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Conjugate heat transfer on leading edge of a conical wall subjected to external cold flow and internal hot jet impingement from chevron nozzle – Part 2: Numerical analysis

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ABSTRACT

Numerical investigations are performed 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 effects of the chevron length (l/d = 0.1, 0.2, 0.3) and chevron penetration depth (p/d = 0.1, 0.15, 0.2) on the hot-jet impingement heat transfer performance are analyzed for a 6-chevrons nozzle. In the current study, non-dimensional jet-to-leading edge distance (H/d) is varied from 2 to 4 and the jet Reynolds number (Re_j) is varied from 7800 to 39,400. In relative to the conventional nozzle, the presence of chevrons increases the jet core velocity and produces more intensive jet fluctuation, thereby improves the heat transfer in the vicinity of the conical surface leading edge, particularly under a small jet Reynolds number or a smaller jet-to-leading edge distance. In general, the local circumferentially-averaged heating effectiveness is improved with the increase of chevron penetration depth ratio for a fixed chevron length ratio or decrease of chevron length ratio for a fixed chevron penetration depth ratio. Due to a large curvature of conical surface, the circumferentially-averaged heating effectiveness under $H/d = 4$ is greater than that under $H/d = 2$ at the same chordwise location once s/d is beyond 6.

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. Although numerous investigations have been conducted to achieve the understandings of the jet impingement heat transfer [1–3], it is still attractive to many researchers due to the increasing requirement of heat transfer enhancement. For instance, anti-icing on the aircraft engine intake surfaces (such as the nacelle lip, guide strut, nose cone, etc., as seen in Fig. 1) is currently achieved by using hot air impingement. The hot-jet impingement surfaces are usually contoured confinement, resulting in different flow and heat transfer regime from that on a regular target surface. In addition, as the hot air is drawn from engine compressor, vast utilization of the hot air for anti-icing will degrade the engine performance and thus the enhancement of heating effectiveness for the hot air impingement is an important issue. The configurations of jet nozzle and target surface are concerns of the present investigation, featured as chevron nozzle and conical concave surface.

The configuration of target surface is an important factor affecting the jet impingement heat transfer. Lee et al. [4] 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. Cornaro et al. [5] presented a flow visualization of a round jet impinging on cylindrical surfaces with relative curvature ranging from 0.18 to 0.38. It was suggested that flow exiting the concave surface has a significant affecting on free jet. Furthermore, flow visualizations show that vortex structure decreased with the increasing of relative curvature. Chio et al. [6] 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. Gilard and Brizzi [7] 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

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Nomenclature

d	diameter of jet hole (mm)
D_c	inner diameter of coolant channel (mm)
D_i	inner diameter of conical impinging plate (mm)
D_t	inner diameter of conical target plate (mm)
h	convective heat transfer coefficient (W/m^2·K)
H	normal impinging distance between jet nozzle and leading edge (mm)
k	turbulent kinetic energy (m^2/s^2)
l	chevron length (mm)
Nu	Nusselt number
p	chevron penetration depth (mm)
q	heat flux (W/m^2)
r	leading edge radius (mm)
Re_j	jet Reynolds number
s	chordwise direction
T	temperature (K)
U	jet velocity at nozzle inlet (m/s)
W_e	width of exhaust slot
x	x-direction
y	y-direction
z	z-direction

Greek letters

α	angle of linear (°)
β	angle of exhaust slot (°)
λ	thermal conductivity (W/(m^2·K))
ν	kinematic viscosity (m^2/s)
η	heating effectiveness

Subscripts

j	relative to jet
w	relative to wall
c	relative to cold air
ave,s	circumferentially-averaged
ave	area-averaged in a specified zone

measurements. Eren et al. [8] 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. Terekhov et al. [9] carried out an experimental investigation to study the flow and heat transfer characteristics for a jet impingement on the spherical cavity. It was found that the cavity at a value of depth generates the large-scale toroidal vortex, essentially influencing on the heat transfer. Sharif and Mothe [10] carried out a parametric study of the turbulent slot-jet impingement heat transfer on concave cylindrical surfaces. It was indicated that surface curvature has a significant influence on the heat transfer process while the local heat transfer is not very sensitive to the jet-to target spacing under a higher relative curvature value. Yang et al. [11] numerically studied the flow field and heat transfer characteristics of a slot turbulent jet impinging on a semi-concave surface. The effect of jet exit Reynolds number, dimensionless jet-to-surface distance, dimensionless jet width and the heat flux were examined. Oztekin et al. [12,13] studied a turbulent slot jet impinging on concave surfaces with varying surface curvature, the pressure coefficient, the local and average Nusselt numbers were obtained both experimentally and numerically. Imbriale et al. [14] experimentally studied the heat transfer by a row of jets impinging an airfoil leading edge. They found the maximum heat transfer enhancement due to streamwise vortices is obtained at low jet pitch. Fenot [15] carried out an experimental investigation of hot round jets impingement on a concave surface. The effect of high relative curvature was investigated by changing the jet tube diameter while impinging surface diameter remaining constant. Fregeau et al. [16,17] numerically investigated an array circular jets impingement on a circular concave surface related to anti-icing system of aircraft wings. They deduced the dimensionless correlations between the average and the maximum Nusselt number and nozzle pitch, spacing of nozzle to target surface and hot air jet Mach number. Bu et al. [18] made an experimental study of jet impingement heat transfer on a variable-curvature concave surface. The effects of jet Reynolds number, relative piccolo tube-to-surface distance, jet-holes arrangement on the performance of jet impingement heat transfer in the specific structure were addressed.

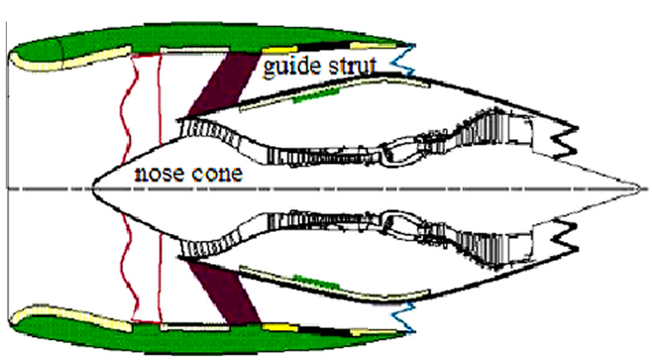

Fig. 1. Schematic of anti-icing parts in an aero-engine intake.

It is found that the curved impingement targets adopted by most of the previous studies are featured as semi-circular or hemi-spherical concave/convex surfaces. Another issue being concerned in the present is the nozzle geometry. It was well illustrated by some previous investigations that the nozzle geometry has a significant effect on the heat transfer produced by the jet impingement [19–23]. In the augmentation of convective heat transfer by impinging gas jets, some innovative jet nozzles were presented by using the turbulence promoter and fluidic excitation. Gao et al. [24] 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 [25] 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. Violato et al. [26,27] 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. [28,29] 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