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Technical Note

Turbulent heat transfer from a flat surface to a swirling round impinging jet

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1. Introduction

Impinging jets have been widely used for the heat transfer augmentation in a variety of engineering applications such as cooling of hot steel plates, tempering of glass, drying of papers and films, cooling of turbine blades and electronic components. The common feature of impinging jet is the heat transfer enhancement in the stagnation region and a rapid decay of heat transfer in the wall jet region due to the boundary layer buildup on the target surface.

One of the important parameters affecting impinging jet heat transfer is the flow condition at the nozzle exit. The swirl flow at the nozzle exit would alter the jet-spreading rate, flow entrainment and turbulence characteristics before its impingement on the surface. Swirl flows result from the effect of a spiraling motion (i.e., tangential component) imparted in a flow which could be generated by swirl vanes or axial-plus-tangential flow entry to the main axial flow. It is important to understand the swirling effect on flows and heat transfer so that distinctions between favorable and undesirable effects of swirl to many flow and heat transfer processes could be made. In the swirling jet, the degree of jet growth, entrainment of ambient air, and jet decay are affected by the degree of swirl.

A few papers have been published to investigate heat transfer characteristics with a swirling impinging jet. Ward and Mahmood [1] used naphthalene sublimation technique to investigate the effect of mass and heat transfer on a flat surface from a swirling impinging jet. They concluded that the swirl has an unfavorable effect on heat transfer in terms of both local and average value for the parameters tested. Huang and El-Genk [2] used a swirl generator made of a cylindrical plug with four narrow channels to provide swirl to a single and multiple air impinging jets. They reported that for the single jet with swirl, the radial heat transfer distributions become more uniform with higher degree of swirls and larger nozzle-to-surface distance. Owsenek et al. [3] carried out numerical investigations of impinging jet with superimposed swirls. However, their study was limited to the laminar flow regime.

In the present study, the local Nusselt numbers are measured for a swirling round turbulent jet impinging on the flat plate. The experiments are made for the jet Reynolds number ($Re = 4\dot{m}/\pi\mu d$, where $\dot{m}$ is the mass flow rate measured by the orifice flow meter and d is the pipe nozzle diameter) of $Re = 23,000$, nozzle-to-plate distance of $L/d = 2$–10 and swirl number of $S = 0$–0.77.

2. Experimental apparatus and analysis

A schematic diagram of the apparatus is shown in Fig. 1. The apparatus consist of a blower, a heat exchanger, an orifice flow meter, a long straight pipe with an inner diameter of $d = 3.4$ cm and a length of $Z = 194$ cm, the vane-type swirl generator, and a heated flat plate. The swirl generator is located at the end of the pipe nozzle. A heat exchanger is used to maintain the jet temperature at the nozzle exit within ±0.2°C of the ambient temperature.

The test model is made of 0.5 cm thick Plexiglass plate to which the gold film Intrex (a gold-coated polyester substrate sheet) is glued. An electrically heated gold film Intrex is used to create a uniform heat flux on the impinging plate surface. The temperature on the surface is determined using a thermochromic liquid crystal (Hallcrest "R35C1W") sprayed on the Intrex surface and a digital color image processing

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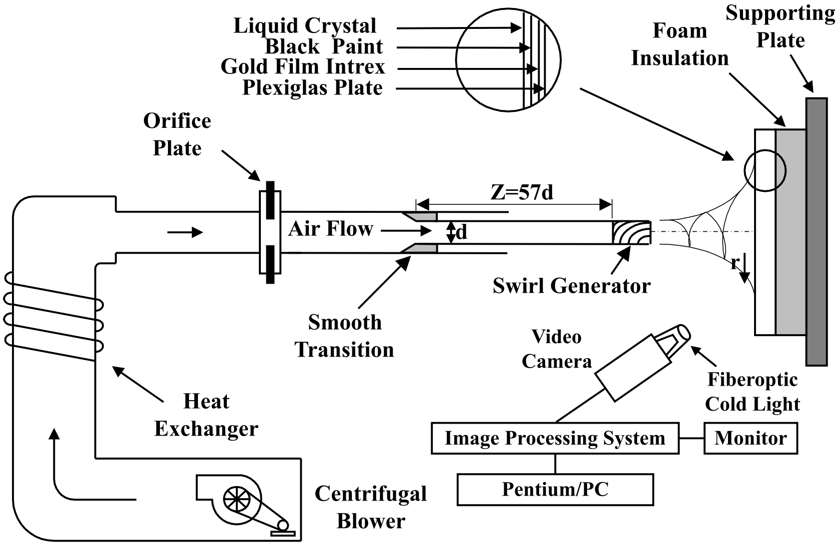

Fig. 1. Schematic diagram of the apparatus for the swirling impinging jet experiment.

system as a means of the quantitative color determination on the liquid crystal. A detailed description of the digital color image processing system is given in [4].

Fig. 2 shows the schematic designs of four vane-type swirl generators used in the experiment. The swirl generator is made of aluminum. It is $l = 4$ cm long with its outer radius of $R = 1.7$ cm and inner radius of $r_1 = 0.8$ cm and consists of eight vanes each having a thickness of $t = 2$ mm. The swirl number suggested by Kerr and Fraser [5] is calculated from

$$S = \frac{2}{3}\left[1 - \left(\frac{r_1}{R}\right)^3 / 1 - \left(\frac{r_1}{R}\right)^2\right] \tan\theta, \tag{1}$$

where θ is angle between swirl vane and vane axis. In the present research, the four swirl generators with $S = 0(\theta = 0°)$, $0.21(\theta = 15°)$, $0.44(\theta = 30°)$ and 0.77

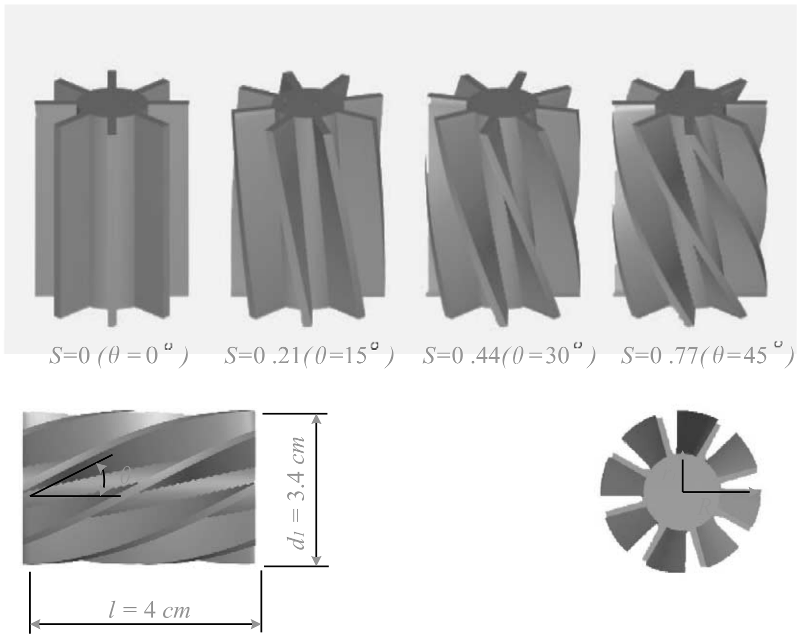

Fig. 2. Schematic designs of the vane-type swirl generators.

($\theta = 45°$) are used. The measurement technique in this study, described by Lee et al. [6,7], provides a method for determining the surface isotherms using liquid crystals. By electrically heating a thin gold-coating on the Intrex, an essentially uniform wall heat flux condition is established. The heat flux can be adjusted by changing the current through the Intrex, which changes the surface temperature. Under the uniform heat flux condition, an isotherm on the Intrex surface corresponds to a contour of a constant heat transfer coefficient. The local Nusselt number at the position of the particular color being observed is calculated from

$$Nu = q_v d / k(T_w - T_j), \tag{2}$$

where, T_w is the wall temperature determined by liquid crystal, T_j is the jet temperature and q_v is the net heat flux obtained by subtracting the heat losses due to radiation and conduction from the total heat flux on the Intrex.

The uncertainty analysis has been carried out using the method by Kline and McKlintock [8], and the maximum uncertainty in the Nusselt number for $L/d = 10$, $S = 0.77$ and $r/d = 4.56$ at $Re = 23{,}000$ is 3.33%. The present uncertainty estimates are based on 20:1 odds (i.e., 95% confidence level of both the precision and bias errors).

3. Result and discussion

Fig. 3 shows that the stagnation point Nusselt number (Nu_{st}) has a strong dependence on the swirl number. It is observed that Nu_{st} at the same Reynolds number of $Re = 23{,}000$ is higher with $S = 0$ than with no swirl generator up to $L/d = 10$. This is attributed to the fact that for $S = 0$, the flow passing through the swirl generator resembles the multiple jets, issuing from the multiple nozzles, thereby enhancing the heat transfer rate by the interaction between the jets. However, Nu_{st} are smaller with $S = 0.44$ and 0.77 than with no swirl generator case. The decrease in Nu_{st} with an increasing swirl number for the same L/d may be associated with the corresponding reduction in the jet arrival velocity at the impinging surface. Besides, when the swirling jet travels further down from the nozzle exit, an axial flux of the tangential momentum becomes weaker due to a strong mixing of the spreading jet, resulting in the decrease of Nu_{st}.

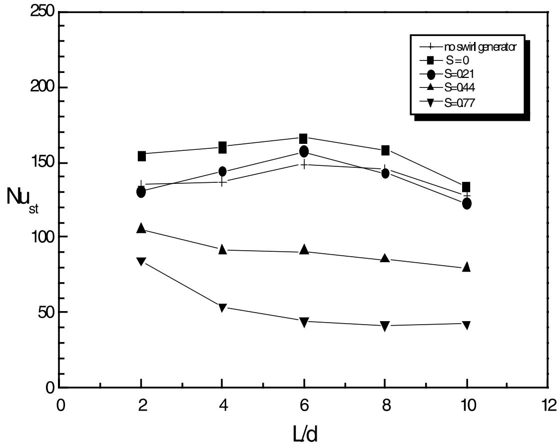

Fig. 3. Swirl effect on the stagnation point Nusselt number.

Fig. 4(a) shows the swirl effect on the radial Nusselt number distributions for $L/d = 2$. The Nu_{st} is smaller for all cases except for $S = 0$ than for no swirl generator. It is also seen that for $L/d = 2$, the location of maximum Nusselt number (Nu_{max}) is displaced from the center of the jet to the radial position, $r/d = 0.53, 0.74, 0.91$ and 1.2 for $S = 0$, 0.21, 0.44 and 0.77, respectively. This displacement of Nu_{max} location may be due to either the blockage at the center of the swirl generator for small swirl numbers of $S = 0$ and 0.21 or the high spreading rate for high swirl numbers of $S = 0.44$ and 0.77. The highest Nu_{max} occurs for $S = 0.21$, which may be due to the fact that for $S = 0.21$ both the multiple jets and swirling jet flow effects simultaneously occur at the same time, resulting in the heat transfer enhancement. The effect of the swirling motion of the flow is rarely seen at the wall jet region corresponding to $r/d \geqslant 4.0$, but Nu_{st} decrease with an increasing swirl number. It is also found from Fig. 4(a) that the local Nusselt numbers for the swirling jet flow are all higher in the region beyond $r/d \cong 0.7$ than those for the flow without swirl generator. This may be attributed to the fact that because the nozzle-to-surface distance is short ($L/d = 2$), the swirl flow passing through the swirl generator not only maintains the original momentum, but also becomes multiple jets with swirling motion. Fig. 4(b) shows the swirl effect on the local Nusselt number distributions for $L/d = 6$. For $S = 0$ and 0.21, the Nusselt numbers are higher than those without swirl generator in the entire region. This may be due to the fact that for $S = 0$, the jet possesses the multiple jet characteristics, and for $S = 0.21$, it has the characteristics of both the multiple jets and the swirling flow. On the contrary for $S = 0.44$ and 0.77, the local Nusselt numbers are smaller than without swirl in the region $r/d < 1.0$ because of the larger spreading rate of the swirling jet flow, which results in the reduction of heat transfer rate. In addition, it is observed that the Nu_{st} is largest for $L/d = 6$ because of the favorable interaction between the jets. For $L/d = 6$, the original characteristics of the swirling flow disappear as the flow travels a longer distance and the flow loses the multiple jet characteristics. It is also found that for $L/d = 2$, Nu_{max} occurs not at the stagnation point, but at $r/d = 0.74$ because of the blockage at the center of the

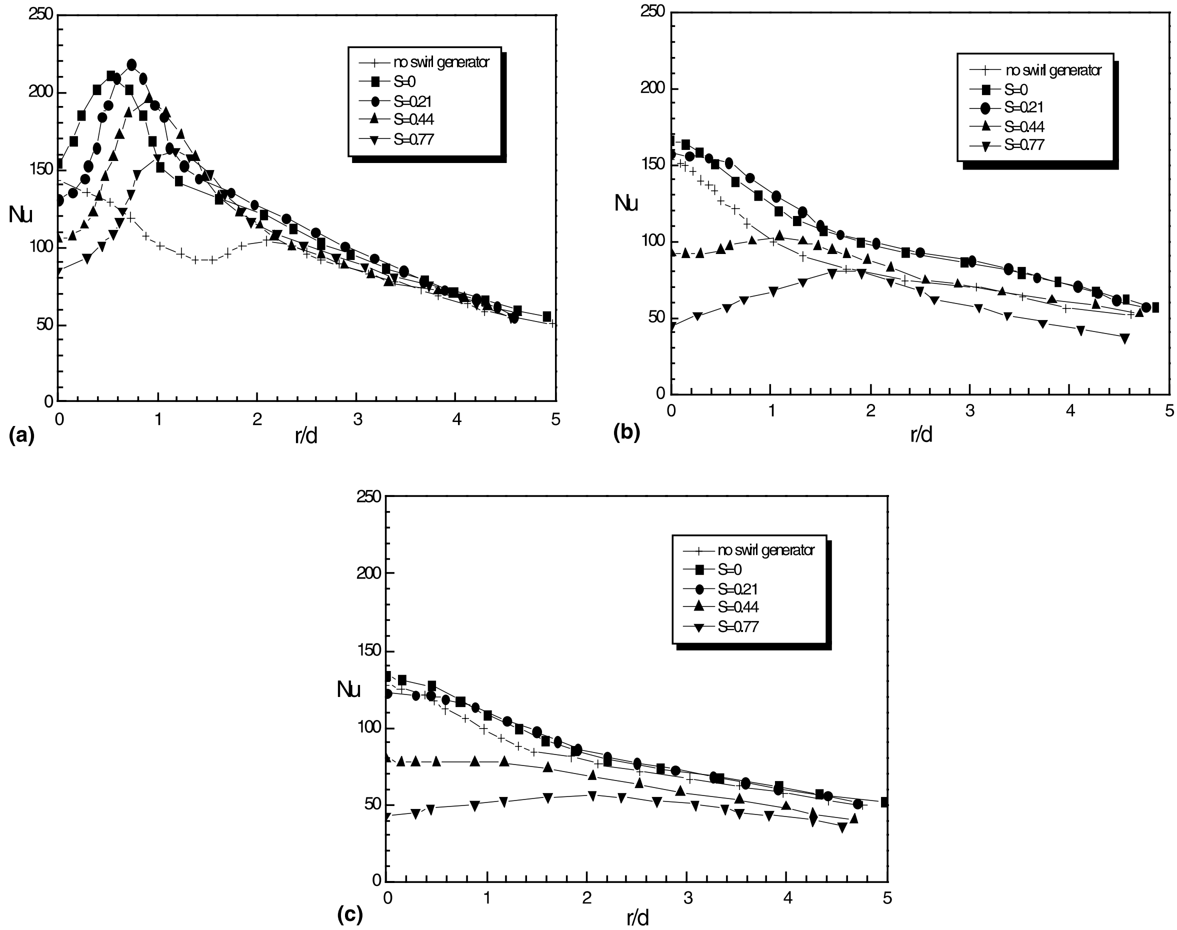

Fig. 4. Swirl effect on the local Nusselt number distributions along the plate: (a) $L/d = 2$; (b) $L/d = 6$; (c) $L/d = 10$.

swirl generator. It is attributed to the fact that the multiple jets and swirling jet flow effect become the maximum at the jet edge where a strong shear layer is created with large momentum. On the other hand, for $L/d \geqslant 6$, the heat transfer rate is largest at the stagnation point. Therefore, it is concluded that the shorter the nozzle-to-surface distance, the stronger the jet edge effect. Fig. 4(c) shows the case for $L/d = 10$. The trends are very similar to the case of $L/d = 6$. However, the differences between with swirl generator ($S = 0$ and 0.21) and without swirl generator are small and the local Nusselt numbers are nearly the same at the wall jet region beyond $r/d \cong 2$. On the other hand for $S = 0.44$ and 0.77, the Nusselt numbers are smaller than those without swirl in the entire region. It is worthy to note that the variation of Nusselt numbers for $S = 0.77$ is smallest within ±15–20% of the average Nusselt number in the entire region. Therefore, this configuration can be utilized for the uniform heating or cooling applications.

Fig. 5 shows the average Nusselt number (Nu_{avg}) distributions for the flows with and without swirl gen-

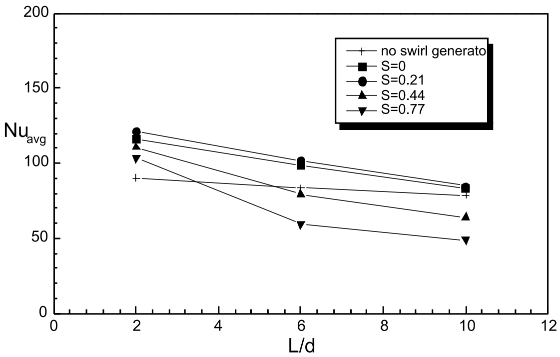

Fig. 5. Swirl effect on the average Nusselt number for target area of $0 \leqslant r/d \leqslant 0.48$.

erator. For $L/d = 2$, the average Nusselt numbers for the swirling flows are 28.84%, 34.74%, 22.54% and 14.94% larger than those for the non-swirling flow (without swirl generator) in the case of $S = 0,\ 0.21,\ 0.44$

and 0.77, respectively. It is due to the fact that when the nozzle-to-surface distance is short, the flow passing through the swirl generator becomes the multiple jets, and maintains the original force with a minimum spreading rate. On the contrary, the average Nusselt numbers for $S = 0.44$ and 0.77 at both $L/d = 6$ and 10 are 5.5–38.2% lower than that for the non-swirling flow. This behavior may be owing to the large spreading rate of the flow and small tangential momentum for these particular cases. It can also be speculated from Fig. 5 that for $S = 0.44$ and 0.77, the effect of the swirling flow is rarely seen for $L/d > 10$.

4. Conclusions

The experimental study has been carried out to investigate the heat transfer characteristics by a swirling round jet impinging upon the flat plate surface. The effect of the swirling jet flow is mainly represented near the stagnation point region and the highest Nu_{max} occurs for the swirl number of $S = 0.21$ and $L/d = 2$. For small nozzle-to-surface distance, $L/d = 2$, the average Nusselt numbers of the swirling jet flows are larger than with non-swirling flow (without swirl generator) for all swirl numbers. But, for large nozzle-to-surface distance, $L/d > 10$, the effect of the swirling jet flows is rarely seen. The variation of Nusselt numbers for $S = 0.77$ at $L/d = 10$ is smallest within ±15–20% of the average Nusselt number in the entire region. Therefore, this configuration can be utilized for the purpose of the uniform heating or cooling applications.

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