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Interferometric study of nanofluid-based heat transfer phenomena in compact channels

Kingsley Ernest Paul P, D. Haridas, Atul Srivastava*

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

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ABSTRACT

The present work is concerned with the interferometric measurements of dilute nanofluid-based heat transfer enhancement in compact rectangular channels. The heat transfer experiments have been conducted in forced convection regime for a range of Reynolds number. Simultaneously developing flow regimes have been considered. Al_2O_3-based dilute nanofluids with volume concentrations of 0.01% and 0.05% have been employed with deionized water as the base fluid. A Mach–Zehnder interferometer has been used to record the line-of-sight images of the convective fields inside the channel. Interferometry experiments have been performed in infinite as well as wedge fringe-setting mode of the interferometer. The images recorded in infinite fringe setting mode have been qualitatively interpreted to understand the effect of increasing volume concentration of nanofluids on phenomena like disruption of thermal boundary layer, temperature gradients etc. The interferograms corresponding to the wedge fringe-setting mode have been quantitatively analyzed to retrieve the whole field temperature distribution inside the compact channel, local variation of heat transfer coefficient for the range of volume concentration of nanofluids and Reynolds numbers studied in the present work. Results have been presented in the form of interferometric images, the contours of two-dimensional temperature distribution, local variation of thermal boundary layer thicknesses and heat transfer coefficients along the length of the channel and percentage enhancement in heat transfer rates due to increasing volume concentration of nanofluids for each Reynolds number. The experimental study clearly reveals a reduction in the thickness of the thermal boundary layer with increasing volume concentration of nanofluids and hence the increasing strength of the thermal gradients. An overall enhancement of heat transfer coefficient by a factor of about 1.7–2 in the case of nanofluid is observed in comparison with that obtained with the base fluid.

1. Introduction

With the advancements in the modern day technology, electronic components and electronic systems are rapidly shrinking in size, due to which the power density associated with these components is increasing drastically. As a consequence, it is a great technological challenge to design and develop appropriate cooling systems that will aid in maintaining the operating temperatures of electronic components below a certain prescribed value. In order to meet these challenges, new cooling techniques are required to be identified. In this context, among other cooling technologies, fluid flow through small dimension channels and the concept of heat transfer enhancement using nanofluids have attracted considerable attention. The small dimension channels can be classified into micro, mini and macro/conventional channels depending on the length scales of the smallest dimension of the channel [1,2]; and the nanofluids are the new generation heat transfer fluids engineered by uniformly dispersing nanometer-sized particles in the base fluids [3].

Heat transfer using small dimension channels with nanofluids as coolant medium has emerged as one of the effective methods for achieving high heat dissipation rates with potential applications in areas like compact heat exchangers, heat pipes etc. Nanofluids are mainly preferred due to their higher thermal conductivities even at low volume concentrations [4–7] and high stability of properly dispersed particles. Heat dissipation using mini/macrochannels with nanofluids has the additional advantage of less pumping power, smooth and clogging free flow inside the channel. The distinct advantages of the applications of nanofluids in small dimension channels for achieving high heat transfer rates have encouraged

* Corresponding author. Tel.: +91 22 25767531; fax: +91 22 25726875.
E-mail addresses: atulsr@iitb.ac.in, atuldotcom@gmail.com (A. Srivastava).

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Nomenclature

A	background intensity
B	amplitude
D_h	hydraulic diameter
f	friction factor
f_0	constant vector corresponding to the tilt of reference mirror of the interferometer
h	heat transfer coefficient
I	intensity of laser beam
k	thermal conductivity
L	geometrical path length covered by the test beam while passing through the test section
n	refractive index
n_0	ambient refractive index
Δp	pressure drop
Pr	Prandtl number
$\vec{r}$	spatial vector
Re	Reynolds number
Rx	inclination of the Gaussian phase in the x-direction
T	temperature
V	velocity
x, y, z, t	direction co-ordinates and time

Greek symbols

α	thermal diffusivity
δ	boundary layer thickness
φ	volumetric concentration
ϕ	phase
ρ	density
ν	kinematic viscosity
λ	wavelength of laser beam

Subscripts

avg	average
f	coolant fluid
nf	nanofluid
np	nanoparticle
Ref	reference
v	velocity boundary layer
t	thermal boundary layer

various researchers. In one of the early investigations, Park and Choi experimentally determined the convective heat transfer characteristics of metallic nanoparticles (γ-Al_2O_3 and TiO_2) suspended in water flowing through a circular tube in turbulent fully developed flow regimes [8]. Experimental results concluded that even though the Nusselt number increases with volume concentration and Reynolds number, the enhancement in heat transfer coefficient is less compared to pure water at 3% volume concentration of nanofluids. Experimental studies carried out by Wen and Ding [9] in laminar flow regimes using γ-Al_2O_3 nanoparticles contradict the results of Pak and Cho [8] and the study reported a significant increase in the heat transfer coefficient particularly at the entrance region of the channel. A similar trend of enhancement in heat transfer coefficient has been reported by Nguyen et al. [10]. Heris et al. [11] used water-based Al_2O_3 nanofluids in a circular tube with constant temperature boundary conditions for studying the effect on convective heat transfer enhancement and concluded with similar observations.

Heat transfer and friction factor determination of nanofluids in rectangular micro channels have been experimentally carried out by Jung et al. [12]. The authors employed Al_2O_3/DI and Al_2O_3/EG nanofluids of varying concentrations. Xie et al. [13] performed a detailed experimental study on convective heat transfer characteristics of nanofluids in a circular pipe using water and engine oil as the base fluids. The work reported around 252% enhancement in heat transfer coefficient using MgO nanoparticles and the enhancement is around 40% and 18% respectively for Al_2O_3 and ZnO. A similar order of magnitude of enhancement in heat transfer coefficients (32%) with Al_2O_3/DI water-based nanofluids has been experimentally demonstrated by Heyhat et al. [14] under laminar flow conditions. Experimental investigations on forced convective heat transfer enhancement using Al_2O_3/water-based nanofluids were performed in an array of micro [15] and mini channels [16] by Ho et al. The authors reported an enhancement of 35–72% in heat transfer coefficient. In another study reported by Hojjat et al. [17], the heat transfer performances of γ-Al_2O_3, CuO and TiO_2-based nanofluids were compared under forced convection environment.

Chandrasekar et al. [18] determined heat transfer augmentation in a uniformly heated horizontal tube with and without wire inserts. Al_2O_3/water-based nanofluids were employed as the coolant. Suresh et al. [19] employed CuO/water-based nanofluids in a helically dimpled channel with constant heat flux boundary conditions. The heat transfer and pressure drop characteristics of a uniformly heated circular tube were experimentally investigated using Al_2O_3–Cu/water and TiO_2/water based nanofluids in laminar and turbulent flow regimes respectively [20,21]. These experiments reported an increase in Nusselt number of 8% and 10% respectively as compared to the base fluid. Arani and Amani experimentally investigated the effect of volume concentration [22] and particle size [23] on the heat transfer characteristics and pressure drop of TiO_2/water-based nanofluids in a horizontal double tube counter flow heat exchanger in turbulent flow regimes. It was observed from the experiments that the Nusselt number increases slightly with increasing volume concentration.

The survey of the literature, as presented above, on the applications of nanofluids under forced convection regime has revealed a significant enhancement in the heat transfer coefficient as compared with that obtained with the base fluids. The enhanced thermal performance of nanofluids has primarily been attributed to the increased thermal conductivity of these fluids compared to the conventional coolant fluids. A select group of authors has also proposed the theory of disruption of the thermal boundary layer due to the presence of nanoparticles. According to the theory proposed, the addition of nanoparticles in the base fluid leads to the dispersion and fluctuation of the particles in the flow, especially near the walls of the channel resulting in an overall increase in the energy exchange, which effectively enhances the heat transfer coefficient [24,25]. Hence, the significant enhancement in the heat transfer performance of nanofluids has been attributed to the coupled effects of increased thermal conductivity and the possible disruption of thermal boundary layer region. While an increase in the overall thermal conductivity of nanofluids is understandable, the plausible role played by the nanoparticles in altering the thermal boundary layer profiles has not been well understood in the context of heat transfer processes through channels of small dimensions.

It is pertinent to note here that in the above-mentioned studies reported in the context of heat transfer measurements through