# Heat Transfer Visualization of Swirling Impinging Jets Using Nozzle with Centrally Hollow Helical-Tape

Smith Eiamsa-ard, Kengkla Kunnarak, and Khwanchit Wongcharee
Department of Mechanical Engineering, Faculty of Engineering, Mahanakorn University of Technology, Bangkok, Thailand
Email: smith@mut.ac.th, kengkla.k@hotmail.com, khwanchit99@gmail.com

Varesa Chuwattanakul*
Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand
*Corresponding author: varesaatkmitl@gmail.com

***Abstract*— The present research was conducted to determine the heat transfer visualization of swirling impinging jets (*SIJ*s) induced by nozzle with centrally hollow helical-tape using a thermochromic liquid crystal (TLC) sheet. The effects of jet-to-plate spacing ratios (*L*/*D*= 2.0, 4.0, 6.0 and 8.0) and Reynolds numbers (10,000 ≤ *Re* ≤ 20,000) on the radial uniformity and intensity of convective heat transfer were investigated. The experimental results of *SIJ*s were compared with those of conventional impinging jets (*CIJs*). The formation of swirl flow of swirling impinging jet (*SIJ*s) helped in improving the uniformity of local heat transfer or Nusselt number (*Nu*) and also average Nusselt number, as compared to those of conventional impinging jets (*CIJs*). Furthermore, the average Nusselt number (*Nu*) increased as jet-to-plate spacing ratio (*L/D*) decreased while Reynolds number (*Re*) increased for both conventional impinging jets (*CIJs*) and swirling impinging jets (*SIJ*s). The highest Nusselt number (*Nu*) of swirling impinging jet (*SIJ*) was obtained at the jet-to-plate spacing ratio (*L*/*D*) of 4.0 and Reynolds number (*Re*) of 20,000. The maximum Nusselt number (*Nu*) of swirling impinging jet (*SIJ*) was higher than that of conventional impinging jets (*CIJs*) at similar conditions by around 5.3%.**

***Index Terms*— Heat transfer, centrally hollow helical-tape, swirl flow, swirling impinging jet**

## I. Introduction

Impinging jet is one of the active heat transfer enhancement method that have been widely various fields instant, automotive, gas turbine cooling, electronic cooling food-processing (including drying, toasting and freezing), glass quenching and paper drying due to its direct, localized heating or cooling and high heat fluxes. To extend its applications, some researchers have focused on the effect of swirling impinging jet (*SIJ*) on the heat transfer enhancement [1-10].

Sharif [11] studied the heat transfer from a heated plane circular surface using round turbulent submerged swirling jet impingement. They found that at low-to mid-range swirl strength, the heat transfer rate dropped mildly as swirl number was increased. Xu *et al*. [12] reported the effect of a novel swirler (circumferential screw grooves) on the uniform cooling at high heat transfer rates. Their results showed that the novel swirler was effective in improving the radial uniformity of heat transfer as compared to that of a multi-channel conventional impinging jet. Mohamed Illyas *et al*. [13] generated swirling impinging jets by using helicoid inserts. They observed that the axial component of velocity of jet leaving triple helicoid at the stagnation region was relatively lower than those obtained by using single and double helicoids due to the presence of axial recirculation zones and the increased tangential velocity component. Eiamsa-ard *et al*. [14] reported the effect of swirling impinging jet (*SIJ*) induced by nozzle fitted with helical rod inserts on the radial uniformity of heat transfer and average heat transfer rate. Their results revealed that the swirling impinging jet (*SIJ*) at the larger diameter ratio (*d*/*D*) of 0.64 provided higher heat transfer rate than that with smaller diameter ratio (*d*/*D*) of 0.46 by around 6.4% and higher than that of the conventional jet (*CIJ*) by around 35%. The literature review shows that various swirlers possess different effects on jet impingement and heat transfer performance.

For the present study, centrally hollow helical-tape was employed for swirling flow inducing. The thermochromic liquid crystal (TLC) sheet was applied to visualize the temperature-field and heat transfer behavior on the impinging surface. The study focused on enhancing heat transfer uniformity. The effects of jet-to-plate spacing ratios (*L*/*D*) of 2.0, 4.0, 6.0 and 8.0) and Reynolds number (10,000 ≤ *Re* ≤ 20,000) on the radial uniformity and intensity of convective heat transfer were investigated.

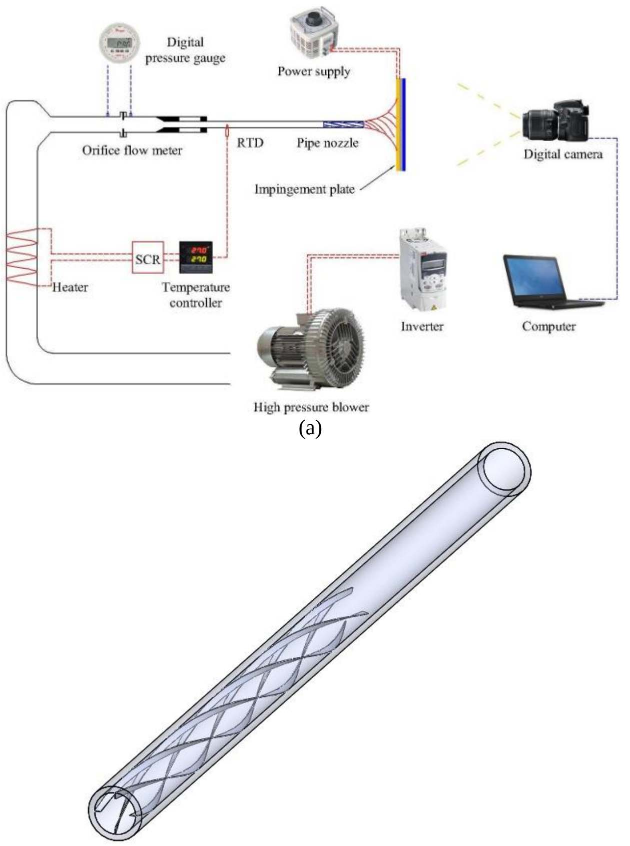
## II. Experimental Facility

The schematics of the experimental facility for thermal visualization and the nozzle are shown in Fig. 1(a) and 1(b).

Manuscript received July 7, 2019; revised April 1, 2020.



doi: 10.18178/ijmerr.9.5.673-678




(b)

Figure 1. Layout of experimental facility and nozzle with centrally hollow twisted tape

In the present investigation, the heated impinged surface was cooled by the swirling impinging jets (*SIJ*s) or conventional impinging jets (*CIJ*s). The swirling impinging jet was induced by the centrally hollow helical-tape inserted into the nozzle. The impinged surface was made of a stainless-steel foil (SUS304) with the length, width and thickness of 250 mm, 250 mm and 0.03 mm, respectively. A thermochromic liquid crystal (TLC) sheet was attached on the rear of the thin stainless foil sheet with binder. A thermochromic liquid crystal (TLC) sheet is temperature sensitive, its color changes from black to brown, red, yellow, green and blue when temperature changes from 29 ℃ to 36 ℃. The nozzle having a diameter of 20 mm was made of UPVC clear pipe with the length of 500 mm. The swirl generator (centrally hollow helical-tape) had four multi-channels with swirl angle of $\theta$ = 15 °) and tape thickness of 0.4 mm. Direct current was supplied to the stainless-steel foil from a power supply unit via the copper bus bar electrodes, which were attached to a stainless-steel foil and an acrylic plate. The experimental results indicated that the boundary condition of uniform heat flux could be achieved on the impinged surface. The input power to the stainless-steel foil was evaluated from the power supply electric current and the resistance of stainless foil. When the temperature distribution on impinged surface, as indicated by the color pattern of the TLC, reached a steady state, the color pattern on TLC sheet was recorded by a digital camera. Because the stainless-steel foil used in this study was extremely thin, the temperature of the target could be assessed from the color pattern of the thermochromic liquid crystal (TLC) sheet on the rear side. The recorded image was then converted from RGB (red, green, blue) to HSI (hue, saturation, intensity) color domain. Subsequently, the distribution of hue was converted to surface temperature via calibration curve between hue and temperature. The correlation of the curve was achieved by calibration against thermocouples. Heat transfer results are presented in the form of Nusselt number. Local heat transfer results are presented in the form of local Nusselt number (*Nu*). The local convective heat transfer coefficient (*h*) and local Nusselt number are determined from

$$h = \dot{q} / T_w - T_j \tag{1}$$

$$Nu = hD/k \tag{2}$$

## III. Results and Discussion

To assess the reliability of the results obtained in the present work, the local Nusselt number at jet-to-plate spacing ratio (*L*/*D*) of 8.0 were validated with previous standard data under the similar test conditions as depicted in Fig. 2. Evidently, the local Nusselt number of the present conventional impinging jet (*CIJ*s) agree well with those obtained from Barkirci and Bilen [15] work within ±16.5% (0 < *r*/*D* < 2) at Reynolds number (*Re*) of 10,000 and ±8.1% (0 < *r*/*D* < 2) at Reynolds number (*Re*) of 20,000.

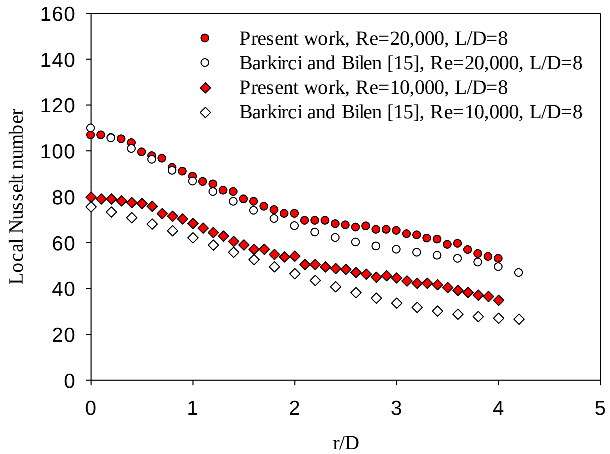



Figure 2. Comparison between the present and previous studies.

The local Nusselt number, temperature field and Nusselt number distributions in the impinged plate of both conventional impinging jets (*CIJs*) and swirling impinging jets (*SIJs*) are demonstrated in Figs. 3-5. For the conventional impinging jets (*CIJ*s), Nusselt number diminished along the radial direction and the secondary peak heat transfer appeared in donut shape (Fig. 4) especially at low jet-to-plate spacing (*L*/*D*). This is attributed to the transition of the low turbulence in a stagnation region to a turbulent wall jet.

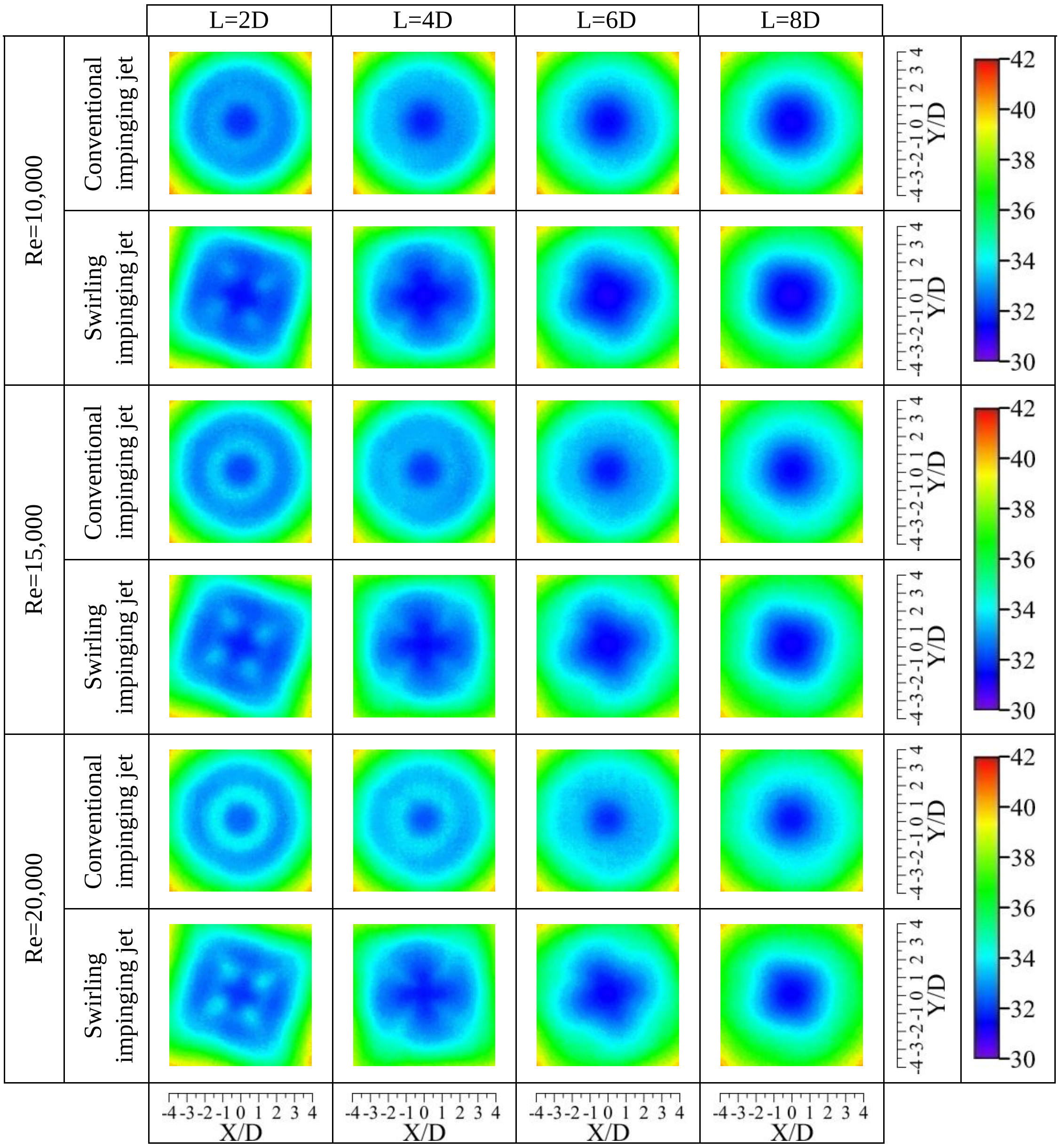
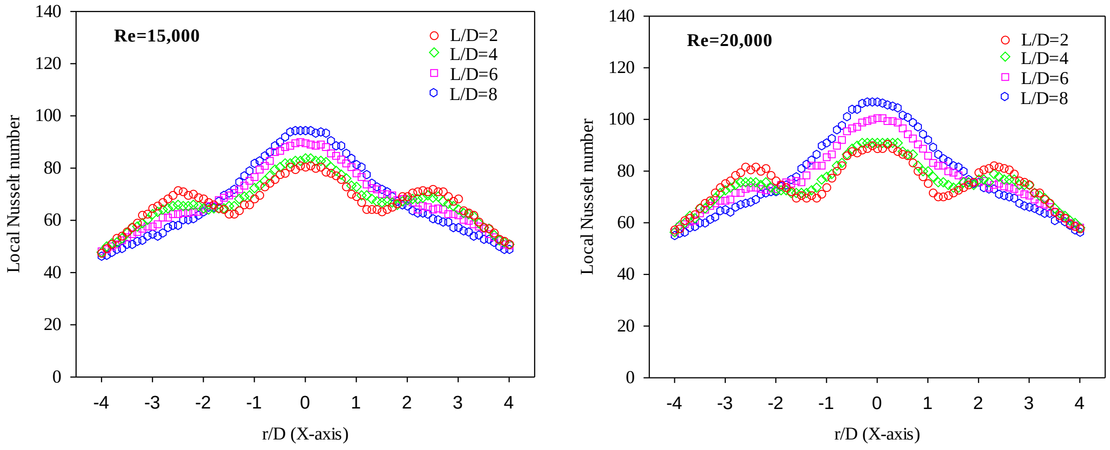



Figure 3. Temperature distribution on impinged plate.




(a) (b)

Figure 4. Effect of the nozzle-to-plate spacing (*L/D*) on local Nusselt number distribution of the conventional impinging jet (*CIJ*).

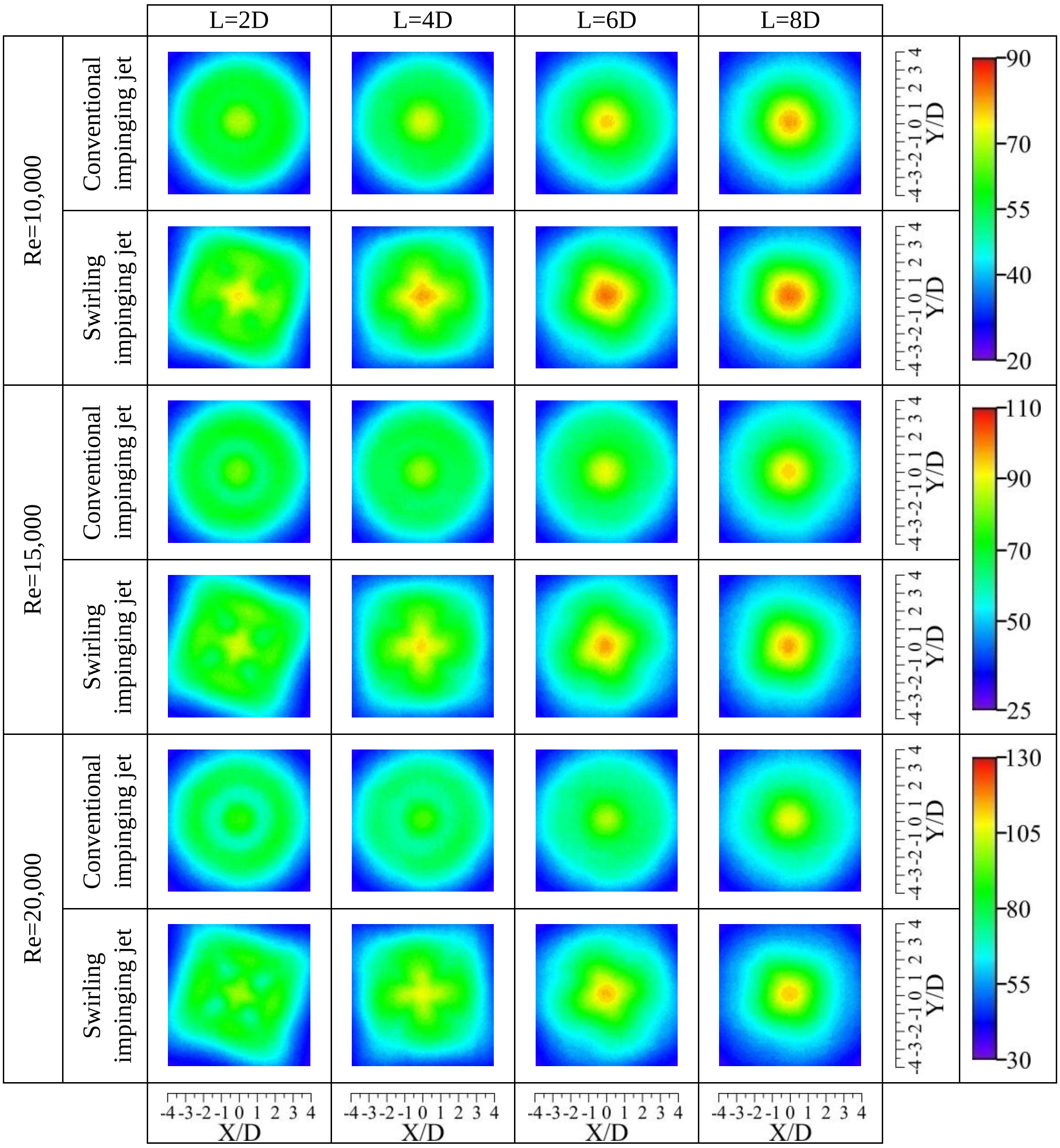
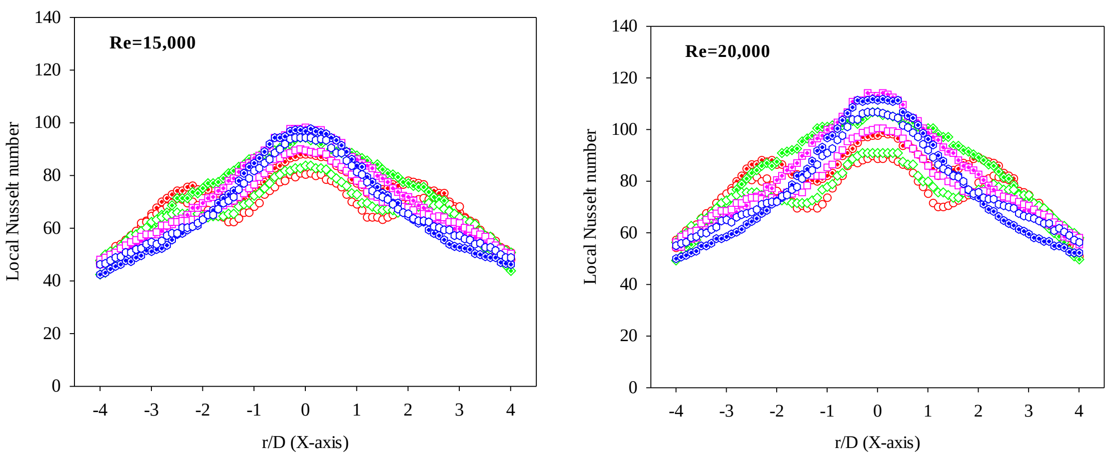



Figure 5. Nusselt number distribution on impinged plate.




(a)

(b)

Figure 6. Effect of the nozzle-to-plate spacing (*L/D*) on local Nusselt number distribution of the swirling impinging jet (*SIJ*)

For the swirling impinging jets (*SIJs*), the intensified heat transfer regions were separated due to the blockage by nozzle fitted with centrally hollow helical-tape. The separation became notable as the jet-to-plate spacing decreased. The impinged areas for conventional impinging jets (*CIJ*s) were in symmetrical shape while those for swirling impinging jet (*SIJ*) were in asymmetrical shape, due to the swirling effect. The formation of swirl flow of swirling impinging jets (*SIJ*s) helped in improving the uniformity of local heat transfer or Nusselt number and also average Nusselt number, as compared to those of conventional impinging jets (*CIJ*s). At similar test conditions, the swirling impinging jets (*SIJ*) impinged at jet-to-plate spacing (*L*/*D*) of 2.0, 4.0 and 6.0 yielded higher averaged Nusselt number than the conventional impinging jet (*CIJ*s) up to 3.7%, 5.3% and 1.4%, respectively. However, at jet-to-plate spacing (*L*/*D*) of 8.0, the swirling impinging jets (*SIJs*) yield lower average Nusselt numbers than the corresponding conventional impinging jet (*CIJ*) by around 3.9% at Reynolds number (*Re*) of 20,000.

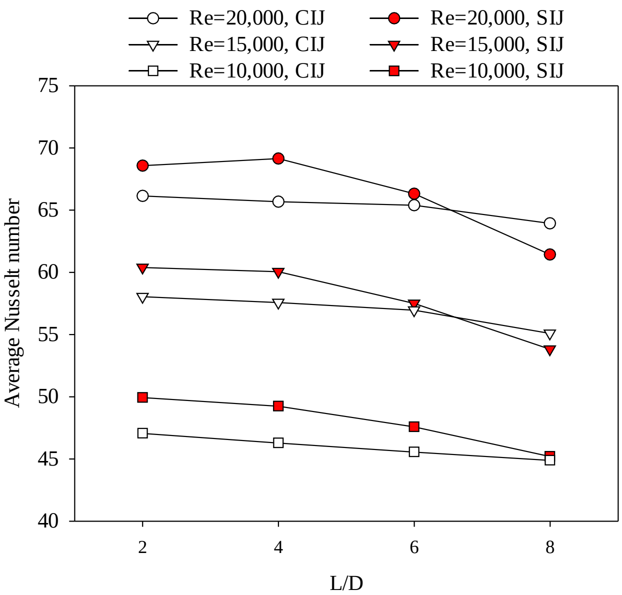



Figure 7. Effect of multi-channel twisted tape on average Nusselt numbers.

Influences of the jet-to-plate spacing ratio (*L*/*D*) and Reynolds number (*Re*) on the average Nusselt number (*Nu*) of both conventional impinging jet (*CIJ*s) and swirling impinging jets (*SIJs*) are shown in Fig. 7. For both conventional impinging jet (*CIJs*) and swirling impinging jets (*SIJs*), average Nusselt number (*Nu*) increased as jet-to-plate spacing ratio (*L*/*D*) decreased while Reynolds number (*Re*) increased since jets possessed higher axial velocity or higher jet momentum when impingements occurred. The results showed that the average Nusselt numbers (*Nu*) of conventional impinging jet (*CIJ*s) impinged at jet-to-plate spacing (*L*/*D*) of 2.0, 4.0 and 6.0 were higher than that impinged at the jet-to-plate spacing (*L*/*D*) of 8.0 by around 3.4%, 2.7% and 2.3% at Reynolds number (*Re*) of 20,000, respectively while those of swirling impinging jets (*SIJs*) impinged at jet-to-plate spacing (*L*/*D*) of 2.0, 4.0 and 6.0 were higher than that impinged at the *L*/*D* of 8.0 by around 11.6%, 12.5% and 7.9% at Reynolds number (*Re*) of 20,000, respectively.

## IV. Summary

In the present work, the temperature field and Nusselt number distribution on the impinged surface of conventional impinging jets (*CIJ*s) and swirling impinging jets (*SIJs*) induced by nozzle with centrally hollow helical-tape were compared. Experiments were carried out at various jet-to-plate spacing ratios and Reynolds numbers. The formation of swirl flow of swirling impinging jet (*SIJ*s) helped in improving the uniformity of local Nusselt number (*Nu*) and also average *Nu*, as compared to those of conventional impinging jets (*CIJ*s). At similar test conditions, the swirling impinging jets (*SIJs*) impinged at jet-to-plate spacing (*L*/*D*) of 2.0, 4.0 and 6.0 yielded higher averaged Nusselt number than the conventional impinging jets (*CIJ*s) up to 3.7%, 5.3% and 1.4%, respectively. However, at jet-to-plate spacing (*L*/*D*) of 8.0, the swirling impinging jet (*SIJ*) yield lower average Nusselt numbers than the corresponding conventional impinging jet (*CIJ*) by around 3.9% at Reynolds number (*Re*) of 20,000. In addition, average Nusselt number (*Nu*) increased as jet-to-plate spacing (*L*/*D*) decreased while Reynolds number (*Re*) increased for both conventional impinging jets (*CIJ*s) and swirling impinging jets (*SIJs*).

## Conflict of Interest

The authors declare no conflict of interest.

## Author Contributions

Smith Eiamsa-ard; conducted the research and wrote the paper

Kengkla Kunnarak; wrote the paper

Khwanchit Wongcharee; analyzed the data

Varesa Chuwattanakul; analyzed the data and wrote the paper

All authors had approved the final version.

## References

[1] C. Nuntadusit, M. Wae-hayee, A. Bunyajitradulya, and S. Eiamsa-ard, "Heat transfer enhancement by multiple swirling impinging jets with twisted-tape swirl generators," *Int. Comm. Heat Mass Transfer*, vol. 39, pp. 102-107, 2012.

[2] V. Hindasageri, R. P. Vedula, and S. V. Prabhu, "Heat transfer distribution of swirling flame jet impinging on a flat plate using twisted tapes," *Int. J. Heat and Mass Transfer*, vol. 91, pp. 1128-1139, 2015.

[3] K. Nanan, K. Wongcharee, C. Nuntadusit, and S. Eiamsa-ard, "Forced convective heat transfer by swirling impinging jets issuing from nozzles equipped with twisted tapes," *Int. Comm. Heat Mass Transfer*, vol. 39, pp. 844-852, 2012.

[4] M. Wannassi and F. Monnoyer, "Fluid flow and convective heat transfer of combined swirling and straight impinging jet arrays," *Applied Thermal Eng*., vol. 78, pp. 62-73, 2015.

[5] S. Eiamsa-ard, K. Nanan, and K. Wongcharee, "Heat transfer visualization of co/counter-dual swirling impinging jets by thermochromic liquid crystal method," *Int. J. Heat Mass Transfer*, vol. 86, pp. 600-621, 2015.

[6] B. Markal, "Experimental investigation of heat transfer characteristics and wall pressure distribution of swirling coaxial confined impinging air jets," *Int. J. Heat and Mass Transfer*, vol. 124, pp. 517-532, 2018.
[7] K. Wongcharee, V. Chuwattanakul, and S. Eiamsa-ard, "Influence of CuO/water nanofluid concentration and swirling flow on jet impingement cooling," *Int. Comm. Heat and Mass Transfer*, vol. 88, pp. 277-283, 2017.
[8] A. Ianiro and G. Cardone, "Heat transfer rate and uniformity in multichannel swirling impinging jets," *Applied Thermal Eng*., vol. 49, pp. 89-98, 2012.
[9] K. Wongcharee, V. Chuwattanakul, and S. Eiamsa-ard, "Heat transfer of swirling impinging jets with $TiO_2$-water nanofluids," *Chemical Eng. and Processing: Process Intensification*, vol. 114 pp. 16-23, 2017.
[10] K. Nanan, and P. Eiamsa-ard, "Heat transfer of swirling jet impinging on a flat surface with swirl generators," *J. Res. App. Mech. Eng*., vol. 2, pp. 103-110, 2014.
[11] M. A. R. Sharif, "Numerical investigation of round turbulent swirling jet impingement heat transfer from a hot surface," *Computational Thermal Sciences*, vol. 8, pp. 489-507, 2016.
[12] L. Xu, J. Lan, Y. Ma, J. Gao, and Y. Li, "Numerical study on heat transfer by swirling impinging jets issuing from a screw-thread nozzle," *Int. J. Heat and Mass Trans*., vol. 115, pp. 232-237, 2017.
[13] S. M. Illyas, B. R. Ramesh Bapu, and V. Venkata Subba Rao, "Heat transfer and flow visualization of swirling impinging jet on flat surface using helicoid inserts," *J. Vis*., vol. 21, pp. 729-749, 2018.
[14] S. Eiamsa-ard, C. Nuntadusit, K. Wongcharee, and V. Chuwattanakul, "An impingement cooling using swirling Jets induced by helical rod swirl generators" *Int. J. Turbo and Jet Engines*, vol. 35, pp. 241-250, 2018.
[15] K. Bakirci, K. Bilen, "Visualization of heat transfer for impinging swirl flow," *Exp. Therm. Fluid Sci*., vol. 32, pp. 182-191, 2007.



**Smith Eiamsa-ard** is an Associate Professor of mechanical engineering at Mahanakorn University of Technology, Thailand. He obtained his D.Eng. in mechanical engineering from King Mongkut's Institute of Technology Ladkrabang (KMITL). His research interests include heat and fluid flow, passive heat transfer enhancement, heat transfer enhancement with swirl flow devices, and computational fluid dynamics.

**Kengkla Kunnarak** received B. Eng. in Mechanical Engineering from South-East Asia University and M. Eng. from Mahanakorn University of Technology, Thailand. He is currently D. Eng. candidate in Department of Mechanical Engineering, Mahanakorn University of Technology, Thailand. His main research is focused on heat transfer enhancement with active and passive methods.

**Khwanchit Wongcharee** is an Associate Professor of chemical engineering at Mahanakorn University of Technology, Thailand. She received her Ph.D. in Chemical Engineering from University of New South Wales. Her research focuses on heat transfer enhancement and renewable energy.

**Varesa Chuwattanakul** is an Assistant Professor at the Department of Food Engineering at King Mongkut's Institute of Technology Ladkrabang (KMITL), Thailand. She obtained her M.Eng. and D.Eng. degrees from Osaka University, Japan. Her main research is focused on food processing, drying technology, drying process with impinging jet, application of food biotechnology, and food microbiology.