International Journal of Heat and Mass Transfer xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Conjugate heat transfer on leading edge of a conical wall subjected to external cold flow and internal hot jet impingement from chevron nozzle – Part 1: Experimental analysis

Tao Guan [a], Jing-zhou Zhang [a,b,*], Yong Shan [a], Jin Hang [a]

[a] College of Energy and Power Engineering, Jiangsu Province Key Laboratory of Aerospace Power System, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[b] Collaborative Innovation Center of Advanced Aero-Engine, Beijing 100191, China

ARTICLE INFO

Article history:
Received 17 January 2016
Received in revised form 5 April 2016
Accepted 28 June 2016
Available online xxxx

Keywords:
Conjugated convective heat transfer
Hot jet impingement
Conical surface
Chevron nozzle

ABSTRACT

Experimental investigations were carried out to study the conjugated convective heat transfer on the leading edge of a conical wall subjected to external cold flow and internal hot jet impingement by a single chevron nozzle. The geometric effects, including the chevron penetration depth (p/d ranging from 0.1 to 0.2) and chevron length (l/d ranging from 0.1 to 0.3) on the conjugated convective heat transfer performances were experimentally analyzed for a typical 6-chevrons nozzle under non-dimensional jet-to-leading edge distance (H/d) of 2–4 and jet Reynolds number (Re_j) of 7800–39,400. The results show that the chevron jet is proved to be capable of improving the heating effectiveness in the vicinity of the conical surface leading edge, especially under a small jet Reynolds number. For the specified zone with a chordwise length of 5d apart from the leading edge, the area-averaged heat effectiveness could be increased approximately 20% by the chevron nozzle in relative to the conventional nozzle. The heat transfer enhancement is improved with the increase of chevron penetration length for a fixed chevron length or the decrease of chevron length for a fixed chevron penetration length. The influence of chevron penetration depth or the chevron length on the specified area-averaged heating effectiveness becomes weaker gradually as the jet Reynolds number increases. For the current conditions, the non-dimensional jet-to-leading edge distance seems to have little influence on the specified area-averaged heating effectiveness.

1. Introduction

Jet impingement is extensively used in a wide variety of practical applications, such as the tempering and shaping of glass, the drying of textile and paper products, the cooling of turbine blades and electronic equipment, and the anti-icing of aircraft wings and engine inlets, etc. [1–3]. Although numerous investigations have been conducted to achieve the understandings of the jet impingement heat transfer, it is still attractive to many researchers by now due to the increasing requirement of heat transfer enhancement. For instance, the prevention of ice accumulation on the aircraft engine intake surfaces (such as the nacelle lip, guide strut, nose cone, etc.) is practically realized by using hot air anti-icing system. As the hot air is drawn from the engine compressor, the vast utilization of the hot air for anti-icing will degrade the engine performance and the enhancement of heating effectiveness for the hot air impingement is an important issue.

In a recent review presented by Carlomagno and Ianiro [4], the major strategies for jet impingement heat transfer enhancement are classified as passive strategies (such as the use of shaped nozzle, the use of vortex and turbulence generators in the nozzle geometry, impinged surface modification, etc.) and active strategies (such as jet pulsation, synthetic jet, etc.). Previous investigations on the passive strategies were mainly concentrated on the shape of the nozzle. Garimella and Nenaydykh [5] conducted an experimental study to clarify the effect of nozzle geometry on the local heat transfer coefficients from a small heat source. Their results indicated that the local heat transfer coefficients drop sharply when the nozzle aspect ratio is increased from 1 to 4. While the aspect ratio is increased up to 8–12, the heat transfer coefficient increases gradually. Colucci and Viskanta [6] experimentally studied the effect of nozzle geometry on the local convective heat transfer coefficients for confined impinging jets. It was suggested

* Corresponding author at: College of Energy and Power Engineering, Jiangsu Province Key Laboratory of Aerospace Power System, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China.

E-mail address: zhangjz@nuaa.edu.cn (J.-z. Zhang).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.101
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Nomenclature

d	base diameter of jet nozzle (mm)
G	normal distance between exhaust slot and leading edge (mm)
H	normal distance between jet nozzle and leading edge (mm)
l	chevron length (mm)
p	chevron penetration depth (mm)
r	leading edge radius (mm)
Re_j	jet Reynolds number
v	Velocity (m/s)
s	chordwise distance from leading edge (mm)
T	temperature (K)
U	jet velocity at nozzle inlet (m/s)
W_e	width of exhaust slot (mm)
x	x-direction
y	y-direction
z	z-direction

Greek letters

α	angle of linear section (°)
β	circumference angle corresponding to exhaust slot (°)
ν	kinematic viscosity (m^2/s)
η	heating effectiveness

Subscripts

j	relative to jet
w	relative to wall
c	relative to coolant air
ave, s	line-averaged along chordwise direction
ave	area-averaged in a specified zone

that the heat transfer produced by the orifice nozzle with contoured outlet is higher than that produced by a simple orifice nozzle. Royne and Dey [7] conducted an experimental study to investigate the effect of nozzle configuration on the stagnation and average heat transfer coefficients as well as the pressure drop for an array of submerged jets. Four nozzles including short/straight, long/straight, sharp-edged and contoured nozzles were parametrically studied. Brignoni and Garimella [8] made an investigation on the pressure drop and local heat transfer produced by confined air jet impingement. They found that the pressure drop produced by the chamfering nozzle is higher than the square-edged nozzle, while the average heat transfer coefficient is not strongly affected. Lee and Lee [9] experimentally studied the effects of nozzle exit configuration on turbulent heat transfer for an axisymmetric submerged air jet impinging normal to heated flat plate. Three orifice nozzles, including sharp edged, standard edged and square edged nozzle were tested. It was found that the sharp-edged orifice jet yields significantly higher heat transfer rates than either the standard-edged orifice jet or square-edged orifice jet in the stagnation region, due to larger velocity gradient and higher turbulence intensity. Gulati et al. [10] performed an experimental investigation to study the effects of the shape of the nozzle, jet-to-target surface distance and Reynolds number on the local heat transfer distribution on smooth and flat surface. Three different nozzles were chosen as circular, square and rectangular, respectively. It was indicated that the heat transfer produced by the rectangular jet is higher in the stagnation region than those of circular and square jets while the pressure loss coefficient is highest for rectangular jet.

Advanced passive strategies on improving jet impingement heat transfer are related to the use of vortex and turbulence generators, which have been received considerable interest recently. Gao et al. [11] performed an experiment to characterize the heat transfer enhancement produced by a turbulent round impinging jet issuing from a long pipe by adding arrays of triangular tabs to the jet exit. It was reported that the local heat transfer is increased more than 25% in a series of distinct regions surrounding the impingement region for small jet-to-target distances. Martin and Buchlin [12] performed a parametric study on the jet impingement heat transfer from lobed nozzles. The parameters, including the lobe geometry, the jet Reynolds number and jet-to-target distance, were taken into account. Nanan et al. [13] investigated the forced convective heat transfer by swirling impinging jets issuing from nozzles equipped with twisted tapes. They reported that swirling impingement jet provides higher average Nusselt number than conventional impinging jet. Violato et al. [14,15] experimentally investigated three-dimensional vortex dynamics and convective heat transfer in circular and chevron impinging jets. It was revealed that the circular impingement shows the shedding and pairing of axisymmetric toroidal vortices with the later growth of azimuthal instabilities. In the chevron case, instead, the azimuthal coherence is replaced by counter-rotating pairs of streamwise vortices that develop from the chevron notches. In addition, it was reported that the chevron jet exhibits higher heat transfer enhancement than the circular jet. Yu et al. [16,17] investigated the heat transfer produced by single row of impinging jets inside a confined channel with different tab orientations of the triangular tabs at the jet exits. The effects of the tab oriented angle, tan penetration length and tab number on the impinging jet heat transfer characteristics were investigated under different jet-to-target distance and jet Reynolds number.

It is noted that the heat transfer enhancement on a flat target by chevron impinging jets or tabbed impinging jets was previously investigated. However, the usage of vortex and turbulence generators in jet impingement on a concave cavity has not been well studied by now. As the impinged target influences the impinging jet flow field, the convective heat transfer on a curved target behaves different coherent feature from that on a flat target. Gau and Chung [18] studied the effect of surface curvature on the slot jet impingement on both convex and concave surfaces. They suggested the formation of Taylor–Gortler vortices improve heat transfer along the concave surface. Lee et al. [19] experimentally studied the fully developed circular turbulent jet impingement on a hemispherical concave surface. They noted that the Nusselt numbers on both stagnation point region and wall jet region increases with the increase of surface curvature. Choi et al. [20] carried out an experimental study on flow and heat characteristics for jet impingement cooling on a semi-circular concave surface. Variations of jet Reynolds number, nozzle-to-target spacing as well as the distance from the stagnation point in the circumferential direction were taken into consideration. Eren et al. [21] studied 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 [22] investigated the influence of the wall curvature radius on the aerodynamics of a slot jet impinging on a concave wall by conducting flow visualizations and particle image velocimetry velocity measurements. Terekhov et al. [23] carried out an experimental investigation to study the flow and heat transfer characteristics

Please cite this article in press as: T. Guan et al., Conjugate heat transfer on leading edge of a conical wall subjected to external cold flow and internal hot jet impingement from chevron nozzle – Part 1: Experimental analysis, Int. J. Heat Mass Transfer (2016), http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.101