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# Technical Notes

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## Experimental Analysis of Surface Flow on a Delta Wing by Infrared Thermography

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### I. Introduction

DELTA wings are extensively adopted for high-performance aircraft configuration design. Combat aircraft have been historically, as well as currently, expected to be controllable within their maneuver envelopes. At the extremes of the envelope an alteration of flow characteristics may occur with the expected dual impact of lift and controllability loss.[1]

As regards delta wings, at moderate angles of attack the leeward flowfield is dominated by highly organized vortical flow structures created by the separation of the boundary layer at the leading edge. A remarkable increase of wing lift is observed in high-angle-of-attack subsonic flight due to the contribution of these vortices.[2,3]

The complex delta wing surface flow is detailed by Delery,[4] who has demonstrated that the surface flow delimited by the primary reattachment and the secondary separation is typically transitional. In this region a remarkable phenomenon can be observed: the boundary-layer development is related to the deflection of the secondary separation line when transition occurs. This effect is the consequence of higher stability of turbulent surface flow, which delays the secondary separation in presence of the significant adverse (spanwise) pressure gradient underneath the primary vortex. Therefore, the secondary separation depends upon boundary-layer transition, and the trace of the secondary separation line is influenced by Reynolds number and angle of attack. On the contrary, the primary separation line is marginally sensitive to these two parameters, as the generation of the main vortex is dominated by the leading-edge geometry for conventional unprofiled delta wings.

To gain some new insights into this field of investigation, a 65-deg delta wing has been extensively tested[5–7] in the D3M low-speed wind tunnel of Politecnico di Torino. Part of this research program is based on measurements made by means of a computerized infrared (IR) scanning radiometer, which is employed to characterize the boundary-layer development over the delta wing by measuring the temperature distribution over its heated surface. The validity of the IR technique and its ability to describe such a complex flowfield is demonstrated.[8]

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The infrared scanning radiometer (IRSR) represents an effective investigation tool in convective heat transfer, in both steady-state and transient techniques.[9] The possibility of applying a computerized IR imaging system to measure convective heat transfer coefficients and to analyze the surface flow behavior in a variety of physical situations, where different data reduction methods may be used, is discussed in Refs. 10, 11, and 12. The IR technique appears to be a suitable and effective diagnostic tool for aerodynamics research in a wind tunnel due to its nonintrusivity, the full two dimensionality of the measurement, and the possibility of treating the video signal output by digital image processing.

### II. Experimental Setup

Experimental tests were carried out in the D3M low-speed wind tunnel of Politecnico di Torino, which is a closed circuit tunnel with a maximum airspeed $V_\infty = 90$ m/s. The test section is circular (3 m in diameter).

The IR thermography measurements were performed in steady conditions (airspeed ranges from 20 to 40 m/s and Reynolds number ranges from $1.10 \times 10^6$ to $2.2 \times 10^6$) at different angles of attack ($\alpha = 5, 10, \ldots, 45$ deg). Note that Reynolds number is based on model root chord. Only symmetric flow conditions were considered (sideslip angle $\beta = 0$ deg).

The effect of induced transition was investigated in a limited number of tests: a strip was placed along wing span at $x/c = 0.18$.

The model is a 65-deg delta wing, with sharp leading edges. Its dimensions are wing semispan $s = b/2 = 396.5$ mm, root chord $c = 850$ mm, wing area $S = 0.337$ m$^2$, bevel angle 30 deg, wing thickness 20 mm. It was suspended almost at the center of the test section in a 90-deg rotated position (Fig. 1). The C-shaped sting support was able to rotate about the vertical axis (to vary the angle of attack $\alpha$) and the motion was driven by a servomechanical unit placed under the floor of the test chamber. A step motor was interfaced by a digital unit with the control computer.

The underwing fuselage (used as a fairing for sting support connections) has a semicircular section and an ogival nose. The upper wing surface is manufactured in polyurethane foam fixed on a layer of plywood and an iron plate used for fuselage and support connections. The top surface is made of a printed circuit board that is

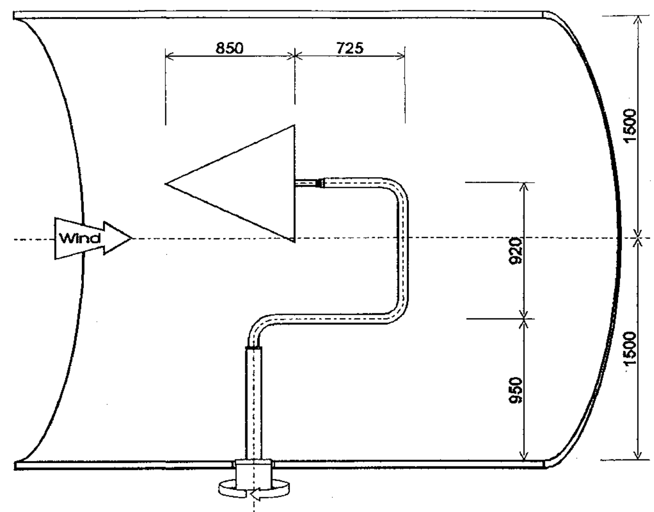


**Fig. 1 Experimental setup.**

glued over the polyurethane foam (20-mm thickness); the circuit is used to generate, by Joule effect, a uniform heat flux on the delta wing surface, whereas the polyurethane layer thermally insulates the model face not exposed to the wind.

The printed circuit board is designed so as to achieve a constant heat flux boundary condition over the model surface. Therefore, the thickness and width of its conducting tracks are realized with very close tolerances. Tracks are 35 $\mu$m thick and 6 mm wide. The overall thickness of the board is 0.3 mm. The viewed surface of the board is coated with a thin layer of black paint that has an emissivity coefficient equal to 0.95 in the wavelength of interest.

The IR thermographic system is based on an AGEMA Thermovision 880 scanner. The field of view (which depends on the optical focal length and on the viewing distance) is scanned by a Hg-Cd-Te detector in the 8–12 $\mu$m window. Nominal sensitivity, expressed in terms of noise equivalent temperature difference, is 0.1°C when the scanned object is at ambient temperature. The scanning spatial resolution is 175 instantaneous fields of view per line at 50% slit response function (SRF). A 20 × 20 deg lens is used during the test at a distance of about 1.8 m.

The thermal image is digitized in a frame of 8 bits 140 × 140 pixels. An application software has been developed to correlate the measured temperatures to heat transfer coefficients. The IR camera takes temperature maps of the wing surface, and these maps are correlated to the local heat transfer coefficient by means of the so-called heated-thin-foil technique. In particular, for each pixel, the convective heat transfer coefficient is calculated as

$$h = \frac{q_j - q_l}{T_w - T_a} \tag{1}$$

where $q_j$ is the Joule heating, $q_l$ is the heat loss (including radiation and internal conduction), and $T_w$ and $T_a$ are the wall (measured by IRSR) and the ambient temperatures, respectively. The radiative thermal losses are computed from the measured $T_w$ whereas the conductive ones through the back side of the circuit, i.e., towards the polyurethane foam, are neglected. Typical heat fluxes are of the order of $10^3$ W/m$^2$.

## III. Experimental Results

In discussing the results hereafter presented, it should be considered that when the model top surface is electrically heated in wind on conditions, regions where higher temperatures are detected are characterized by lower heat transfer coefficients [see Eq. (1)], i.e., lower wall friction coefficients $c_f$, and vice versa.

The thermogram shown in Fig. 2 ($\alpha = 10$ deg and $Re = 1.10 \times 10^6$) recovers all of the features of the separated flow typical of delta wings. Freestream temperature is equal to 27.5°C.

The central region of the wing surface is characterized by an almost two-dimensional flow. Moving from the model apex in streamwise direction along the root chord, a gradual increase in temperature is first observed, followed by a sharp drop. This kind of distribution is attributed to the laminar boundary-layer development (clear arrow-shaped area), so that the initial temperature increase is due to the growth of boundary-layer thickness. After laminar-to-turbulent transition, the heat transfer is intensified and the temperature decreases. Finally, the thickening of turbulent boundary layer produces another slighter positive temperature gradient. In the vicinity of the leading edge a second region characterized by a relatively high heat transfer is clearly evident. Moving along the wing span (from the root chord) a well-defined decrease in temperature is found, even if a local maximum can be clearly identified close to the leading edge. Indeed, the locus of such local temperature maxima is a straight line originating from the wing apex and should be correlated with the secondary separation line.

By increasing Reynolds number it was found that transition is promoted, and the laminar region reduces its extension. The region where secondary separation occurs is split in two parts, the second one being shifted outboard. This behavior can be explained considering that boundary-layer development in the crossflow plane influences separation and keeping in mind that transition delays separation.

At higher angle of attack, the laminar core becomes larger and transition is delayed, as a consequence of the reduction of the axial velocity component.

Furthermore, if transition is artificially induced, the laminar region disappears, and downstream of the line marked by the strip, the temperature drops abruptly. The secondary separation presents turbulent characteristics too.

Quantitative heat transfer distributions (in terms of Stanton number) are going to be described hereafter. Local Stanton number is defined as $h/(\rho c_p V_\infty)$, where thermophysical quantities are evaluated at film temperature.

The chordwise distribution of Stanton number as a function of Reynolds number is presented in Fig. 3. When the condition $Re = 1.65 \times 10^6$ is considered, a minimum of heat transfer coefficient is found at $x/c \approx 0.4$. The decrease of Stanton number moving away from the wing apex recovers the analogous trend of the heat transfer coefficient (and so the skin friction $c_f$) for laminar boundary layer on a flat plate. For $x/c \geq 0.4$ the sharp increase of Stanton number demonstrates that transition occurred, so that a maximum is detected when surface flow becomes completely turbulent ($x/c \approx 0.55$). Finally, moving towards the trailing edge, the Stanton number slowly decreases. It may be observed that the increment of Reynolds number has an evident promoting effect on transition (Fig. 3), as the minimum of the Stanton number moves forward.

The strong effect of Reynolds number on the secondary separation (Fig. 4) can be evaluated by comparing the position of spanwise Stanton number minima (i.e., the $y/s$ locations where secondary separation occurs) for $Re = 1.1 \times 10^6$ and $2.2 \times 10^6$, which are located at $y/s = 0.66$ and $y/s = 0.82$, respectively.

The comparison of measurements made with and without transition trip (Fig. 5) demonstrates that transition, when the strip is present on the model top surface at $x/c = 0.18$, is immediate. The magnitude of the Stanton number peak, associated with the high skin-friction coefficient, is higher when transition is induced, even

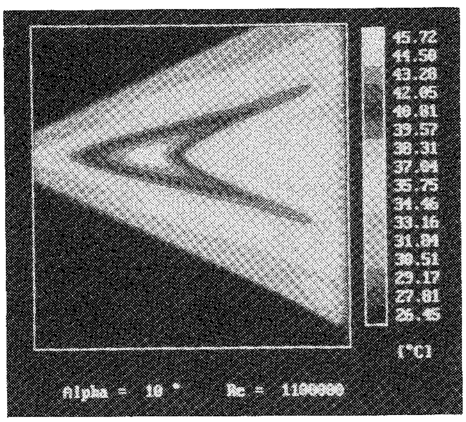


**Fig. 2 Temperature distribution on the model surface ($\alpha$ = 10 deg and $Re$ = 1.1 × $10^6$).**

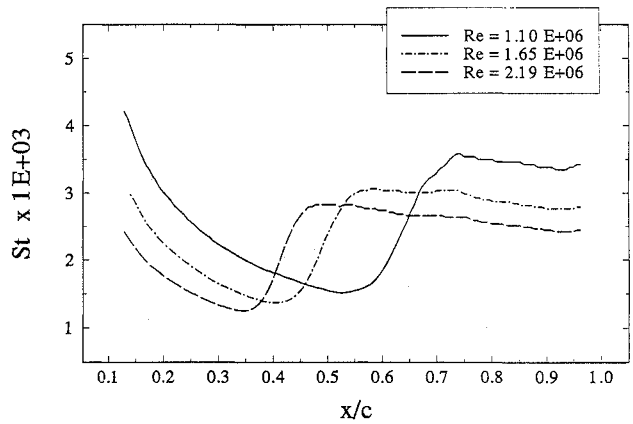


**Fig. 3 Chordwise Stanton number distribution as a function of Reynolds number ($\alpha$ = 15 deg and $y/s$ = 0.0).**

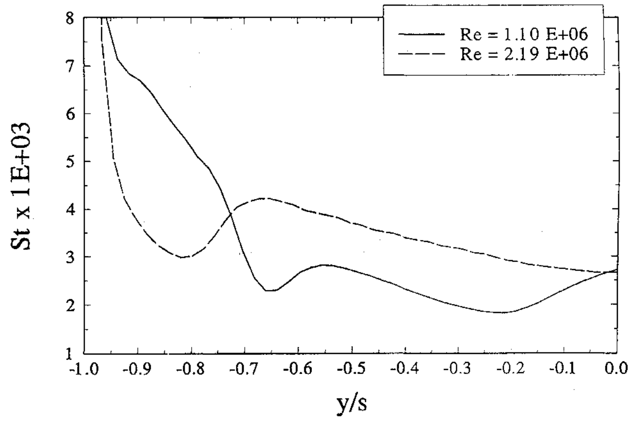


**Fig. 4 Spanwise Stanton number distribution as a function of Reynolds number ($\alpha$ = 15 deg and $x/c$ = 0.65).**

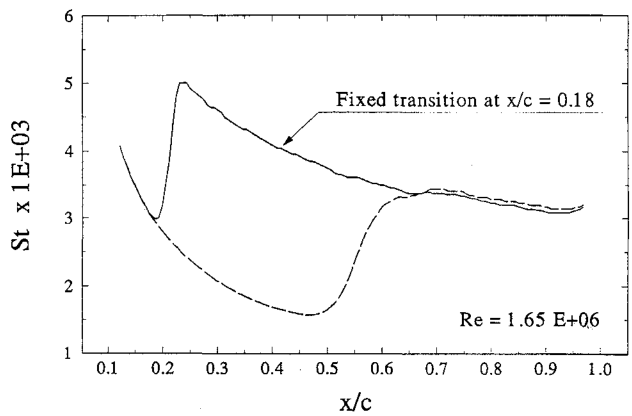


**Fig. 5 Effect of induced transition on chordwise Stanton number distribution ($\alpha$ = 20 deg and $y/s$ = 0.0).**

if at the model apex and nearby the trailing edge the two Stanton number trends overlap.

## IV. Concluding Remarks

IR thermography has been employed for heat transfer measurements and surface flow visualizations on a 65-deg delta wing model. Experimental results generally confirm the capability of the IR technique to analyze such a complex surface flowfield by means of convective heat transfer coefficient measurements.

In the central part of the wing, where nearly parallel flow conditions are established, a laminar core is present, followed by a transitional region, after which the boundary layer becomes turbulent. Data obtained by increasing angle of attack and Reynolds number have proved that the behavior of this portion of surface flow can be correctly explained with current boundary-layer theories.

In the region influenced by crossflow, a significant effect of Reynolds number is confirmed: the secondary separation line is deflected outboard in the $x/c$ location where transition occurs.

The effectiveness of a strip in triggering transition has been found to be very remarkable.

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# Prediction of Separation Bubbles Using Improved Transition Criterion with Two-Equation Turbulence Model

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## Introduction

THE transitional separation bubble developed on the airfoil surface, that comprises the laminar separation, transition, and reattachment as a turbulent boundary layer, has been studied extensively due to its importance in many engineering applications. Among various analytic procedures in the literature,[1–4] one more successful and rigorous than the others is the Navier–Stokes approach developed recently by Choi and Kang.[4] The use of the Navier–Stokes equations in place of the reduced equations of boundary-layer type improved the results significantly, especially for the leading-edge bubbles.

A key ingredient in the analysis is knowing where to trigger the onset of transition. As the precise location of transition is not available experimentally, it needs to be deduced from the numerical calculation in order to devise a transition criterion. Here, the calculation is performed with the transition point prescribed; the point is varied continuously to find the one that gives the best results compared with the measured data, i.e., velocity profiles, pressure, etc. The transition is assumed to occur at that point. The criterion used in Ref. 4, which relates the Reynolds number at transition to that at separation, as was similarly used in Kwon and Pletcher,[1] was satisfactory in predicting the pressure distribution. It was also noted then, however, that since the nature of the flow was so sensitive a

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