Experimental Thermal and Fluid Science 78 (2016) 199–207

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Jet impingement heat transfer on a concave surface in a wing leading edge: Experimental study and correlation development

Xueqin Bu [a], Long Peng [b], Guiping Lin [a], Lizhan Bai [a,c,*], Dongsheng Wen [c]

[a] Laboratory of Fundamental Science on Ergonomics and Environmental Control, School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, PR China
[b] Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, PR China
[c] School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK

ARTICLE INFO

Article history:
Received 16 February 2016
Received in revised form 2 June 2016
Accepted 8 June 2016
Available online 8 June 2016

Keywords:
Jet impingement
Heat transfer
Wing anti-icing
Experiment
Correlation

ABSTRACT

Extensive experimental studies of the heat transfer characteristics of jet impingement on a variable-curvature concave surface in a wing leading edge were conducted for aircraft anti-icing applications. The experiments were performed using a piccolo tube with three rows of aligned jet holes over a wide range of parameters: the jet Reynolds number (Re_j) from 50,000 to 90,000, the relative tube-to-surface distance (H/d) from 1.74 to 20.0, the jet impingement angle (α) from 66° to 90°, and the relative chordwise arc length in the jet impingement zone (r/d) from 13.2 to 34.8. Experimental results indicated that the heat transfer performance at the stagnation point was enhanced with increasing Re_j and α, and an optimal H/d existed to achieve the best heat transfer performance at the stagnation point corresponding to specific operating parameters. It was found that the attenuation coefficient curve of jet impingement heat transfer in the chordwise direction exhibited an approximate bell shape with the peak located at the stagnation point, affected only by r/d in the peak zone. In the non-peak zone, however it was affected significantly by a variety of factors including Re_j, H/d and r/d. Experimental data-based correlations of the Nusselt number at the stagnation point and the distribution of the attenuation coefficient in the chordwise direction were developed and validated, which contributes significantly to the future design of a wing anti-icing system with three rows of aligned jet holes.

1. Introduction

Jet impingement promises excellent heat transfer performance, which has attracted worldwide interests for decades. As an effective measure to enhance the local heat transfer coefficient, it has been applied in a wide variety of fields, such as glass tempering, metal annealing, food and paper drying, and gas turbine blade and electronics cooling [1–5]. Because jet impingement is a very complex heat and mass transfer process, which is influenced by many parameters such as the shape and size of the nozzle, the nozzle layout, the nozzle to target surface distance, the jet Reynolds number, the impingement angle and the curvature of impinging surface, comprehensive experimental and theoretical studies have been conducted especially for jet impingement on a flat or cylindrical surface [6–13].

In the aviation industry, anti-icing or de-icing system is generally used in both civil and military aircraft to guarantee flight safety. The wing leading edge hot-air anti-icing system (WHAAIS) has been widely employed so far, where jet impingement heat transfer of hot air introduced from the engine compressor and sprayed from the jet holes on a piccolo tube is utilized to prevent the occurrence of icing on the external surface of a wing leading edge, as shown schematically in Fig. 1 [14]. Fig. 2 shows the schematic of the jet impingement on a variable-curvature concave surface in a wing leading edge hot air anti-icing system. Comparing to the common jet impingement on a flat surface, there are some notable differences in a WHAAIS as summarized below: (1) the pressure of the hot air supplied is usually very high, and the air in the jet holes is in the choked state with the outlet velocity reaching the speed of sound; (2) the jet hole profile is very sharp, and the air at the outlet of the jet holes may be still under expansion; (3) the piccolo tube usually has a single one, two or three rows of jet holes, and the circumferential angle of jet holes on the piccolo tube can significantly affect the fluid flow and heat transfer processes on the target surface; and (4) for piccolo tube with two or three rows of jet holes, the interaction of jets between adjacent holes further

---

* Corresponding author at: Laboratory of Fundamental Science on Ergonomics and Environmental Control, School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, PR China.

E-mail address: bailizhan@buaa.edu.cn (L. Bai).

http://dx.doi.org/10.1016/j.expthermflusci.2016.06.006
0894-1777/© 2016 Elsevier Inc. All rights reserved.

Nomenclature

A	attenuation coefficient
C_n	spanwise distance between adjacent jet holes, mm
d	jet hole diameter, mm
G_m	mass flowrate, kg/s
h_x	local convective heat transfer coefficient, W/(m^2 K)
H	piccolo tube-to-surface distance, mm
H_a	attenuation height
M	attenuation coefficient
N	number of jet holes
Nu_x	local Nusselt number
Nu_{stag}	stagnation Nusselt number
q	heat flux, W/m^2
r	arc length between jet stagnation points, mm
x	chordwise arc length from the middle stagnation point, mm
Re_j	jet Reynolds number
T_{aw}	adiabatic wall temperature, K
T_j	jet total temperature, K
T_{wx}	local temperature on the internal surface of the wall, K

Greek symbols

α	jet impingement angle (°)
ρ	density, kg/m^3
θ	circumferential angle of jet holes on the piccolo tube (°)
λ	thermal conductivity, W/(m K)
v	kinetic viscosity, m^2/s
μ	dynamic viscosity, Pa s
ξ_x	attenuation coefficient of Nu, Nu_x/Nu_{stag}

increases the complexity. The jet impingement in a WHAAIS is also much more complicated than that on a cylindrical concave surface due to its continuous variable curvature character in the leading edge.

For the jet impingement heat transfer in a WHAAIS, only very limited experimental and theoretical studies has been reported to date. Jusionis [15] reported perhaps the first experimental study of jet impingement heat transfer on an enclosed surface in 1970. A piccolo tube with a single one row of jet holes was used in his study, and the correlation of the average heat transfer coefficient over the target surface was obtained considering the influences of the jet Reynolds number, the distance from the jet holes to the target surface and the circumferential angle of the jet holes on the piccolo tube. Brown et al. [16] investigated the performance of a piccolo tube with three rows of jet holes, and developed a correction of the average convective heat transfer coefficient on the jet impingement region, where the distance between the jet holes and the jet Reynolds number were considered. The review from Wright [17] suggested that Goldstein correlation [18] could be used for a first order estimation on the piccolo tube performance.

In 2003, by using the computational fluid dynamics (CFD) method, Fregeau et al. [19] studied the thermal performance of a 3-D hot air jet flow impinging on a normal semicircular concave surface instead of the leading edge of an aircraft wing. The correlations of the average and stagnation Nusselt number were obtained. In their study, only the layout of single one row of jet holes was considered. The average Nusselt number was found to be remarkably dependent on the tube-to-surface distance. The maximum Nusselt number occurred at the jet stagnation point, and the distance between adjacent jet holes had negligible effect on it. In 2008, Saeed [20] conducted a simulation study to further understand the jet impingement heat transfer performance employing a piccolo tube with single one row and two rows of staggered jet holes impinging on the internal surfaces of a typical aircraft wing/slat. The 3-D distributions of the Nusselt number and heat transfer coefficient on the target surface were illustrated, and the results showed that the jet impingement heat transfer performance for the piccolo tube with single one row and two rows of 20 deg staggered jet holes was better than that with two rows of 10 deg staggered jet holes. In 2009, Fregeau et al. [21] simplified the single one row of jet holes as one-quarter of the jet to reduce the size of computational domain, and the simulation results indicated that the local Nusselt number distribution on the surface was enhanced with the decrease of the tube-to-surface distance and increase of jet Mach number and the distance between adjacent jet holes.

In 2006, Papadakis and Wong et al. [22–24] performed an extensive parametric study to investigate the influence of tube-to-surface distance, jet hole location, the diffuser geometry, hot air temperature and mass flow rate on the jet impingement heat transfer performance of a bleed air ice-protection system by both experimental and numerical methods. The impinging surface simulated the NACA 23012 airfoil leading edge shape, and three rows

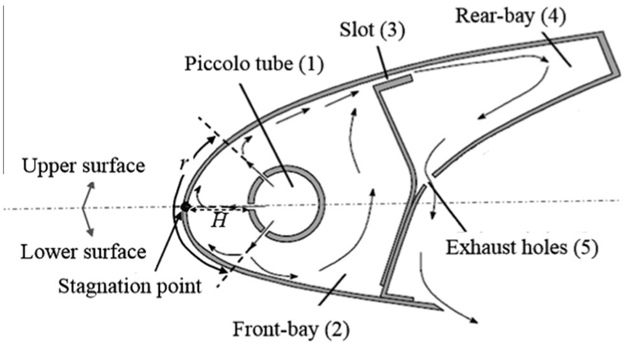

Fig. 1. Schematic of a typical wing leading edge hot-air anti-icing cavity.

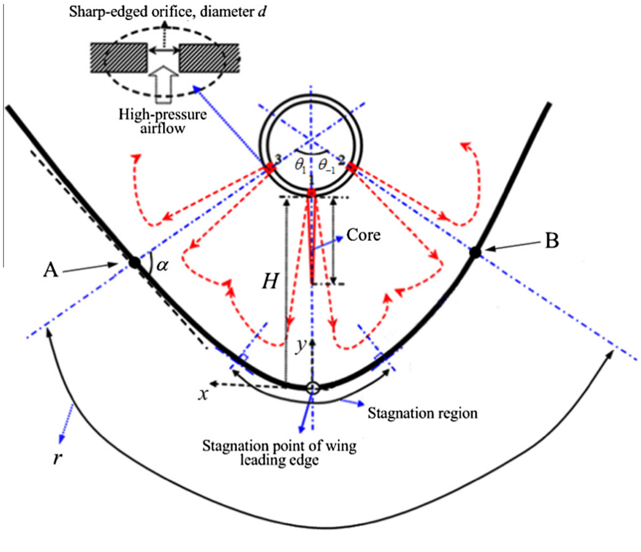

Fig. 2. Schematic of jet impingement on a concave surface from a piccolo tube.