HEAT TRANSFER ENHANCEMENT ON A SURFACE UNDER ARRAYS OF IMPINGING JETS: EFFECT OF JET FLOW ARRANGEMENT

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Abstract: In this article, the effect of jet arrangement on flow and heat transfer patterns on a surface under multiple impinging jets were studied. An array of impinging jets with in-line and staggered arrangement were considered. The effect of crossflow exit orientations; a single and a double outlet were also investigated. The temperature distribution on an impinged surface was visualized by using thermochromic liquid crystal sheet (TLCs) and Nusselt number distribution was evaluated by using image processing method. The flow characteristic on the impinged surface was visualized by using oil film technique. The results show that an interaction between jet and crossflow can increase heat transfer at stagnation region with appropriated velocity ratios between jet velocity and crossflow velocity. The heat transfer rate of in-line arrangement was higher than the staggered arrangement 3.7 % for the single outlet and 25.7 % for double outlet.

Key Words: Array of impinging jets, Jet arrangement, Heat transfer enhancement, Liquid crystal sheet

1. INTRODUCTION

Impinging jets are widely used in many industries which required high heat transfer rate on surface like cooling of gas turbine blade, electronic device, combustion wall and compact high efficient heat exchanger. However, the heat transfer rate is high only in jet directly impinging region. When the high and uniform heat transfer distribution is required over a wide area for example: drying of film sheet, heating of steel sheet, multiple of impinging jets is usually used instead. An accumulated spent jet flow in a confined channel can be produced a crossflow. The crossflow is defined as the fluid flow in the direction perpendicular to the impingement flow [1].

Brizzi et al [2] illustrated the flow and temperature patterns on the impinged surface of array of jets with an in-line arrangement. The results of the flow pattern corresponded to the temperature pattern. Katti and Prabhu [1] studied the heat transfer rate of in-line arrangement of the array jet. The results showed the jet-to-jet distance at 4D better than 2D and 6D (D is nozzle diameter) and jet-to-plate distance at 1D and 2D have higher heat transfer rate.

Previous studies have been investigated on impingement heat transfer with the crossflow. There found the crossflow significantly reduced the heat transfer on impingement surface [3, 4 and 5]. In this research, the effect of both the in-line and staggered arrangement and the outlet orientation of spent air were studied. The investigations carried out of the array of jet impingement with jet-to-plate spacing for two time of jet diameter. The characteristics of local heat transfer and flow visualization on the impinged surface were investigated.

2. EXPERIMENTAL MODEL AND PARAMETERS

Fig. 1. Sketch of the confined channel with different crossflow exit orientations
The model in this experiment, the jets were discharged from array of circular orifices and then impinged normal to heated surface on opposite surface of rectangular duct. Fig.1 presents the sketch of two different exit orientations; the first is the single outlet (Fig.1 (a)) and the second is the double outlets (Fig.1 (b)). For the single outlet, the spent air was allowed to flow out from the test section with only one direction. For double outlets, the spent air allowed to flow out from the test section with opposite direction. An origin of the Cartesian coordinates was located at the impinged surface as shows in Fig.1. The X, Y and Z-axis are the streamwise, normal to the impinged surface and spanwise direction of duct, respectively.

Fig.2 illustrates the array of jet arrangement are the in-line and staggered arrangement and both arrangement are same number of 6x4 jet holes. A diameter of nozzle was D=13.2 mm. The jet-to-jet distance was fixed at S=3D and jet-to-plate distance was fixed at H=2D. All experiments were carried out at constant Reynolds number Re=12,700. In case of the staggered arrangement as shows in Fig. 2 (b), the confined wall of the lateral side was given jet-to-wall distance for S/2 (=1.5D) and this confined wall was given with same dimension for in case of the in-line arrangement as shows in Fig. 2 (a).

3. EXPERIMENTAL SETUP AND METHOD

3.1. Experimental setup

Fig.3 shows schematic view of the experimental apparatus. The blower (3HP) is used for generated the air jet. The air flows through a temperature controlled chamber and towards the orifice flow meter. The air subsequently passes through a jet chamber with constant cross-section 360-mm-wide, 360-mm-long and 850-mm-high. The jet chamber was equipped with two of
perforated plates and two of mesh plates to ensure that uniform flow approached to the nozzle plate. For all experimental conditions, the jet flow was controlled with constant flow rate at \( \text{Re} = V D / \nu = 12,700 \) and at constant temperature \( T_p = 27 \, ^\circ C \). The test section was mounted upon the jet chamber. In case of single outlet, the test section was mounted by wall with space 1.5D (S/2) from the column 1 as shows in Fig. 1 (a).

### 3.2. Heat transfer measurement

Fig. 3 shows the detail of test section for heat transfer measurement. The air with constant temperature was discharged from an orifice plate and impinged upon the heat transfer surface. The heat transfer surface was made of stainless steel foil (30-μm-thicknesses) which attached with TLC sheet on the rear side of jet impinged surface. The stainless steel foil was stretched between couple of copper bus bars. The heat transfer surface was heated by DC power supply that can supply current up to 40A passes through copper bus bars. An amount of electrical energy is dissipated in the stainless steel foil and it can be calculated from equation

\[
\dot{Q}_{\text{input}} = I^2 \cdot R \tag{1}
\]

where here, \( I \) is the electrical current and \( R \) is the electric resistance of stainless steel foil.

Then, the heated impinged surface was cooled by impinging jets. Hence, the local values of heat transfer coefficient (\( h \)) by force convection of jets can be evaluated from equation

\[
h = \frac{\dot{Q}_{\text{input}} - \dot{Q}_{\text{source}}}{A(T_w - T_j) - \dot{q}_c - \dot{q}_r} \tag{2}
\]

where \( \dot{q}_c = \sigma \varepsilon_{\text{TLC}} (T_w - T_j) \) and \( \dot{q}_r = h (T_w - T_j) \) are the heat loss transferred to the environment by radiation and convection, respectively. The \( T_w \) and \( T_j \) are the wall and jet temperature, the \( \sigma \) is a Stefan-Boltzmann constant, the \( \varepsilon_{\text{TLC}} \) is a emissive coefficient of the black background paint and the TLCs that has been given in [6], \( T_s \) is a surrounding temperature and \( h_c \) is a natural heat transfer coefficient that was calculated from natural convective heat transfer from the horizontal plate orientation to the surrounding.

The wall temperature (\( T_w \)) on the impinged surface was measured by using TLC sheet that attached on the rear side of jet impinged surface. The CCD camera was used to capture colour on TLC sheet. The images of colour pattern on TLC were converted from the RGB (Red, Green and Blue) colour system to the HSI (Hue, Saturation and Intensity) colour system. The Hue (H) value provides a convenient way to correlate the colour of TLC to their temperature in range of 28-40°C. The TLCs was calibrated with same location on the test section to keep all external factors constant. The local Nusselt number was calculated from

\[
Nu = \frac{hD}{k} \tag{3}
\]

where \( D \) is the diameter of orifice and \( k \) is a conductivity of air jet. An average Nusselt number was calculated from

\[
\overline{Nu} = \frac{hD}{k} \tag{4}
\]

where here, the average heat transfer coefficient \( h \) was calculated from Eq.(2) by replacing \( T_j \) to \( T_w \) that is a averaged temperature on the impinged surface.

### 3.3. Flow visualization on the impinged surface

The flow visualization on the impinged surface was illustrated by using oil film technique. The oil film was mixed by liquid paraffin, titanium dioxide and oleic acid. A transparent plastic plate was coated by oil film and it was replaced to the impinged surface. The CCD camera was captured the oil film flow on the impinged surface at each different time (30 second/frame).

### 4. RESULTS AND DISCUSSION

#### 4.1 Flow patterns on an impinged surface

Fig. 4 and 5 show the flow visualization on the impinged surface in case of double outlet (\( \text{Re}=12,700 \), After jet impinged 1200 second)
Fig. 5. Flow patterns on the impinged surface in case of single outlet (Re=12,700, After jet impinged 1200 second)

Fig. 6. Illustrate the crossflow passes through the array of jets with different nozzle arrangement

Fig. 5 shows the effect of nozzle arrangement on flow characteristics on the impinged surface in case of the single outlet. The flow pattern in case of in-line arrangement, the stagnation point (Small white point) of jet column 4-6 were shifted to the direction of crossflow. The distance between center of nozzle and stagnation point increased with increasing the number of column. For the column 4, 5 and 6, the shifted distance between center of nozzle to the stagnation point are 0.5D, 1.0D and 1.3D, respectively as shows in Fig. 5 (a). This deflection of jet can be illustrated the effect of crossflow on the jet flow, especially, the jet which located at last column (Column 6) near the outlet. The stagnation region was shifted far away from the center of jet. Moreover, the jets which located at last column (Column 6) in case of staggered arrangement (Fig.5 (b)), the stagnation region was located at over considered area (disappear on the considered area). The different characteristics of crossflow passes through the jets flow of the in-line and staggered arrangement were illustrate in Fig.6.

4.2 The detail of Nusselt number on the impinged surface

Fig. 7 and 8 show the local Nusselt number distribution on the impinged surface. The heat transfer rate in jet impingement regions of each jets was higher than heat transfer rate in region between jet and around it. The characteristic of heat transfer corresponded to the flow pattern on the impinged surface with same experimental condition. Similarly, the peak of heat transfer occured at the same location of the jet impinged region as show in Fig. 4 and 5.

Fig. 9 shows the spanwise averaged Nusselt number. In case of double outlet (Fig. 9 (a)), the peak of heat transfer of in-line arrangement dominated the peak from the staggered arrangement for all location of X-axis.
Otherwise, the location of peak of heat transfer of the single crossflow depended on the jet arrangement as show in Fig. 9 (b). The location of X>3D, the peak of heat transfer of the staggered arrangement dominated the peak from the in-line arrangement. Otherwise, the location of X<-1D, the peak of heat transfer of the in-line arrangement dominated the peak from the staggered arrangement.

![Fig. 9. Spanwise averaged Nusselt number (Tj=27°C, Re=12,700, Arrow represents the location of nozzle)](image)

5. CONCLUSION

In present study, the effects of jet flow arrangement and outlet orientations were experimentally investigated. The main results were shown as follows;

(1) The flow pattern on the impinged surface was corresponded to the heat transfer characteristic on the impinged surface with same experimental condition.

(2) The interaction between the jet and the crossflow can increase heat transfer at stagnation region with appropriated velocity jet and crossflow, otherwise, very high velocity of crossflow can decrease heat transfer in jet impingement region.

(3) The heat transfer rate of in-line arrangement was higher than the staggered arrangement 3.7 % for single outlet and 25.7 % for double outlets.

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