International Journal of Heat and Fluid Flow 64 (2017) 55–65

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

# Performance evaluation of compact channels with surface modifications for heat transfer enhancement: An interferometric study in developing flow regime

Gulshan K. Sinha, Rahul H. Dharmaraj, D. Haridas, Atul Srivastava*

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

ARTICLE INFO

*Article history:*
Received 17 June 2016
Revised 31 January 2017
Accepted 2 February 2017
Available online 17 February 2017

*Keywords:*
Surface-roughened compact channels
Heat transfer enhancement
Interferometry
Thermal boundary layers
Whole field temperature distribution

ABSTRACT

Performance evaluation of surface roughened compact channels for heat transfer applications has been investigated using non-intrusive, real time laser-based interferometric technique with water as the coolant medium. The lower wall of the channel has been roughened by creating hemispherical inward dimples. Projection data of the temperature field has been recorded using a Mach Zehnder interferometer. In order to facilitate direct comparison, experiments have also been conducted in smooth channel of similar dimensions. Results have been presented in the form of thermal boundary layer profiles, whole field temperature distributions and local variations of heat transfer coefficients. Direct interferometric measurements clearly reveal the disruption of thermal boundary layer due to the presence of inward dimples. Near wall temperature gradients were seen to be stronger in the case of dimpled channel in comparison with that of the smooth one resulting into a clear enhancement in heat transfer rates. At low Reynolds numbers, variation of heat transfer coefficients along the length of the dimpled channel showed the presence of local maxima. On the other hand, the corresponding profiles for the smooth channels showed a monotonic decrease with respect to the axial direction. The dynamic measurements, that are purely non-intrusive, revealed an improved thermal performance of surface roughened compact channels.



## 1. Introduction

Rapid advancement in electronic industry demands efficient and compact cooling systems, especially in the area of small scale heat exchanger systems (Tuckerman and Pease 1981; Peng and Peterson 1995; Mehendale et al. 2000; Kandlikar et al. (2001, 2003)). Advancements in cooling technologies have involved various surface modifications and have shown immense potential to enhance the heat transfer rate. A range of passive heat transfer enhancement techniques have been proposed including treated surfaces, protrusions, indentations etc. Of the various possibilities for achieving surface modifications, creation of dimples on the thermally active wall(s) of the plates has found considerable interest in the scientific community. These modifications may be in the form of outward protruding and/or inward dimples and may be arranged in various configurations (in-line, staggered, zig-zag etc.). The central idea behind the use of any given configuration of dimples arrangement is to create secondary flow structures, continuous/periodic breaking of boundary layer, flow separation and the subsequent flow re-attachments at a certain distance from the dimple location in the downstream direction etc. These flow phenomena lead to better fluid mixing, which in turn lead to significant enhancement in the heat transfer rates.

With regard to the usage of dimples (of various shapes, sizes etc.) for possible heat transfer enhancement in internal flows, the concerned available literature reveals that attempts have been made, experimentally as well as through numerical simulations, in elucidating the possible impact of these surface modifications on the overall heat transfer rates. Some of the notable experimental studies include the work reported by Ligrani et al. (2001, 2003) wherein the authors carried out investigations over a dimpled surface inside the conventional sized channels (hydraulic diameter of 47.8 mm) and demonstrated the formation of secondary flow structures. The work employed dimples of various print diameters and the experiments were conducted with air as the working fluid. The research group of Xiao et al. (2009) employed the principles of infrared tomography to study the spatially-resolved temperature distributions along the bottom surface of a channel

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

http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.02.002
0142-727X/

having surface modifications. The experiments were carried out under laminar flow regime and the results were presented in the form of spatially-resolved Nusselt numbers and friction factor. Kim et al. (2012) investigated the effects of dimples on the heat transfer performance of a rotating channel using liquid crystal technique. The experimental study provided a general understanding of the heat transfer enhancement rates using roughened surfaces in rotating heat exchangers. In one of the recent experimental studies, Katkhaw et al. (2014, 2016) investigated the thermal performance of ellipsoidal dimples created on an otherwise flat channel with air as the working fluid.

In addition to experimental approaches, efforts based on numerical simulations have also been made in the past to understand the possible impact(s) of dimples in influencing the heat transfer phenomena through channel flows. In this direction, Park and Ligrani (2005) numerically investigated the effects of dimples on the heat transfer characteristics of a channel with a hydraulic diameter of 94.2 mm. CFD simulations were used to study the thermal-fluid behaviour of groove enhancements placed in a minichannel flow by Conder and Solovitz (2011). Lan et al. (2012) numerically investigated the flow characteristics and heat transfer performances for different combination of smooth, dimpled and protrusions surface using water as the coolant fluid. Bi et al. (2013) presented a numerical analysis of local heat transfer characteristics in mini-channels with dimples, cylindrical grooves and low fins. Very recently, Aneesh et al. (2016) investigated the effects of surface modifications made in the form of hemispherical dimples in the flow passage of a single banked printed circuit heat exchanger (PCHE) on its thermo-hydraulic performance. Numerical investigations were carried out using a software *ANSYS Fluent 13* with helium as the working fluid.

The above presented literature indicates that the importance of surface modifications created in the form of outward protruding and/or inward dimples on an otherwise flat surface of a given channel for possible heat transfer enhancement has been realized in the past. Majority of experimental efforts made in this direction have primarily employed air as the working fluid. On the other hand, the performance evaluation of dimpled surfaces for heat transfer enhancement using water as the coolant medium has not yet been fully explored. The studies that have been reported in the available literature employing water as the working fluid have primarily been performed through numerical simulations and experimental works are still very scarce. It is also to be noted that most of the experimental studies that are available in literature have primarily employed thermocouples for temperature measurements. External physical probes like thermocouples intrude with the physical system under study and hence disturb the flow phenomena. Moreover, thermocouples provide spatially-averaged temperature data with a finite response time, thus such measurements are limited by spatial and temporal resolutions.

Against this backdrop, the present work reports non-intrusive real time investigation of thermal performance of compact channels. The lower thermally active wall of the channel has been modified by creating hemispherical inward dimples along the length of the channel. In contrast to the studies already available in the literature that primarily employ air as the coolant medium, the present set of experiments have been performed with water as the working fluid. Choice of water as the working fluid has been made by virtue of the fact that the heat transfer properties of water are significantly better than that of air, which in turn makes it a promising coolant medium for achieving high heat flux removal in various applications e.g. small scale heat exchangers. This potential is expected to get even more amplified when this coolant fluid is coupled with surface roughened compact channels, as is the focus of the present experimental work.

Whole field real time measurements of temperature distributions have been made using laser interferometry. It is important to mention here that while laser interferometry has found its extensive applications in heat transfer studies in the past as well, its potential in the context of performance evaluation of dimpled and small length scale channels with water as the working fluid has not been explored in the available literature. Its importance in such applications further gets amplified in view of the fact that from a single measurement tool, one can infer qualitative information on the possible flow phenomena (e.g. thermal boundary layer profiles, flow separation at the edges of the inward dimples and subsequent flow re-attachments in the downstream direction etc.) as well as whole field quantitative data in the form of temperature distributions, local variations of heat transfer rates etc. Exploring these inherent advantages of this variant of refractive index-based measurement technique, the interferometric images recorded in the present work have first been discussed in qualitative terms for understanding the effect of channel surface modification on phenomena such as thermal boundary layer profiles. Subsequently, the whole field temperature distributions have been determined through quantitative analysis of the interferometric images using the data reduction methodology developed in house. Local variation of heat transfer coefficient, average heat transfer rates etc. for a range of Reynolds numbers have been reported. A direct comparison of thermal performance of dimpled channel with that of the smooth (with no surface modifications) one has also been presented.

## 2. Apparatus and instrumentation

The test rig allows interferometric measurements of smooth and surface roughened compact channels. The test apparatus consists of an acrylic body housing a rectangular channel of hydraulic diameter 5.6 mm having dimensions of 86 mm ($L$) × 15 mm ($W$) × 3.5 mm ($d$). Thermal gradients have been applied across the top and bottom horizontal walls of the channel. These thermally active walls of the channel are made up of copper plates of thickness 1 mm (top) and 3 mm (bottom). In the case of channel with surface modifications, the bottom wall has been roughened with eight hemispherical inward cavities of radii 1.5 mm and a pitch of 8 mm, as shown in Fig. 1 (a and b). An electrical resistance heater has been fixed beneath the bottom plate of the channel and provides a constant heat input of 2.3 W, while the top horizontal wall has been maintained at ambient temperature.

Optical quality glass windows (Quartz, surface flatness: $\lambda/6$) fixed on the two opposite side walls of the channels enable the undisturbed propagation of the light beam for interferometric measurements. A total of 5 $K$-type thermocouples mounted on the back side of the top and bottom walls provide the temperature of thermally active walls of the channel. A set of thermocouples have been fixed at the entry and exit sections of the channel to measure the mean inlet and outlet fluid temperatures. Complete three-dimensional drawing of the experimental apparatus has been shown in Fig. 1(c). Fig. 2 shows the schematic of the Mach–Zehnder interferometer that employs 100 mm diameter optics used in the present set of experiments. Beam splitters and mirrors have been aligned at an angle of 45° with respect to the direction of the laser beam. As shown in the figure, the path lengths of the two arms of the interferometer have been matched by placing a compensation chamber in the reference arm of the interferometer, while the test arm houses the compact channel with thermal gradients employed across its two horizontal walls. The Mach Zehnder interferometer has been operated in infinite as well as wedge fringe setting mode for recording the projection data of the temperature field. Details of the optical configuration of the interferometer and the experience of the authors of the present study