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STUDY OF OPTICAL TECHNIQUES FOR THE AMES UNITARY WIND TUNNEL PART 5. INFRARED IMAGERY

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STUDY OF OPTICAL TECHNIQUES FOR THE AMES UNITARY WIND TUNNEL PART 5. INFRARED IMAGERY

Summary

A survey of infrared thermography for aerodynamics has been made. Particular attention was paid to boundary layer transition detection. IR thermography flow visualization of 2-D and 3-D separation was surveyed. Heat transfer measurements and surface temperature measurements were also covered. Comparisons of several commercial IR cameras were made. The use of a recently purchased IR camera in the Ames Unitary Plan Wind Tunnels was studied. Optical access for these facilities and the methods to scan typical models was investigated.

Introduction

Optical thermal mapping techniques are valuable tools for flow visualization and quantitative measurement. They have been used for global temperature measurements, heat transfer measurements, boundary layer transition measurements, and visualization of separated flows, vortex and shock impingement. Among the several classes of optical thermal mapping methods which includes color sensitive paints, phase change paints, liquid crystals, and thermographic phosphors, the infrared camera is the most versatile and non-intrusive. The first documented use of the IR camera was by Thomann and Fisk¹ for heat transfer aerodynamics over 25 years ago. Recently with the ever improving commercial infrared camera systems in terms of accuracy, resolution, image processing and display, speed and lower costs, there has been a renewed interest in using the infrared camera for research and production wind tunnel testing. One problem of great interest is the detection of boundary layer transition.

The routine detection of boundary layer transition in production size wind tunnels like the Ames 11 x 11 Foot Transonic Wind Tunnels is important and crucial for data quality and productivity. This tunnel operates in a Reynolds number regime where the boundary layer on most transport models will stay laminar to wing midchord where the shock wave will cause local separation and transition to turbulent flow. This unrealistic situation does not occur in flight, and can be avoided by tripping the boundary layer on the

wind tunnel model with a transition trip. However, the gain size of the transition strip must be chosen so that transition occurs exactly on the strip, but the strip must not be too high to cause excess trip drag. The infrared camera is an idea candidate for this job.

Boundary layer transition detection with IR camera is also important to other wind tunnel programs from low speeds to supersonic speeds. For example, new airplanes with laminar flow wings require quick and accurate ways to measure the laminar flow regions and transition. For fighter models at high angles of attack, knowing the state of the boundary layer on the forebody of the fuselage is necessary for extrapolation of the tunnel data to full scale flight conditions.

Another potential application for IR imaging is in the field of pressure sensitive paints. These luminescent paints when illuminated with ultraviolet light emits visible light with an intensity proportional to the local air pressure on the model surface. This technique makes it possible to measure the entire pressure distribution of the model by taking an image of it. One major problem is that those paints are sensitive to temperature. IR imagery offers an easy way to make the temperature measurements. The IR image can be digitized and superimposed on the pressure sensitive paint image to make the temperature corrections.

IR thermography has applications in flow visualization. This includes separated flows in both two and three dimensions. Heat transfer studies and propulsion studies are natural candidates for the IR camera. Verification of CFD calculations is another possible application. With all these applications in mind, but primarily transition detection and pressure paint, the Ames Unitary Plan Wind Tunnel purchased a state of the art commercial IR camera system.

Purpose

The purpose of this study is to review IR thermography as a technique for the routine detection of boundary layer transition. The problems of implementation of the IR camera system in terms of optical access and the generation of the necessary temperature differences between the flow and the model will be studied. The application of IR thermography for flow separation and heat transfer will be reviewed.

Heat Exchange Mechanism

In order to understand the use of IR thermography for aerodynamic measurement,^{2,3} the heat exchange mechanism by which the model surface temperatures are established must be understood. It is the surface temperature that the IR camera detects by sensing the emitted radiation in the infrared spectrum to which the sensor is sensitive. Most commercial IR cameras are sensitive to either the 3 to 5 or 9 to 13 micron bandpass. The thermogram recorded by the IR camera is thus a record of the energy exchange process between the model and the flow. The three processes are convection, conduction, and radiation.

- Convection is generally the process that the flow heats the model through kinetic heating. For compressible flow, the driving force is the boundary layer recovery temperature and the model surface temperature. The recovery temperature depends on the viscous characteristics of the flow, i.e. laminar, transitional, turbulent, or separated.

- Conduction is the heat transfer process by which the convective heat goes into the model. This leads to the type of model material used, from insulators, metals, and painted surfaces. In some cases, this determines if the temperature is steady or transient. To obtain heat transfer data from the IR technique, the conduction process must be understood. For example, models made of insulators typically assumes the "semi-infinite slab" model. With this model, the heat fluxes are solved as a function of the transitory surface temperatures with the heat conduction equations. At the other extreme is the "thin-skin" approximation used for metal models. Here it is assumed that the heat flux is uniformly absorbed and the "thin-skin" version of the heat conduction equation is used. For other types of model construction, i.e. a painted metal model, the solution falls between the two above approximations.

- Radiation is the process by which the IR camera senses the model temperatures. It is also the process by which the model exchange heat with its environment, e.g. tunnel walls, lights. The model radiates energy depending on its absolute temperature, emittance, and its relative attitude to the camera and geometry. The last two items define the angle under which the camera sees the radiation as it scans the model. Because of the peculiar behavior of the directional emittance the two factors can produce surprising

results. For example, there can be an enhancement of the signal at high angles of incidence of polished metals. Also, reflections of radiant energy can occur from polished metals causing errors in the IR data.

Boundary Layer Transition Detection

1. IR thermography detects boundary layer transition by measuring the change in temperatures between the laminar and turbulent regions. Turbulent boundary layers have higher skin friction than the laminar boundary layer and as a result, turbulent regions have higher surface temperatures than laminar regions. Quast⁴ explains the relationship between skin friction and surface temperature by use of the Reynolds Analogy. According to the Reynolds Analogy, the heat transfer is much higher (about a factor of ten) in the turbulent flow than laminar flow. Thus, for any temperature difference between the flow and the model surface, the model will nearly reach the flow temperature in the turbulent region while remaining nearly unchanged in the laminar region. Note that the Reynolds Analogy is valid only for fully established laminar or turbulent boundary layers but not for transitional or separated flows. Quast describes both flight and wind tunnel experiments to verify and establish IR thermography as a method to detect boundary layer transition. The origin of the temperature difference necessary for good IR pictures were discussed. These included (1) natural heating or kinetic heating from the flow, (2) internal heating of the model with heating elements inside the model, (3) switch the wind tunnel cooling system so that a rapid change in the fluid temperature is created, and (4) the effects of the sun's heat in flight. It was shown that the IR technique can detect the transition line and turbulent wedges or even smaller subcritical disturbances in the laminar boundary layer can be detected. Figure 1 shows a typical IR thermogram of transition along with oil flow. Transition was confirmed independently with the oil flow method. The practical problem of choosing the correct focal length lens was mentioned. For example, too wide a lens will lower the resolution, and will lower contrast so that the transition will be difficult to see. The latter effects is due to the automatic mean temperature adjustment of the IR camera.

2. Hall et al.⁵ compared four different boundary layer transition detection techniques: liquid crystals, very thin hot films, a newly

developed optical interferometer, and the IR camera. The four techniques were to be judged by their sensitivity to transition as well as their ease of use. The liquid crystal and the IR thermograms were also studied to see if they were responding to boundary layer transition at the beginning, middle or at the end of the transition process. The experiment was conducted with a flat plate model in the NASA Langley Unitary Plan Wind Tunnel. The Mach numbers ranged from 1.5 to 2.5 and the unit Reynolds numbers from 1 to 4 million per foot. A steel model was used for the thin film and liquid crystal experiments. A bakelite (insulator) was used for the IR experiments to eliminate surface conduction effects. The liquid crystal was the simplest in that it only needed to be sprayed on and a picture taken. The paint can be used again for another test condition. Some expertise and judgment are needed to choose and mix the liquid crystals. Picking a color whose contrast is clear in the tunnel as well as choosing a temperature reaction range away from the tunnel stagnation temperature are important. The IR thermography is also a simple installation. In contrast to the liquid crystal technique which have to be accessed during the test, data acquisition for the IR is continuous as long as the tunnel is running. The very thin hot films required a large amount of supporting instrumentation and experience. Applying the hot films to the metal cavity plates was a challenge that required specialists skilled in micro electronics. But the results are quantitative and reliable and served as the yardstick for this comparison. The optical interferometer measures the frequency of density fluctuations of the density within the boundary layer to assess that state of the boundary layer. However, this technique did not work because of the high noise levels. It was found that both IR and liquid crystals gave indications of boundary layer transition before the intermittency factor reached 0.5 as measured by the thin film, i.e. transition in the middle of the transition region.

3. Crowder⁶ has evaluated a commercial IR camera for the routine detection of boundary layer transition in subsonic and transonic wind tunnel. Wings made of non-conducting wood, conducting metal, and semi-conducting epoxy paint over steel were tested. At a Mach number of 0.25 with a wooden model, the transition pattern was strongly visible on the IR image. This pattern was collaborated by the sublimation technique. The tunnel temperature gradients were between 2 to 4°F per minute. Even at Mach numbers as low as 0.05, the transition pattern remains faintly

visible. With a painted steel model which represents a more realistic model for an industrial wind tunnel, the IR thermograms were much worse but still usable. The transonic tests were conducted in the Boeing Transonic Tunnel at $M=0.8$ with temperature gradients as high as 40°F per minute. The gradients were generated by quickly opening or closing a door to let in outside air into the wind tunnel. With increasing temperatures, the strongly visible transition pattern is formed with the laminar region appearing colder than the turbulent region since heat is passed more rapidly in the turbulent region to the surface. Conversely, when the doors are opened, a rapidly cooling airstream causes an opposite transition pattern. The fast acting doors affects the flow quality and must be calibrated for door positions. An alternative scheme of injecting liquid nitrogen for cooling the airstream was tried. Good images were obtained. The issue of image resolution was also investigated. The Inframetric model 600 camera had an effective spatial resolution of 140 by 170 pixels which is about half the resolution of broadcast TV. This was rather poor resolution. Another limitation is the 15 to 20 degrees field of view which can cover only about one-quarter of a large semi-span wing model. Choosing a wider angle lens would give better coverage but at the expense of spatial resolution.

4. In 1992, Crowder conducted an IR experiment in the NASA Ames 11 x 11 Foot Transonic Wind Tunnel to investigate the feasibility of switching on and off the wind tunnel cooling system to provide the temperature gradients necessary to detect boundary layer transition. Temperature gradients of 10°F per minute were achieved by opening or closing the water cooling valves at a total pressure of 65" Hg. The gradient drops to about 3°F per minute at total pressure of 16" Hg., see figure 2. The useful time for data acquisition is about 2 minutes. Good IR images were obtained under these conditions. The cooling valves were operated between 25% to 100% opened and the maximum tunnel temperature did not exceed 120°F . Operational procedures written by Ross Shaw of RAF for controlling the 11 x 11 Foot cooling system is given in Appendix A.

5. Schmitt⁷ investigated IR thermography for boundary layer transition detection in the ONERA production size wind tunnel. The first case was to determine whether IR thermography could replace the sublimation method to choose the carborundum grain size used to trip the boundary layer so that transition occurs exactly on the strip. This proved feasible. The next question was - could the strip

cause overthickening of the boundary layer? - and cause errors in the aerodynamic data. The IR method provided a relatively easy way to obtain such data.

6. Horstmann et al.⁸ used IR thermography to detect boundary layer transition to verify the "N-Factor Method" used to predict transition. IR experiments were performed both in wind tunnels and flight. For the flight experiment, a special wing glove was installed on the test aircraft. Figure 3 shows the glove and the IR camera installed in the cockpit. Wind tunnel tests of the real aircraft wing was tested in the 6x8 meter German-Dutch tunnel. Figure 4 shows IR images from the flight and wind tunnel experiments. Transition lines occurred at about 50% chord for both images. It was shown that IR imagery is a simple and reliable technique for detecting transition in both flight and wind tunnel.

7. Brandon, et al.⁹ also conducted flight experiments to evaluate IR thermography for boundary layer transition detection. The IR images show that the transition front from laminar to turbulent flow could be readily identified for a variety of flight conditions. Turbulent wedges were also seen and the flow field observations correlated well with results from previous studies. One important characteristic for a successful IR flow visualization is a low conductivity skin to prevent heat conduction which would even out temperature differences between the laminar and turbulent regions.

8. Peake, et al.¹⁰ used IR imaging for boundary layer detection at supersonic speeds. A flat plate made of Bakelite, an insulator, was tested. In addition to IR thermography, surface Preston tube, sublimation, and surface hot film gages were used to measure the transition pattern. These different techniques gave different transition signatures, but they tend to confirm the fact that the IR thermograms indicate transition mid-way through the transition zone.

9. Elsenauer, et al.¹¹ used the IR camera in conjunction with drag rakes to design and test laminar flow airfoils. A number of techniques: hot film, flush mounted kulite pressure transducers, oil flow, and liquid crystals, were tried for transition detection. It was concluded that the IR camera in combination with continuous wake rake traverses works the best for obtaining the detailed data for analysis of a particular laminar flow airfoil design.

10. The IR technique has been tried for boundary layer transition detection at cryogenic temperatures. Gartenberg, et al.¹² tested a supercritical airfoil in the NASA Langley 0.3 Meter Transonic Cryogenic Tunnel. Of special interest was that image processing was used to enhance the IR image. Only one color shade was assigned to each of the temperature values associated with the respective boundary layer regimes.

11. At low speeds, the kinetic heating is not sufficient to establish a large enough temperature difference for IR detection of boundary layer transition. Heath, et al.¹³ proposed applying an external heat source to create the temperature differences. An 8 watt CO₂ laser was used to scan a wing made of fiberglass epoxy over a polyurethane core. The laser was pulsed from 0.5 to 3 seconds which raised the model surface temperature about 5° to 20°C. The heat conduction equations were solved to obtain the heat transfer distribution along the chord of the airfoil, figure 5. The rapid rise or peak in the heat transfer distribution is interpreted as the transition region. This data was confirmed by liquid crystal data. Gartenberg, et al.¹⁴ also conducted experiments to evaluate the IR method at low speeds. These included the measurement of temperature transients, velocity distributions, boundary layers, separated flows, and vortices.

Detection of Separated Flows

1. The use of IR imagery to detect separated flows, both 2-dimensional and 3-dimensional has been tried. Bandettini and Peake¹⁵ measured the locations of 3-D separated flow regions on a cone at transonic speeds at the NASA Ames 6 x 6 Foot Wind Tunnel. Detailed separation lines could be measured from the thermograms for a cone over an angle of attack range of 0° to 15°. The IR data was collaborated by both oil flow and thermocouple data. Note that the model was made of a non-conducting material. The case of a steel model is still to be done to demonstrate that conduction effects do not even out the temperature differences and blur out the IR images.

2. The use of IR thermography is ideal for low Reynolds number flows where any small disturbance will cause instabilities in the flow. Monti and Zuppardi¹⁶ develop an unsteady computerized IR

technique to detect flow separation in 2-dimensional flow. It is based on using the "thin-skin" approximation to solve the time dependent heat equations - to get the heat transfer coefficients or the Stanton number (for incompressible flow case). The criterion for identification of the separated flow region is based on the heuristic argument that the convective heat exchange between the flow is more efficient for attached flow than for separated flow. Thus the Stanton number is expected to be higher for attached flow than separated flow. The separation line which is the beginning of the separation region should coincide with the line enveloping the minimum Stanton numbers. The experiments consists of a thin shell airfoil which was heated internally. After the heat is turned off, IR images are taken as a function of time. With the temperature data, the Stanton number distribution along the airfoil are solved for from the heat conduction equations. The position of the laminar separation, the turbulent reattachment, and the transition in the shear layer are determined. These results were compared with other experimental data and show that the IR technique can be used to measure 2-D separated flows.

3. Monti and Zappardi¹⁷ extended their IR technique to the detection of 3-dimensional separation. A bluff cylinder was tested at zero angle of attack and a hemisphere-cylinder was tested at zero to 28 degrees angles of attack. The nose of the model was made of wood while the cylindrical portion was made of 0.5mm thick stainless steel. The internal portion of the cylinder was heated by a heat lamp. IR images were taken during the cooling cycle. The separation lines deduced from the Stanton numbers were compared with theoretical results. Good agreement was obtained which verify that IR imagery can detect 3-D separations.

4. Gartenburg, et al.¹⁸ used a scheme with IR in conjunction with aluminum tufts to visualize flow separation. A NACA 0012 was pitched from 0° to 14° when full separation occurs. Within this range, the airfoil goes from attached laminar flow transition, separation bubble, turbulent reattachment, bubble burst, and complete flow separation over the airfoil. Both IR thermography and normal photography were used to visualize the flows. Four rows of aluminum foil tufts, 0.0254mm thick, 2mm wide, and about 0.1 chord long were attached to the airfoil. To enhance the IR visibility of the tufts, the rows of tufts were heated by a heating wire embedded under the surface of the airfoil. This provided a "low

temperature" - low emittance target against a "high temperature" - high emittance background. It was shown that the IR camera can see the motion of the tufts just like the normal camera. For example, the flow reversal in the separation bubble, the higher flutter amplitude of the tufts in the turbulent regions were seen by the IR camera. At the separation bubble, the IR camera recorded a lower temperature region. The drawback of the IR/tuft method was that looking at any one thermogram may be not sufficient temperature information to allow a meaningful interpretation of the flow. But by taking a sequence of thermograms through the entire angle of attack, it does provide sufficient information to evaluate the development of the boundary layer regimes from laminar attached flow through separated flow. The method allows flow visualization and temperature measurements to be made simultaneously.

Aerodynamic Heating

The IR thermography has been used for studies of aerodynamic heating, thermal protective devices, etc. for hypersonic airplanes and spacecrafts. Although the aerodynamic heating effects are relatively small in the Ames Unitary Wind Tunnels, there are common problems and solutions in using the IR thermography throughout the speed range. It is therefore instructive to briefly review the topic of IR measurement of aerodynamic heating. The early work in the 1970 decade^{1,19,20} demonstrated the feasibility of the IR technique in blow-down and continuous flow wind tunnels. It also pointed out the shortcoming of the equipment - namely the bottleneck was data acquisition, storage, and processing. One of the main efforts was to develop data processing systems during this decade. Even so, the work advanced with studies on model materials - thermal and radiative properties were documented so that accurate temperatures can be deduced from the IR measurements. More recent studies²¹⁻²⁴ are proving the viability the commercial IR systems with PC based data acquisition and image processing to quantitatively measure temperature with accuracies comparable with the classical discrete point gauges. Digitization of the data, storage of the IR images, averaging and subtraction of images are making the IR technique more useful and efficient throughout the entire speed range.

IR Camera

Most IR cameras are scanning devices that build up an image like a TV picture. In order to do this, the surface is scanned, the temperature identified and measured point by point along a horizontal line (horizontal scan) and then repeated in rows beneath each other (vertical scan). The scanner*, see figure 6, consists of rotating prisms or mirrors which look at a small surface element typically 0.05 inch in diameter on the model and focus the radiation from that surface element onto a detector. To increase the temperature sensitivity, the detector is cooled to a low temperature. Liquid nitrogen, Argon gas, and Peltier electric cooling are typical cooling methods. Pyro-electric detectors which do not require cooling are also being used. One complete scan of the scene is called a field which has about 200 lines, each line having about 200 pixels. In some cameras, two fields are interlaced to form a frame or image. The scanning rates can vary between 25 to 60 fields per second. Typically, 30 frames per second are used to accommodate VCR recording. The detector output is amplified and can be recorded on VCR, and/or to computers for digitizing, storing, and processing. The system can assign false colors corresponding to the original gray scale in the image to give a visual sensation of temperature of the scene. Software are available for frame averaging, contour smoothing and other forms of image processing.

The IR camera has limitations that may affect the image. Some of the main limitations are: (1) There is a trade-off between response time and resolution. The response time increases by an increase in the scanning rate, but the sensor will be exposed to shorter pulses of energy and it will be less able to respond to the higher energy gradients. (2) The spatial resolution of IR cameras is rather poor. The accepted criterion for an object to be resolved is that its area will fill at least three scanned lines. An unresolved object like a thin wire will appear to have a lower temperature than

*Footnote: The basic scanner design has not changed since the first one built over 25 years ago. However, great improvements in accuracy have occurred. For example, White and Williams¹⁹ first design have a temperature sensitivity of 1°C and about 800 pixels per image. Current models have temperature sensitivity better than 0.1° C and over 80,000 pixels per image. The original readout was an oscilloscope while current readouts are frame grabbers, computers and VCR. Image processing, real-time recording, and software for thermal analysis are commercially available.

its actual temperature. In-situ calibration of the apparent emittance is one way to bypass this limitation. (3) When scanning large objects and the camera is out of focus between the near portion and the far portions, the temperature will be in error. Keeping in mind these characteristics will help in the interpretation of the results.

As mentioned previously, the Ames Unitary Plan purchased an Agema series 900 camera this year. There are several other camera systems commercially available. They are similar in many respects and NASA Langley has used several of these cameras for a range of wind tunnel experiments. NASA Ames chose an Agema camera which allows the camera and the controller-processor to be separated by 10 meters or more. This will allow the camera to be in the 11x11 Foot T.W.T. plenum while the controller-processor will be in the control room. The system also has a 12 bit A/D conversion of the scanner signals which gives it a wider dynamic range. In practical terms, the temperature range controls do not need to be changed to capture large temperature changes. A survey of several commercial IR cameras with their main specifications are given in Table I.

Optical Access

The 11x11 Foot Transonic Wind Tunnel has the best optical access of the three Unitary Plan Wind Tunnels. There are fifteen rectangular windows of approximately 12x48 inches on both sides of the test section. There is at least one window on the ceiling. The windows can be removed and replaced with a metal blank containing the 4x6 inch germanium window. In general, for applications where the IR window is installed in the side walls, it should be located where it least interferes with the Schlieren beam path or other optical instrumentation. For the case of IR window in the ceiling, there is the need of non-interference with the laser vapor screen system located there.

For sting mounted models which pitch in the vertical plane, the IR camera will be normally mounted in the ceiling. This will allow a view of the top planform of the model: the view that is of most interest for boundary layer transition detection. A typical installation, figure 7, would have the Agema camera in the horizontal position so that the liquid nitrogen will not spill. A mirror will be rotated so that the camera can scan the model. For floor mounted

half-models, the camera will be looking in through one of the side windows. Due to the large size of most floor mounted models, a scanning mirror will probably be necessary.

The 9x7 Foot Supersonic Wind Tunnel has two sets of windows on the side of the test section. There is also a small window on the ceiling. The side windows are the most likely ones to be used since the model is pitched in the horizontal plane. The side window in this tunnel is a 48 inch diameter steel blank with a 28 inch glass window inserted on one side. There is sufficient room in the steel portion to insert the IR window see figure 8. There is also a 48 inch diameter steel window blank that could be modified for the IR window. The camera located outside the test section can get a direct view of the model. The 8x7 Foot Supersonic Wind Tunnel has similar side windows like the 9x7 Foot Supersonic Wind Tunnel. However, the model is pitched in the vertical plane. To get a view of the top side of the model, the camera will have to look in at a shallow angle; about 20°. This tunnel has the poorest optical access.

The Agema system has four lenses available of which the 20°x 10° and the 40°x20° were purchased. The scanned area at a set distance between model and camera are given in figure 9. The nominal distance for the 11x11 T.W.T. is about 2 meters and the image area covered is about 0.7 by .35 meters for the 20° x 10° and about twice as large as the 40° x 20° lens. Depth of focus data is also given. This information will determine the choice of lens and the need to scan the model.

Recommendations

1. The Agema IR camera should be deployed in the Ames Unitary Plan Wind Tunnel for the detection of boundary layer transition on wind tunnel models. Both natural transition and tripped transition can be detected by IR thermography.

2. A permanent deployment of the camera should consider both sting models and floor mounted half-models in the 11x11 Transonic Wind Tunnel. Plans by John Schreiner and Dennis Koga of RAC for the floor mounted models are being considered. The sting mounted case should be done at the same time.

3. There is a need to detect transition in both the 9x7 and 8x7 Supersonic Wind Tunnels. Preliminary designs to deploy the Agema

camera in these facilities should be done. The design should consider window design: e.g. where to locate IR window, type of IR material, size of window, and location of camera. An effort should be made in window design to withstand the pressure differential of the tunnel and atmosphere. This would allow the camera to operate under ambient conditions.

4. The technique of varying the cooling water flow in the 9x7 and 8x7 tunnels to obtain sufficient temperature gradients on the model should be tested.

5. Further research on using IR thermography for flow separation detection should be considered.

6. Temperature measurements on models in support of the pressure sensitive paints should be considered.

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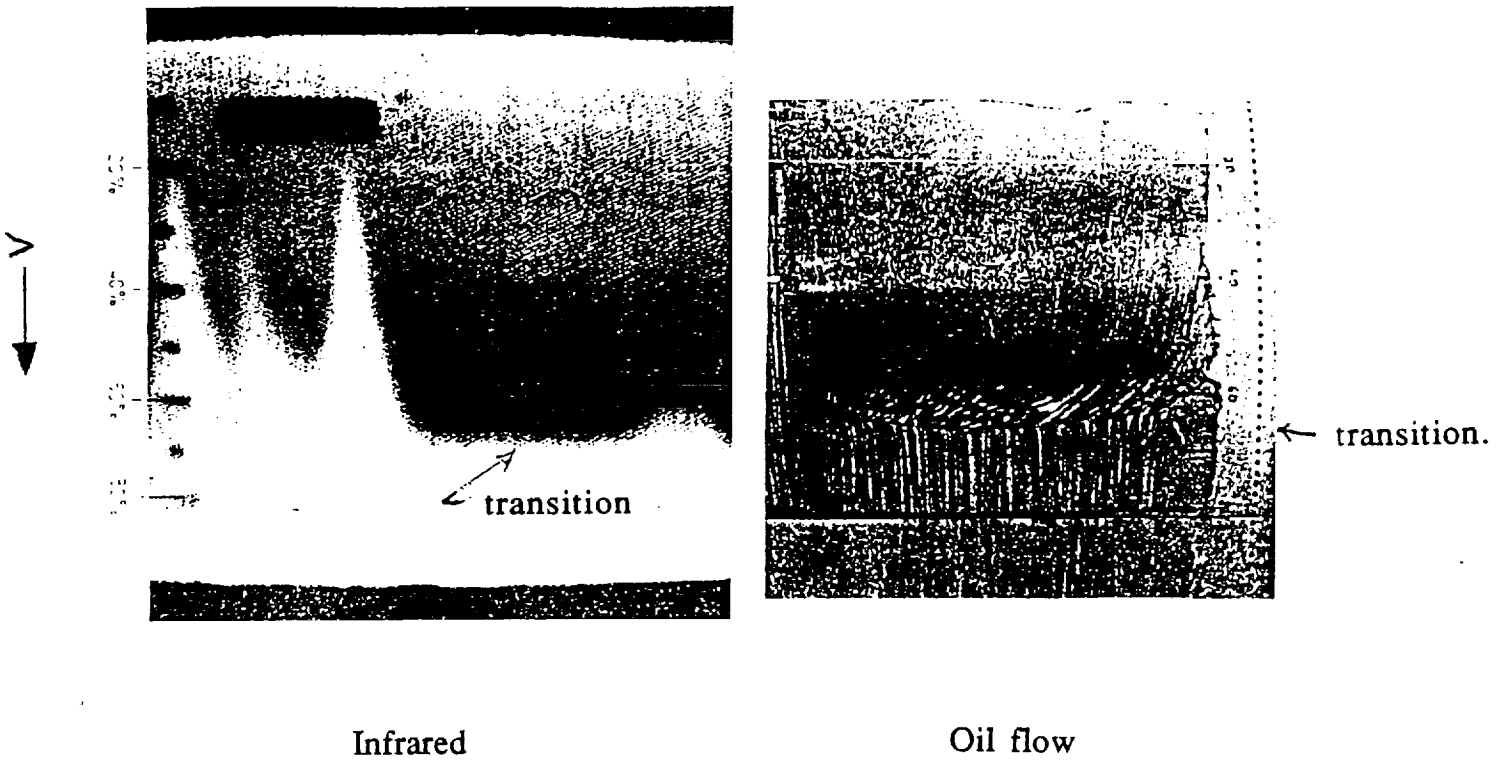


Figure 1. Comparison of infrared and oil flow images of boundary layer transition. (after Quast)

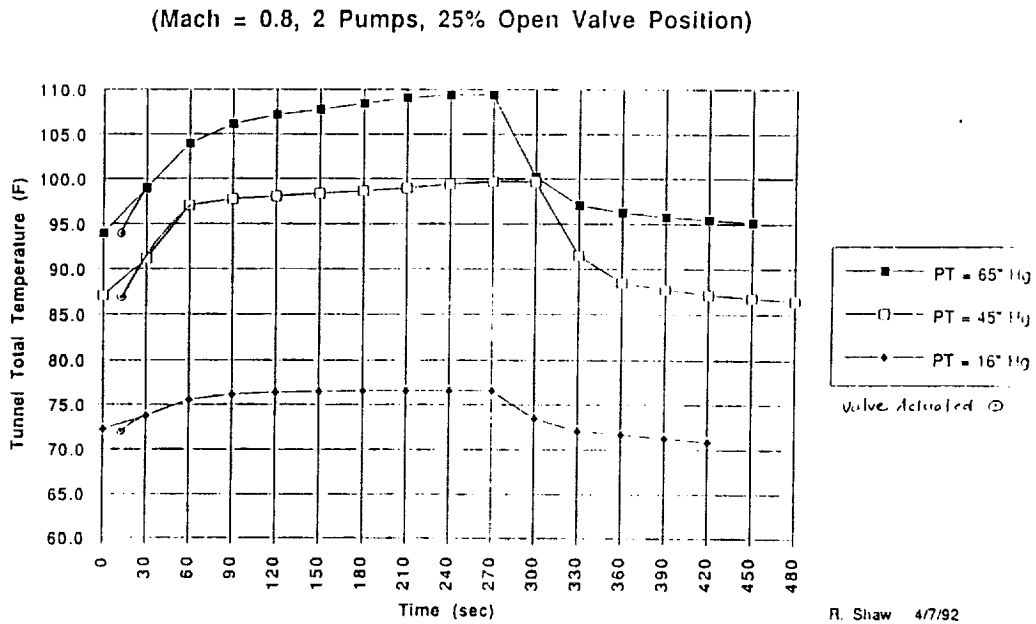


Figure 2. 11x11 Foot Transonic Wind Tunnel temperature gradients obtained by varying water flow rates. (after Shaw)

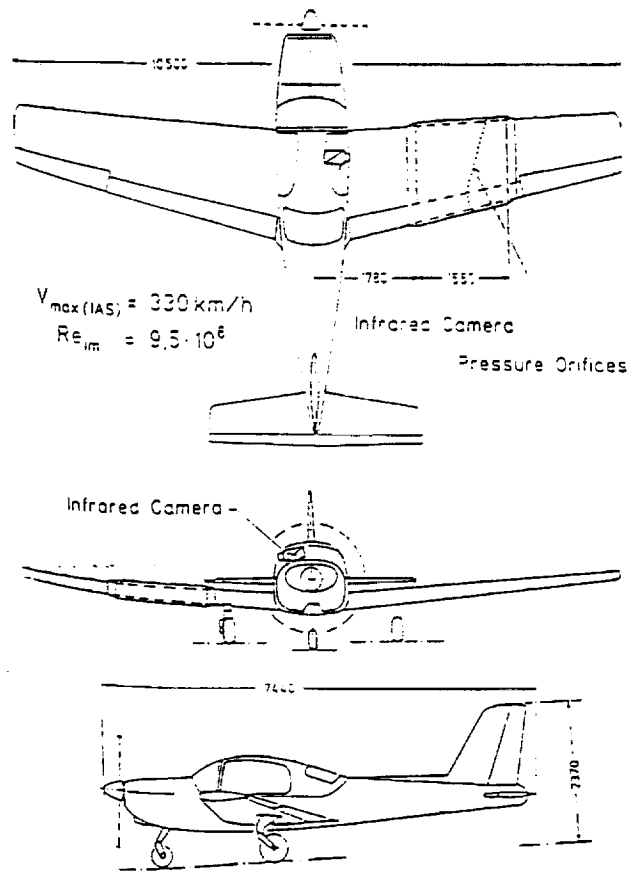
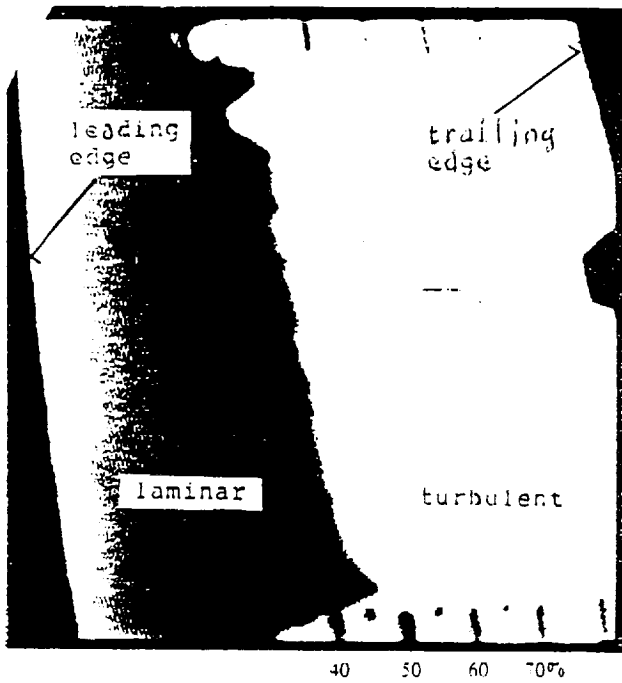
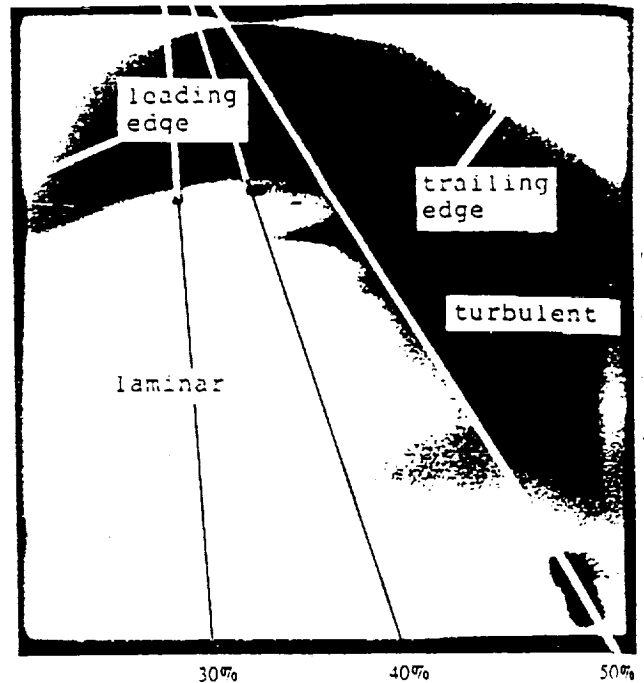


Figure 3. Wing glove and IR setup for flight transition detection. (after Horstmann)

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Infrared image of the glove in DNW.



Infrared image of the glove in flight.

Figure 4. Comparison of flight and wind tunnel transition images. (after Horstmann)

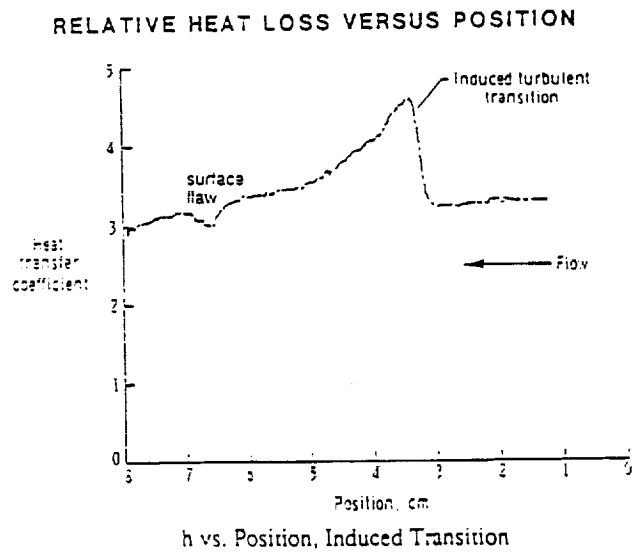


Figure 5. Heat transfer coefficient distribution indicating transition. (after Heath)

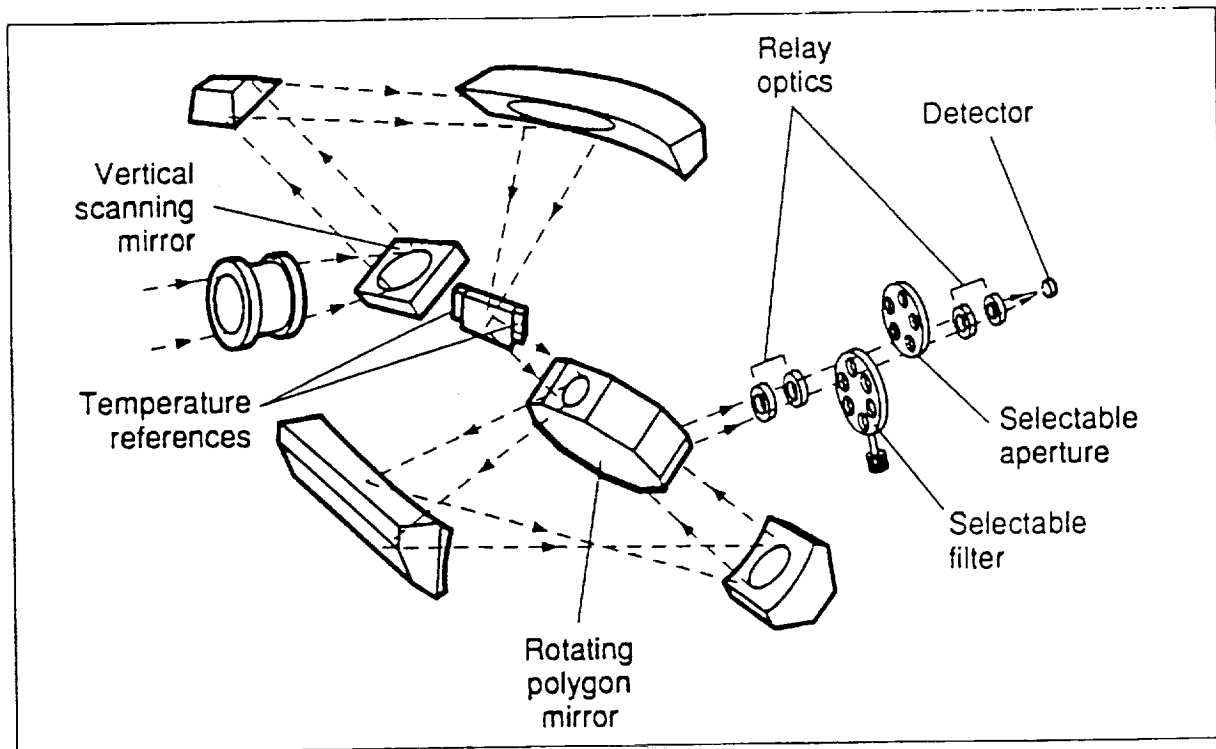


Figure 6. A typical IR scanner design. (from Agema)

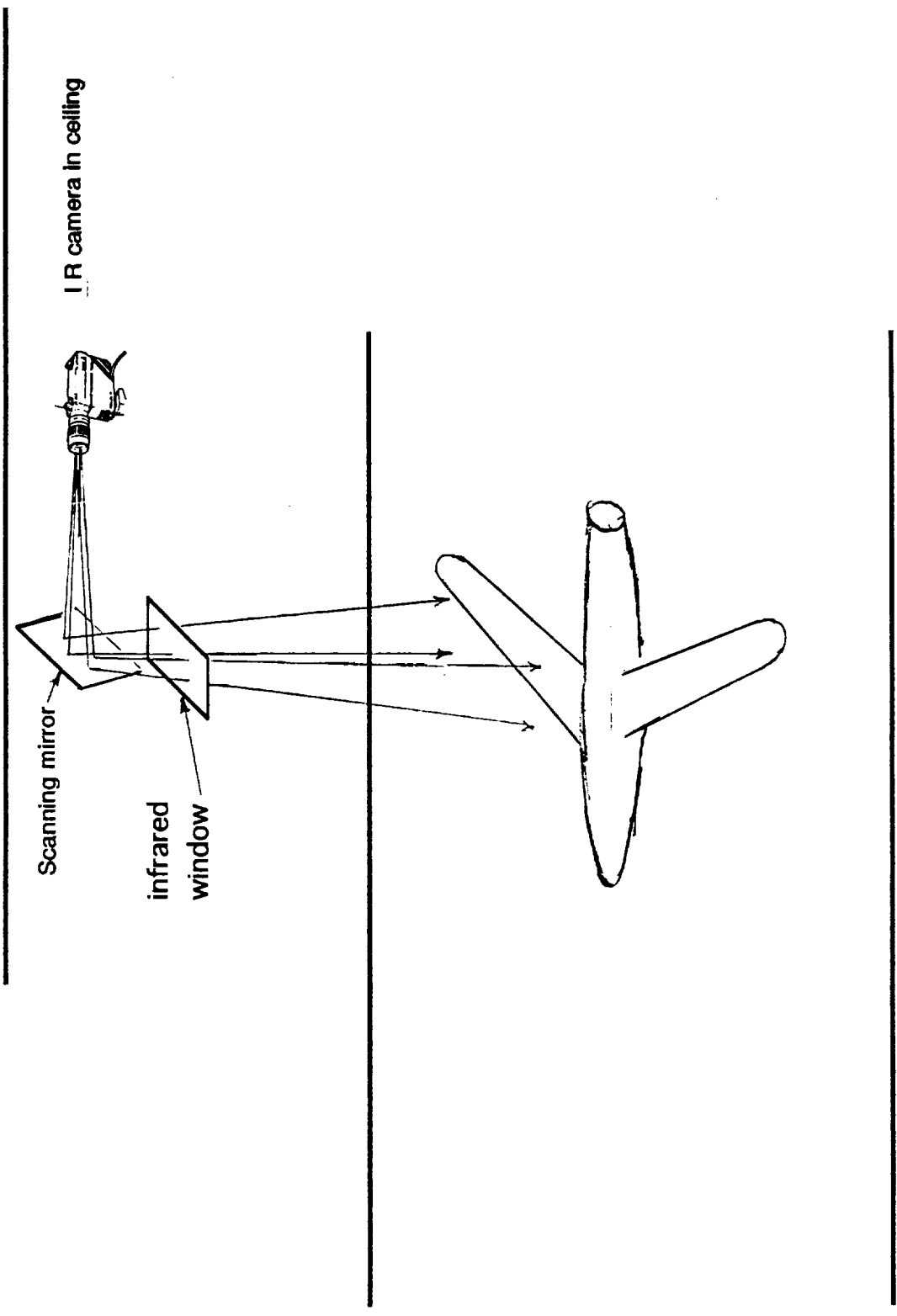


Figure 7. IR camera setup in 11x11 Foot Wind Tunnel.

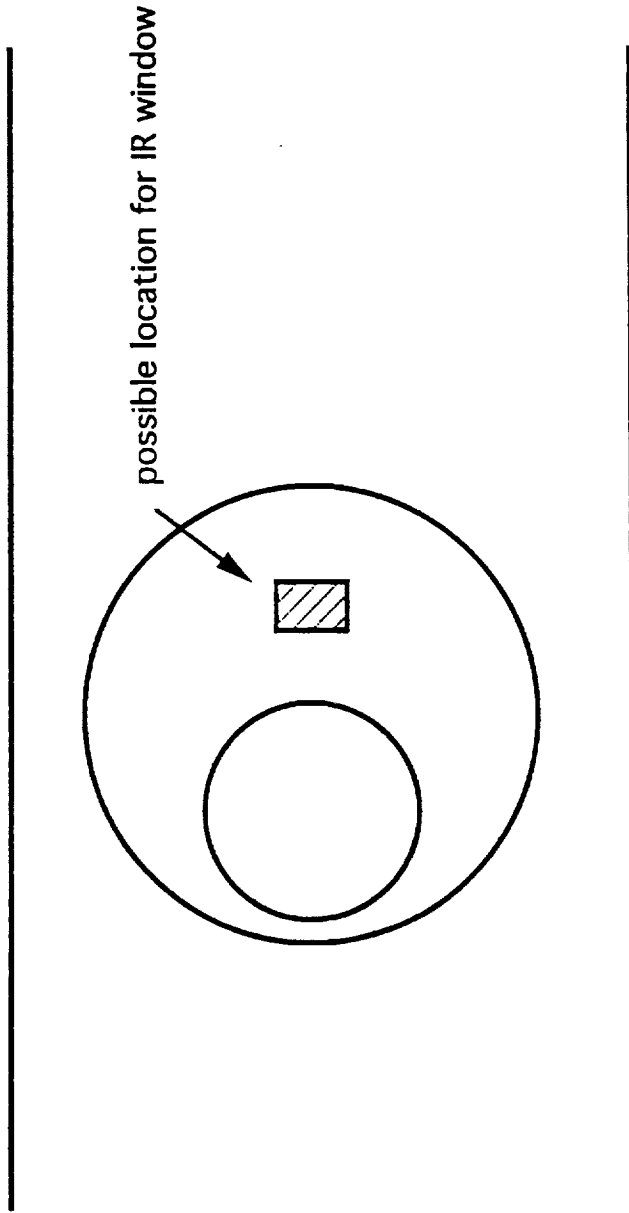
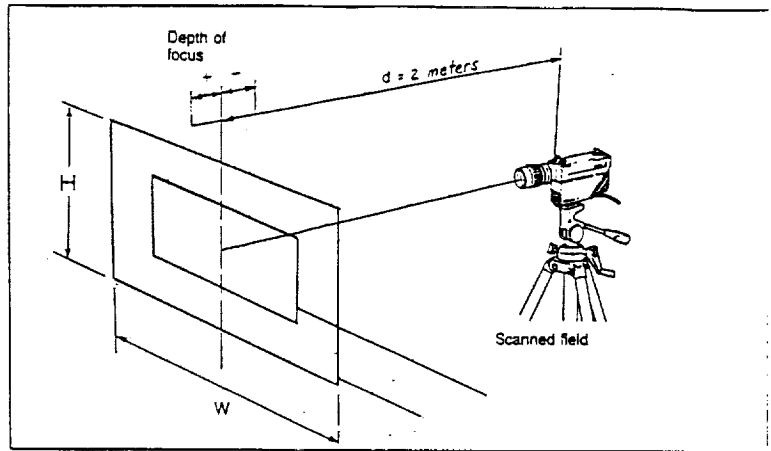


Figure 8. Location of IR window in 9x7 Supersonic Wind Tunnel.



Dimensions of scanned surfaces with various lenses at a specific object-distance

Lens	W	H	+	-
degrees	meters			
20x10	1.40	.70	1.9	.60
40x20	.70	.35		1.3

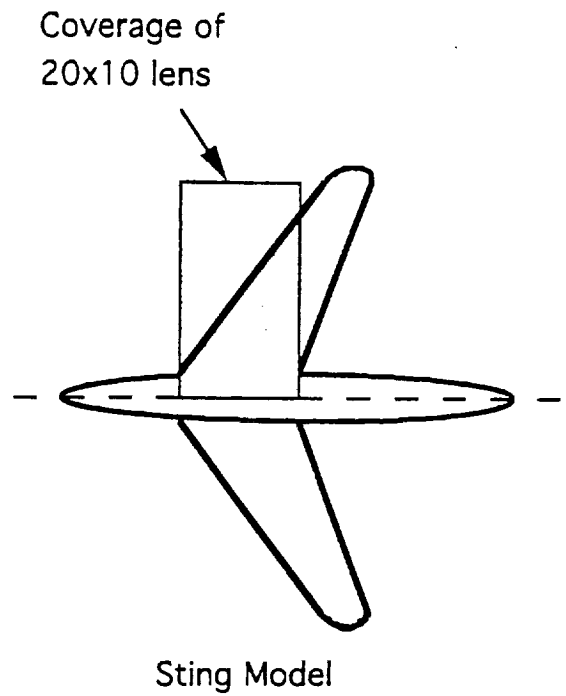
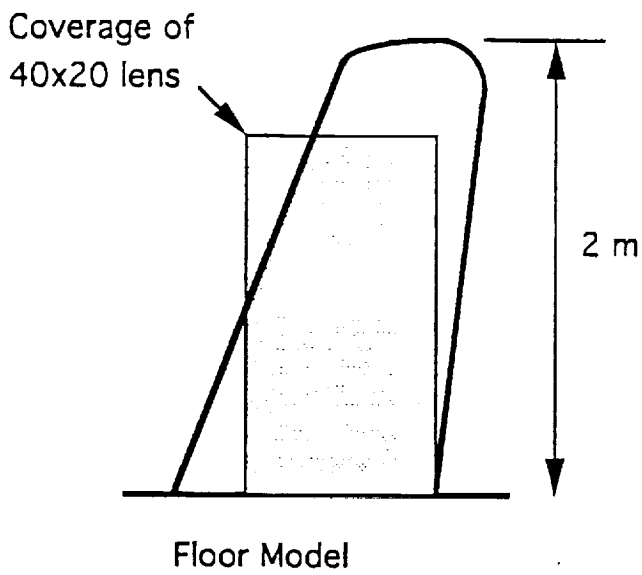


Figure 9. Coverage of 40x 20 and 20x10 degree lenses for floor and sting models in the 11x11 Foot Transonic Wind Tunnel.

TABLE I

Manufacturer	Temperature Range C	Sensitivity C	Spatial Resolution per line	Output Horizontal Lines	Detector	Coding	Range of Lens
Agenda/Thermavision 900	-20 to 1500	0.08	230	136	HgCdTe	Liquid N	Yes
Inframetrics/ Series 600	-20 to 1500	0.1	256	200	HgCdTe	Liquid N	Yes
Hughes/ Probeye 7300	-20 to 1500	0.1	214	240	HgCdTe	Peltier-electric	Yes
Nippon/ TVS-5000	-40 to 2000	0.05	256	200	InSB	Agron Gas	Yes
ISI/ Therm 94	-30 to 1100	0.15	-	270	Pyroelectric	Not Required	No

Appendix A

11-FT TWT AFTERCOOLER WATER FLOW CONTROL VALVE

INTEGRATED SYSTEMS TEST RESULTS

PURPOSE

The purpose of the IST was to verify the functionality and safety of the water flow remote control system at test conditions to be used for Thermography on Test 153-1-11. The IST was similar to the 11-FT Aftercooler test run in July except control of the water flow valve system was placed in the 11-FT control room. The ability to control the tunnel total temperature from the 11-FT Control Room to meet Boeing's requirements was achieved successfully.

TEST PROCEDURE

The IST was conducted and completed April 6, 1992. During the test the water flow valves were throttled from 100% open to 25% open and back to 100% open. The water flow valves were controlled from the control room instead of at the Foxboro control station. The pressure signal line from the Foxboro to the pilot line was overridden by a three-way normally open solenoid valve to either vent the line or allow the system to react normally. A green and a red light in the control room indicate whether the solenoid valve is de-energized or energized. The green light indicates the solenoid valve is de-energized, or the water flow valve is 100% open, and the red light indicates the solenoid valve is energized, or the water flow valve is 25% open. To prevent the possibility of shutting off the water flow through the aftercooler, 25% open mechanical stops were installed at the valve test positions.

The test conditions were Mach 0.8, tunnel Total Pressures of 16, 45, and 65" Hg. To enhance the rate of temperature rise, only two of the four 700 Hp water pumps were active instead of four pumps as usual. System monitoring during the IST consisted of observing the pressure gage reading on the water supply lines, watching that the system is actuating, and noting the tunnel total temperature as the water flow valves are throttled from 100% open to 25% and back to 100% open over a time interval of 3 to 5 minutes.

The test procedure, run at tunnel total pressures of 16, 45, and 65" Hg, was as follows:

1. Install 25% mechanical stops.
2. Start 2 water pumps.
3. Set tunnel conditions (Mach = 0.8, PT).

Appendix A

4. Wait for tunnel conditions to stabilize.
5. Close water flow valves to 25% open position.
6. Open water flow valves to 100% open position.

For each data run at fixed Mach number and total pressure, the temperature versus time was recorded after the valves were suddenly closed or open.

TEST RESULTS

The results of the IST indicate that Boeing was able to obtain good data from the temperature changes obtained. It also indicates that control of the water flow valves from the control room is possible without any problems. During the IST, Boeing checked-out their Infra-red Thermography System at each test condition to verify whether the tunnel total temperature change obtained was adequate to meet their IR Thermography requirements.

Table 1 shows the temperature readings for each test condition at 30 second intervals. Figure 1 shows the temperature profile as the water flow valves are in the 25% and 100% open positions. The curves have a sharp rise at the beginning because there is a 10 to 15 second delay between the time of actuation and the time of complete travel when the water flow valves are moved to the 25% and 100% open positions.

TIME (sec)	TEMPERATURE		
	PT = 65" Hg	PT = 45" Hg	PT = 16" Hg
0	94.0	87.1	72.3
30	99.0	91.2	73.8
60	104.0	97.1	75.6
90	106.2	97.8	76.2
120	107.2	98.1	76.4
150	107.8	98.4	76.5
180	108.5	98.7	76.6
210	109.1	99.0	76.6
240	109.4	99.4	76.6
270	109.4	99.7	76.6
300	100.2	99.7	73.5
330	97.1	91.5	72.1
360	96.3	88.5	71.7
390	95.8	87.8	71.3
420	95.5	87.2	70.9
450	95.2	86.8	
480		86.5	

Table 1. Time Variation of Total Temperature for Various Total Pressures

Appendix A

Table 2 shows the rate of temperature increase and decrease at each test condition. The table shows that when the water flow valve is suddenly changed from 100% to 25% open or vice versa, the required 10 deg/min criteria is achieved. At low power, the 10 deg/min criteria is not met, but Boeing has determined the temperature change is sufficient for their Infra-red Thermography System.

Tunnel Conditions	Max dT/dt (DEG/MIN)	
	Increase	Decrease
PT = 65" Hg	10.0	-12.0
PT = 45" Hg	8.0	-11.0
PT = 16" Hg	3.3	-4.5

Table 2. Rate of Temperature Increase and Decrease for Each Tunnel Condition

CONCLUSION

Throttling the water flow control valves has been shown experimentally to be an effective means to control the rate of the tunnel total temperature rise. To control the tunnel total temperature from the control room as requested for the Boeing test, a solenoid valve was used to override the pressure signal from the Foxboro control system. This IST shows that the override system successfully controlled the tunnel total temperature from the control room. The IST also verifies that adequate data can be obtained with two active water pumps at the test conditions specified by Boeing when the water flow valves are actuated to the 25% open position or back to the 100% open position. Higher rates of temperature change were obtained when the valves were moved from 25% to 100% open than for the reverse. At the tunnel total temperature of 16" Hg condition, the rates were marginal but acceptable.

In its current configuration, the override system for the Foxboro can be easily disconnected and reconnected should the need arise. When the Boeing test is complete the system will be restored to its normal configuration for pneumatic control. If the solenoid control system is to be used on a future test, it should be reactivated only after approval through a TRR or ORR. In general, the water flow valve control system should be replaced with a "safer" system. At present, should the Foxboro lose supply pressure and the 100% open mechanical stops are not in place, the water flow valve would fully close and could potentially cause catastrophic failure of wind tunnel components due to an excessive rise in tunnel total temperature. Instead of using a pneumatic control system a digital control system could be considered to control the water flow valves, especially in light of the upcoming modernization project.

**FIGURE 1: 11-FT Tunnel Total Temperature Change
(Mach = 0.8, 2 Pumps, 25% Open Valve Position)**

