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Boundary-Layer Transition-Detection in a Cryogenic Wind Tunnel Using Infrared Imaging

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Cryogenic wind tunnels are currently the only option available to test models of medium to large transport airplanes at high Reynolds numbers identical to those encountered in flight. This matching in Reynolds numbers is required for reproducing the flow viscous effects, most notably the laminar to turbulent boundary-layer transition. Infrared imaging is particularly attractive for transition detection in cryogenic wind tunnels because it is nonintrusive, fast, and provides a global view of the boundary-layer status on the model. An experimental method using a commercial 8- to 12-μ infrared imaging system was developed for transition detection in cryogenic wind tunnels. So far, transition has been detected at temperatures down to 170 K. At this temperature, tunnels with a pressurization capability of only a few atmospheres can generate transonic flows at Reynolds numbers beyond 3×10^8 per meter.

Nomenclature

M = Mach number
P_t = total pressure
R/m = Reynolds number per meter
R_c = chord Reynolds number
T_t = total temperature
α = angle of attack
ΔT_t = total temperature step set in the wind-tunnel flow

Introduction

DURING the last decade, infrared (IR) imaging has matured into a valuable experimental method for boundary-layer studies on models in wind tunnels and on airplanes in flight, particularly for transition detection from laminar to turbulent flow.[1] However, wind-tunnel measurements are not directly applicable to full-scale designs of large airplanes owing to the "Reynolds number gap." This expression refers to the difficulty of reproducing in wind tunnels the viscous effects as they occur in flight because of the Reynolds number disparity between the airplanes and the scaled-down models. Current large transport airplanes may fly at Reynolds numbers up to $R_c = 60 \times 10^6$, based on the mean aerodynamic chord, whereas current (conventional) wind-tunnel testing is limited to $R_c = 15 \times 10^6$. Testing in cryogenic wind tunnels can solve this Reynolds number disparity. By combining low flow temperatures and modest pressurization, Reynolds numbers in excess of $R/\mathrm{m} = 3 \times 10^8$ can be generated. For application in cryogenic wind tunnels, IR imaging has, in principle, the right attributes. It is nonintrusive, it provides a global picture of the boundary-layer regimes on the wing, it does not require repeated surface preparations, and thus, it is conducive to high productivity. Other than Ref. 2, upon which this paper is based, Ref. 3 is the only reference found concerning IR imaging detection of boundary-layer transition at low temperatures, down to 240 K. This paper describes an experiment aimed at determining to what extent an off-the-shelf IR imaging system can be used for this application.

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Experimental Setup

The experiment was carried out in the NASA Langley Research Center 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT), which has a 0.33- ×0.33-m square test section. Liquid nitrogen is injected continuously into the tunnel to generate flows at stagnation temperatures as low as 100 K, stagnation pressures as high as 620 kPa, Reynolds numbers up to 300×10^6 per meter, and Mach numbers ranging between 0.2 and 0.95. A key feature of the 0.3-m TCT is its capability to vary the Reynolds number of the flow independently of the Mach number. The wind-tunnel operating conditions (temperature, pressure, Mach, and Reynolds numbers) are regulated continuously by an automated control system with on-line updating capability. This results in a flow that is thermally very stable; the total temperature standard deviation from the average is 0.2 K, with the maximum deviation being about 0.5 K independent of the operating conditions.[4]

The wind-tunnel model was a modified supercritical SC(3)-0712 airfoil 12% thick, with a 22.9-cm chord and a 33.0-cm span, made of a maraging steel spar wrapped in epoxy coated fiberglass. This type of construction promised improved signal-to-noise ratios for the thermograms because of the low heat dissipation rate into the substrate and the high surface emittance of the skin. Four thermocouples were embedded in the skin flush with the surface, at equal spacing along the chord, to allow continuous temperature monitoring of the model throughout the experiment. This capability is required to ensure thermal equilibrium between the model and the flow prior to the taking of data.

Theoretical considerations based on Planck's law for blackbody radiation indicate that targets at decreasingly lower temperatures emit most of their IR radiation at increasingly longer wavelengths. Therefore, an IR camera designated to scan targets at very low temperatures, say 100 K, should work in a wave band centered around 30 μ. However, the commercial market of IR imaging systems offers cameras that work either in the 2- to 5-μ, or in the 8- to 12-μ wave bands. These wave bands are also known as atmospheric windows to indicate the restricted character of air transparency to IR radiation. For this application, an 8- to 12-μ IR imaging system was chosen. Although its operation wave band is best suited for scanning targets at ambient temperatures, this system was chosen because its performance came closest to the present needs. The 2- to 5-μ imagers match the peak radiation wavelength occurring in higher temperature applications and therefore would have been a very poor choice for the cryogenic environment. The optical path from the imager to the airfoil included two IR transparent windows and two mirrors, as shown in Fig. 1. The outer (plenum) window is round; the inner (test section) window is shaped similarly to a block letter D lying on its flat side. The inner window frame partially obscures the viewed area, which is about 15 x 7 cm along the wing chord. The demarcation of the airfoil area viewed by the IR camera is shown in Fig. 2. In the initial phase of the experiment, a microthin hot film was used to validate the transition detection with the IR system. Later on, grit (No. 120) glued at a point located at 20% of the chord on the airfoil surface helped verify the thermal signature of transition as it showed on the thermograms. Reference 2 describes in detail the various components of the test setup and their performance.

For airfoils with chords identical to the one used in this investigation, the operational envelope of the 0.3-m TCT offers aerodynamic testing up to $R_c = 75 \times 10^6$, a value likely to occur at the wing root sections of large transport airplanes. However, the purpose of this experiment was not to maximize the Reynolds number of the flow, but rather to determine the minimum flow temperature where transition could still be detected with the commercial IR imaging system on hand. The option to maximize the Reynolds number at any temperature through flow pressurization was not investigated.

Discussion and Results

Boundary-layer transition is characterized thermodynamically by an increase in the recovery temperature of the turbulent regime relative to the laminar. Accordingly, a surface exposed to a flow where the boundary layer goes through transition should, under thermal equilibrium, exhibit a similar temperature distribution. This is the principle upon which transition detection using IR imaging was originally conceived. However, at low temperatures, there are some difficulties with this technique. The first difficulty is the sharp drop that occurs in the radiated energy with decreasing target temperatures (Planck's law) accompanied by a continuous shift of its peak value to longer wavelengths (Wien's law). As the target temperature decreases, the reduced radiated energy and the measurement at off-peak radiation wavelengths affect the output of the IR imager that scans in a wave band optimized for higher temperatures. The second difficulty is that the difference in the recovery temperature values between the turbulent and the laminar regimes decreases with decreasing freestream temperature. The third difficulty is that the sensitivity of the IR imager deteriorates as the target temperature decreases. The temperature at which the IR imager sensitivity approaches the difference in the recovery temperatures between the turbulent and the laminar regimes is the limit below which transition detection with a given imaging system is no longer possible. These difficulties combine to pose significant obstacles to using commercial IR systems in aerodynamic research at low temperatures.

To enhance the thermal signature of transition on the airfoil surface, the flow in the tunnel was set to undergo a fast temperature increase (smaller than 1% of the total temperature), thus inducing a transient heat transfer to the model. As expected, the thermal response of the surface revealed the airfoil area under the turbulent boundary layer through its higher heating rate relative to the area under the laminar boundary layer. The observation of this process through IR imaging was made possible by the low thermal diffusivity of the model composite skin. This property caused the surface layer to heat, temporarily conforming with the local convective heating pattern, before the substrate reached thermal equilibrium by lateral and in-depth heat dissipation. However, locating the boundary-layer transition on the thermograms still required a trained eye to discern between effects of surface temperature variations and nonuniformities in the emittance distribution. At this point, the raw thermograms had to be processed digitally to enhance the transition location on the airfoil.

The thermograms produced by the IR system are digitized and stored on a computer; color may be used to create a visual representation of the target temperature. In this experiment, the interest is on the temperature differences between the laminar and the turbulent areas of the airfoil, rather than with the absolute temperature of the target at a given time. By subtracting the temperature values of the target measured before and

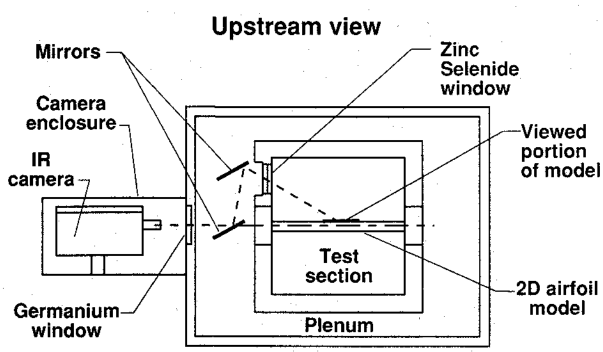

Fig. 1 Optical path of IR radiation from airfoil to IR imaging system in the 0.3-m TCT.

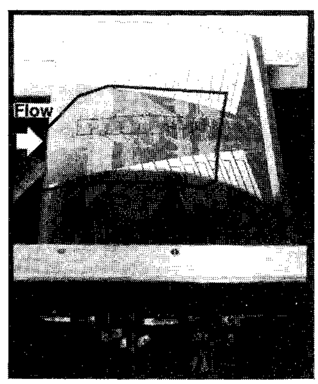

Fig. 2 Airfoil area scanned by the IR camera.

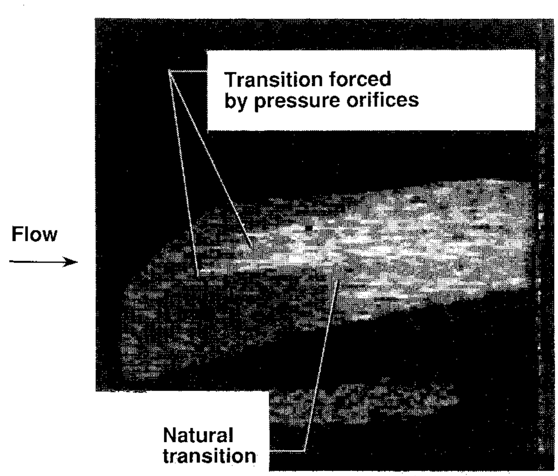

Fig. 3 Transition detection at 190 K by IR imaging: $\Delta T_t = 1.5$ K; $\alpha = -2$ deg; $M = 0.60$, $R_c = 6.5 \times 10^6$.

immediately after the temperature step was imposed on the flow, the dynamic range of the thermograms was reduced, focusing attention on the net thermal effects of the transition. This process also removes effects associated with variations in the airfoil surface emittance and background reflection. A sample result of transition detection at $T_t = 190$ K is presented in Fig. 3. The irregular pattern exhibited on the upper side of the thermogram is due to transition forced by pressure orifices (0.254-mm diam.) located in that area. A problem that may arise in transonic testing is masking of transition underneath a shock wave or a possible confusion between the two similar thermal signatures.[2,3] The doubt of ambiguity can be eliminated by measuring the static pressure distribution, or by gluing grit at a point near the leading edge for purposely tripping the boundary layer into transition locally.

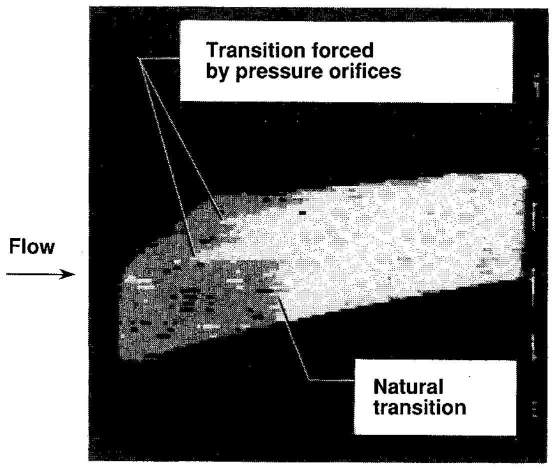

Fig. 4 Transition detection at 220 K by IR imaging and image enhancement: $\Delta T_t = 1.0$ K; $\alpha = -1.5$ deg; $M = 0.56$; $R_c = 4.7 \times 10^6$.

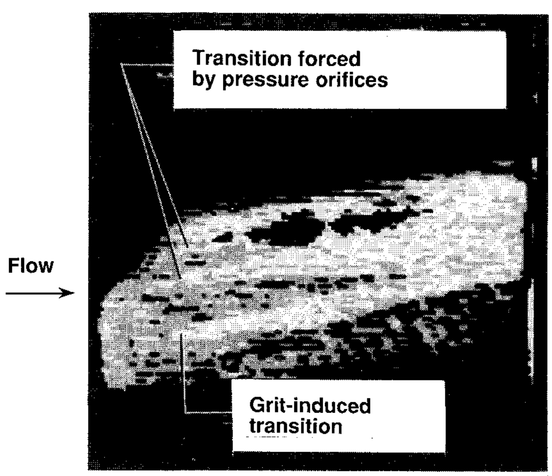

Fig. 5 Transition detection at 170 K by IR imaging and image enhancement: $\Delta T_t = 1.5$ K; $\alpha = -5$ deg; $M = 0.66$; $R_c = 8.5 \times 10^6$.

For presentation and reproduction purposes, it is proposed to distinguish between the laminar and the turbulent boundary layer by assigning only one color to all of the values of the temperature difference associated with each of the boundary-layer regimes. A result of this ad hoc procedure for image enhancement, herein designated as binary shading, is displayed in Fig. 4, as applied to a thermogram obtained at $T_t = 220$ K. The experiment was stopped at $T_t = 170$ K, where the raw signal indicating transition almost vanished but still could be enhanced through the binary shading method, as shown in Fig. 5. The significance of these findings is that 8- to 12-μ IR imaging systems can detect boundary-layer transition on composite-built models in transonic flows up to $R/\text{m} = 36 \times 10^6$ at ambient pressures. Using flow pressurization, it may be possible to boost this value; say, at $M = 0.85$, the 0.3-m Transonic Cryogenic Tunnel can generate flows up to $R/\text{m} = 135 \times 10^6$, whereas the National Transonic Facility can go up to $R/\text{m} = 195 \times 10^6$.

Conclusions

Boundary-layer transition-detection studies using an IR imaging system were carried out in the 0.3-m Transonic Cryogenic Tunnel on a composite-built airfoil. The purpose was to determine the minimum flow temperature where commercial IR imaging systems operating in the 8- to 12-μ wave band can still detect transition on models in low-temperature, high Reynolds number flows. The experiment was designed to benefit from a combination of factors including the flow control system of the wind tunnel, the construction materials of the model, and the image-processing options of the IR system.

The results indicate that 170 K is the lowest temperature limit where transition detection is possible with 8- to 12-μ commercial IR systems. At this temperature, and with modest pressurization, the 0.3-m Transonic Cryogenic Tunnel can generate flows up to 135×10^6 R/m. Ultimately, testing at the full high Reynolds number capability of cryogenic wind tunnels (at temperatures down to 100 K) may require IR imaging systems operating at longer wavelengths, ideally in wave bands centered around 30 μ.

Acknowledgment

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