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Heat transfer visualization of co/counter-dual swirling impinging jets by thermochromic liquid crystal method

S. Eiamsa-ard [a,*], K. Nanan [a], K. Wongcharee [b]

[a] Department of Mechanical Engineering, Faculty of Engineering, Mahanakorn University of Technology, Bangkok 10530, Thailand
[b] Department of Chemical Engineering, Faculty of Engineering, Mahanakorn University of Technology, Bangkok 10530, Thailand

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The objective of the experimental study is to investigate heat transfer of co/counter-dual swirling impinging jets (*Co-DSIJs/C-DSIJs*) on the impingement surfaces under uniform wall heat flux boundary condition. Two twisted-tapes were inserted into pipe nozzles with different arrangements: (1) each tape was twisted in the same direction as the co-dual tapes for producing co dual swirls and (2) each tape was twisted in the different directions as the counter-dual tapes for inducing counter dual swirls. The effect of the *Co-DSIJs/C-DSIJs* with baffles placed between the tapes for jet confinement on heat transfer was also investigated. The effects of jet Reynolds number ($5000 \leqslant Re \leqslant 20{,}000$), jet-to-plate spacing ($1 < L/D < 8$) and tape twist ratio (y/W = 3, 4, 5 and 6) were examined. In addition, the experiments using a single swirling impinging jet (*SIJ*) and a conventional impinging jet (*CIJ*) were also carried out, for comparison. The temperature distributions on impinged surfaces were recorded via a thermochromic liquid crystal (TLC) sheet and then Nusselt number distributions were obtained by a liquid crystal thermography technique. The experimental results revealed that for all *Co-DSIJs and C-DSIJs*, heat transfer increased with decreasing nozzle-to-plate spacing (L/D) and increasing Reynolds number. For the *Co-DSIJs and C-DSIJs* without baffle, heat transfer increased with increasing twist ratio (decreasing swirl number) while the opposite trend was found for the *Co-DSIJs and C-DSIJs* with baffle. At similar conditions, the *Co-DSIJs and C-DSIJs* with baffles offered higher heat transfer than the ones without baffle, owing to the combined effect of swirling flow and jet confinement. For small jet-to-plate spacings (L/D = 1 and 2), all swirling jets possessed considerably higher average Nusselt numbers than the conventional jets, at similar conditions. At large jet-to-plate spacings (L/D = 4, 6 and 8), the average Nusselt numbers of the conventional and swirling jets became comparable. For the studied range, the maximum average Nusselt number of 110 was achieved by using *C-DSIJs* with baffle at L/D = 1, y/W = 3 and Re = 20,000.

1. Introduction

Impinging jets have been extensively utilized for several purposes in industrial applications such as tempering of glass, drying of textile/paper, textile and film, chemical vapor deposition (CVD), cooling of hot steel plate, turbine blade and electronic components. This technique offers extremely high heat transfer rate on impinged surfaces. In general, the flow structure of an impinging jet can be classified into three regions: a free jet region, which forms around jet exit with $V(r)$ velocity distribution [1], an impingement (stagnation) flow region, which forms upon jet impact and deflection, and a wall jet region, which forms due to the re-acceleration of the flow along a confining surface as seen in Fig. 1. High heat transfer coefficients are obtained in the stagnation region. In addition, the wall jet region, which possesses a larger transfer area, can potentially contribute to further heat transfer enhancement. To enhance the heat transfer on an impinged surface, a swirling jet has been adopted instead of a conventional jet. Generally, heat transfer on an impinged surface strongly depends on jet characteristics. For a conventional impinging jet, Nusselt number peak takes place in the vicinity of the stagnation point, then decreases sharply with radial spacing from the point. This leads to the limitation for some applications such as CVD and cooling of electronic components, in which radial uniformity of heat transfer is necessary.

Swirling impinging jet concept was proposed for improving the radial uniformity of heat transfer by introducing a tangential flow into the main air flow [2]. However, the use of a swirl generator consisting of a straight tube with narrow slots resulted in lower Nusselt number as compared with that of a conventional impinging jet. Huang and EL-Genk [3] employed swirl generators with 4 narrow

* Corresponding author.
E-mail address: smith@mut.ac.th (S. Eiamsa-ard).

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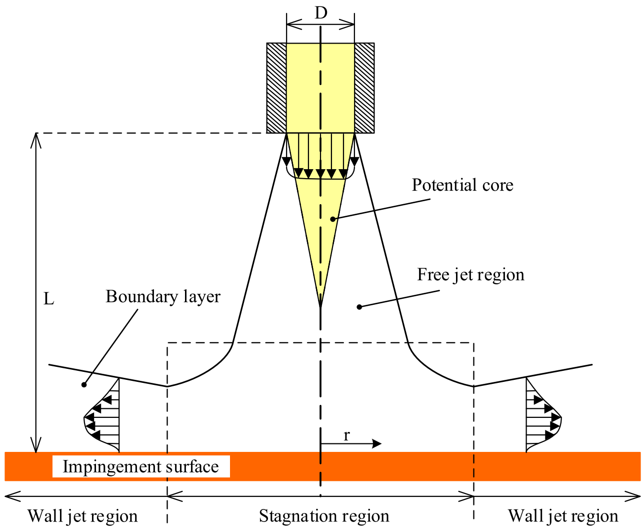

Fig. 1. Flow structure of an impinging jet on an impingement surface [1].

channels and swirl angles from 0° to 45°. Their results revealed that both radial distribution and value of Nusselt number were improved significantly as compared with those reported by Ward and Mahmood [2]. In addition, Ward and Mahmood [2] and also Lee et al. [4] reported that the heat transfer enhancement by a swirling jet became more significant with decreasing jet-to-surface spacing. Senda et al. [5] studied the heat transfer enhancement and fluid flow of the swirling round impinging jet by using the thermosensitive liquid crystal sheet and laser dropper velocimetry (LDV) for swirl numbers of 0.0, 0.22, and 0.45. They found that as swirl number increased, the radial heat transfer distribution became more uniform. Alekseenko et al. [6] employed a stereo PIV technique to study the local structure of a turbulent swirling impinging jet. They found that the swirling impinging jet possessed greater spread rates and faster decay in absolute velocity compared with a conventional jet. Yakkatelli et al. [7] examined the flow behavior of the single round jet issuing from a straight tube and impinging on a foamed aluminum heat sink at different jet-to-surface distances using a smoke-wire technique. It was observed that an increase in Reynolds number from a laminar jet to a turbulent jet allowed the flow to penetrate the porous media more consistently and diminished the recirculation at the exit of the foam. Bakirci and Bilen [8] carried out a comparative study of heat transfer enhancement by swirling impinging jet (SIJ), multi-channel impinging jets (MCIJs) and conventional impinging jet (CIJ) using a liquid crystal technique. In their experiments, the swirling jet assembly consisted of a housing tube and a solid swirl generator insert which had four narrow slots machined on its surface. They observed that as swirl angle increased, the radial Nusselt number distribution became more uniform and the optimum result was achieved at the swirl angles of 50° and the jet-to-surface distance of $L/D = 14$. Wen and Jang [9] performed flat surface cooling by impinging jet issuing through two different swirling strips including a longitudinal swirling-strip and a crossed swirling-strip at different nozzle-to-plate distances. A smoke flow visualization was also used to observe the swirling flow jet impinging. Yang et al. [10] investigated the impinging annular jet behavior induced by swirling motion. Their results showed that at short and intermediate separation distances (jet-to-surface distance), the swirling annular jet gave non-uniform wall pressure and Nusselt number distributions on the impinged surface. Nuntadusit et al. [11] studied the flow and heat transfer characteristics of swirling impinging jets at constant nozzle-to-plate distance (L/D) of 4. The swirling jets were generated by twisted tapes with twist ratios (y/W) of ∞ (straight tape), 3.64, 2.27, 1.82, and 1.52. The flow patterns of the free swirling jet and the swirling impinging jets were visualized by mixing dye with the jet streams while an oil film technique was performed for flow visualization on the impinged surface. They found that the jet with straight tape insert and the swirling jet with swirl number of 0.4 gave superior heat transfer to the conventional jet (CIJ) while the jets at larger swirl numbers ($Sw^* = 0.78$ and 0.94) gave poorer heat transfer than CIJ, due to the significant spreading of the jets prior to impingement. Nuntadusit et al. [12] examined the flow and heat transfer characteristics of multiple swirling impinging jets (M-SIJs) on impinged surfaces. The flow patterns on the impinged surfaces were visualized using an oil film technique while the distributions of temperature field and Nusselt number on the impinged surfaces were evaluated via a thermochromic liquid crystal (TLC) sheet coupled with image processing technique. The experimental results showed that at the same jet-to-jet distance (S/D), the M-SIJs offered higher heat transfer rate on impinged surfaces than the M-CIJs. Ianiro and Cardone [13] studied heat transfer enhancement by the multichannel jets with five different swirl number values (0, 0.2, 0.4, 0.6 and 0.8) and five different nozzle-to-plate distance values (2, 4, 6, 8 and 10 diameters) by using the infrared thermography and with the heated thin foil sensor. They found that at the same nozzle-to-plate distance, the increase of jet swirl number led to jet broadening and the decrease of overall heat transfer. Nanan et al. [14] employed twisted tapes with 4 different twist ratios (twist ratio is defined as twist length to tape width) as swirl generators for impinging jets. The results indicated that the swirl generators with larger twist ratios provided superior heat transfer enhancement.

In common, heat transfer by an impinging jet is governed by two important factors: (1) the axial flow velocity and (2) turbulence intensity. For efficient heat transfer, both axial flow velocity and turbulence intensity should be high. According to the literature, both overall heat transfer rate and radial heat transfer uniformity have to be taken into consideration for choosing the optimum condition for the heat transfer by swirling impinging jets. One key of producing the swirling impinging jet with good properties is the appropriate design of a swirl generator. Insertion of twisted tape is one of the promising techniques to produce a swirl flow. Twisted tapes are inexpensive, can be easily installed to the existing system and effective in increasing heat transfer rate. Most twisted tapes are thin strips with light weights. In the present work, dual twisted tapes are adopted for inducing the co/counter swirling impinging jets (*Co/C-DSIJs*) with and without baffle. In addition, the results of the single swirling impinging jet (*SIJ*) induced by a single twisted tape and a conventional impinging jet (*CIJ*) with and without baffle are also reported, for comparison. It was expected that the interaction between the swirling flows induced by the dual swirling impinging jets would improve the heat transfer uniformity as compared to that given by the single swirling impinging jet. Moreover, the presence of baffle as a semi-confined configuration was expected to prolong a potential core and thus, improve the heat transfer rate on the impinged plate. For an understanding of heat transfer behaviors of all studied jets, the thermochromic liquid crystal (TLC) technique was applied together with an image processing technique to acquire the Nusselt number distributions on the impinged plate. The study encompasses (a) Reynolds numbers between 5000 and 20,000, (b) nozzle-to-plate spacings (L/D) of 1, 2, 4, 6 and 8 and (c) tape twist ratios (y/W) of 3, 4, 5 and 6, and (d) radial distances from stagnation point (r/D) of ±2.0.

2. Experimental facility

The experimental facility is shown in Fig. 2. The system consisted of (1) a high pressure blower, (2) a three phase inverter for