International Journal of Thermal Sciences 59 (2012) 234–246

Contents lists available at SciVerse ScienceDirect

International Journal of Thermal Sciences

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

Experimental investigation of impinging jet array heat transfer from a surface with V-shaped and convergent-divergent ribs

S. Caliskan [a,*], S. Baskaya [b]

[a] Department of Mechanical Engineering, Hitit University, 19030 Çorum, Turkey
[b] Department of Mechanical Engineering, Gazi University, 06570 Maltepe, Ankara, Turkey

ARTICLE INFO

Article history:
Received 13 September 2011
Received in revised form
5 April 2012
Accepted 11 April 2012
Available online 18 May 2012

Keywords:
Confined impinging jets
Multiple jets
Rib-roughened surface
Local heat transfer

ABSTRACT

Detailed heat transfer measurements over a surface with V-shaped ribs (V-SR) and convergent-divergent shaped ribs (CD-SR) by a circular impinging jet array was investigated using thermal infrared camera. Both V-SR and CD-SR configurations with an angle of 45° are considered. In-line jet arrays with different exit flow orientations were also considered. The range of parameters for the analysis has been decided on the basis of practical considerations of the system and operating conditions. The effects of different rib heights on the impinging heat transfer along the wall are studied. Five different ribbed surfaces with different rib height and shapes were selected. The rib pitch (p) to rib height (e) ratio is 6. During the experiments, the Reynolds number was varied from 2000 to 10,000, the jet diameter-to-rib height ratio from 0.6 to 1.2, and jet-to-plate spacing from 2 to 12. The heat transfer results of the rib-roughened plate are compared with those of a smooth plate. The heat transfer from the rib-roughened wall may be enhanced or retarded. Best heat transfer performance was obtained with the V-SR arrangements. The presence of rib turbulators on the target plate produces higher heat transfer coefficients than the smooth plate. The average Nusselt number values for the V-SR plate showed an increase ranging from 4% to 26.6% over those for the smooth plate. Correlations have been developed for the average Nusselt number for the rib-roughened surfaces.

1. Introduction

Impingement heat transfer is considered as a promising heat transfer enhancement technique. Among all convection heat transfer enhancement methods, it provides significantly high local heat transfer coefficient. At the surface where a large amount of heat has to be removed, this technique can be employed directly through a very simple design involving a plenum chamber and orifices. Due to their widespread applications ranging from electronics equipment and turbine blade cooling to drying of textiles and glass tempering, impinging jets have been studied extensively in the literature.

A rough surface consisting of cube roughness elements was used by Chakroun et al. [1]. Heat transfer distributions over rib-roughened surfaces under impinging jets were studied by several investigators. Miyake et al. [2], Cha et al. [3] and Hrycak [4] have investigated the impinging jet heat transfer from rib-roughened flat surfaces and presented some optimum conditions (i.e. rib height, shape, pitch, jet-to-plate distance, etc.) for the maximum heat transfer. Rib-roughened non-flat surfaces (curved surfaces; such as convex, semi-cylindrical or cylindrical) were used by Hsieh et al. [5], Yan and Mei [6], Jia et al. [7] and Chung et al. [8]. It was seen that the heat transfer may increase up to 20–30% for the roughened surfaces, compared to smooth surfaces [5,8].

Gardon and Akfirat [9,10] have investigated the dependence of heat transfer on parameters such as Reynolds number, jet-to-plate distance and turbulence for the range of Reynolds numbers 450–22,000 and dimensionless jet-to-plate distances 1/3–80. Yan et al. [11,12] performed experimentally a series of impinging jet heat transfer studies over a smooth surface under in-line and staggered jet arrays with circular or elliptic jet holes. The roughened wall was made from parallel rectangular ribs attached to a heated wall. It was found by Gau and Lee [13] that in some situations the heat transfer along the roughened wall is indeed significantly enhanced. The detailed heat transfer measurements of three impinging jet arrays issued from grooved orifice plates are performed to study the combined effects of groove and nozzle-size distribution on heat transfer with various S/D and Reynolds number values [14].

The heat transfer characteristics in an in-line impingement model with high Reynolds number on a flat and micro-rib-roughened plate

* Corresponding author. Tel.: +90 312 5823469; fax: +90 312 2308434.
E-mail address: sinancaliskan2000@yahoo.com (S. Caliskan).

1290-0729/$ – see front matter © 2012 Elsevier Masson SAS. All rights reserved.
doi:10.1016/j.ijthermalsci.2012.04.013

have been investigated by Xing et al. [15] using both experimental techniques and numerical methods. From the investigated configurations, the jet-to-plate spacing $H/D = 3$ resulted in the highest heat transfer coefficients for both the flat and the micro-rib-roughened plate. Overall heat transfer performance on the micro-rib-roughened plate was always best for the minimum crossflow case. The heat transfer enhancement ratio increases with increasing Reynolds number. The highest enhancement caused by the presence of micro-ribs is 9.6% for the maximum crossflow.

Chang et al. [16–18] made a series of investigations on the impingement heat transfer on rib-roughened surfaces for Reynolds numbers ranging from 7000 to 20,000. They found that the relative position of the jet hole to the ribs has a great effect on the impingement heat transfer. The jet hole in between the ribs is the best arrangement of the flow and heat transfer characteristics. They analyzed the effect of geometric parameters on the heat transfer characteristics and expressed a correlation by the regression of the experimental results.

Florschuetz et al. [19] studied the effect of initial crossflow on impingement heat transfer. Their results show that the initial crossflow lowers the impinging heat transfer performance. Can et al. [20] investigated the heat transfer from a hexagonal array of round nozzles. They found a maximum area-averaged heat transfer at $S/D = 5.5$, regardless of the value of H/D. Huber and Viskanta [21] used a square array of nozzles. They found a maximum at $S/D = 6$ very close to the result of the Can et al. [20].

Obot and Trabold [22] have investigated the influence of crossflow on multiple impinging jet heat transfer. Three crossflow schemes, named minimum, intermediate, and maximum crossflow, were investigated. They found that crossflow lowers heat transfer coefficients, because spent fluid from upstream jets in an array can sweep away the downstream jets and delay impingement. Matsumoto et al. [23] investigated heat transfer from an impinging jet array with the same crossflow schemes. Their results agree well with the theory of Ref. [22].

Weigand and Spring [24] have investigated a review of the heat transfer characteristics of systems of multiple impinging air jets. The flow and heat transfer characteristics of multiple impinging jets are introduced and compared to single impinging jets. In addition, the suitability of the present CFD tools in predicting local heat transfer rates for multi-jet systems is discussed. They presented empirical correlations for both total average and locally resolved heat transfer coefficients. Yan et al. [25] used a 1-D transient liquid crystal scheme to investigate the impingement heat transfer on rib-roughened surfaces. The rib angle to achieve the best heat transfer performance was found to be 45°.

Chiu et al. [26] experimentally investigated the effects of jet geometry and the arrangement of film holes on the target plate. In addition, three arrangements of film hole on the target plates, named side-, middle- and staggered-types, are tested, respectively. Their experimental results show that the Nusselt number increases with the increase of jet Reynolds number. Better heat transfer is noted for the cases with smaller jet-to-plate spacing. For the effect of the arrangement of pores on the target surface, the heat transfer on middle-type plate is more significant than the other two, for smaller jet-to-plate spacings. As for the effect of aspect ratio, results indicate that the optimal heat transfer performance is found with a circular jet of AR = 1.

Gao et al. [27] showed that the presence on the surface of equally spaced 45° triangular tabs makes it possible to increase the average Nusselt number from 10% to 25%. Their study, carried out with a jet Reynolds number of 23,000, concentrates on R/D values ranging from 0 to 4.

Salamah and Kaminski [28] numerically investigated the heat transfer from an array of turbulent slot jets impinging on a flat plate. A local maximum Nusselt number between two adjacent jets was also found. In addition, their modeling approach successfully captures both the stagnation region behavior and the transition to turbulence in the wall jet region. Multi-jet systems with rib-roughened target plates were investigated numerically by Jia et al. [29].

The objective of the current study is to investigate the heat transfer values for an in-line impinging array on smooth, V-SR and CD-SR surfaces. Although the results in literature mentioned above provide many insights into the heat transfer performance on roughened plates, none of them investigated such rib-roughened arrays. The local and average Nusselt number distributions along the rib-roughened and smooth surface are measured. The obtained results are meant to serve as comparison data for further investigations of heat transfer performance on rib-roughened plate. The present study, various parameters such as Reynolds number, the rib height-to-jet diameter ratio (e/D), the jet-to-plate spacing (H/D) and exit flow orientations are chosen to explore the possibility to enhance heat transfer.

2. Experimental set-up and data reduction

The equipment for the experiments consists of blower, frequency controller, plenum, jet plate, Dantec 2-D LDA system, 3-D traverse system, an infrared thermal imaging system, and LabVIEW software system. Fig. 1 shows a sketch of the experimental setup. The required flow rate of air has been supplied by a centrifugal blower. In order to obtain the desired flow rate for the range of Reynolds numbers of interest a frequency controller (Siemens, Cinamics G110) has been connected to the blower. The blower was connected to the plenum with a flexible pipe of 900 mm length and 200 mm inner diameter. Air is carried to the plenum through the connecting flexible pipe from the blower. The plenum made of 10 mm thick Plexiglas is an 800 mm long rectangular duct with an inner rectangular cross section of 100 × 150 mm. Bottom section of the plenum was cut off to easily mount and demount the orifice plates containing the jet array. In order to measure the plenum air temperature two holes were drilled at approximately 700 mm from the plenum inlet to insert a T-type thermocouple. Circular sharp-edged holes are used to generate the impinging jets. Their diameter D is equal to 5 mm. Length-to-diameter ratio (L/D) of 1.0 is studied experimentally. In the experiments a uniform flow was achieved at the jet exit. Velocity measurements were made with a Dantec 2-D LDA system. The system operates in backscatter mode and is used in conjunction with a 300 mW Argon Ion laser. The infrared thermography system, which includes a ThermaCAM SC500 camera from FLIR systems and a PC with AGEMA Researcher software, can measure temperatures from −20 °C to 1200 °C with an accuracy of ±2%. The infrared camera uses uncooled focal plane array detector with 320 × 240 pixels, which operates over a wavelength range of 7.5–13 μm. The field of view is 25 × 18.8/0.4 m; the instantaneous field of view is 1.3 mrad, and the thermal sensitivity is 0.07 °C at 30 °C. The images captured by the infrared camera are displayed and recorded using a computer for further analysis. The NI SCXI 1303 DAQ module interfaced using LabVIEW software is used to acquire the jet inlet and impingement surface temperatures.

The target plate assembly is shown schematically in Fig. 2a. The heater, made of stainless steel foil which also acts as a target plate, is firmly clamped and stretched between two copper bus bars (see Fig. 1b).

Views of the V-SR and CD-SR roughened plates are shown in Fig. 2b and c. Ribs are actively transferring heat since they are made of high conductivity aluminum material. The ribs are attached to the foil plates by a thin layer of super-glue, with negligible contact