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Convective heat transfer of a row of air jets impingement excited by triangular tabs in a confined crossflow channel

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ABSTRACT

Computational and experimental studies were conducted to investigate the conjugated convective heat transfer produced by single row of impinging jets inside a confined channel with non-uniform initial crossflow issued from discrete holes. The effects of the crossflow-to-jet Reynolds number ratio and crossflow holes arrangement (inline or staggered in relative to the impinging jet holes) on the jet impingement behaviors were studied providing the same total cooling air mass flowrate. Particular attention was paid to examine the tab-excited jet impingement behaviors in a confined channel with non-uniform crossflow. The results show that the tabbed excitation on the improvement of convective heat transfer in the vicinity of impingement region is not as well as the situation where no initial crossflow is present. For the inline arrangement of crossflow holes, the location corresponding to the peak laterally-averaged Nusselt number is moved downstream and the peak laterally-averaged Nusselt number is decreased significantly under larger crossflow-to-jet Reynolds number ratios. While for the staggered arrangement of crossflow holes, the location corresponding to the peak laterally-averaged Nusselt number is not affected by the crossflow but the peak laterally-averaged Nusselt number is decreased monotonously with the increase of crossflow-to-jet Reynolds number ratio. Under small crossflow-to-jet Reynolds number ratio, the initial crossflow arrangement has little influence on the laterally-averaged Nusselt number distribution. Among three crossflow-to-jet Reynolds number ratios ranged from 0.5 to 2, the maximum relative difference of peak laterally-averaged Nusselt numbers between two different crossflow arrangements is occurred under crossflow-to-jet Reynolds number ratio of 1.

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1. Introduction

Jet impingement heat transfer is considered as a promising heat transfer enhancement scheme, witch has been widely applied in a wide variety of practical applications that aim to achieve intense heating, cooling or drying rates. The heat and mass transfer produced by the turbulent impinging jets had been characterized in a number of investigations reviewed by Viskanta [1], Weigand and Spring [2]. Basic investigations on single impinging jet with and without cross-flow were conducted for example by Goldstein and Behbahani [3], Baughn and Shimizu [4], and Lee et al. [5]. It has been illustrated that the heat transfer produced by an impinging jet depends mainly on a number of parameters, including the jet Reynolds number, the jet-to-target spacing, the presence of a confining wall, and the Prandtl number, etc. Recently, convective heat transfer enhancement, increase in the heat transfer rate uniformity, improvement in the coverage of the impingement surface, and decrease in the coolant mass flow rate by using passive and active means are still some of the concerns of jet impingement.

It is well known that the nozzle geometry has a significant effect on the heat transfer produced by the jet impingement. Colucci and Viskanta [6], Brignoni and Garimella [7] made investigations on the heat transfer produced by the orifice nozzles with contoured outlets. They found that the heat transfer produced by the orifice nozzles with contoured outlets was up to 20–30% higher than that produced by a simple square orifice nozzle. These changes in the orifice geometry modified the heat transfer to the impinging jet because they affected the development of the jet before it impinged on the plate. Three orifice nozzles having different nozzle exit configuration (such as the sharp-edged, standard

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Nomenclature

Bi	Biot number
d	diameter of jet hole (m)
h	convective heat transfer coefficient (W/m^2 K)
H	channel height or jet-to-target spacing (m)
L	channel streamwise length (m)
$\dot{m}$	total mass flow rate (kg/s)
n	number of discrete holes
Nu	Nusselt number
P	spanwise pitch between adjacent jets (m)
q	heat flux (W/m^2)
Re	Reynolds number
S	streamwise pitch between impinging jet and initial crossflow outlet (m)
T	temperature (K)
U	flow velocity (m/s)
W	channel spanwise width (m)
x	x-direction, streamwise distance
y	y-direction
z	z-direction

Greek letters

δ	target thickness (m)
ε	emissivity
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Ns/m^2)
ν	kinematic viscosity (m^2/s)
σ	Stefan–Boltzmann constant

Subscripts

a	ambient
av	spanwise-averaged
b	back
c	relative to crossflow, convection
inj	jet at inlet
j	relative to jet
r	relative to radiation
s	relative to solid plate
w	relative to wall

edged and square-edged orifices) were tested by Lee and Lee [8]. In the stagnation region, the sharp-edged orifice jet yielded significantly higher heat transfer rates than either the standard-edged orifice jet or square-edged orifice jet. For the dimensionless jet-to-target spacing of 2, the stagnation point Nusselt numbers of orifice jets were nearly 25–55% higher than those of fully-developed pipe jets and approximately 50–75% higher than those of contoured nozzle jets. They pointed out that the heat transfer enhancement by the orifice jet was attributed to the large velocity gradient and high turbulence intensity. The variation in nozzle exit configuration altered the initial flow structure at the nozzle exit, and hence influenced on the local heat transfer characteristics. Koseoglu and Baskayab [9] investigated the effects of jet inlet geometry and aspect ratio on local and average heat transfer characteristics of totally nine confined impinging jets including circular, elliptic and rectangular jets with different aspect ratios. It was suggested that the impinging jet with higher aspect ratio could be used as a passive enhancement technique for localized heating or cooling especially at small jet-to-target distances. It was also found that generally lower heat transfer rates were attained for higher aspect ratio jets in the wall jet region, especially at small jet-to-target distances.

In the augmentation of convective heat transfer by impinging gas jets, turbulence promoter and fluidic excitation have also been received considerable interest. Shuja et al. [10] studied the swirling confined jet impingement on an adiabatic wall. They found that the jet axis tilted toward radial direction as the swirl velocity increased and the lowering of the velocity profile number enhanced the entropy generation due to heat transfer. Wen and Jang [11] examined flat surface cooling by the impinging jets issuing through two different swirling strips including a longitudinal swirling-strip and a crossed swirling-strip at various jet-to-target distances. They also derived the correlations of Nusselt number as a function of jet-to-target distance and Reynolds number for all nozzle types. Alekseenko et al. [12] performed visualization of impinging jets and found that the swirling impinging jet possessed a greater spread rate and a faster decay in absolute velocity compared to conventional jet. Yang et al. [13] demonstrated detailed impinging annular jet behaviors induced by a swirling motion. They reported that at a short and intermediate jet-to-target, swirling annular jet provided non-uniform wall pressure and Nusselt number distributions on the impinged surface. Nuntadusit et al. [14] studied the flow and heat transfer characteristics of swirling impinging jet at constant jet-to-target distance of 4 diameters. The swirling jet was generated by inserting twisted tapes within a pipe nozzle, with different twist ratios. The experimental results demonstrated that there appeared to be two peaks of heat transfer in the jet impingement region. The heat transfer enhancements in the jet impingement region could be achieved at a low twist ratio of 3.64 which corresponded to the swirl number of 0.4. Nanan et al. [15] investigated the forced convective heat transfer on the impinged plate associated with swirling impinging jets issuing from nozzles inserted by twisted tapes. The experiments were performed by locating nozzle at four different jet-to-target spacings of 2, 4, 6 and 8. The jet Reynolds number varied between 4000 and 16,000. Attributing to a high momentum transfer rate, an efficient heat transfer was obtained by using the jet with a small jet-to-target spacing and the twist tape with a large twist ratio at high Reynolds number. At small jet-to-target spacing, swirling impinging jets gave higher heat transfer rate than the conventional impinging jets while at large jet-to-target spacing, the opposed result was obtained. Over the range examined, only the swirling impingement jet at a twist ratio of 6 consistently provided higher average Nusselt numbers than the conventional impinging jet. Liu and Sullivan [16] examined the heat transfer enhancement could be achieved by acoustically forcing round impinging jets with jet-to-target distances of 0.625–2 diameter. They found that the forcing caused a small change in the heat transfer at the stagnation point and in the impingement region. There was a significant change in the secondary peak of the heat transfer that occurred at a radius of approximately 1.5–2 diameters. The heat transfer at the secondary peak could be increased by up to 10% when the jet was forced at its natural frequency but suppressed by 10% when the jet was forced at lower frequencies. This behavior had been confirmed for a similar geometry by O'Donovan and Murray [17]. An effective fluidic excitation for improving jet impingement was demonstrated by Gao et al. [18]. Experiments were performed to characterize the heat transfer enhancement produced by adding arrays of triangular tabs to the exit of turbulent round impinging jets issuing from a long pipe. For small jet-to-target distances the local heat transfer was increased more than 25% in a series of distinct regions surrounding the impingement region. The largest

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