-Benard convection has been reported with the conventional fluids (air, water) as the working medium, literature on the application of nanofluids in this configuration is quite scarce. Of all the limited number of studies available, focus has primarily been on theoretical and/or numerical approaches and the experimental studies have been quite limited in number. For instance, Abouli and Ahamdi theoretically studied the thermal performance of Al_2O_3 and CuO nanofluids under natural convection regime in six enclosure shapes [51]. Abu-nada [52] presented numerical models to examine the influence of convection currents in the fluid layer and temperature distribution for varying nanoparticles concentration in a differentially-heated rectangular cavity. Convective instabilities in the fluid layer by varying vertical temperature gradients and changes in heat transfer rates of Al_2O_3 nanofluid has been reported by Jake et al. [53]. On the other hand, apart from the works reported by Ho et al. [54], Kim et al. [55], Rao and Srivastava [32], the configuration of Rayleigh-Benard convection with nanoparticles-added basefluids has not been experimentally studied and further efforts are required to be made in this direction, which forms the motivation of the present work.

The experimental work reported in the present manuscript is a natural extension of our recent work concerned with the whole-field investigation of convective phenomena in a differentially-heated fluid layer with dilute nanofluids as the working medium [32]. The work reported in [32] was limited to the two-dimensional (path integrated) measurement of temperature distribution using laser interferometric technique. The present study is concerned with the reconstruction of the three-dimensional temperature field distribution in a differentially heated fluid layer with Al_2O_3/water-based dilute nanofluids. Interferometric technique has been coupled with the principles of