Effect of Orifice Geometry on Heat Transfer Characteristics of Array of Impinging Jets in Confined Channel

Makatar WAE-HAYEE and Chayut NUNTADUSIT
Energy Technology Research Center and Department of Mechanical Engineering,
Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla, 90112 Thailand
E-mail: wmakatar@eng.psu.ac.th

Abstract
The objective of this research is to study the attack angle effect of elongated orifice with aspect ratio of $AR = 8$ on the flow and heat transfer characteristics of jet impingement array. Both the inline and staggered arrangements, having arrays of 6×4 nozzles and attack angles at $\theta = 0^o$, $15^o$, $30^o$ and $45^o$, were examined. The jet-to-plate distance ($H$) and the jet-to-jet distance ($S$) were fixed at $H = 2D_E$ and $S = 3D_E$, respectively (where $D_E$ is the equivalent diameter). The experiments were carried out under jet Reynolds number at $Re = 13,400$. Temperature distributions on the impingement surface were measured using Thermochromic Liquid Crystal sheet (TLCs). Flow characteristics on the impingement surface were visualized using the oil film technique. Numerical simulation was employed to gain insight into the fluid flow via Computational Fluid Dynamics (CFD). The results indicate that the average heat transfer on the impingement surface tends to decrease when the attack angle becomes larger. However, local heat transfers at impingement regions in the upstream channel with attack angles of $\theta = 30^o$ and $45^o$ are higher than those at $\theta = 0^o$ and $15^o$, especially in the case of staggered arrangement.

Key words: Array of impinging jets, Elongated orifice, Heat transfer enhancement, Orifice arrangement, Thermochromic Liquid Crystal sheet (TLCs), Oil film technique, CFD

1. Introduction

Impinging jets are widely used in thermal industrial processes to efficiently enhance the heat transfer rate on an impingement surface. Their applications include cooling in gas turbine blades and electronic components, textiles and paper drying, glass and metal sheet quenching, and heating in solar air heater system (Viskanta, 1993; Brevet, et al., 2002; Chang, et al., 2007; Chauhan and Thakur, 2013). Many previous works have been devoted to study the flow and heat transfer characteristics of multiple impinging jets in a confined space (Brizzi, 2000; Dano and Liburdy, 2007; Geers, et al., 2008). Flow and heat transfer characteristics of multiple impinging jets are influenced by the interaction between adjacent jets before impingement on the surface and the wall jets formed by the adjacent jets colliding on the impingement surface (San and Lai, 2001). One other factor that influences multiple impinging jets in a confined space is the cross-flow, defined as the accumulated fluid from jet after impinging flows in the direction perpendicular to the jet impingement flow. Cross-flow has been found to significantly reduce the heat transfer of downstream impinging jets (Florschuetz, et al., 1981; Dano, et al., 2005; Katti and Prabhu, 2008). In more recent work, drilling of effusion holes, on the nozzle plate (Rhee, et al., 2003; Hoberg, et al., 2010), and at the impingement surface (Chiu, et al., 2009), in confined channel to eliminate the cross-flow have been attempted to enhance the heat transfer rate.

Nuntadusit, et al. (2012) have replaced conventional round orifices with elongated orifices to reduce the effect of cross-flow in a jet impingement array. They found that the heat transfer rate using impinging jets issuing from these substituted orifices is more uniform and higher than those from conventional round orifices. Another approach to enhance the heat transfer rate is to produce longitudinal vortices near the inclined rectangular blocks mounted on a smooth surface (Biswa, et al., 1996; Tian, et al., 2009). To apply the inclination interaction between the cross-flow and the jet issuing from the elongated orifice, the attack angle, defined as the major axis of the elongated orifice to the
cross-flow direction, should be examined.

The aim of the present study is to investigate the heat transfer enhancement due to the attack angle effect of the elongated orifice. The inline and staggered arrangements were also investigated. The temperature distribution on the impingement surface was measured using a Thermochromic Liquid Crystal sheet (TLCs), and the Nusselt number distribution was then evaluated using an image processing method. The oil film technique was used to visualize the characteristic of the flow on the impingement surface. The numerical simulation employed to gain insight into the fluid flow was visualized via commercial software, ANSYS ver. 13.0 (Fluent).

2. Experimental setup and method
2.1 Experimental model and parameters

An experimental model of jets discharging from orifices and impinging normal to the opposite surface in a confined rectangular channel is shown in Fig. 1. The spent jet flowing parallel to the channel exit, called cross-flow, is exhausted at the end of channel with one side opening. The origin of the Cartesian coordinate system was located on the impingement surface as shown in Fig. 1. The Y-axis is normal to the impingement surface, while the X- and the Z-axes are, respectively, along the streamwise and the spanwise directions of the cross-flow.

The array of jet configuration for the inline and the staggered arrangements has 24 jet holes distributed in 6 columns and 4 rows as shown in Fig. 2. All orifices having aspect ratio of $AR = 1$ and 8 have the same exit area of 136.8 mm$^2$, and each round orifice has an equivalent diameter ($D_E$) of 13.2 mm, as shown in Fig. 3. The attack angle, defined as the angle between the major axis of the elongated orifice to the cross-flow direction (X-axis), was varied at $\theta = 0^\circ, 15^\circ, 30^\circ$ and $45^\circ$, shown also in Fig. 3. The jet-to-plate distance was fixed at $H = 2D_E$, and both arrangements have the same jet-to-jet distances of $S = 3D_E$. The experiments were carried out at jet Reynolds number of $Re = 13,400$, based on the average velocity and equivalent diameter. More details regarding the experimental model have been described in the recent sequential works (Nuntadusit et al., 2012; Wae-hayee et al., 2013).

2.2 Experimental apparatus

The schematic diagram of this experimental apparatus is shown in Fig. 4. Temperature controlled air was forced through a calibrated orifice flow meter and flowed into the jet chamber. To ensure a uniform flow field approaching the
orifice plate, the jet chamber was equipped with two layers of perforated plates and two layers of mesh plates. It should be noticed that the nature jet flow of each orifice related to location of each orifice distributed on jet plate in confined channel. The jet temperature, referred to as the inlet temperature of the test section, was controlled at 27.0°C (± 0.2 °C).

<table>
<thead>
<tr>
<th>AR=1</th>
<th>AR=8</th>
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<tbody>
<tr>
<td>D_e=13.2 mm</td>
<td>L= 33.6 mm</td>
</tr>
<tr>
<td>W = 4.2 mm</td>
<td></td>
</tr>
<tr>
<td>Attack angle</td>
<td>θ = 0°, 15°, 30° and 45°</td>
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Fig. 3 The details of orifice geometries with identical cross-section area and attack angle.

2.3 Heat transfer measurement and data reduction

The air jets with constant temperature discharging from the orifice plate were impinged on the heated surface for cooling. The wall temperature on the impingement surface was measured by using the TLC sheet attached on the rear of this surface. The CCD camera was used to capture color patterns on the TLC sheet, and the images of the color patterns were subsequently translated into temperatures via a calibration (Nuntadusit, et al., 2012; Wae-hayee, et al., 2013).

The local heat transfer coefficient by forced convection of the impinging jet on the heated surface can be evaluated from

\[
\dot{q}_{\text{input}} = \frac{I^2 \cdot R}{A} \quad (1)
\]

\[
h = \frac{\dot{q}_{\text{input}} - \dot{q}_t - \dot{q}_c}{T_w - T_j} \quad (2)
\]
where, $I$ and $R$ are the electrical current and the thermal resistance of the stainless steel foil, $\dot{q}_e$ and $\dot{q}_r$ are the heat loss to the environment by radiation and convection, $T_w$ and $T_j$ are the wall and jet temperatures, respectively.

The local Nusselt number can be calculated from

$$ Nu = \frac{h \cdot D}{k} $$

(3)

where $k$ is a jet thermal conductivity. The uncertainty of Nusselt number is between 3.33% and 4.86% using calculation method that suggest by Kline and McClintock (1953).

2.4 Flow visualization on the impingement surface

Flow visualization on the impingement surface was carried out using the oil film technique. The oil mixture was prepared from liquid paraffin, titanium dioxide and oleic acid. A transparent plastic plate was used as the jet impingement wall and was uniformly painted with the oil. A video camera was used to record the change of oil film patterns on the impingement surface after jet impinging.

2.5 Numerical simulation

Flow characteristics of the impinging jets in the confined channel were investigated using Computational Fluid Dynamics (CFD) technique (The heat transfer characteristics were not investigated). The commercial software, ANSYS ver.13.0 (Fluent), was used in this present study. The numerical model is shown in Fig. 5, and is was identical to the experimental model in its geometries, dimensions, and jet Reynolds number. Computations were conducted by solving Reynolds average continuity and Navier-Stokes equations under existing boundary conditions with the SST $k-\omega$ turbulence model. This turbulence model has been adopted in solving many numerical simulations of jet impingement problems (Chandratilleke, et al., 2010; Heo, et al., 2011).

![Fig. 5 CFD model of impinging jet array in confined channel](image)

The non-uniform grid system was finely generated for regions near the orifice holes and the impingement surface. The number of generated grids was varied to achieve an accurate solution with low computational cost. The steady flow without effect of gravity was considered. All boundary conditions applied were identical to those specified in the experimental conditions. A solution method was based on SIMPLE algorithm with second order upwind for all spatial discretization. Solutions were considered to be convergent when the normalized residual of all algebraic equations was less than the prescribed value of $1 \times 10^{-4}$. Details of numerical techniques employed in this article have been described in Wae-hayee, et al. (2013).

3. Results and discussions

3.1 Flow characteristics

Flow patterns of impinging jets on the impingement surface using the oil film technique are shown in Fig. 6. The
black regions represent the impingement regions where the oil film has been completely removed, and the white regions represent those region with oil film. The velocity vector and contour of velocity in the Y-axis direction on Z-X plane near the impingement surface (1 mm above the surface) are shown in Fig. 7. Because the condition at the surface is no-slip, this position was chosen to represent the plane sufficiently near the surface. The Y-component velocity represents the velocity in the direction normal to the impingement surface, with positive direction towards the downstream of the jet that impinges on the wall. Area of high Y-component velocity contour identifies the impingement region of each cell. The velocity contours of both jet arrangements agree well with the flow patterns on the impingement surface as shown earlier in Fig. 6 by notifying the area of high Y-component velocity of CFD corresponding to the black area of wall. This high degree of agreement can be correspondingly used to explain the characteristics of jet flow from the CFD results on the heat transfer behavior in the next section.

Fig. 6  Flow patterns of impinging jets on the impingement surface using the oil film technique were shown. The black regions represent the impingement regions (oil film completely removed), and the white regions represent the region with oil film. The impingement region of each cell was shifted to the downstream direction due to the effect of cross-flow.

In the case of $AR = 1$ for both inline and staggered arrangements as shown in Fig. 6(a) and (b), the impingement region (Black area) of each cell is shifted to the downstream direction due to the effect of cross-flow. This cross-flow effect on jet impingements with inline arrangement is less significant than on those with the staggered arrangement. The flow characteristic can be explained by the observation that the cross-flow easily passed through space between rows of inline jets, whereas it was blocked by downstream jets in the case of staggered arrangement (Wae-hayee, et al., 2013). This can be seen at the cancellation of the impingements at downstream region ($13 \leq X/D \leq 20$). Especially in the last jet column, there are no impingement regions as shown in Fig. 6(a) and no areas of high Y-component velocity contour as shown in Fig. 7(a). It can also be observed that the deflection of downstream impinging jets with staggered arrangement as shown in Fig. 8(b) is stronger than those with the inline arrangement as shown in Fig. 8(a).

In the case of orifice with $AR = 8$ at $\theta = 0^\circ$ for inline arrangement, it was found that the cross-flow effect could be minimized by these elongated orifices, indicated by getting the larger impingement regions (Black areas) of $AR = 8$ (Fig. 6(c)) than those the $AR = 1$ (Fig. 6(a)). For the case of staggered arrangement, the impingement regions at the downstream area ($10 \leq X/D \leq 20$) of $AR = 8$ (Fig. 6(d)) are larger than those the $AR = 1$ (Fig. 6(b)).

In the case of $AR = 8$ with $\theta = 15^\circ$ for the inline arrangement as shown in Fig. 6(e), the impingement region of each cell is directly extended in the X-axis and obliquely extended in the Z-axis. However, when the attack angle becomes
\( \theta = 30^\circ \) and \( 45^\circ \), the impingement regions at \( 4 \leq X/D \leq 20 \) seem to be smaller, as shown in Fig. 6(g) and (i). Particularly for the case of the largest attack angle, \( \theta = 45^\circ \), there is no impingement region in the downstream area (\( 13 \leq X/D \leq 20 \)) because the high cross-flow velocity strikes on the jet flow with the large attack area. This can be seen in Fig. 8(e) for the case of \( AR = 8 \) at \( \theta = 45^\circ \) that the downstream impinging jets (columns 5 and 6) tend to cross-flow the pathline and are almost completely cancelled.

The extension on the impingement regions can found in two characteristics. (1) The extension of the impingement regions to the downstream direction is due to the cross-flow effect. (2) The oblique extension of impingement regions to the +Z direction is from the attack angle effect. The jets are deflected in the +Z direction along the orifice configurations. This deflection is stronger when the location of the jets is far from the first jet column. Moreover, the deflection of jets with staggered arrangement is larger than the inline arrangement.

3.2 Heat transfer characteristics on the impingement surface

Contours of local Nusselt numbers on the impingement surface for \( Re = 13,400 \) for both inline and staggered arrangements are shown in Fig. 9, respectively. These contours correspond to the oil film patterns on the impingement surface in Fig. 5 and the contours of the Y-component velocity near the impingement surface in Fig. 7. Areas of high Nusselt number (\( Nu \geq 180 \)) are impingement regions that relate to the black areas of flow patterns on the surface (Fig. 6) and areas of high Y-component velocity contours on flow fields above the surface (Fig. 7). Generally, the Nusselt number distributions on the surface of impinging jets for \( AR = 8 \) at \( \theta = 0^\circ \) are higher than those for \( AR = 1 \), and the areas of high Nusselt number are shifted further downstream. The Nusselt number distributions of inline arrangement are less significantly effected by the cross-flow than those with staggered arrangement expressing larger high heat transfer areas and more uniform Nusselt number distributions on the surface (Nuntadusit, et al., 2012).

The characteristics of Nusselt number distributions for the case of a small attack angle, \( \theta = 15^\circ \), are comparable to those with the attack angle of \( \theta = 0^\circ \), but are quite different from the case of large attack angles at \( \theta = 30^\circ \) and \( 45^\circ \). The Nusselt number in the downstream region (\( 10 < X/D < 20 \)) of both inline and staggered arrangements abruptly decreases...
when the attack angle is larger due to increasing attacking area between the cross-flow and the impinging jets, as discussed earlier. However, when the specific area on this surface is considered, local heat transfer at the upstream region for large attacking angles $\theta = 30^\circ$ and $45^\circ$ is found to be higher than those for attacking angles $\theta = 0^\circ$ and $15^\circ$, especially in the case of staggered arrangement. These results are also confirmed by flow visualization on the region with larger impingement area.

Fig. 8 The velocity vectors and the velocity contours on X-Y from CFD results are shown. The jets deflected to downstream direction due to cross-flow effect. This deflection was stronger when the location of the jets was far from the first jet column, and the deflection of jets with staggered arrangement was larger than the inline arrangement.

Fig. 9 Contours of local Nusselt number on the impingement surface from experimental results are shown. The Nusselt number distributions of inline arrangement are less significantly affected by the cross-flow than those with staggered arrangement.

The areas of high Nusselt number (corresponding to impingement regions) of each impingement cell for inline arrangement with $AR = 8$ at $\theta = 0^\circ$ and $15^\circ$ (Fig. 9(c) and (e)) are uniformly distributed throughout X-axis. These areas become smaller when the attack angle becomes larger, $\theta = 30^\circ$ and $45^\circ$. Especially for the case of $AR = 8$ at $\theta = 45^\circ$, there are no impingement regions for the last jet column as shown in Fig. 9(i) corresponding to the cancellation of impinging jet at the same column as shown in Fig. 8(e). This is due to a large blocked area from the long circumference of orifice with $AR = 8$ and the large attack angle with significant cross-flow effect at downstream direction as discussed.
earlier in flow characteristics. These areas become smaller at downstream areas as is clearly seen for the case of the staggered arrangement shown in Fig. 9.

Indeed, the areas of high Nusselt number ($Nu \geq 180$) in each impingement cell are extended in the $X$-axis and obliquely extended in the $+Z$-axis when the attack angle is larger. This corresponds well to those impingement regions on the surface as shown before in Fig. 6 from the oil film technique and in Fig. 7 from CFD results. The extension of these high value areas in the $X$-axis is from the effect of cross-flow, and the oblique extension of these areas in the $+Z$-axis is from the effect of attack angle.

4. Conclusions

In this work, the effects of attack angle of elongated orifice with $AR = 8$ on flow and heat transfer characteristics of impinging jet array with inline and staggered arrangements were examined experimentally and numerically. The main finding can be summarized as follows:

1. The effect of small attack angle ($\theta = 15^\circ$) from the elongated orifice on the flow and heat transfer of impinging jet array are rather similar to the case of attack angle at $\theta = 0^\circ$. It is, however, quite different when the attack angle become larger at $\theta = 30^\circ$ and $45^\circ$. At downstream regions especially, heat transfer rapidly decreases and deflection of the jets veers towards the downstream direction without actual impingement. The decrease in heat transfer and deflection of the jets around these downstream regions for staggered arrangement is more prominent than those of the inline one arrangements.

2. Generally, heat transfer on the impingement surface decreases more when the attack angle becomes larger. However, when the specific area on this surface is considered, local heat transfer at the upstream region for large attack angles $\theta = 30^\circ$ and $45^\circ$ is found to be higher than those for attack angles $\theta = 0^\circ$ and $15^\circ$, especially in the case of staggered arrangement. These results are also confirmed by flow visualization on the region with larger impingement area.

Acknowledgments

This research is supported by grants from the Thailand Energy Policy and Planning Office, Ministry of Energy and the Engineering faculty of Prince of Songkla University.

References


**Nomenclatures**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$AR$</td>
<td>Aspect ratio of elongated orifice, -</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter of orifice, m</td>
</tr>
<tr>
<td>$DE$</td>
<td>Equivalent diameter of orifice, m</td>
</tr>
<tr>
<td>$H$</td>
<td>Jet-to-plate distance, m</td>
</tr>
<tr>
<td>$h$</td>
<td>Heat transfer coefficient, W/m²·K</td>
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<tr>
<td>$k$</td>
<td>Jet thermal conductivity, W/m·K</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of elongated orifice, m</td>
</tr>
<tr>
<td>$Nu$</td>
<td>Nusselt number, -</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number of jet, -</td>
</tr>
<tr>
<td>$S$</td>
<td>Distance from air-augmented duct outlet to surface, m</td>
</tr>
<tr>
<td>$W$</td>
<td>Width of elongated orifice, m</td>
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**Greek symbols**

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\theta$</td>
<td>Attack angle, °</td>
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