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Convective heat transfer by a row of tab-excited impinging jets on a wedge-shaped concave surface

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ABSTRACT

A Computational study was conducted to investigate the convective heat transfer characteristics by a row of tab-excited air jets impingement on a wedge-shaped concave surface having larger curvature than semi-circular concave surface. The geometric effects, including the tab number and tab penetration ratio, as well as the offset-jets arrangement, on the impinging jet flow and heat transfer behaviors are analyzed under several non-dimensional jet-to-leading edge distances (6, 9, 12) and the jet Reynolds numbers ranging from 6900 to 26,100. The results show that both the jet offset-arrangement and tab-excitation are proved to be capable of improving the convective heat transfer in the vicinity of jet impingement region. Either for the conventional round jet or tab-excited jet, it appears that an optimum non-dimensional jet-offset distance is about 1.5. The heat transfer enhancement is improved as the increase of tab number (ranging from 4 to 8), as well as tab penetration ratio (ranging from 0.13 to 0.25). The influence intensity of non-dimensional jet-offset distance on the convective heat transfer inside a concave cavity is more significant for the tab-excited jet impingement than that for the conventional round jet impingement. In general, the effects of jet offset-arrangement and tab-excitation on the jet impingement heat transfer enhancement behave more significant under larger jet Reynolds number as well as smaller impingement distance.

1. Introduction

Jet impingement is an effective means for heat transfer enhancement, which has been widely used in a variety of engineering applications such as drying of textile and paper products, cooling of turbine blades and electronic components, as well as the anti-icing of aircraft wings and engine inlets, etc. Numerous studies have been conducted on the heat and mass transfer produced by the turbulent impinging jet for decades. As illustrated in the detailed reviews presented by Viskanta [1], Weigand and Spring [2], the jet impingement heat transfer characteristics are influenced by a number of factors, including the jet Reynolds number, the jet-to-target spacing, the nozzle geometry, target surface orientation, the crossflow and confinement effects, the pattern of the exhaust, etc. It is due to the extensive and increasing applications as well as the interesting and complex flow physics that jet impingement heat transfer is still attractive to many researchers by now.

Among the complicated factors affecting jet impingement heat transfer, two geometric factors are addressed in the present, referring to wedge-shaped concave target surface and tab-excited jet nozzle. The reasons for doing such research are elaborated in the following.

With regard to the influence of target surface orientation on the jet impingement heat transfer characteristics, a great majority of the investigations were involved in semi-circular or hemi-spherical target configurations. Lee et al. [3] experimentally studied fully developed round turbulent jet impingement on hemi-spherical concave surfaces. It was found that the Nusselt numbers for both stagnation point region and wall jet region are increased with the increase of surface curvature which is character by the ratio of nozzle diameter to inner diameter of the concave hemisphere. Yang et al. [4] experimentally studied jet impingement cooling on a semi-circular concave surface. Three different slot nozzles were taken into consideration as round shaped nozzle, rectangular

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Nomenclature

d	diameter of jet hole (m)
h	convective heat transfer coefficient (W/(m^2 K))
H	normal impinging distance between nozzle and leading edge (m)
k	turbulent kinetic energy (m^2/s^2) or thermal conductivity of the fluid (W/(m K))
l	tab penetration length (m)
L	offset distance of jet (m)
n	number of tabs
Nu	Nusselt number
P	spanwise pitch between adjacent jets (m), pressure (Pa)
q	heat flux (W/m^2)
Re_j	jet Reynolds number
s	chordwise direction
T	temperature (K)
U	jet velocity at nozzle inlet (m/s)
W	width of the impinging plate (m)
W_e	width of exhaust slot
x	x-direction
y	y-direction
z	z-direction

Greek letters

α	apex angle of tab (°)
ν	kinematic viscosity (m^2/s)
ω	vorticity (1/s)

Subscripts

j	relative to jet
w	relative to wall
c	relative to coolant air

shaped nozzle and 2D contoured nozzle. Markedly different flow and heat transfer characteristics were observed depending on different nozzle shapes. Kayansayan and Kucuka [5] carried out an experimental and numerical study on impingement cooling of a semi-cylindrical concave channel by confined slot air jet. The channel height effect on the stagnation region heat transfer was accounted. Eren et al. [6] investigated the nonlinear flow and heat transfer dynamics of a slot jet impingement on a slightly curved concave surface. The effects of jet Reynolds number on the jet velocity distribution and circumferential Nusselt numbers were examined. Gilard and Brizzi [7] studied the aerodynamics of a slot jet impinging on a concave wall. They investigated the influence of the radius of the wall curvature, the impingement height and the Reynolds number on the flow field by conducting flow visualizations and particle image velocimetry velocity measurements. Jefferson-Loveday and Tucker [8] numerically studied turbulent heat transfer impinging on a concave surface by using large-eddy type simulations. Sharif and Mothe [9] conducted a parametric study of the turbulent slot-jet impingement heat transfer from concave surfaces by using the RNG k–ε model with the two-layer enhanced wall treatment approach. The results indicated that while the jet-exit Reynolds number and the surface curvature have a significant effect on the heat transfer process, it is relatively insensitive to the jet-to-target spacing. Oztekin et al. [10,11] studied a turbulent slot jet impinging on concave surfaces with varying surface curvature. It was disclosed that the average Nusselt number increases when the dimensionless curvature radius (defined as the ratio of radius to trace length of concave surface) is bigger than 0.725. The best cooling performance was obtained for the dimensionless curvature radius of 1.3 approximately. As regards as multi-jets impingement are concerned, Fregeau et al. [12,13] made some numerical investigations for array of hot-air jets impinging on 3-dimensional concave surface. Corrections for the averaged and maximum Nusselt number to jet-to-jet spacing, jet-to-surface height, and hot-air jet Mach numbers typical of those in a hot-air anti-icing system were deduced. Fenot [14] made an experimental study on hot round jets impinging a concave surface. The effect of high relative curvature was investigated by changing the jet tube diameter while impinging surface diameter remaining constant. It was illustrated that curvature has different effects over the adiabatic wall temperature and Nusselt number distributions. Kumar and Prasad [15] investigated experimentally flow and heat transfer characteristics for single and multiple rows of circular jets impinging on a concave surface. A performance number named Thermo Hydrodynamic Ratio (THPR) was introduced to evaluate different configurations on the basis of a combined pressure drop and heat transfer. It is suggested that usage of multiple jets appears to offer much better THPR than that of single jet or single row of jets for a chosen plenum condition. More recently, Heo et al. [16] performed a parametric study and optimization of staggered inclined impinging jets on a concave surface for heat transfer augmentation. The inclination angle of the staggered jet nozzles and the distance between the jets nozzles were chosen as the design variables. It was found that the overall heat transfer increases with the pitch of vertical jet nozzles and the staggered inclination of jet nozzles improves the heat transfer on the concave surface with a fixed total mass flow rate from the nozzles. Fechter et al. [17] carried out an experimental and numerical investigation to study the effects of jet-to-target plate distance and impinging hole offset position from the channel center line in a narrow straight channel consisting of a single row of five impinging holes. It was found that the inline jet pattern provides a better coverage of the target surface and thus a higher area averaged heat transfer coefficient than the ones with hole offset arrangements. Imbriale et al. [18] experimentally studied the influences of jet angle, jet-to-jet spacing and Reynolds number on jet impingement heat transfer onto a concave surface. A modified heat transfer correlation over the impinging area was proposed.

Another issue being concerned in the present is the shape of jet nozzle. It is well known that the nozzle geometry has a significant effect on the heat transfer produced by the jet impingement. Colucci and Viskanta [19] made an investigation 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 is higher than that produced by a simple square orifice nozzle. Three orifice nozzles having different nozzle exit configuration (such as the sharp-edged, standard edged and square-edged orifices) were tested by Lee and Lee [20]. It was found that the sharp-edged orifice jet yielded significantly higher heat transfer rates than either the standard-edged orifice jet or square-edged orifice jet in the stagnation region. The authors pointed out that the heat transfer enhancement by the orifice jet is attributed to the large velocity gradient and high turbulence intensity. Koseoglu and Baskayab [21] investigated the effects of jet inlet geometry and aspect ratio on local and average heat transfer characteristics. It was suggested that the impinging jet with higher aspect ratio could be used as a passive enhancement technique for localized heating or cooling