International Journal of Heat and Mass Transfer 108 (2017) 1140–1153

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Exploring the potential of nanofluids for heat transfer augmentation in dimpled compact channels: Non-intrusive measurements

Gulshan Kumar Sinha, Atul Srivastava *

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

A R T I C L E I N F O

Article history:
Received 1 September 2016
Received in revised form 22 November 2016
Accepted 23 December 2016
Available online 9 January 2017

Keywords:
Compact channels
Inward hemispherical dimples
Nanofluids
Heat transfer augmentation
Non-intrusive diagnostics

A B S T R A C T

Potential of the combination of nanofluids and dimpled channels for possible heat transfer enhancement has recently been demonstrated by Li et al. (2014) [36] in the context of small length scale channels through numerical simulations. The present work reports real time, non-intrusive experimental investigation of this concept wherein the convective heat transfer enhancement has been achieved with the coupled effects of Al_2O_3/water-based dilute nanofluids and surface roughened compact channels. One of the thermally active walls of the channel has been engraved with hemispherical inward dimples of 3 mm diameter with a pitch of 8 mm. Forced convection experiments have been conducted with water and Al_2O_3/water-based dilute nanofluids as the coolant medium for a range of Reynolds numbers. Real time measurements have been made in a completely non-intrusive manner using a Mach Zehnder interferometer and the images of the convective fields have been recorded in infinite as well as wedge fringe setting modes of the interferometer. Results revealed a clear influence of the combination of nanoparticles and surface protrusions on phenomena such as disruption of thermal boundary layer profiles, periodic flow separation and re-attachments along the principal wall of the channel. The coupled effects of inward dimples and nanoparticles resulted into a clear reduction in the thickness as well as flattening of the thermal boundary layer in comparison with that achieved with the base fluid. An enhancement by ≈66.5% in the average heat transfer coefficient with 0.05% volumetric concentration of alumina nanoparticles was achieved with respect to that of the de-ionized water at a Reynolds number of $Re = 350$.

1. Introduction

Recent year's rapid advancements in electronic devices in terms of their compactness and upgraded capabilities in data processing have led to the need for exploring the innovative and efficient ways for high heat flux dissipation. In this direction, microscale heat exchanger technology has captured enormous attention of various researchers after the pioneering work of Tuckerman and Pease [1]. As a result, a large gamut of numerical and experimental works has been reported in the area of micro and mini channel-based heat transfer [2–5]. However, the limitations associated during their fabrication processes such as shape distortion, non-uniform roughness and dimensional inaccuracy at micro and mini scale levels seem to have an adverse effect on their performances [6]. Further to augment the thermal performance of such heat exchanger systems, numerous passive (as well as active) heat transfer enhancement techniques have been proposed in the literature, such as extended surface (ribs and protrusions), treated surface, roughened surfaces and swirl flow device [7,8]. The central idea behind these heat transfer enhancement techniques is to increase the strength of disturbances in the fluid, maneuvering the (viscous) thermal boundary layer profiles developed near the principal wall of the channel and to promote effective mixing of the near wall fluid with the fluid in the core region of the channel. Among the passive techniques, enhancing the heat transfer rates through the usage of surface roughened principal walls of the channels has been one of the commonly employed methods, especially while working with gaseous medium as the coolant fluid such as air. The central idea is to generate the secondary flow structures in the flow field and disturb the thermal boundary layer profiles close to the thermally active surface of the channel. However, the overall percentage enhancement in heat transfer rates that can be achieved with these methods do not justify the higher levels of additional power requirements. Ligrani et al. [9] compared several such passive heat transfer augmentation techniques and reported that the introduction of dimples exhibit better thermal performance with lesser power consumption than the other techniques including ribs,

---

* Corresponding author.
E-mail addresses: atulsr@iitb.ac.in, atuldotcom@gmail.com (A. Srivastava).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.12.085
0017-9310/

Nomenclature

A	background intensity
B	local intensity
D_h	hydraulic diameter
f_0	constant vector for a given angular deviation of the reference mirror of 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
Re	reynolds number
T	temperature

Greek symbol

δ	boundary layer thickness
ϕ	phase
φ	volumetric concentration
λ	wavelength of laser beam

Subscripts

avg	average
b	bulk fluid
f	coolant fluid
nf	nanofluid
Ref	reference
s	surface

pin-fin, rough surface, etc. A number of experimental and numerical studies can be found on the dimpled surface channels that primarily focus on the optimization of dimple dimensions, aspect ratio, etc. at macro and mini scale levels [10–15]. Lan et al. [16] studied the flow features and thermal performances for various arrangements of dimpled and protrusions surfaces numerically in rectangular microchannels. Bi et al. [17] numerically investigated the flow resistance and thermal characteristics in mini-channels for low fins, cylindrical grooves and dimples using water as the working fluid.

Recent advancements in the field of nanotechnology have introduced a new high performance heat transfer fluid termed as nanofluid, which is one of the effective means of improving the heat removal capabilities of cooling systems. Nanofluids can be prepared by homogeneously dispersing non-metallic or metallic nanoparticles in the parent fluid. In the past few decades, nanofluids have been widely acknowledged as one of the ideal candidates for effective heat removal after the pioneering works of Choi et al. [18]. Thereafter, in addition to exploring the potential of nanoparticles for heat transfer enhancement in several engineering applications, a range of researchers have tried attempting to provide plausible mechanisms and/or explanations that lead to the enhancement in heat transfer properties of such fluids. These plausible mechanisms include improved thermal conductivity, particle collision, Brownian motion, Nano-layering, particle clustering, thermophoresis effects, etc. [19–27]. In addition to an extensive range of literature focused on the study of nanofluids-based heat transfer using the conventional temperature measurements techniques (e.g. thermocouples) that has been reported by various researchers, recent years have also seen significant developments in the application of flow visualization techniques as well to characterize the nanofluids performance. Of all these recent studies, the notable ones include the experimental work of Yousefi et al. wherein the authors made use of a Mach Zehnder interferometer for visualizing convective phenomena over a resistively heated vertical metal strip [28]. Li et al. presented an experimental study on two-phase flow in an oscillating heat pipe with water and SiO_2-based nanofluids using a CCD camera to capture the flow patterns inside the evaporator [29]. Rana et al. performed experiments in subcooled flow boiling of low volumetric concentration ZnO-water nanofluids in horizontal annulus test section for a range of heat fluxes and varying flow rates. For optical visualization, the authors employed a high-speed video camera to capture the bubble images and the impact of flow rates on parameters such as bubble diameter and bubble density were reported [30]. Potential of refractive index-based imaging techniques (e.g. interferometry, rainbow schlieren deflectometry, etc.) in qualitative as well as quantitative investigation of heat transfer characteristics of dilute nanofluids has been explored by the authors of the present study also in recent time. These studies have been performed in natural as well as forced convection regimes and discuss the impact of some of the plausible mechanisms of nanofluids e.g. thermal boundary layer disruption, Brownian motion, etc. in influencing the heat transfer rates [31–33].

Through the studies reported in the literature, researchers have argued that due to the presence of nanoparticles, significant disturbances are created in the near wall region, which lead to an overall reduction in the thermal boundary layer thickness, eventually increasing the strength of near wall thermal gradients as well as the convective heat transfer rates. By virtue of these mechanisms, the potential of nanofluids as the means of efficient heat removal system has been explored in various applications. For instance, Xuan and Li reported single phase forced convection study of Cu-water nanofluid under turbulent flow and constant heat flux conditions in a tube of 10 mm diameter [34]. Another convective heat transfer study in the entry region has been documented by Wen and Ding [35] using Al_2O_3 based nanofluids. The authors reported maximum percentage increase of ≈47% in the heat transfer coefficient with respect to water. Along with the increased thermal conductivity of the coolant fluid, the authors discussed the possibility of reduction in the thickness of thermal boundary layer due to the addition of nanoparticles as one of the possible reasons behind the observed enhancements in the heat transfer rates. It has been widely reported that the rate of heat transfer increases with increase in the flow rate as well as nanofluid concentration. Very recently, Li et al. reported a numerical study for understanding the coupled effects of dimple and protrusion with Al_2O_3 based nanofluid in channels of small dimensions of different geometric configurations of the flow passages [36].

On the backdrop of these studies available in the literature, the present experimental work, carried out in a purely non-intrusive manner, couples the potential of two possible heat transfer enhancement techniques, namely the usage of dimples on the thermally active wall of the channel and nanoparticles uniformly suspended in the base fluid, with an overall aim of disrupting/altering the thickness of thermal boundary layer formed near one of the principal walls of the compact channel. We report an experimental investigation of the combined influence of dimples (inward protrusions) and Al_2O_3-water based nanofluids of low concentrations on the overall heat transfer characteristics of small length scale