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# Twenty-Five Years of Aerodynamic Research with Infrared Imaging

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## I. Introduction

THROUGHOUT the history of aerodynamic research, aeronautical engineers faced the need to know more about boundary-layer flows, or ignoring the need were forced to pay the price. At times, the capability to define and integrate boundary-layer effects in a new design may impact on the success of an entire project. The commercial introduction of infrared (IR) imaging systems in the midsixties opened the possibility to visualize viscous interactions between a body and the surrounding airflow by mapping the surface temperature distributions on configurations of interest. The momentum and heat exchange occurring across the boundary layer were related classically through the Reynolds analogy.[1] Invoking this analogy, surface temperature distributions are known to contain information related to both the heat transfer and the skin-friction processes occurring at the wall. Therefore, the capability of IR imaging systems to produce in real-time thermograms that can be interpreted both globally and locally makes them attractive for skin-friction and heat transfer aerodynamic studies.

Space exploration activities sparked interest in high-supersonic and hypersonic flight, and inevitably motivated the need to measure and define thermal loads. Most notable are the re-entry conditions of the Space Shuttle. Starting in the early seventies, the increase in fuel price had a deep impact on the air transportation industry. The response to the challenge of improving flight economy in the subsonic and transonic regimes was initially focused on power plant efficiency. Later, the attention turned toward the aerodynamic efficiency through drag reduction, with the friction component getting much attention.

The resurrection and the success of activities addressing all flight regimes depend critically upon the evaluation and understanding of the viscous flow effects. In the supersonic and hypersonic regimes, the boundary-layer status affects both the friction drag and the thermal loading of the structure, two items of high consideration in any design. In the subsonic and transonic regimes, sustaining laminar flow over a significant part of the wings is a major challenge of current aerodynamic interest.

In spite of the significant potential demonstrated by IR imaging systems for aerodynamic research, the method was not widely accepted and recognized for its full capability until relatively recently. Two problems delayed acceptance of the method in its earlier stages of development. The first was a lack of easily accessible capability to store and manipulate data. This drawback was naturally solved with the commercial introduction of videocassette recorders (VCRs) and personal computers. The second was the realization that the temperature information contained on thermograms results from a multifaceted process encompassing aerodynamics, heat conduction, geometry, and radiation.[2]

The reduction of experimental data, from temperatures to heat flux distributions via the thermal response of the substrate, can be simplified if the physical reality can be mathematically modeled based on assumptions leading to analytical solutions. At one end there are models made of thermal insulating materials, where it is plausible to assume that deep in the substrate there is a layer that virtually keeps its temperature constant throughout the test (if its duration is not too long). This case is known as the "semiinfinite slab" model, for which the heat conduction equation can be solved analytically for the heat flux as a function of the transitory surface temperature distribution. At the other end there are hollow, "thin-skin" models, where it can be assumed that the heat flux is uniformly absorbed in-depth the material with the temperature changing uniformly across the model skin. This case can be approximated by the "thin-skin" model of the thermal energy equation. Other types of model construction may fall in between these two classifications, as they are affected by

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the filler or the spar underneath the skin. It follows that understanding the direct and indirect factors influencing experimental results is critical for the determination of the data-reduction technique. Therefore, designing aerodynamic experiments based on IR imaging and extracting data from the thermograms are very challenging processes.

Utilization of this technique has yielded a wealth of experience and aerodynamic results, but the subject has not been adequately reviewed. As recently as 5 years ago, a paper on developments in flow visualization[3] mentioned only two references about aerodynamic research performed with IR imaging systems, although by that time the method was known for 21 years. This paper is a wide-ranging review of the applications that IR imaging has seen in aerodynamic research. It should benefit in particular those contemplating the use of the method. After a brief description of IR imaging systems, a few overview papers describing and analyzing the IR imaging technique for aerodynamic research will be mentioned. Attention will turn then to supersonic and hypersonic, and in turn subsonic and transonic applications—two areas where these systems made distinctive contributions. The survey will then proceed to some specific applications in flow visualization, propulsion, fluid mechanics, and heat transfer. Before concluding, a quick look will be taken at current trends and expected developments in the application of IR imaging to aerodynamic research.

## II. IR Imaging Systems and Data Processing

Most of commercial IR imaging systems are similar in concept to those built 25 years ago. A single detector, cooled by liquid nitrogen, is exposed to the incoming radiation from the target on which the objective lens is focused. To obtain a field of view (FOV), FOVs offered by the camera scans the scene both horizontally and vertically, with rotating prisms or mirrors, producing lines for the video display. The area projected at any single time on the detector is subtended in the instantaneous field of view (IFOV). The output of the detector is transmitted to a black-and-white video display, where lighter shades are associated with higher temperatures. Usually, a single pixel displays the sensor output from one IFOV. To give some specific number,[4,5] commercial imagers are sensitive to IR radiation either in the 3–6 $\mu$m (short wave) or in the 8–12 $\mu$m (long wave) bands, also identified as infrared atmospheric windows. Shorter wavelength imagers are better suited to scan high-temperature targets and vice versa. The FOVs offered by commercial objective lenses range between 2.5–40 deg. One complete scanning of a scene is called a field. To improve the visual quality of the display, two or four fields are usually interlaced to produce a frame. Thus, the camera produces fields, but the human eye perceives frames. A field has about 200 lines, each line having about 200 pixels. The scanning rate may vary between 25–60 fields per second. Gauffre and Fontanella[6] give a particularly concise and useful description of IR imaging systems that introduces the reader to camera figures of merit, including sample calculations.

The systems can be connected to VCRs for analog recording and playback, and to personal computers equipped with dedicated software for digitizing, storing, and processing of individual fields or frames. A key feature of such a software is the gradual assignment of artificial colors (from black through blue, green, and so on to red, yellow, and white) for corresponding gray shades in the original image, thus producing a visual sensation of the temperatures over the scanned target. Recent IR imaging models have a false coloring option built in their display units. Under some circumstances, the thermograms may have to be enhanced when their quality is not adequate for data interpretation or presentation. Simple ad-hoc methods, such as averaging frames or images integration, may produce satisfactory results.[7] In more problematic cases, more complex processing methods are required, such as smoothing contours and time-based interpolation.[8]

As it frequently happens, the information contained on a thermogram will not make sense to the experimentalist, and he/she may be constrained to evaluate the actual performance and limitations of the IR imaging and data-acquisition system. In those rare cases, where the target temperature distribution is considered well-behaved and known, the system may be evaluated on an input-vs-output basis.[9] In other cases, specific performance functions, e.g., the modulation transfer function (MTF) of the system may have to be evaluated, to account for missing information and allow data restoration.[10]

In most aeronautical applications, the camera is installed either outside the wind tunnel, scanning a model in the test section or, inside an airplane cabin or cockpit, scanning the wing. For the radiation to pass through, the wind tunnel or the airplane need special windows transparent to IR radiation. There is a large selection of commercial IR transparent materials.[11] The choice will depend upon the transmittance in the waveband of the specific sensor used, mechanical considerations, environmental compatibility, and cost. Antireflective coating may improve the transmittance of some of these materials, at the expense of the reflectance.

## III. Method Reviews

Some of the papers documenting aerodynamic or fluid mechanics experiments feature lengthy introductions describing IR imaging systems, data acquisition and processing hardware, specific peripherals, theoretical underlying principles, general and specific applications, etc. Although the main value of the papers is found in the rather specific work done by the authors, some of them are a good starting point for forming an idea about this technique.[12–23] Some references document studies that were repetitively presented with additions, changes, and refinements. These successive publications present before the reader the development of the technique, as they give the feeling of the obstacles that were overcome in gaining mastery and implementation. Some of the above references originated in lecture notes and were published later elsewhere.

## IV. Supersonic and Hypersonic Studies

The first documented use of IR imaging in aeronautical research was reported in 1967 by Thomann and Frisk[24] of the Aeronautical Research Institute of Sweden. In a wind-tunnel experiment performed at Mach 7, the temperature distribution on an elastomeric paraboloid was measured as it evolved in time. From the temperature rate of change, the heat flux at the model surface was deduced using the "semiinfinite slab" solution[25] for the unsteady heat conduction equation. The short test run (seconds) combined with the low thermal diffusivity material justify use of that solution. This data-reduction concept was borrowed from the fusible paint technique,[26] and it is still in use. The experiment showed the IR imaging to be as accurate as other competing techniques for heat flux determination, with the advantage that without requiring surface preparation before or in-between runs, it is quite expedient. More than a decade later, Balageas and Ory[27] proposed a data-reduction method that incorporated the finite thickness of the skin and the boundary conditions at the internal wall, expanding the applicability of the technique to thin-skin models.

After this technique was shown to work, there were more attempts to evaluate and improve it, e.g., scanning the model against a water-cooled plate to reduce the background radiation noise.[28] However, for a few years the method was far from being productive enough to be directly applicable to project designs. Compton[29] at NASA Ames Research Center realized that the bottleneck of the technique was the data acquisition, storage, and processing. One should realize that the heat flux distribution is calculated from the temperature readings on a pixel-by-pixel basis that was generated at rates of approximately 88,000 IFOVs per second. The solution was devised to record the data on an analog tape, to digitize and read it into a computer for processing, and thereafter to display and plot the results. This engineering concept set the pattern for similar systems to this very day. Automating the data-processing system gave access to all of the information produced during a test. In particular, it was understood that monitoring the history of the heating rate for relatively long periods of time could indicate if the boundary-layer transition front moved on the model during the test.

In 1973, the Arnold Engineering Development Center (AEDC) embarked on a large-scale program to develop the capability of extensive heat transfer testing in the hypersonic regime with an IR imaging system.[30,31] The von Karman facility Tunnel B was designated for that purpose, and engineering modifications were made to allow hosting an IR imaging system for test series that extended over long periods of time. An automated data-processing system was developed that accepted input from the IR camera, thermocouples on the model, and temperature and pressure probes providing the operational parameters of the wind tunnel. In parallel, materials used for model manufacture were screened for compatibility with the technique and the environment, and their thermal and radiative properties were documented. Accurate numerical values of these properties are critical for processing the IR imager output and deducing of the temperature distributions on the model. To assess the accuracy of the technique, calibration procedures were developed; the repeatability of the measurements was evaluated; and a measurement error model was implemented.[32,33] The results were confirmed also by other experimental means and were found to agree well with theoretical predictions. On the negative side, it was found that step changes in the temperature distribution could not be resolved, the response being blurred and smeared over a few adjacent pixels. Moreover, the camera displayed a consistent measurement error when the target temperature gradient exceeded a certain value. These shortcomings were blamed on the relatively large size of the imager's IFOV, but this aspect was not pursued enough to a full understanding. Although a smaller IFOV will allow a better capture of abrupt changes in the temperature distribution, the blur effect will always occur because of the optical transfer function (OTF) of the camera.

The infrastructure and expertise developed at AEDC in the 1970s were used to measure convective heating rates on a 0.04-scale model of the Space Shuttle orbiter under flow conditions prevailing during the re-entry phase (Fig. 1). The test flow conditions were typically: Mach 8, temperature 1300°R, Reynolds number $0.5 \times 10^6$–$3.5 \times 10^6$ per foot, angle of attack 30–45 deg. The data obtained were incorporated in the design of the thermal protection system of the orbiter.[34,35] Besides project-oriented applications, general heating studies of elastomeric materials were carried out,[36] the results giving insights to phenomena that were harder to access with other diagnostic tools. For example, in a testing program run at Mach 10, the surface heating was observed to be nonuniform to a greater extent than could have been forecast. Hot streaks that may have been caused by wing-tip crossflow effects were detected, and increased heating rates were observed when bubbles caused by local failure of adhesive bonds formed in the substrate. Even though part of the data could not be reduced using the "semiinfinite slab" solution, the underlying assumptions being no longer valid, some of these effects could still be quantified, and operational conclusions could be drawn.

Tests under rarefied flow conditions at very high Mach numbers, say Mach 20, are characterized by a short duration of a very few seconds and heat fluxes that may get as low as 0.5 kW/m$^2$. In these cases, solid models may no longer be acceptable because the relatively long time required for the temperature pattern to become established is unavailable. For this application, thin-skin models and a conforming data-reduction model may be the only way to get useful results.[16] Balageas et al.[13-15] extended the use of thin-skin models to low Mach numbers (down to Mach 2.0) through "stimulated thermography." According to this concept, the model in the

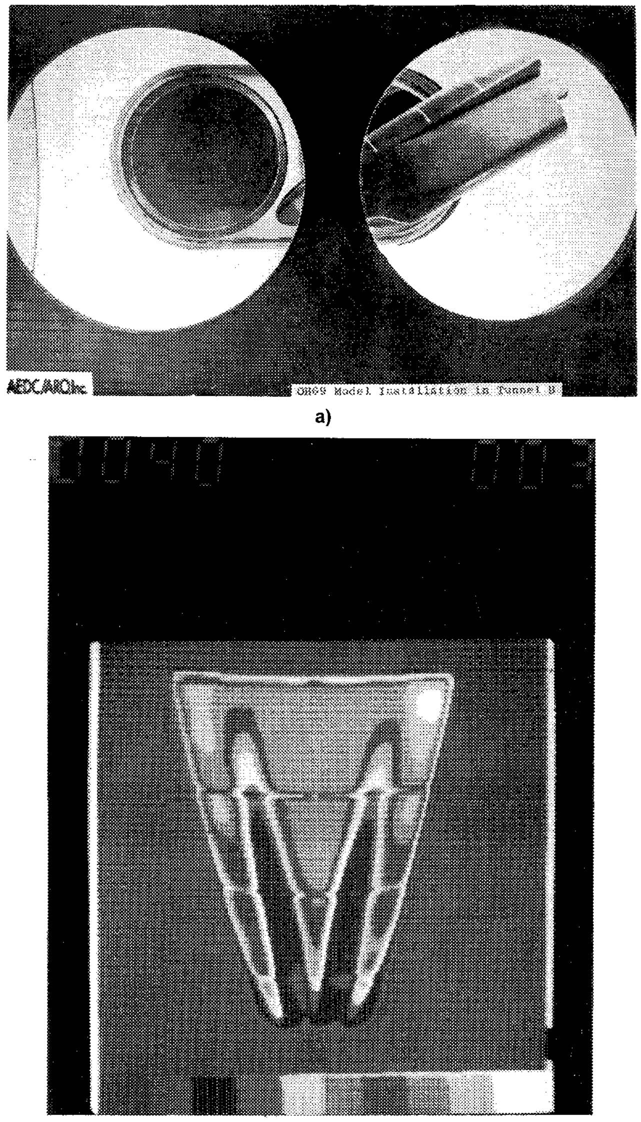


**Fig. 1 a) Space Shuttle forebody model in Tunnel B at AEDC von Karman gas dynamics facility during hypersonic heating test; b) Typical heating pattern on the windward side as captured by the IR imaging system[35] (Courtesy NASA, reprinted with permission).**

wind tunnel is heated by a bank of lamps over a preset period of time, and the heat transfer coefficient is determined from the temperature response of the model, under wind-off and wind-on conditions, integrated over a period of time. This approach is less susceptible to curvature effects of the surface and noise, with the data reduction being based on integration and not on differentiation.

Next to determination of heat fluxes, location of boundary-layer transition to turbulence was always a major subject of interest to aerodynamicists. Turbulent boundary layers have higher skin friction than the laminar ones. On the other hand, the laminar boundary layer is more susceptible to separation, especially in the supersonic and hypersonic regimes where shock-wave interaction can cause strong adverse pressure gradients. With the increase in skin friction, the transition to turbulence also induces higher heat fluxes, and under some speed and flight time combination, the structure may require special thermal protection. Therefore, the capability to detect boundary-layer transition may have far-reaching consequences for the development and verification of designs.

The thermal signature of transition on a model can be caused by one of two effects. The first is the near-term thermal response of the model, occurring as long as it does not reach thermal equilibrium with the recovery temperature in the boundary layer. Under these circumstances, heat transfer takes place between the flow and the model, the area exposed to the turbulent regime changing its temperature faster.[37] The second effect is the long-term response, occurring when the model and the surrounding flow come to quasisteady thermal equilibrium. In this case, the wall temperature tends towards the adiabatic value, the latter being higher under the turbulent-vs-laminar boundary-layer regime.

Peake et al.[38] carried out a boundary-layer transition detection test in a blow-down tunnel at Mach number 3.85 using a stainless-steel flat plate equipped with a bakelite insert surface. The transition location appeared on the thermograms as a localized hot front that was attributed to the difference in the recovery temperature between the laminar and the turbulent regime; it was also confirmed by other experimental means. In a subsequent experiment, an all-stainless-steel flat plate painted black was used as a target, but the distinct transition pattern could not be observed anymore. The inadequacy of the IR imaging technique to detect transition on stainless-steel models is caused by the relatively high thermal diffusivity of the metal that levels-out temperature differences along and in-depth through the model. In cases where the surface is polished, the situation is further aggravated. The high reflectance and the low emittance of the surface decrease the signal-to-noise ratio on the thermograms to an extent that renders the method useless. It may be speculated that at high Mach numbers the very intense heat transfer may offset the detriments of polished stainless-steel models by raising very rapidly the surface temperature to relatively high values. Collier et al.[39] tried this approach on a polished stainless-steel cone at Mach 14 but, unfortunately, no reliable temperature readings could be obtained.

Identifying the indication of transition on thermograms with a precise locus inside the evolving transition process is critical in evaluating the merit of the method. In more concrete terms, the problem is that on thermograms the transition to turbulence appears to happen abruptly, while actually the process may develop over a significant portion of the aerodynamic surface. Hall et al.[40] compared the diagnosis of transition from an IR imaging system with that of hot films on a flat plate at Mach numbers 1.5, 2.0, and 2.5. The results indicate that on thermograms the transition appears at various stages of its development. As expected, it always appears before the 50% intermittency; this intermittency value decreases as the Mach number increases.

Besides transition, flow separation and reattachment are features of much interest, especially on configurations of longitudinal symmetry. As the angle of attack increases, the flow will separate along the sides of the models, developing into large-scale vortices that reattach on the leeward side. These features are detectable through the surface temperature variation, minimum at separation and maximum at reattachment, and are induced by the respective behavior of the skin friction and heat transfer. Bandettini and Peake[41] carried out a separation detection study on a 10-deg fiberglass cone at different angles of attack at Mach 1.8, comparing the results with oil-flow visualization. Although the IR imaging and the oil-flow visualization were performed at somewhat different Reynolds numbers ($3 \times 10^6$ for the former and $9 \times 10^6$ for the latter, based on the model length), the vortices separation and reattachment could be identified on the thermograms as areas of higher and lower temperatures. An investigation of a somewhat more complicated flow pattern was carried out by Arai and Sato[42] on a 12.84/7-deg, bent-nose biconic made of epoxy resin at various angles of attack at Mach 7. This geometry is a leading candidate for the forebody of the Aeroassisted Orbital Transfer Vehicle. Arai and Sato[42] results are very similar to those of Bandettini and Peake,[41] confirming that vortical flow reattachment can cause heating on the leeward side at positive angles of attack.

The experiments reviewed so far address temperature signatures of flowfields on models of circular geometry or longitudinal symmetry. Lately, Henckels and Maurer[43] published the results of an experiment addressing a Mach 8.7 flow along a corner, produced by the intersection of two perpendicular plates, at various pitch and yaw angles. This is a highly three-dimensional flow, involving interaction of two perpendicular shock waves originating at the leading edge of each plate, and the formation of an embedded vortex underneath the slip surface produced by the interacting shocks. The thermograms were used to deduce heating rates on the walls, with the stipulation that the influence of the flow scaling on the results could not be inferred.

#### Space Shuttle Flight Experiments

The Space Shuttle program deserves a special place in the history of IR imaging in aerodynamic engineering and research. As it was previously mentioned, the method was used during the engineering phase of the program to determine the atmospheric re-entry heating rates on its forebody. After the orbiters became operational, they were designated for two daring IR imaging flight experiments aimed at mapping their surface heating during the actual re-entry phase.

In the InfraRed Imaging of the Shuttle (IRIS) experiment,[44–46] the windward side of the Space Shuttle re-entering the atmosphere was observed from below through an astronomical IR telescope mounted on a "chasing" C-141 aircraft, known as the Kuiper Airborne Observatory. In spite of useful and promising results regarding the evolvement of the actual heating rates and the progression of the boundary-layer transition front,[47] this experiment was discontinued because of its cost, the complex coordination work, and restricted availability of the airborne observatory.

In the ongoing Shuttle Infrared Leeside Temperature Sensing (SILTS) experiment, an IR imaging camera installed atop the vertical stabilizer of the Space Shuttle Columbia (Fig. 2) is scanning the leeside of that vehicle during the atmospheric

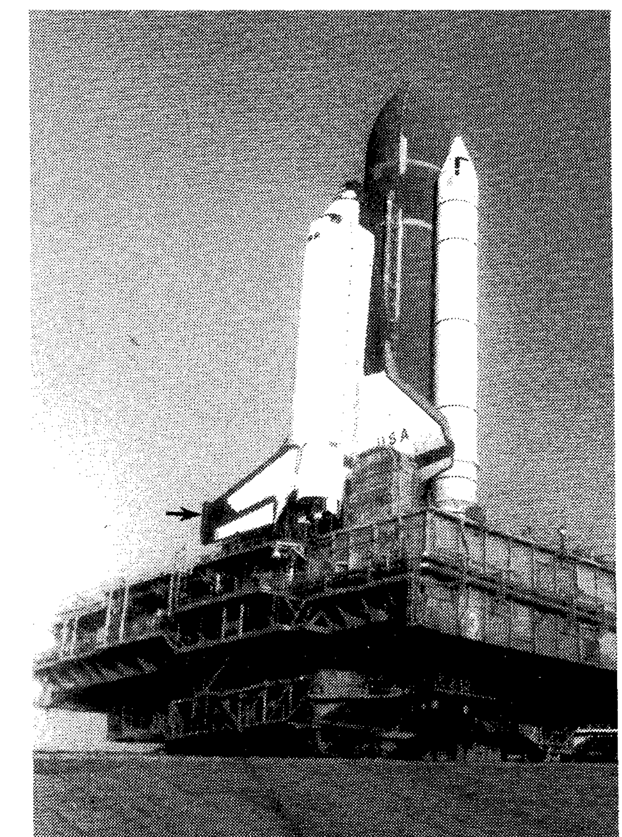


**Fig. 2 Space Shuttle Columbia atop the Mobile Launcher Platform. The Shuttle Infrared Leeside Temperature Sensing (SILTS) pod is installed atop the vertical stabilizer (Courtesy NASA, reprinted with permission).**

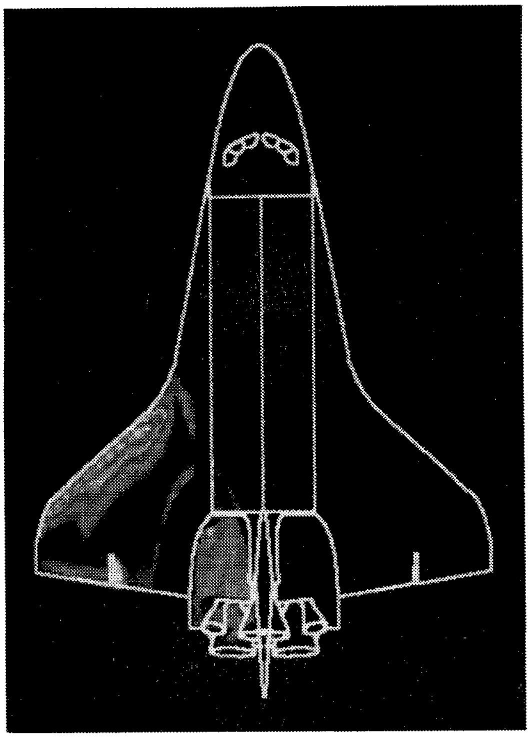


**Fig. 3 SILTS data of Space Shuttle heating pattern during atmospheric re-entry, projected on the orbiter planform[51] (Courtesy D. Throckmorton and V. Zoby, NASA Langley, reprinted with permission).**

re-entry phase of its flight.[48,49] Zones of intense heating were observed along the leading edge and the upstream part of the wing, the inboard/outboard elevon gap, and the orbital maneuvering system pod (Fig. 3), atop which the vertical stabilizer is mounted.[50,51] In general, the heating pattern indicates a highly vortical flow, convecting high-temperature compressed air from the windward side of the orbiter to its leeside. This behavior is typical to delta-like configurations at high angles of attack experiencing leading-edge flow separation. The real payoff from this experiment will materialize when the heating patterns observed in flight will be reproduced in numerical simulations of the flow. Thereafter, the in-depth thermal response of the wing substrate could be analyzed in detail, promoting the understanding necessary for future thermal protection designs.

## V. Subsonic and Transonic Studies

The possibility of using IR imaging for subsonic and transonic aerodynamic research was raised only in the early eighties.[7] Since then, the application of this technique got to the point where some industrial wind tunnels offer IR imaging diagnosis as part of their standard data-acquisition process.[52] The interest in thermography for these flow regimes is mainly for boundary-layer transition research. The method is particularly attractive because it produces global views of the configurations of interest, mainly airfoils and wings, where the behavior of the boundary layer can be deduced through a quick visual inspection.

The preoccupation with laminar flow for drag reduction reappears periodically in the aerodynamic research. In the past, it was used mainly as a means for range extension. More recently, the global energy crisis has caused the subject to resurface. New designs of transport airplanes are required to reduce their fuel consumption and their resulting direct operating costs. One avenue to achieve this goal is to design the wings to sustain laminar boundary layer to the largest possible extent. In the current laminar-flow research, the IR imaging technique is an integral part of the effort to make this aerodynamic technology available. The effort encompasses wind-tunnel technology,[53] wind-tunnel and flight testing,[54–56] and aerodynamic design philosophies.[57–59]

In 1983, Bouchardy et al.[7] from Office National d'Etudes et de Recherches Aerospatiales (ONERA) Chatillon reported the first transition detection study in a thermally stable wind tunnel. They addressed the effect of positive step change in the adiabatic wall temperature induced by the difference in the recovery temperature of the turbulent-vs-laminar regime. Using models fabricated of thermally insulating materials, current IR imaging systems are sensitive enough to detect transition down to Mach 0.5, at ambient conditions. For lower air velocities, down to Mach 0.1, the transition detection is still feasible through image processing enhancement of the thermograms. Among the thermally passive approaches to transition detection, this is the only aerodynamic effect that can be used in open circuit or thermally stable wind tunnels, where the stagnation temperature is constant.[60] The first systematic investigation of transition detection in wind tunnel and flight testing was published by Quast from Deutsche Forschungs-und Versuchsanstalt fur Luft-und Raumfarht (DFVLR) Braunschweig.[61] He pointed out that the increased heat transfer coefficient of the turbulent-vs-laminar regime is a remarkably useful attribute that makes the transition detectable on raw thermograms even at very low speeds, if the temperature of the model is different from the temperature of the flow. When exposed to this effect, the area underneath the transitional and turbulent boundary layer will change its temperature faster than its counterpart under the laminar regime, thus enhancing the temperature contrast between the two areas on the thermogram. In fact, the heat transfer effect is dominating over the recovery temperature influence, and today it is used in the majority of transition-detection experiments. It is convenient in use and interpretation, especially implying the Reynolds analogy between convective heat transfer and skin-friction coefficients. This effect occurs in closed-circuit wind tunnels, where the air heats naturally during their operation.[62] It can also be observed in wind tunnels equipped with a cooling system.[61] Another option is to use electrical[19,20,63] or laser[64] heating of the model surface, or to blow hot air through a hollow model,[17,18] and to observe the cooling effect of the flow. In flight testing, this effect occurs naturally when an airplane is flying an ascent or descent path through the atmosphere.[55] Although active heating of the substrate is very attractive and simple to implement, the surface overheat value should be kept at the absolute necessary minimum to prevent a premature triggering of transition.

When the significance and potential of IR imaging became evident for boundary-layer research, the effort turned towards a full evaluation of the diagnostic capabilities of the method. In an effort to make the method more quantitative, it was shown that the active heating method can identify changes in the boundary-layer regime by tracking the behavior of the experimentally deduced heat transfer coefficient. Provided laminar boundary layer is established downstream of the leading edge, the maximum heat transfer coefficient is indicative of transition to turbulence, and its following minimum occurs at separation.[17–20,63–65] If the passive method is applied, the transition is identified visually at the location of the step change in the surface temperature.[7,12,55,61,62,66,67] At higher incidence, the onset of turbulent separation is identified by the emergence of a second zone of increased heat transfer caused by local vorticity shedding.[62]

The next step was to apply the IR imaging method to boundary-layer transition research that eventually would lead to "laminar" airplane designs. For this application, one has to identify on thermograms the various modes of boundary-layer transition, since the development of each mode can be attributed to a particular design feature of the wing under consideration. Generally speaking, at low Reynolds numbers and no sweep, the laminar boundary layer will separate under adverse pressure gradient, the subsequent expansion of the flow will reattach the boundary layer as turbulent, and a lam-

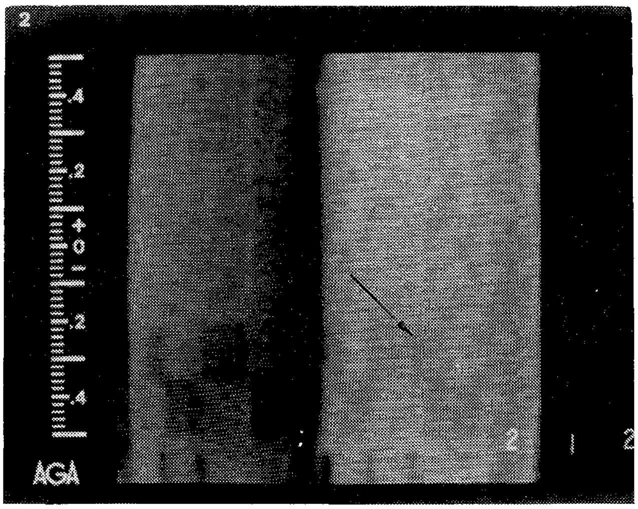
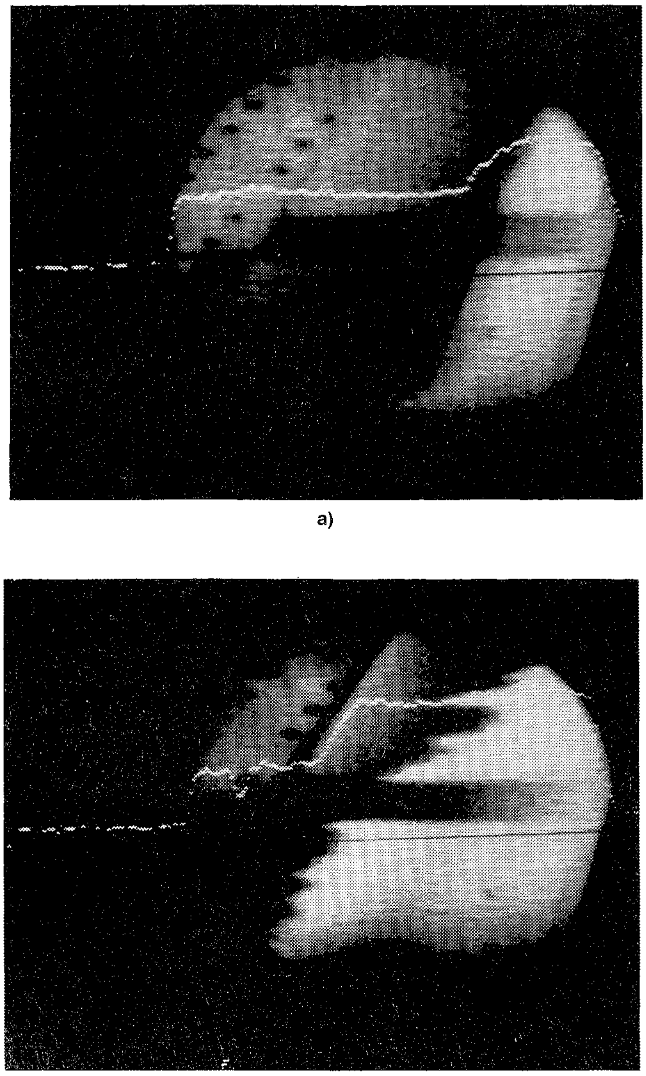



**Fig. 4 Transition via laminar separation bubble. The bubble is indicated by the colder (darker) straight strip between the laminar (dark) and turbulent (light) areas (Courtesy A. Quast, DLR Braunschweig, reprinted with permission).**



a)

b)

**Fig. 5 Characteristic transition patterns: a) Tollmien-Schlichting (TS) waves;[12] and b) crossflow (CF).[69] Dark area indicates laminar regime and light area indicates turbulent regime. Notice the saw-teeth pattern characteristic to CF instability (Courtesy G. Gauffre and V. Schmitt, ONERA Chatillon, reprinted with permission).**

inar separation bubble (Fig. 4) will be contained in-between the two regimes.[61,62] This bubble can be identified on thermograms as a narrow, elongated region of low heat transfer preceding the turbulent regime. At zero-to-moderate sweep and higher Reynolds number (but outside the critical conditions for attachment line transition), the transition will be caused by Tollmien-Schlichting waves characterized on the thermograms by a relatively smooth transition line (Fig. 5a).[68] As the sweep angle increases beyond a certain limit, the crossflow mechanism will prevail, with the transition front on thermograms resembling a "saw-teeth" pattern (Fig. 5b).[69]

The main obstacle to getting wider acceptance for this method, especially in the aeronautical industry, is that models are usually made of aluminum or stainless steel with high-quality surface finish. The problems mentioned with this type of model in the previous section, i.e., high thermal diffusivity, and low emittance and high reflectance, only render the method more difficult to apply. In some cases, the problem may be solved satisfactorily by applying an insulating film, 1 or 2 mm in thickness, in specially machined grooves.[69] Crowder[66] suggested, as a partial solution to this problem, to cover the model with an insulating paint, and to spray liquid nitrogen into the tunnel, upstream of the test section. The rapidly cooling flow produces a thermal effect on the metallic surface that is strong enough to make transition visible (Fig. 6).

Viewed in the perspective of a very few years, it seems that the IR imaging technique opened new horizons in the laminar-flow research and applications. The method was used extensively in wind-tunnel and flight test programs in Germany by the Deutsche Forschungsanstalt fur Luft-und Raumfahrt (DLR) and Deutsche Airbus,[68,70–74] in France at ONERA,[69,75] and in USA at NASA,[55,67] to investigate the occurrence of the various transition modes. The DLR/Deutsche Airbus program was a particular large-scale effort. It combined flight tests on small- and medium-sized airplanes with laminar-flow gloves mounted on the wings, with wind-tunnel tests performed in different facilities. As part of this effort, an extensively instrumented VFW-614 twin-jet medium-sized aircraft designated the Advanced Technologies Testing Aircraft System (ATTAS) was dedicated to laminar-flow research over a period of a few years (Figs. 7a,b). The unique capability of IR imaging to provide repetitively global views of the transition pattern on the wing allowed an immediate identification of the prevailing mechanism under given test conditions (Fig. 7c). The combined use of IR imaging with hot films throughout the program helped elucidate the correlation between the actual mechanisms of transition development and numerical predictions designed to verify the $e^N$ method, which correlates the instability to transition laminar run with the disturbance amplification ratio expressed as exp N. At NASA, the effort focused on comparative flight testing of different competing,

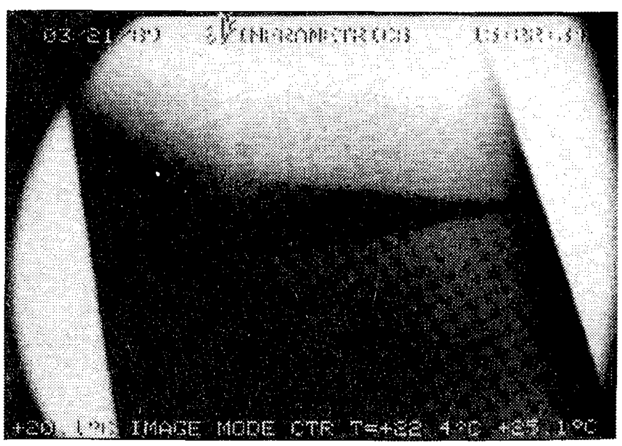



**Fig. 6 Turbulent wedge and transition captured on a painted stainless-steel model by injecting liquid nitrogen into the wind-tunnel flow[66] (Courtesy J. Crowder, Boeing, reprinted with permission).**

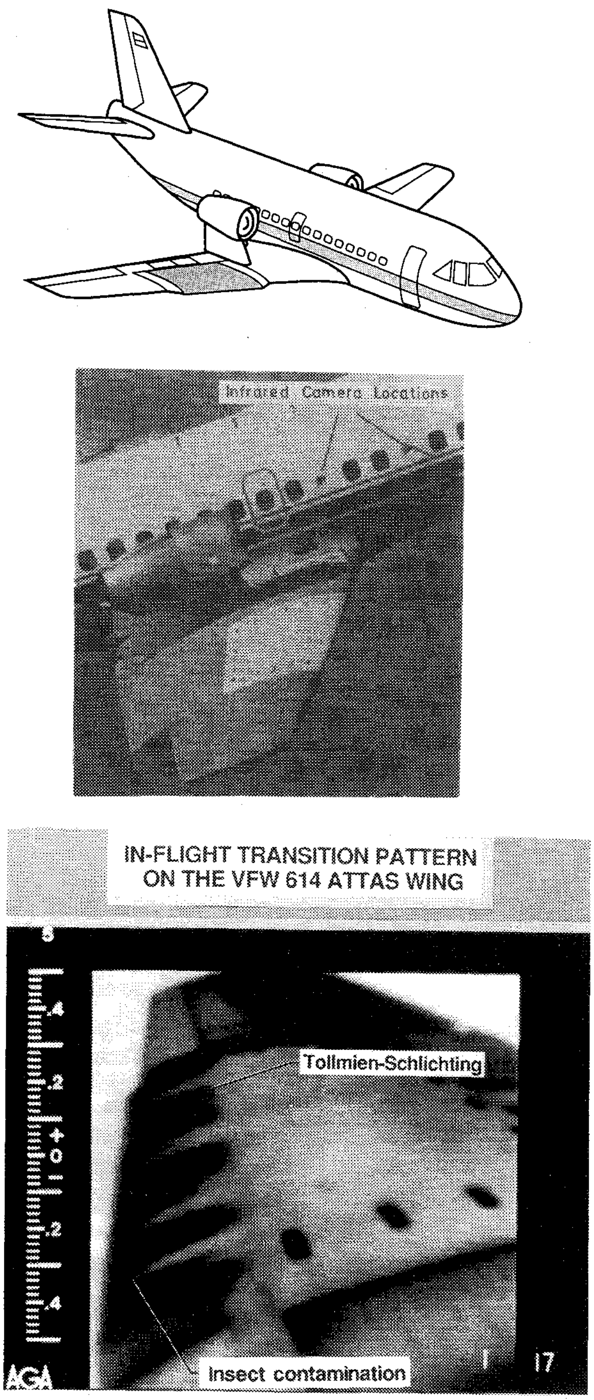



**Fig. 7 The VFW-614 Advanced Technologies Testing Aircraft System: a) schematic drawing; the laminar flow glove, marked gray, is outboard the engine pylon;[57] b) close-up view of the wing area; notice the laminar glove and the IR cameras locations;[71] and c) in-flight transition pattern induced by Tollmien-Schlichting waves and insect contamination (turbulent wedges) (Courtesy A. Quast, DLR Braunschweig, reprinted with permission).**

or supplementing, methods for transition research.[55] At ONERA, the technique was used to confirm designs specifically aimed at obtaining significant runs of laminar flow on aerodynamic surfaces.[69] Unfortunately, none of these experiments illuminated the question surrounding the identification of the precise location in the transition process that is detected by this technique.

The main drawback with transition studies made in conventional wind tunnels is the scale of the models and the resulting inconsistency between the Reynolds number of the model and that of the flying airplane. This discrepancy is pivotal in the search for ground-testing methods capable of generating high Reynolds-number flows. There are two main reasons for concern about this subject. The first is that transition, being a viscous effect, is critically influenced by the Reynolds number of the airplane in flight. The second is that, as of yet, there are no proven scaling methods for flows, especially not at large Reynolds numbers. To solve this problem, cryogenic wind tunnels have been devised, where combinations of low temperatures, down to 100 K, and moderate pressurization can generate flows with Reynolds numbers in excess of $10^8$ per meter. For these wind tunnels, nonintrusive, global and productive transition-detection techniques are of fundamental importance. Despite the physical laws governing IR radiation working against this application, the IR imaging method showed promising results[76] and, so far, transition was detected at total flow temperatures down to 170 K.[77]

## VI. Propulsion Studies

The application of IR imaging to propulsion studies is very diverse in nature, the technique being used in cold and hot flow environments for studies ranging from flows in turbine cascades, through heat transfer measurements, to hot flows and plumes visualization.

### Cold Flows

One of the earliest applications to jet engine research was to study the effectiveness of film cooling for turbine blades.[78,79] In these applications the relative temperatures of the main flow and of the film flow are reversed. The "cooling air" that is injected through transpiration holes in the turbine blades is heated, to be visualized by IR imaging. This effect is possible because both the carbon dioxide and the water vapor in the air start to emit IR radiation at relatively low overheat temperatures. IR imaging was also used to inspect the film-cooled nozzle of a high-temperature wind tunnel for blockage areas on the transpiration surface.[80]

Braunling et al.[81] used IR imaging to study boundary-layer/shock interaction in a cascade flow simulating a jet engine turbine. This is an extension of transonic flow studies—the complex geometries very much complicating the flow and its diagnosis. The study succeeded to identify laminar and turbulent boundary layers, shock waves, separation bubbles, and longitudinal vortices on the blades, but more work will be required to elucidate the findings.

### Hot Flows

Combustion gases present another opportunity for IR imaging research. Streby,[82] mapping the flow temperatures in an operating ramjet combustor, presented the temperature distribution of the reacting gases through topographic plots that greatly helped analyze and interpret the data. Byington et al.[83] used IR imaging to visualize and study the effectiveness of transpiration cooling in the hydrogen injection area of a supersonic combustor at flow temperatures up to 2000 K. Their investigation produced a very detailed picture of the flow, including the upstream shock interaction between the injected fuel and the main flow, the cool core of the injected fuel, and the lateral and downstream extent of the fuel mixing zone.

IR imaging systems also have been used to visualize exhaust gases of jet engines. There was special interest in surveying the plumes of VTOL aircraft hovering close to ground[84,85] because the interaction of the hot gases with the surrounding flow largely determines the aerodynamic capability and stability of these vehicles at takeoff and landing. In a different application, the exhaust plume of a fighter airplane on the ground was visualized to identify flow structures causing radiation of low-frequency acoustic waves.[86] Presumably, those waves were the source of trouble for electronic testing equipment placed nearby.

## VII. Heat Transfer Studies

Relative to the obvious qualifications of the method for heat transfer studies, the scarcity of applications is relatively surprising. Meroney[87] made a wind-tunnel study of convective heat transfer of buildings using an actively heated model. The heat transfer coefficients were estimated, but lack of a data-acquisition and processing system hampered progress on the work. Page et al.[88] investigated the flow of a radial jet on a stagnation surface. Using a heated jet impinging on a cold surface, they inferred the heat transfer occurring in the stagnation region from thermograms of the heated surface. Carlomagno and de Luca[19,89] performed a similar investigation with interest in the heat transfer of both a single jet and an array of jets. In this case, however, a cold airflow impinged on a heated metallic foil. Another jet-impingement experiment was performed by Eppich and Kreatsoulas.[90] In their case, the surface upon which the jet impinged was a thin layer of an insulating material laid atop a constant-temperature substrate. Therefore, they could deduce the heat flux across the top layer directly from the measurements of the surface temperature, the thickness of the top layer, and the constant temperature of the substrate. Gartenberg and Roberts[9] proposed a method of mapping velocities by measuring the temperature distribution along a thin, electrically heated wire placed across the flow of interest. The velocities can thus be derived from established, convective heat transfer correlations, provided the error measurement of the IR imaging system is known, especially when the wire displays high temperature gradients in the scanner field of view. Spence[91] examined the possibility of determining heat transfer coefficients on vanes used for missile thrust vector control from wind-tunnel tests on a model vane under identical flow conditions. Henry and Guffond[92] made temperature measurements on a helicopter blade in an icing tunnel to validate computer code predictions of de-icing effectiveness of blade heaters. Other examples of heat transfer applications include convective heat transfer from a heated cylinder at moderate Reynolds numbers,[93] and external mapping of the temperatures of a gun barrel during firing.[94]

## VIII. A View to the Future

A review of past achievements must conclude with a view to the future. Further progress in this field will be contingent on two factors: the technical developments in IR imaging technology and the continuation of experimental exploration and aerodynamic research based on this technique. Current trends in the electro-optic and semiconductor industries point to future IR imaging systems incorporating focal plane detector arrays. Such systems will offer improved performance in terms of spatial resolution, temperature sensitivity, and frame-rate generation. Optionally, they will trade higher frame rates for lower temperature sensitivity. In parallel, as increasingly powerful personal computers become available, they will be used to increase the frame-rate acquisition and storage. This option will allow capture of faster thermal transients and promote the application of the method in very short test duration facilities. Currently, capture of fast temperature transients is possible only through one-dimensional line scanning,[29,95] thus losing the advantages of the two-dimensional imaging technique.

The testing needs at high Reynolds numbers in cryogenic wind tunnels at low temperatures will require imaging systems built around detectors sensitive to longer wavelength IR radiation, possibly up to 30 $\mu$m.[96] In parallel, there will be requirements for window materials with high transmittance in selected bandwidths; good mechanical, thermal, and chemical properties; and compatible antireflective coatings.

At the high-temperature end of aerothermodynamic research, nonequilibrium, reactive, and high-temperature flow research will require multispectral IR imaging for measurement of wall thermal response, flow visualization, and tracing of the evolving concentration of chemical species through their absorption bands.

In aerodynamic testing, the challenge is either to solve the transition detection on metallic models or to compromise with other materials, either as inserts at locations of interest, or as model skins. The exact location where transition is indicated on thermograms is still undefined. More comparative work is needed to define the location on the transition process that is detected, and to determine in what way the flow, substrate, and IR imaging system parameters influence the identification of that location.

In general, each flow feature has a thermal signature of its own that should be identifiable on thermograms of models of interest. As the use of this technique expands, new features appearing on thermograms will puzzle engineers in their quest to identify their cause. Separation, shock waves, and vortices have already been observed and identified in the past, and continuing research will lead the IR imaging technique to become a widely accepted diagnostic tool in aerodynamic research.

## IX. Conclusions

In the years that have passed since 1967, the infrared imaging of aerodynamic surfaces gained recognition as an experimental tool with unique capability for fast mapping of surface temperatures. This capability is used in hypersonic research to determine heat flux distributions from local temperature measurements and in subsonic research to give a global view of the boundary-layer transition to turbulence. With time, other flow features were identified on thermograms such as shock waves, separation, reattachment, and vortices. The use of the technique was gradually expanded to other disciplines, most notably propulsion and basic heat transfer research.

The technique had a relatively slow start, due to sporadic experiments, obscure documentation, and lack of data-processing capability. When viewed in the perspective of the long period of time it took to mature and get recognition, it seems the technique was "invented" too soon. However, the ever-increasing number of publications reporting use of IR imaging in aerodynamic research is convincing proof that the method has passed through the development stage and is assuming the status of a routine experimental procedure.

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