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Research Paper

Effect of offset-jets arrangement on leading edge hot-air heating effectiveness of engine inlet guide strut

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HIGHLIGHTS

- Assessing effect of offset-jets arrangement on hot-air heating effectiveness.
- Illustrating offset-jets flow and heat transfer features inside concave cavity.
- Offset-jets shorten impinging distance and introduce recirculation flow structure.
- An optimal non-dimensional offset-jets distance is proposed.
- Effect of offset-jets is dependent on normal jet-to-leading edge distance.

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ABSTRACT

An experimental investigation is conducted to study the effect of offset-jets arrangement on the conjugated heat transfer performance for a specifically wedge-shaped concave surface subjected to external cold flow and internal hot jet impingement. The external flow Reynolds number (Re_c) defined on the base width of wedge-shaped concave surface is fixed as 54,000. The jet Reynolds number (Re_j) is varied in the range of 7900–31,700. Four non-dimensional jet-hole offset distances (L/d) ranging from 0 to 2.5 and four non-dimensional jet-to-leading edge distances (H/d) ranging from 6 to 15 are considered respectively. In order to illustrate the effect of offset-jets arrangement on the flow and heat transfer features inside the wedge-shaped concave cavity, numerical simulations are also performed. The results show that the offset-jets arrangement generally has a significant impact on improving the overall heating effectiveness in the vicinity of concave wall leading edge due to the reduction of normal jet impinging distance and the formation of recirculation flow structure inside the concave cavity. In current study, $L/d = 1.5$ is confirmed to be a superior offset-jets arrangement for achieving the highest specified area-averaged heating effectiveness. It is also noted that the effect of offset-jets arrangement on the leading edge hot-air heating effectiveness is tightly dependent on the normal jet-to-leading edge distance. Under $H/d = 15$, the offset-jets distance has a weak effect of on the internal hot-jet impingement heat transfer. In this situation, the offset-jets arrangement has nearly no effect on improving the hot-jet heating effectiveness.

1. Introduction

In-flight icing is a serious hazard to the flight safety under natural icing conditions [1,2]. Ice accretion on the aircraft wing and engine intake will change the aerodynamic profile and thus degrade the flying performance. Once the ice is broken away from the surface, it might be suctioned into the engine, causing catastrophic accidents. To avoid such events, anti-icing systems are obligatory to be equipped in aircraft for preventing or removing ice accretion on the critical surfaces (such as the nacelle lip, guide strut, and nose cone). Among anti-icing systems, hot-air anti-icing is an effective means which has been widely used. As the hot air used for anti-icing purpose is bled from the engine compressor, vast exploit of hot air undoubtedly induces engine performance penalties. Therefore, the improvement of wall heating effectiveness by hot-air impingement is a remarkable issue so as to minimize high-temperature bleed-air usage [3–5].

Jet impingement is extensively used in a wide variety of practical applications, either for highly intensive cooling or heating

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Nomenclature

d	diameter of jet hole (mm)
G	normal distance between exhaust slot and leading edge (mm)
H	normal distance between jet nozzle and leading edge (mm)
h	convective heat transfer coefficient (W/(m^2·K))
k	thermal conductivity (W/(m·K))
L	Offset-jets distance (mm)
m	mass flow rate (kg/s)
n	number of jet holes
Nu	Nusselt number
P	hole-to-hole pitch (mm)
p	pressure (Pa)
q	heat flux (W/m^2)
Re	Reynolds number
r_1	curvature radius in leading edge (mm)
r_2	curvature radius in middle section (mm)
s	distance from leading edge along curved surface (mm)
T	temperature (K)
u	velocity (m/s)
W	base width of concave cavity (mm)
W_e	exhaust slot width (mm)
x	x-direction, streamwise distance (mm)
y	y-direction
z	z-direction, spanwise distance (mm)

Greek letters

α	linear angle in middle section (°)
β	linear angle in trailing section (°)
η	heating effectiveness
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa·s)
ω	vorticity (1/s)

Subscripts

ave, s	laterally-averaged along curved surface
ave	area-averaged in a specified zone
c	relative to cold air or primary flow
j	relative to jet
w	relative to wall

[6–8]. In the viewing of jet impingement heat transfer augmentation, a lot of passive strategies have been presented, such as changing the nozzle shape [9–11], modifying target surface [12–14], etc. Although the advanced means using vortex and turbulence generators for enhancing jet impingement receives much concern recently [15–19], the simple but effective jet impingement enhancement is still needed to be further investigated in many practically engineering applications, including the hot-air anti-icing system.

The hot air impingement in anti-icing configurations is reasonably classified as a confined jet impingement on concave surfaces. Previous investigations had revealed that the surface curvature has a significant influence on the jet impingement heat transfer process. For examples, Lee et al. [20] 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. Eren et al. [21] performed an experimental and numerical study to investigate the nonlinear flow and heat transfer of a slot jet impingement on a slightly curved concave surface. The effect 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. [22] performed an experimental study of flow characteristics and heat transfer for jet impingement onto a spherical cavity. It was found that the cavity generates the large-scale toroidal vortex at a value of depth, essentially influencing on the heat transfer. The cavity flow becomes unstable, exhibiting low-frequency pulsations of local heat fluxes. Heo et al. [23] 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. Oztekin et al. [24] 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. Imbriale et al. [25] 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. Taghinia et al. [26] performed a numerical investigation to evaluate the performance of three turbulence models in predicting the heat transfer and flow physics of jet impingement on concave surfaces. The findings revealed that the predictions of large eddy simulation with the use of zero-equation subgrid-scale (SGS) models are in better agreement with experiments than the Reynolds averaged Navier-Stokes simulation coupled with RNG k-ε model. It was also concluded that at higher jet-to-surface ratios, all three models produced almost similar results. With regard to jet impingement enhancement in a confined concave target, a means by using concave cavity as a vortex chamber through tangential jet injection was attractive to a lot of researchers [27–29]. It was confirmed that the vortex pairs inside the vortex chamber produce pronounced influences on heat transfer improvement.

It is noted that the concave surfaces involved in the previous investigations are generally regular, i.e., cylindrical and hemispherical. In practice, the curved surfaces often have more complex curvature than semicircular and hemispherical concave surfaces. For instance, the leading edge of a guide strut in engine intake may be featured as a wedge-shaped concave surface, which has a narrow trace length and a long chordwise length of concave surface with variable-curvatures. To our knowledge, little effort had been devoted for the jet impingement heat transfer on this complex concave surface. Bu et al. [30,31] 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. Guan et al. [32] carried out a numerical study to investigate the convective heat transfer on a wedge-shaped concave surface impinged by a row of air jets. Both the jet offset-arrangement and tab-excitation were proved to be capable of