International Journal of Thermal Sciences 102 (2016) 26–38

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Experimental and numerical study on heat transfer characteristics of various geometrical arrangement of impinging jet arrays

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ARTICLE INFO

Article history:
Received 28 June 2015
Received in revised form
9 November 2015
Accepted 10 November 2015
Available online 12 December 2015

Keywords:
Heat transfer
Arrangement of slot jet arrays
Nusselt number distribution
Mach–Zehnder interferometer

ABSTRACT

In present work, the effects of jet Reynolds number and geometrical parameters including non-identical jet-to-jet spacings, nozzle-to-plate spacing and non-identical slot widths on the local Nusselt number distribution are investigated for quadruple slot jet arrays. Experiments are conducted for Reynolds number ranging from 144 to 505 based on jet hydraulic diameter (D_h), jet-to-target plate distance from $2.3D_h$ to $3.1D_h$, jet-to-jet spacing in the range of $0.1D_h$ to $0.8D_h$, and slot width of $0.2D_h$ to $0.8D_h$ at a constant wall temperature (70 °C). Local Nusselt number corresponding to the impingement region, relative minimum and stagnation point increase for any configuration when the Reynolds number is increased and plate spacing-to-jet hydraulic diameter ratio is decreased. The differences between the values of stagnation and maximum Nusselt number are strong function of Reynolds number and geometrical variables. Moreover, more uniform Nusselt number distributions over an isothermal target plate are seen for the cases of $w_2/D_h > w_1/D_h$. In addition, the isothermal curves' concentration at the stagnation region decreases when the Reynolds number is increased for the cases of $w_2/D_h < w_1/D_h$. The stagnation Nusselt numbers decreases at a constant Reynolds number by increasing jet-to-jet spacing. Furthermore, correlations are derived for the average and stagnation Nusselt number based on experimental data. Mach–Zehnder interferometer, non-contact and non-intrusive method, is used to calculate local heat transfer from visualized undisturbed temperature fields of infinite fringe interferograms with the high accuracy. Finite volume based code is employed for numerical analysis; good agreement between numerical analysis and experimental results is observed.

1. Introduction

In recent years, impingement jet arrays have been more employed in the industrial applications due to the higher removal heat flux with lower energy consumption rate compared to the other methods. Ebadian and Lin [1] compared the different methods of high-heat-flux heat removal including micro-channels, jet impingements, sprays, wettability effects, and piezo-electrically driven droplets. They found that jet impingement had higher heat flux removal than the other cooling technologies. Fabbri et al. [2] concluded that using micro-jet arrays was more affordable with respect to the sprays for the same flow rate because there is always a combination of geometrical and flow parameters that yields the same heat transfer coefficient as that of the spray at a much lower energy cost. Due to their effectiveness in removing large amount of heat from the target surface, impingement jet arrays are used in many industrial applications such as food industry [3,4], baking oven [5], bread baking [6], drying [7], and electronic devices [8].

Experimental procedures and numerical analyses have been two usual approaches to investigate the effective parameters of impingement jet arrays on the heat transfer of heated surface. Martin [9] had reviewed researches on impingement flow including arrays of round jets and slot jets. He classified and developed the previous correlations for different range of parameters. Gardon and Akfirat [10] presented correlations for local and average heat transfer coefficients of an isothermal target surface in terms of Reynolds number, Prandtl number, jet-to-surface distance and jet diameter.

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http://dx.doi.org/10.1016/j.ijthermalsci.2015.11.007

Su and Chang [11] investigated the effect of different size of three inline impinging jet arrays, issued from grooved orifice plates, on the heat transfer and jet-to-jet interactions to achieve the optimal jet-to-jet spacing for producing higher average Nusselt number. Xing and Weigand [12] compared different variations of plate spacing-to-jet diameter ratios on Nusselt distribution in an inline impingement array over a flat plate at high Reynolds number by using a transient liquid crystal technique. The optimum jet-to-plate spacing to jet diameter ratio was found to be $H/d = 3$, higher heat transfer performance with higher cross flow. Brevet et al. [13] achieved optimized values of the distance between a row of circular jets and plate, where maximum heat transfer rates occurred, for different Reynolds numbers and spanwise spacing between two holes of the row. Fabbri and Dhir [14] obtained an optimal configuration of the geometrical parameters of micro-jet arrays by minimizing the coolant flow rate and the power required to pump the liquid. Kim et al. [15] considered the objective function to optimize design variables of the spacing between the impinging jets and effusion holes, the channel height from impinging jet to effusion surface, the mass flux ratio of the cross flow to the impinging jet flow, and the main flow temperature, which led to lowest thermal stress around film cooling holes. Also, San and Lai [16] achieved the optimum jet-to-jet spacings, which were attributed to suitable jet interference before impingement and jet fountain between two adjacent jets, for different jet height to jet diameter ratios and Reynolds numbers.

Geers et al. [17] performed experiment measurements to find the dependency of jet interactions on the jet-to-plate distance and jet-to-jet spacing for hexagonal and inline arrays of impinging jets. Katti and Prabhu [18] found that the effect of spanwise jet-to-jet spacing on the local heat transfer was more significant at higher pitches for an in-line rectangular array of multiple circular air jets. The effect of jet-to-jet spacing to diameter ratio on flow patterns were investigated numerically by Bao et al. [19] for an inline square jet array. Mehryar and Giovannini [20] observed twisted symmetry pattern of flow field and heat transfer on the target surface in square inline configuration of circular jet arrays at low Reynolds number. San and Chen [21] studied the effects of jet-to-jet spacing to jet diameter ratio (s/d) and the jet height to jet diameter ratio (H/d) on local Nusselt distributions for five equilaterally staggered arrays of circular air jets. They observed uniform Nusselt number distribution in the region directly covered by the jet array for $s/d = 2$ and $H/d \geq 2$ values. Huber and Viskanta [22] investigated the influence of jet-to-jet spacing on the uniformity of heat transfer coefficients for square arrays of circular air jets. They concluded that more uniform Nusselt distribution was achieved when the effect of the low convection coefficients corresponding to the wall jet region were minimized. Ozmen [23] performed an experimental study to investigate the effect of nozzle-to-plate spacing, jet-to-jet spacing and Reynolds number on the pressure distribution for confined twin impinging jet at high Reynolds numbers. It was found that pressure distribution was function of nozzle-to-plate spacing and jet-to-jet spacing. The effects of jet-to-jet spacing and aspect ratio of elliptic jet arrays on the heat transfer were performed by Chiu et al. [24]. They concluded that the heat transfer increased by decreasing jet-to-jet spacing and circular jets had a best performance with respect to other aspect ratios. Koseoglu and Baskaya [25] studied different aspect ratios of circular and rectangular jet exit geometries. They found that the local heat transfer corresponding to stagnation region increased with the increment of aspect ratios. Nuntadusit et al. [26] experimentally investigated different orifice geometries to obtain lower cross flow with the higher rate of heat transfer. An enhancement in heat transfer from concave surface which was impinged by a single row of round jets was observed by Martin et al. [27], when jet-to-plate distance and jet-to-jet spacing were reduced. Heo et al. [28] considered average Nusselt number as an objective function to achieve higher heat transfer augmentation for the case of staggered inclined impinging jets on a concave surface; angle of the staggered jet nozzles and the jet-to-jet spacing were chosen as the design variables. Katti et al. [29] concluded that the static pressure coefficient of semi-circular concave surface, which was impinged by a single row of circular jets, decreased when jet-to-plate distance was increased.

Rady and Arquis [30] concluded that the confined surface protrusion was effective not only in enhancing the heat transfer rates, but also in reducing the interaction between inlet of slot jet arrays and exhaust flows. Aldabbagh and Sezai [31] carried out numerical investigation to study the effects of jet-to-jet spacing and nozzle to plate spacing of square jet arrays with spent fluid removal on the local heat transfer coefficient. It was found that the effect of spent fluid removal was higher for the smaller jet-to-jet spacing due to more intense jet interactions and cross flow effects. Oblique impingement configurations of circular jet arrays were compared to normally impinging ones to achieve higher average Nusselt number by Parida et al. [32]. The higher heat transfer was obtained at 70° impingement jets in their experimental measurements; the angle was measured with respect to the target surface. Afroz and Sharif [33] performed the numerical study of the inclination angle of the twin oblique jet to the impingement surface effects on heat transfer from a constant surface temperature for different Reynolds number, jet-to-jet spacing and jet-to-plate distance. Maximum Nusselt number decreased when the impingement angle was reduced from normal impingement. Caliskan [34] carried out an experimental study to investigate the effect of perforated ribs, solid ribs and smooth surface of a multiple circular jet array on heat transfer and fluid characteristics for air jet impingement by using infrared thermal imaging technique and laser-Doppler anemometry, respectively. The presence of rib perforation produced the best and higher heat transfer coefficients than the smooth plate and solid ribs surfaces. Also, Caliskan and Baskaya [35] compared heat transfer of V-shaped ribs and convergent-divergent shaped ribs with an angle of 45° to smooth plate for inline circular impinging jet arrays. They found that the V-shaped ribs arrangements had a best heat transfer performance than the others.

The preceding studies have not yet considered the effect of air impingement jet arrays with non-identical jet-to-jet spacing and slot jet widths on the heat transfer from the heated plate. In the similar researches to this study, for instance, Shariatmadar et al. [36] studied both experimentally and numerically the effects of number of slot jets, identical width and jet-to-jet spacing on the distribution of local Nusselt number for different jet Reynolds numbers. In another study, Forouzanmehr et al. [37] developed a numerical algorithm in order to obtain an optimal configuration of four planar impinging slot jets to produce uniform heat flux along an isothermal heated flat plate; the results were verified by performing experiments by Mach–Zehnder interferometer. In response to this deficiency, the authors performed experimental and numerical study to understand the effects of Reynolds number and geometrical parameters including non-identical jet-to-jet spacings, nozzle-to-plate spacing and non-identical slot widths on the local Nusselt number distribution. Moreover, correlations are derived for average and stagnation point Nusselt number based on experimental results.

2. Experimental apparatus

Fig. 1 shows a schematic of the experimental apparatus. The compressed air is directed to desiccant dryer in order to eliminate