AN EXPERIMENTAL STUDY OF AN ANTI-ICING HOT AIR SPRAY-TUBE SYSTEM

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Abstract

Within a cooperation between DETEC and Alenia S.p.A., an investigation is made in order to test the performance of an anti-icing device, which is aimed at preventing the formation of ice by using hot air. In details, protection is achieved by warming critical zones by means of a hot air spray-tube inside aerodinamic surfaces as wing leading-edges. Therefore, the analysis of such a system leads up to determine heat transfer coefficients between a concave surface and air jets impinging on it. In the present investigation the convective heat transfer coefficients are measured by means of an infrared scanning radiometer applied to the *heated thin foil* technique. Tests are carried out by varying the diameter of the holes of the spray-tube, the impingement distance and the initial Mach number of the jets. Data, reduced in dimensionless form in terms of the Nusselt number, are expressed as a function of the Reynolds number. For the tested conditions, no significative influence of the impingement distance is found because of recirculation effects within the cavity.

Introduction

Aircraft have been an indispensable means of transport for many years and hence safety has become a prime consideration. The question can be looked at from several points of view involving structural improvements, sophisticated electronic equipment, the development of systems to permit flight in extreme atmospheric conditions and so on. Within the latter context, icing and its adverse effects on aircraft performance have received increasing attention. Thus, studies on the physics of ice are being carried out in an attempt to characterize impact ice and to develop improved ice protection systems.

Ice forms on an aircraft in flight when droplets of water strike the surface whilst the airplane is passing through clouds or through drizzle at temperature below freezing[1, 2]. The supercooled water droplets, impinging on the surface, can freeze immediately or run back and freeze later, resulting in two different forms of icing, Rime-ice or Glaze-ice, respectively. However, there can be no doubt that, whatever the kind of ice, it will result in a change of aerodinamic profiles and degradation of aircraft handling and performance with possible damage to the airframe or engines resulting from ice shedding. Aircraft safety requires the solution of icing problems. In general airfoils may be protected against icing in two ways:

1) anti-icing systems that prevent ice formation in critical areas, by using sprayed fluids, hot gases or electro-thermal heaters;
2) deicing systems that allow the ice to form to a tolerable thickness and periodically remove it by using pneumatic boots, electro-thermal heaters or hot gases.

The intention of the present work is to test the perfomance of an anti-icing device, which is aimed at preventing the formation of ice by using hot air from engines. In details, protection is achieved by warming critical zones by means of a hot air spray-tube inside aerodinamic surfaces as wing leading-edges. Therefore, the analysis of such a system leads up to determine 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[3, 4, 5, 6]. The review, done by Pletcher[7] about turbulent forced convection, includes some considerations about the influence of streamlines curvature. In particular Pletcher[7] points out that convex curvature in the streamvise direction reduces heat transfer while concave curvature augments it. In the light of the available literature, studies of heat transfer from impinging gas jets on an enclosed concave surface done by Jusionis[8] deserve consideration. Jusionis[8] 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[9]. 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 was made for practical convenience since a general literature finding (among others Goldstein et al.[10]) 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 equal to the ambient one) in the case of heated jets, if the adiabatic wall temperature distribution is known.

Experimental apparatus and technique

The test model 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. 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 Fig.1. 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

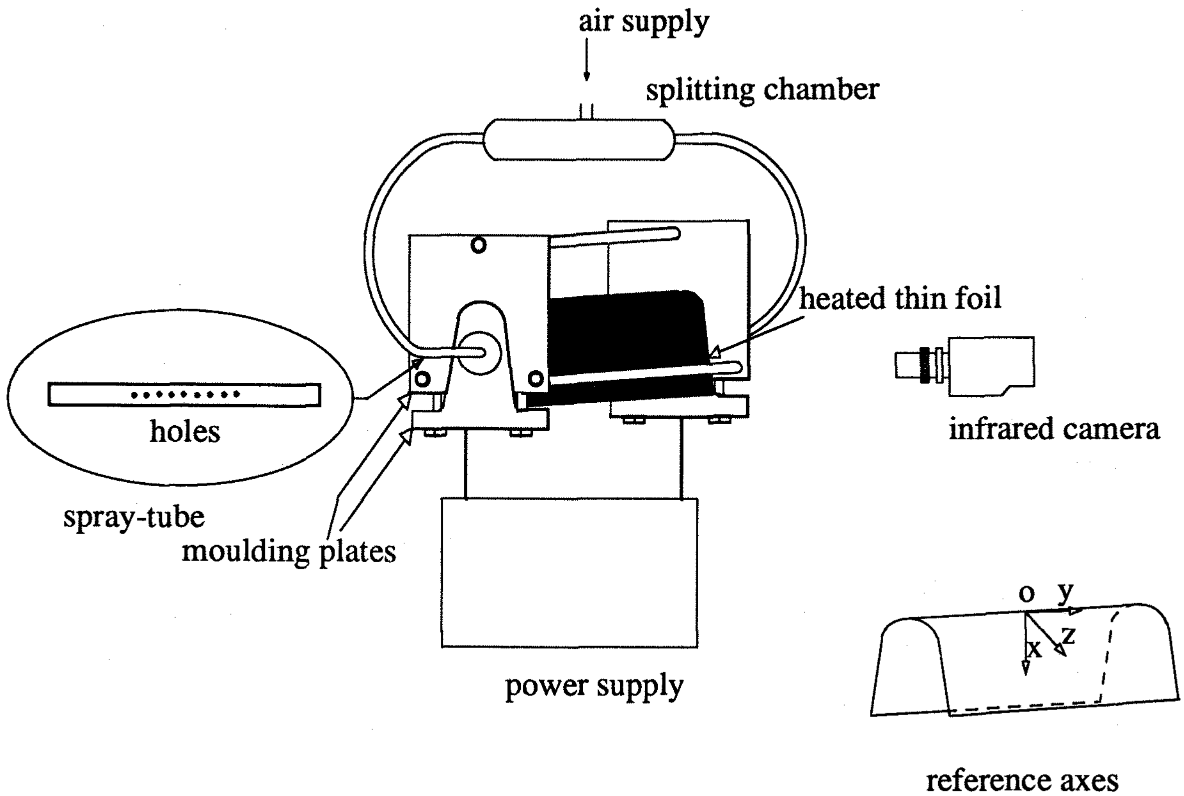

Figure 1 - Experimental set-up

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:

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

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), Tw and Taw are the wall temperature and the adiabatic wall temperature, respectively. 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 d 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 M 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.

Results

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

$$Nu = hd/k \tag{2}$$

with k air thermal conductivity coefficient. The local Nusselt number attains maxima values at the jet impingement points and decreases more or less sharply depending on the impingement distance. The Nusselt number values are averaged ($\overline{Nu}$) spanwise between $y/d=\pm\ 15$ starting from the center nozzle axis (reference coordinates of Fig.1). The distribution of $\overline{Nu}$ against x/c (c wing chord) for d=4*mm*, S/d=10, Z/d=10 is shown in Fig.2 for several Mach numbers. The peak heat transfer coefficient is located at 3.3% of the chord and increases for increasing Mach number.

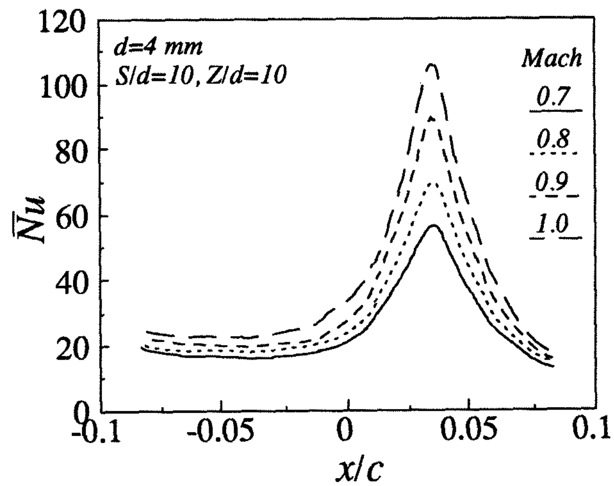

Figure 2 - Chordwise Nusselt number distribution

It has to be outlined that each of the curves shown in Fig.2 is obtained from three different thermographic images taken at the backside ($-0.08 \leq x/c \leq -0.01$), the topside ($-0.01 \leq x/c \leq 0.01$) and the frontside ($0.01 \leq x/c \leq 0.08$) respectively. In the backside region, the heat transfer coefficient attains an almost constant value that slightly increases towards the end because of the presence of the exhaust that is located there.

In general, the maximum and minimum values of $\overline{Nu}$ are found to be approximately 2 and 0.5 times the average one, this seems to be in contrast to the finding of Jusionis(8) (1.4 and 0.7 respectively). The discrepancy has to be ascribed in part to the different reference temperature assumed in calculating the heat transfer coefficients and in part to the different geometry of the employed cavity. Jusionis(8) considered as a reference temperature the gas total temperature To inside the spray-tube instead of the adiabatic wall temperature *Taw* assumed in the present work. Since, at relatively high Mach numbers, the adiabatic wall temperature is not uniformly equal to the stagnation one over the surface, the choice of *Taw* (which is generally smaller than *To* at the stagnation point) leads up to greater values for the heat transfer coefficients in the impingement points. Conversely, the minimum value, far away the impingement zone, may be affected by the different geometry of the test section and the exhaust slot, for which recirculation effects act in a different way (in Jusionis' paper there is no mention of the employed wing profile).

Particular attention is focused on the frontside region ($0.01 \leq x/c \leq 0.08$ the most critical zone for icing occurrence), where data are averaged by following the curvilinear coordinate along the profile and therefore by introducing an average Nusselt number over said region $\overline{\overline{Nu}}$. These data are plotted against S/d in Fig.3 for $M=0.9$, $d=2$, $4mm$, $Z/d=5$, 10, 15. It is evident that $\overline{\overline{Nu}}$ increases for d increasing and S/d decreasing, due to the larger amount of mass flow rate involved. Instead, $\overline{\overline{Nu}}$ seems to be practically independent of the impingement distance; the data spread for $d=4mm$ may be ascribed to the smaller value of D/d (D diameter of the spray-tube), which can result in loss of stagnation conditions.

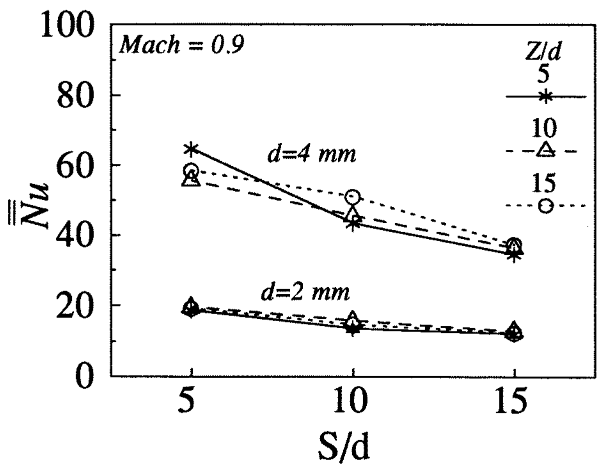

Figure 3 - Influence of *d, Z/d and S/d*

By introducing the modified Nusselt and Reynolds numbers based on the length:

$$s = \pi \; d^2/4S \qquad (3)$$

Jusionis[8] found a data correlation of the type:

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

to include hole diameter and hole spacing. However, it has to be stressed that Jusionis experimented with a single hole diameter. The present data, recasted in the form of $\overline{\overline{Nu}}_s/(Z/s)^{-0.4}$, are plotted against Re_s in Fig.4 together with the Jusionis' correlation.

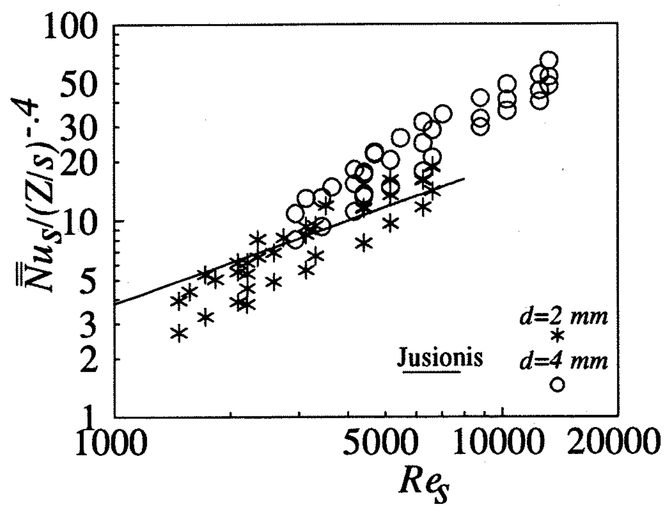

Figure 4 - Comparison with Ref.8

As it can be seen the present data show a consistent deviation from the curve of Jusionis. However, it has to be outlined that the range of applicability of Jusionis' relationship is: $1000<Re<8000$, $50<Z/s<120$, $d=2.5mm$.

As the diagram of Fig.3 shows, the average Nusselt number is not substantially influenced by the impingement distance. So that a general correlation for the modified Nusselt number is attempted as:

$$\overline{\overline{Nu}}_s = aRe_s^n \qquad (5)$$

Surprisingly, all the experimental data relative to the present tests lie over this correlation curve, as shown in Fig.5. It is found that a=1.7x10^{-5}, n=1.39. In particular experimental data of Fig.5 refer to Z/s from 31 up to 286. $\overline{\overline{Nu}}_s$ 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.

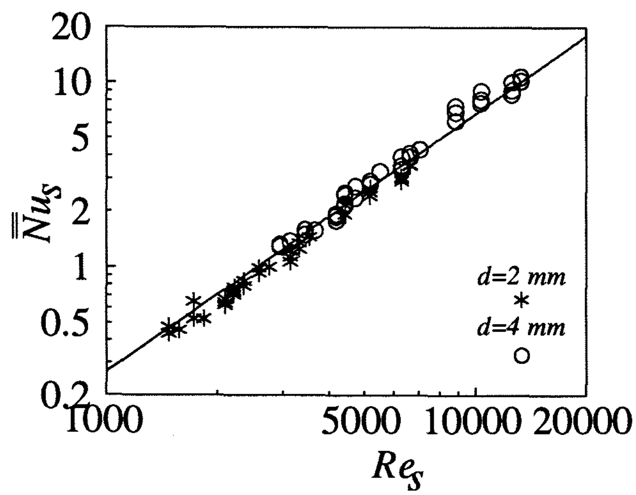

Figure 5 - Data correlation

Conclusions

An infrared scanning radiometer, applied to the *heated thin foil* technique, is employed to test the performance of a hot air spray-tube anti-icing system. Measurements of convective heat transfer coefficients over an enclosed concave surface with air jets impinging on it are made. Several test conditions are considered including the variation of the diameter of the holes, 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 modified Nusselt number is expressed as a function of the modified Reynolds number only. The latter assumption is true insofar as a characteristic length including the hole diameter and the hole-to-hole spacing is considered.

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