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Infrared thermography on testing an anti-icing device

by MEOLA C.*, CARLOMAGNO G.M.*, RIEGEL E.+ and SALVATO F.+

* *DETEC Università di Napoli, Piazzale Tecchio 80, 80125 Napoli, Italy*
+ *Alenia S.p.A., Pomigliano d'Arco Napoli*

Abstract

An infrared scanning radiometer, applied to the *heated thin foil* technique, is employed to test the performance of an anti-icing device, which consists of a hot air spray-tube inside aerodynamic surfaces as leading-edge wing sections. Experimental tests are made in order to determine the convective heat transfer coefficients between the surface of the wing section and the air jets impinging on it. The influence of several parameters such as the Mach number, the impingement distance, the diameter of the holes of the spray-tube and the spacing between holes is considered.

Nomenclature

d	hole diameter
c	wing cord
k	air thermal conductivity
M	Mach number
Nu	Nusselt number
Re	Reynolds number
S	hole-to-hole spacing
T	temperature
Z	impingement distance
x	chordwise coordinate
y	spanwise coordinate

Subscripts

aw	adiabatic wall
o	stagnation
s	characteristic length

1. Introduction

An experimental investigation is made within a cooperation between DETEC and Alenia S.p.A. in order to test the performance of an anti-icing device, which is aimed at preventing the ice formation by using hot air from the engines. In details, protection is achieved by warming critical zones by means of a hot air spray-tube inside aerodynamic surfaces as leading-edge wing sections. The analysis of such a system leads up to define heat transfer coefficients between an enclosed concave surface and air jets impinging on it.

Many studies of jet impingement have been made, yet, to the authors' knowledge, the literature is almost solely for jets impinging on flat plates [1-4]. In the light of the available literature, studies of heat transfer from impinging gas jets on an enclosed concave surface done by Jusionis [5] deserve consideration. Jusionis [5] finds that heat transfer in a closed cavity is affected to a lesser degree by the impingement distance than for the flat plate case because of recirculation currents within the cavity.

In the present work, the reliability of the aforementioned hot air spray-tube anti-icing system is tested by means of an infrared scanning radiometer applied to the *heated thin foil* technique [6]. Tests refer to convective heat transfer measurements between a hot surface and cold jets impinging on it, instead of the effective configuration cold surface and hot jets. The choice of cold jets is made for practical convenience since a general literature finding (among others Goldstein *et al.* [7]) shows that the Nusselt number is practically independent of the difference between the temperature of the jet and the ambient temperature. To this contention, it is possible to use heat transfer coefficients obtained with cool jets (the jet total temperature is

http://dx.doi.org/10.21611/qirt.1994.030
equal to the ambient one) in the case of heated jets, if the adiabatic wall temperature distribution is known.

2. Experimental apparatus and technique

The test model, as schematically sketched in *figure 1*, includes a leading-edge of a 200*mm* long spanwise NACA-0012 wing section 1.5*m* in chord, stopped at 10% of the chord from the leading-edge and a 20*mm* wide exhaust slot.

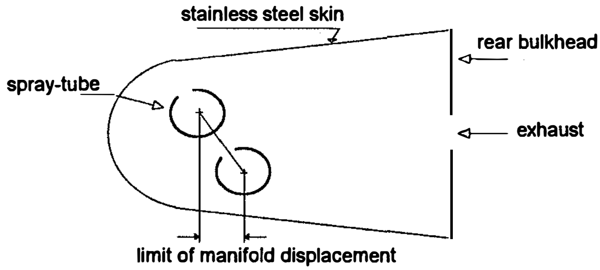

Fig.1. Test model

In particular, two moulding stainless steel plates allow a stainless steel foil (0.04*mm* thick) to reproduce the curved surface of the profile and, at the same time, to perform the function of clamps for electric contacts. Two replaceable flanges, made of insulating material and inserted in the former, allow positioning a spray-tube, 25*mm* OD, inside the cavity. The experimental arrangement is shown in *figure 2*. The air supplied by a compressor goes through a stagnation chamber where is splitted into two equal quantities in order to fed the spray-tube from both of the extremities. Then, the air is spread out by holes, drilled along the spanwise direction of the spray-tube. Three stiffening tools are employed to avoid surface waving of the foil.

The employed IR thermographic system (IRSR) is based on an Agema Thermovision 880LW scanner which is connected via a TIC 8000 A/D converter board to an IBM AT computer. The total field of view (depending on the focal length of the optics and on the viewing distance) is scanned by an Hg-Cd-Te detector (working in the 8-12μm wavelength band). A frame of 280 lines (1:4 interlaced) is produced in 0.16*s*; the line frequency is 2.5*KHz* and the nominal sensitivity, expressed in terms of Noise Equivalent Temperature Difference, is 0.07°*C* when the scanned object is at ambient temperature. In order to make the emissivity coefficient ε of the surface under measurement close to unity, the surface itself is coated with a thin film of black opaque paint. The emissivity coefficient is measured, still by IRSR, by comparing the detected radiation from a specimen heated by means of an ultrathermostat with its real temperature measured by a very accurate mercury thermometer; for the employed paint, ε is found to be equal to 0.95.

The system software used for acquisition and handling of the thermal image (a frame of 140x140 pixels composed by two interlaced fields) is the Computer Aided Thermographic System (CATS). Data may be acquired in both real time and frozen modes; in the latter, data may be stored after time average over 2 up to 255 shots. High speed acquisition of sequences of images is possible too. According to the desired spatial resolution a lens of 7° or 20° can be used; the spatial resolution, at minimum focus distance, is of order of one pixel per millimeter.

In the present case IRSR is applied to the *heated thin foil* technique, which consists in measuring the convective heat transfer coefficient h between the thin metallic foil heated by Joule effect and the air jets impinging on it. The surface temperature distribution is measured by viewing the rear face of the foil (side opposite to the jet impingement) since the Biot number is very small with respect to unity. The convective heat transfer coefficient h is determined from:

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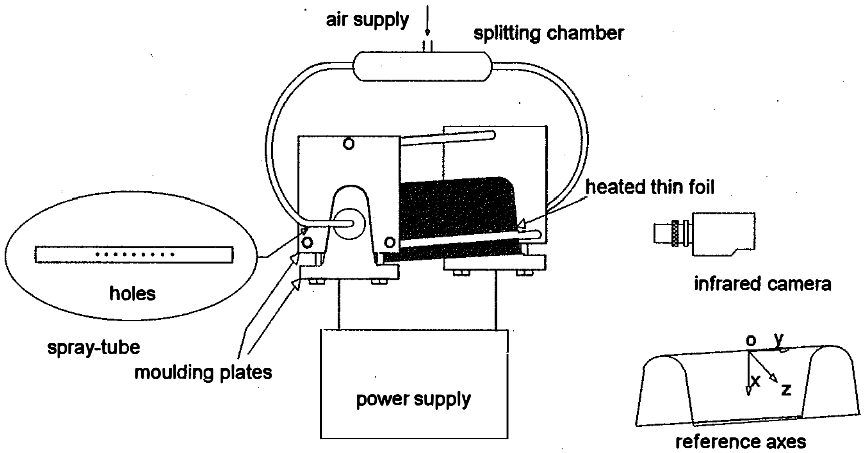

Fig.2. Experimental apparatus

$$h = Q/(Tw-Taw) \qquad (1)$$

where Q is the Joule heating per unit area corrected for conduction radiation and natural convection losses (these losses in the present case were found to be negligible). Therefore, each test run consists of two parts: firstly, electric current off, *Taw* is to be measured and the so-called "cold image" is recorded; secondly, electric current on, *Tw* is to be measured and the "hot image" is recorded. In particular each image is averaged over 16 shots. The possibility of digitizing thermal images by computer makes this procedure (including subtraction between the two images) preferable to standard thermometric measurements more difficult to perform over the whole surface. It has also to be pointed out that in the specific case (multi-jet impingement) interaction effects must be accounted for and different chordwise temperature readings must be taken simultaneously along several spanwise stations. Owing to drawbacks of taking a sufficient number of thermocouple readings, infrared thermography has to be considered as a unique technique, which can be used to measure and visualize surface temperatures because of its nonintrusivity, two-dimensionality and high spatial resolution.

In general, the study is aimed at testing the influence of jet nozzle diameter, jet spacing, jet impingement distance and jet exit velocity. Tests are carried out for jet impingement at 3.3% of the chord, diameter of holes of 2 and 4*mm*; dimensionless jet spacing *S/d* of 5, 10 and 15; dimensionless jet impingement distance *Z/d* of 5, 10 and 15 and the initial Mach number of the jets from 0.7 up to 1.0. Owing to surface curvature and directional emissivity, the entire test section is viewed in three parts: frontside (zone interested directly by the jet impingement), topside and backside.

3. Results

The experimental data are reduced in dimensionless form in terms of the Nusselt number defined as:

$$Nu = hd/k \qquad (2)$$

The Nusselt number depends on the diameter of the holes of the spray-tube, the Mach number, the impingement distance and the hole-to-hole spacing. The local Nusselt number attains maxima values at the jet impingement points (3.3%c) and decreases more or less sharply depending on the impingement distance as can be seen from *figure 3*.

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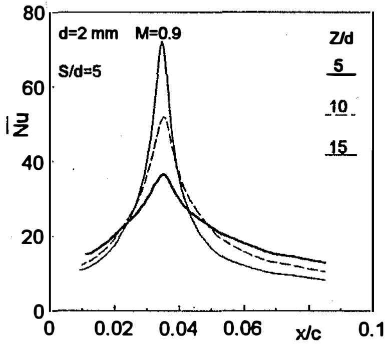

Fig.3. Chordwise Nusselt number distribution influence of the impingement distance

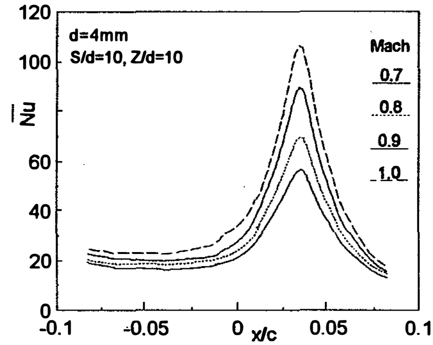

Fig.4. Chordwise Nusselt number distribution influence of the Mach number

With reference to *figure 3* the Nusselt number values are averaged ($\overline{Nu}$) spanwise between *y/d*=±*15* starting from the center nozzle axis (reference coordinates *figure* 2) and plotted against *x/c* for *d*=2, *S/d*=5 and *M*=0.9. The influence of the Mach number is shown in *figure* 4,

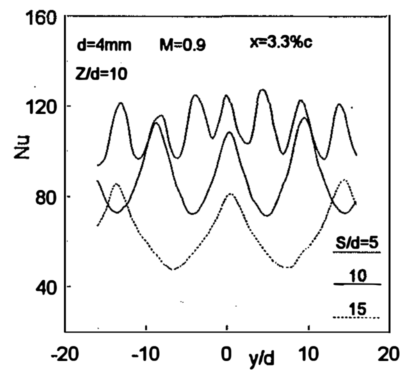

Fig.5. Local Nusselt number distribution in the frontside region

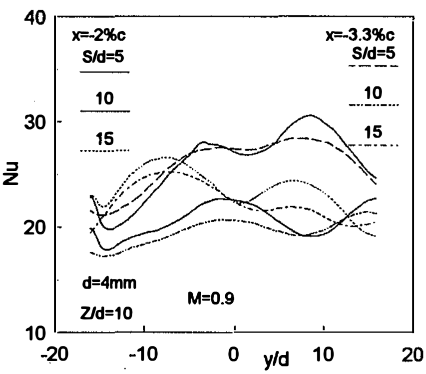

Fig.6. Local Nusselt number distribution in the backside region

which refers to *d*=4*mm*, *S/d*=10 and *Z/d*=10; as it was to be expected, $\overline{Nu}$ increases as the Mach number increases. It is interesting to note that in the backside region (-0.08≤*x/c*≤-0.01) the average Nusselt number value is almost constant with *x/c*. In order to account for the influence of the hole-to-hole spacing, the spanwise distribution of the local Nusselt number in the impingement zone (*x*=3.3%*c*) is reported in *figure* 5 for *d*=4*mm*, *Z/d*=10 and *M*=0.9. As it can be seen the Nusselt number decreases as the spacing is increased. This behaviour is true relatively to the impingement zone (frontside region 0.01≤*x/c*≤0.08), in fact, as one can see from *figure* 6, relative to the backside region (-0.08≤*x/c*≤-0.01), the Nusselt number shows more chaotic distribution. In particular, values relative to *S/d*=15 seems to be higher than those relative to *S/d*=10, this because of recirculation effects within the employed wing section. In addition, it has to be observed that values relative to the line close to the topside (*x*= -2%*c*) are slightly higher than those relative to the line opposite to that of impingement (*x*= -3.3%*c*).

http://dx.doi.org/10.21611/qirt.1994.030

Particular attention is focused on the frontside region ($0.01 \le x/c \le 0.08$) the most critical zone for icing occurrence), where the data are averaged by following the curvilinear coordinate along the profile and therefore by introducing an average Nusselt number over said region $\overline{\overline{Nu}}$. By introducing the modified Nusselt and Reynolds numbers based on the length:

$$s = \pi d^2/4S \tag{3}$$

to include hole diameter and hole spacing. Jusionis [4] found a data correlation of the type:

$$\overline{\overline{Nu}}_s = 0.030(Z/s)^{-0.4}\, Re_s^{0.7} \tag{4}$$

In the present case all the experimental data fit very well a correlation curve of type:

$$\overline{\overline{Nu}}_s = aRe_s^n \tag{5}$$

(with $a=1.7 \times 10^{-5}$ and n=1.39) as shown in *figure 7*.

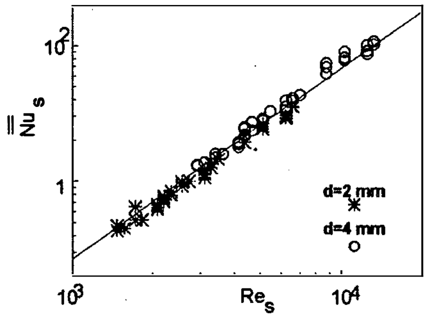

Fig.7.Average Nu correlation

However, it has to be outlined that the range of applicability of Jusionis' relationship is: $1000<Re_s<8000$, $50<Z/s<120$, d=2.5*mm*, while the present experimental data refer to two different diameter of the holes of the spray-tube, Z/s from 31 up to 286 and values of Re_s from 1500 up to about 15000. It is found that $\overline{\overline{Nu}}_s$ seems to be practically independent of the hole diameter and of the impingement distance. This, as already mentioned, is believed to be due to the stronger influence of the recirculation effects within the employed enclosed cavity.

4. Conclusions

An infrared scanning radiometer, applied to the *heated thin foil* technique, is employed to test the performance of an anti-icing system. A NACA-0012 leading-edge wing section is considered, protection against icing is achieved by means of a spray-tube with hot air from engines. The performance of such a system is tested in terms of measurements of convective heat transfer coefficients between a concave surface and air jets impinging on it. Several test conditions are considered including the variation of the diameter of the holes of the spray-tube, the hole-to-hole spacing, the impingement distance as well as the initial Mach number of the jets. The experimental data, reduced in dimensionless form in terms of average Nusselt numbers, show independence of the impingement distance because of recirculation effects within the particular tested section. The experimental data fit very well a correlation curve for which the Nusselt number, based on a characteristic length including the hole diameter and the hole-to-hole spacing, is expressed as a function of the Reynolds number based on the same length.

http://dx.doi.org/10.21611/qirt.1994.030

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