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Conjugated heat transfer improvement on leading edge of a conical wall using center-satellite hot-jet orifices ☆

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ABSTRACT

A new scheme of center-satellite hot-jet orifices was proposed for improving the conjugated heat transfer performance in the vicinity of a conical concave leading edge. To illustrate the role of this scheme, a typical 6-satellite orifice configuration was designed having the same nominal diameter (d) or ejection area of impinging jets as that of the baseline single-orifice, and a series of experimental tests was performed to determine the hot-jet heating effectiveness under non-dimensional jet-to-leading edge distance (H/d) of 2–4 and nominal jet Reynolds number (Re_j) of 7800–39,400. Four non-dimensional axial distances of satellite-orifice location (H_s/d = 0.15, 0.5, 1.0 and 1.5), three non-dimensional center-orifice diameters (d_c/d = 0.6875, 0.812 and 0.9375) were taken into consideration. Besides, numerical simulations were also performed to illustrate the effect of center-satellite orifices on the flow and heat transfer features inside the conical concave cavity. The results confirm that the center-satellite scheme has a significant impact on improving the conjugated heat transfer performance in the vicinity of conical wall leading edge due to more intensive jet impingement. In the current research conditions, the satellite-orifice arrangement with a larger non-dimensional axial distance (H_s/d) or a smaller non-dimensional center-orifice diameter (d_c/d) is suggested to be more favorable for the conjugated heat transfer improvement. However, the center-satellite scheme results in a higher pressure drop related to the baseline single-orifice. It is also noted that the pressure drop of center-satellite scheme is nearly unaffected by the center-orifice diameter and axial distance between center-orifice outlet and satellite-orifice location.

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1. Introduction

Ice accretion on the aircraft wing and engine intake under natural icing conditions changes the aerodynamic profile and thus degrades the flying performance. Once the ice is broken away from the surface, it might be sucked into the engine, causing a serious hazard to the flight safety [1,2]. According to previous investigations on the in-flight icing phenomena, the leading edges of the critical surfaces (such as the nacelle lip, guide strut, and nose cone) are more seriously suffered to the icing threat. To avoid such events, anti-icing systems for preventing ice accretion are obligatory to be equipped in the aircrafts. A lot of efforts have been devoted for the optimal design of hot air anti-icing systems and improvement of anti-icing configurations [3–5]. As the hot air used for anti-icing purpose is drawn from the engine compressor, the improvement of hot-air heating effectiveness is a remarkable issue so as to minimize high-temperature bleed-air exploit.

Jet impingement is extensively used in a wide variety of practical applications, either for highly intensive cooling or heating [6–8]. It is commonly known that the nozzle shape has a significant role on the heat transfer of impinging jets. Colucci and Viskanta [9] performed an experimental study to illustrate the effect of nozzle geometry on the local convective heat transfer of confined impinging jets. It was suggested that the orifice nozzle with contoured outlet produces higher heat transfer than the simple orifice nozzle. Lee and Lee [10] experimentally studied the effects of nozzle exit configuration on turbulent heat transfer for an axisymmetric submerged air jet impinging normal to heated flat plate. It was found that the sharp-edged orifice yields significantly higher heat transfer rates than either the standard-edged orifice or square-edged orifice in the stagnation region because it is able to produce larger velocity gradient and higher turbulence intensity. Gulati et al. [11] performed an experimental investigation to study the

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Nomenclature

d	nominal diameter of center-satellite orifices (mm)
D_i	inner diameter of conical impinging plate (mm)
D_m	inner diameter of main flow or coolant channel (mm)
D_t	inner diameter of conical target plate (mm)
G	normal distance between exhaust slot and leading edge (mm)
H	normal distance between jet nozzle and leading edge (mm)
H_s	axial distance between center-orifice and satellite-orifice (mm)
h	convective heat transfer coefficient (W/(m^2 K))
k	thermal conductivity (W/(m K))
m	mass flow rate (kg/s)
n	number of satellite orifices
Nu	Nusselt number
p	pressure (Pa)
q	heat flux (W/m^2)
Re	Reynolds number
r	leading edge radius (mm)
s	chordwise distance from leading edge (mm)
T	temperature (K)
u	velocity (m/s)
W_e	exhaust slot width (mm)
x	x-direction, streamwise distance (mm)
y	y-direction
z	z-direction, spanwise dirstance (mm)

Greek letters

α	angle of linear (°)
β	angle of exhaust slot (°)
η	heating effectiveness
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
ω	vorticity (1/s)

Subscripts

ave, s	line or circumferentially-averaged along chordwise direction
ave	area-averaged in a specified zone
c	relative to center orifice
in	relative to hot-air plenum inlet
j	relative to jet
m	relative to main flow or cold air
out	relative to exhaust slot outlet
s	relative to satellite orifice
w	relative to wall

Superscripts

*	total

effects of nozzle shape, jet-to-target surface distance and Reynolds number on the local heat transfer distribution on a smooth and flat surface. It was indicated that the heat transfer produced by the rectangular jet is higher in the stagnation region than the circular jet or square jet while the pressure loss coefficient is also highest for the rectangular jet. Gao et al. [12] presented a tabbed-nozzle by adding some triangular tabs to the jet exit. It was reported that the local heat transfer is increased more than 25% related to the conventional round-nozzle in a series of distinct regions surrounding the impingement region under small jet-to-target distances. Violato et al. [13] experimentally investigated three-dimensional vortex dynamics and convective heat transfer of circular and chevron impinging jets. It was reported that the chevron jet exhibits higher heat transfer enhancement than the circular jet. The circular impingement showed the shedding and pairing of axisymmetric toroidal vortices with the later growth of azimuthal instabilities. In the chevron case, instead, the azimuthal coherence was replaced by counter-rotating pairs of streamwise vortices developed from the chevron notches. Recently, impinging jet heat transfer augmentation by tabbed or chevron nozzle received much attention [14–17].

Previous investigations had also revealed that the targeting-surface curvature has an important influence on the jet impingement heat transfer process. For examples, Lee et al. [18] experimentally study the effect of hemispherical concave surface curvature on the local heat transfer of a round impinging jet. It was found that the Nusselt numbers for both stagnation point region and wall jet region increase with increasing surface curvature because the concave surface curvature destabilizes the boundary layer flow and increases the intensity of the turbulent mixing. Chio et al. [19] 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. [20] 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. The local and average cooling rates for the slightly-curved concave surface case were found to be higher than those for the slightly-curved convex surface. Terekhov et al. [21] performed an experimental study of flow and heat transfer characteristics for jet impingement onto a spherical cavity. It was found that the cavity generates large-scale toroidal vortex at a value of depth. The cavity flow became unstable, exhibiting low-frequency pulsations of local heat fluxes. Oztekin et al. [22] 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 is bigger than 0.725. The best cooling performance was obtained for the dimensionless curvature radius of 1.3 approximately. Imbriale et al. [23] performed an experimental investigation for convective heat transfer by a row of jets impinging on a concave surface. The detailed 3D Nusselt maps illustrated the presence of streamwise streaks of local Nu maxima, suggesting the presence of streamwise vortices driven by surface curvature. It was also found that this phenomenon strengthens up with increasing the jets inclination, and so with increasing the curvature in the wall jet. As mentioned above, the concave surfaces involved in the previous investigations are generally regular, i.e., semi-cylindrical and hemispherical. Little effort had been devoted for the jet impingement heat transfer on a specifically conical concave surface which is related to the practical application of anti-icing of the nose cone in an aero-engine intake. Recently, Bu et al. [24,25] conducted 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, and jet holes arrangement on the performance of jet impingement heat transfer in the specific structure were addressed. The present authors [26,27] carried out experimental and numerical studies to investigate the conjugate heat transfer performance on the leading edge of a conical wall subjected to external cold flow and internal hot jet impingement from chevron nozzle. The results showed that the chevron jet is capable of improving the heating effectiveness

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