Infrared Thermography in Blowdown and Intermittent Hypersonic Facilities

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Some results and conclusions from the application of infrared thermography in the measurement of heat transfer in two distinctly different short duration hypersonic facilities are presented. First results from a blowdown tunnel are discussed; they demonstrate the advantage of the infrared technique in providing two-dimensional heat transfer maps as opposed to the zero-dimensional measurements enabled by discrete point gauges. The spatial resolution characteristics of the infrared scanning radiometer are sufficient to sense localized hot spots that may be quantified by concentrating the field of view onto the area of interest. In intermittent facilities, the technique is shown to provide qualitative information on the location of hot spots or, in a single-line scan mode, a heat transfer distribution along one direction. In the latter case, the presence of hot dust in the flowfield may pose problems in arriving at quantitative results.

Introduction

INTEREST at the von Kármán Institute's (VKI) Aeronautics/Aerospace Department has focused in recent years on the study of hypersonic interacting flows. Experimentally, this is carried out in the two hypersonic wind tunnels of the Institute, namely the Mach 15 Longshot intermittent facility and the Mach 6 H-3 blowdown tunnel. Emphasis is placed on the measurement of heat transfer, either around complete reentry vehicle models or simplified configurations simulating parts of the reentry vehicle (Fig. 1).[1]

In either case, the resulting flowfields may be highly three-dimensional and may exhibit shock/shock and/or shock/boundary-layer interactions, yielding heat transfer distributions with sharp gradients in both directions along the model surface and localized hot spots. As a result, thermographic techniques that show the complete surface are much preferred to discrete point measurements performed by such techniques as thin film resistance thermometers or thermocouples.

This paper addresses the development of the infrared thermographic technique[2-4] at the VKI and the first results and conclusions from its application in the two VKI hypersonic tunnels. The paper is divided into two parts. First, the use of infrared thermography in a blowdown facility is discussed; then its use in an intermittent facility is discussed. In each case, problem areas are identified and examples presented.

Facilities

The VKI H-3 wind tunnel[5] is a blowdown facility with a contoured nozzle producing a uniform Mach 6 flow with a useful test core diameter of about 10 cm. Unit Reynolds numbers in the range 8–30 million per meter are achieved, with wall to total temperature ratios of the order of 0.5.

Longshot[6,7] is a heavy free piston gun tunnel producing a uniform Mach 15 flow through a contoured nozzle of duration 20 ms. The useful test core diameter is 24 cm. Unit Reynolds numbers up to 30 million per meter are achieved with wall to total temperature ratios as low as 0.15. During a test the total pressure and temperature decay exponentially due to the finite volume of the reservoir, this resulting in a variation of unit Reynolds number by a factor of 2 over the duration of the test, whereas Mach number remains nominally constant.

Infrared Scanning Radiometer

An Inframetrics Model 525 infrared scanning radiometer (IR camera),[8,9] shown in Fig. 2, is currently employed at the VKI. It is typical of commercially available units. The camera has a total field of view of 14 deg vertical and 18 deg horizontal that is scanned by the mercury cadmium telluride (HgCdTe) infrared sensor (sensitive in the range 8-12 μm) by means of two oscillating mirrors. Liquid nitrogen is used to maintain the sensor at a low temperature, thus enhancing its sensitivity. The framing rate of the IR camera is video-compatible at 50 Hz, as set by the frequency of oscillation of the vertical mirror. The temperature sensitivity is given by the manufacturer as 0.2 K. Recently, the 8-kHz line scan mode of operation has been added to the VKI system; the vertical mirror is fixed, and a single horizontal line is scanned at two times the frequency of oscillation of the horizontal mirror.

Noting that the resolving power of the IR camera is about 150 elements per line and that each frame contains 130 independent lines, the amount of data produced during a test is most conveniently stored on video tape and, thence, chosen information may be transferred to the Vax V780 computer for analysis with the Digital Image Processing (DIP) system. This large amount of data not only causes difficulties with direct digital storage but also makes data reduction cumbersome and some times unrealistic for the complete set of data points.

Data reduction requires a calibration of model surface temperature versus DIP intensity, which is carried out with a setup identical to that of the tests in order to account for the model surface emissivitiy and the transmissivity of the infrared-transparent Germanium window on the tunnel wall. For small temperature ranges, this calibration is rather linear, as shown in the example of Fig. 3. It is noted that effects of large curvature on the model surface emissivity need to be accounted for in the calibration.

The infrared technique is employed with thick skin models, i.e., heat transfer rates are deduced from the time variation of the model surface temperature on the assumption that the model is a semi-infinite slab, so that the back-surface temperature remains constant with time.[10] In most cases, a one-dimensional heat conduction into the model surface is also assumed.

Presented as Paper 89-0042 at the AIAA 27th Aerospace Sciences Meeting, Reno, NV, Jan. 9-12, 1989; received March 10, 1989; revision received July 20, 1989.

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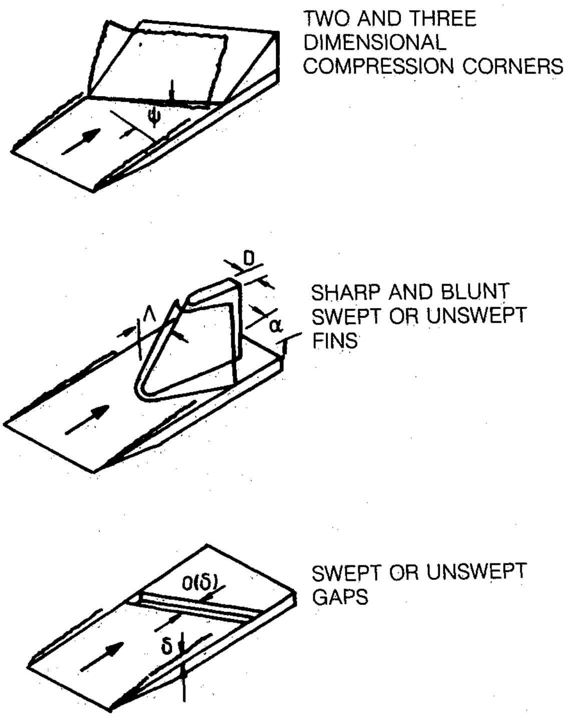

Fig. 1 Configurations tested in the VKI hypersonic tunnels.

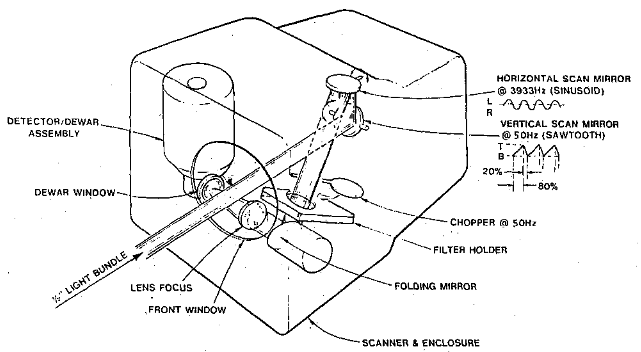

Fig. 2 Inframetrics 525 IR camera—optical schematic.[8]

Application in Blowdown Facilities

General

Typically, blowdown facilities are characterized by test times that are long compared to the framing period of an IR camera (20 ms). Thus, a single frame may be considered to contain instantaneous information on the model surface temperature distribution, and a series of frames can be employed to determine the time rate of change of the model surface temperature and hence heat flux.[10]

It is interesting to note that in facilities such as the VKI H-3 wind tunnel, where the test conditions remain constant with time, the heat transfer rate varies linearly with the model surface temperature, and, thus, data reduction may be done algebraically. In the limit, in the case of low heating rates and/or short running times, the heat transfer rate may be assumed constant, further simplifying the data reduction. The assumption of a time-invariant heat flux may be safely applied to the H-3 results presented herein due to the short test times employed (0.5–1 s). The immense advantages of an algebraic data reduction are immediately realized when one considers the resolving power of the IR camera and the large number of data points scanned.

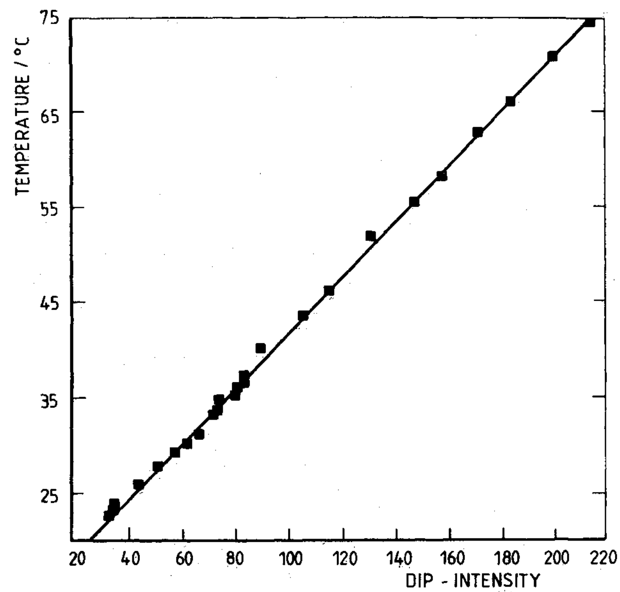

Fig. 3 IR camera calibration curve.

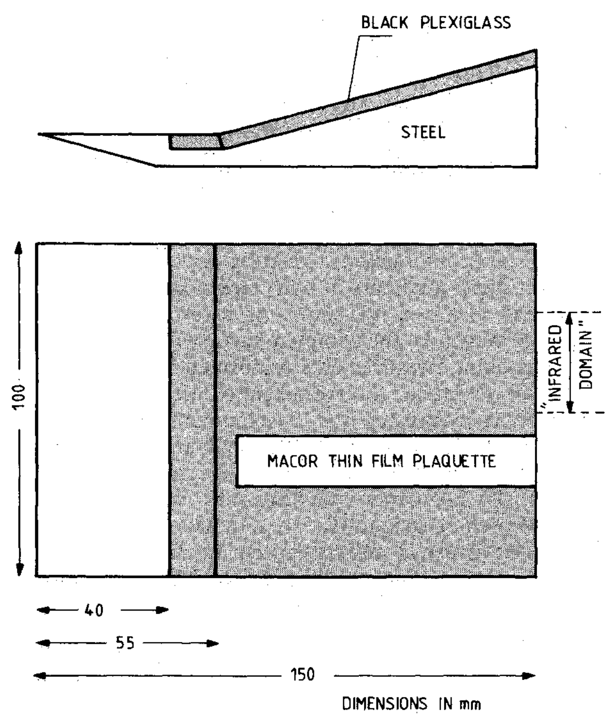

Fig. 4 Thin-film/infrared flat plate/15-deg ramp model tested in the H-3 wind tunnel.

Results presented in this section include heat transfer distributions over a flat plate and over a two-dimensional flat plate/15-deg ramp model shown in Fig. 4. Both models, except for their steel leading-edge pieces, were manufactured of black Plexiglas to provide an acceptable combination of surface emissivity and thermal properties. The operational distance of the IR camera to the model was 1 m.

Global Heat Transfer Distributions

The infrared thermographic technique was originally validated by comparing the heat transfer distribution along a flat plate as measured by the IR camera to that measured by platinum thin-film surface resistance thermometers and to a reference enthalpy prediction. The encouraging result is illustrated in Fig. 5.

Tests were then carried out with the model of Fig. 4, and a comparison between infrared and thin-film measurements along the ramp is shown in Fig. 6. A flat plate reference enthalpy prediction is also included. The infrared curve represents an average distribution over the "infrared domain" of the model defined in Fig. 4. Again, good agreement between the two techniques is found.

The virtues of the infrared technique are illustrated in Fig. 7, a surface plot of the normalized heat transfer distribution over the infrared domain on the ramp of the model of Fig. 4. Clearly, this type of presentation will be of utmost importance to the study of complex three-dimensional configurations.

Detection and Quantification of Local Hot Spots

With reference to Fig. 7, it is noted that the output signal of the IR camera shows some small oscillations of the heat transfer rate across the span of the model. In fact, a sublimation technique applied to a model similar to that of Fig. 4 in the H-3 tunnel has shown that these oscillations correspond to streamwise striations that form in the reattachment region of the ramp (Fig. 8). Such striations have been observed by a number of investigators[11-13] and are attributed to the formation of contrarotating streamwise vortices in reattaching flows. Their spanwise spacing has been found to be of the order of two to three times the upstream undisturbed boundary-layer thickness, which corresponds to 2–3 mm in the H-3 experiments, as confirmed by the result of Fig. 8. This phenomenon, therefore, stands as a good test case for the determination of the capabilities and limitations of the infrared technique in detecting and quantifying localized hot spots.

A plot of the spanwise heat transfer distribution in the region of the peak heating and over part of the span, as determined from the direct output of the IR camera, is shown as curve 1 in Fig. 9. However, the spatial resolution characteristics of the IR camera dictate that, considering its operational distance and the spacing of the streamwise striations, it will sense only a very small fraction of the full amplitude of the spanwise temperature variation. The spatial resolution of the IR camera is described by the modulation transfer function (MTF) of Fig. 10, which is effectively the fraction of the amplitude of a periodic temperature variation sensed by the camera in function of the spatial frequency.

It is, therefore, possible to use the curve of Fig. 10 to correct the oscillating part of the output of the IR camera. To be

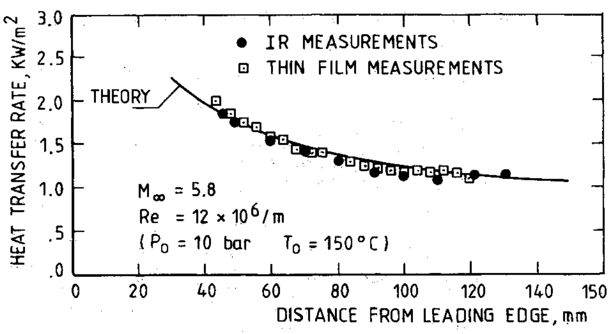

Fig. 5 Heat transfer distribution along a flat plate in the H-3 blowdown tunnel.

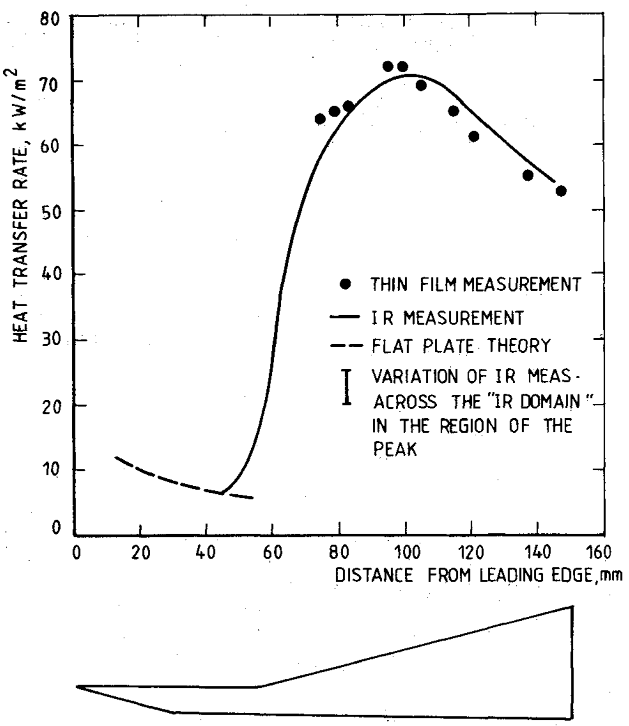

Fig. 6 Heat transfer distribution along the flat plate/15-deg ramp model in the H-3 blowdown tunnel.

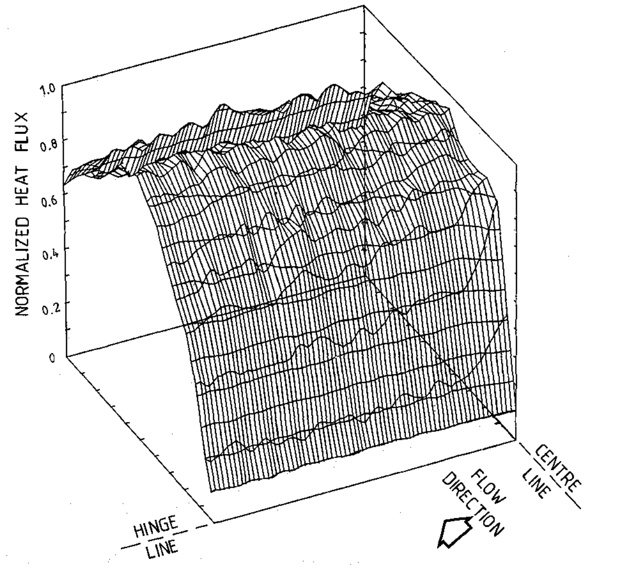

Fig. 7 Normalized heat transfer distribution over the infrared domain of the 15-deg ramp in the H-3 blowdown tunnel.

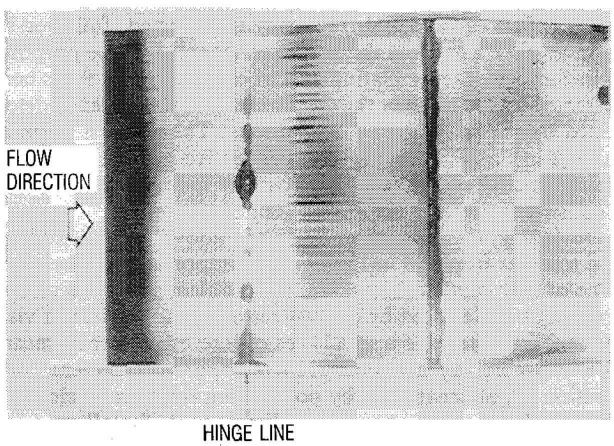

Fig. 8 Sublimation flow visualization of streamwise striations on a flat plate/15-deg ramp model in the H-3 blowdown tunnel.

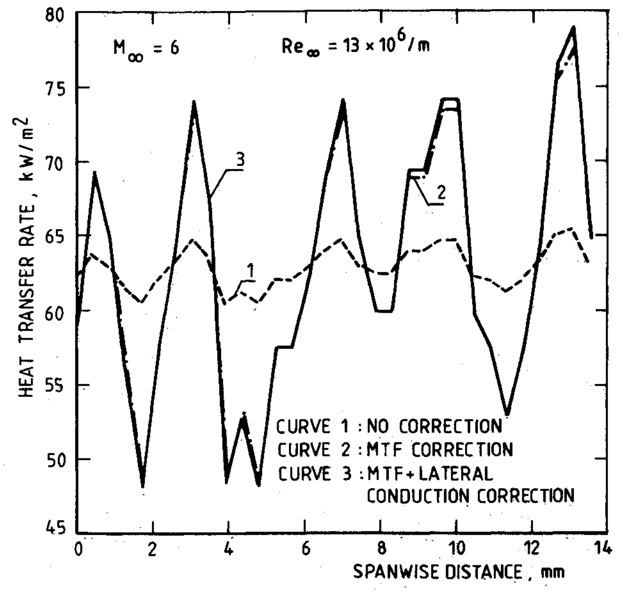

Fig. 9 Spanwise heat transfer distribution over part of the infrared domain near reattachment on the 15-deg ramp in the H-3 blowdown tunnel (test duration ~0.5 s).

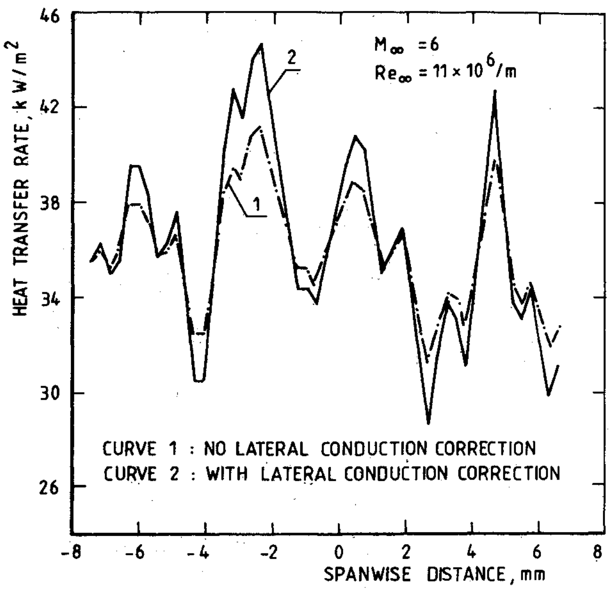

Fig. 11 Effect of lateral conduction on the determination of the spanwise heat transfer distribution on a 15-deg ramp upstream of reattachment in the H-3 blowdown facility (test duration ~5 s).

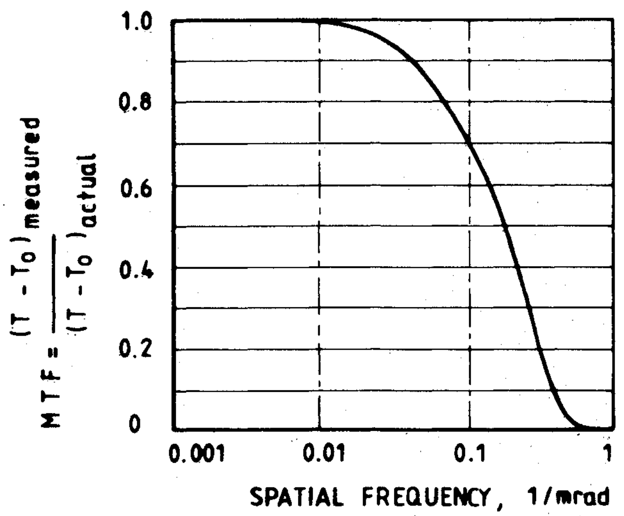

Fig. 10 Modulation transfer function for the Inframetrics 525 (field of view: 14×18 deg).

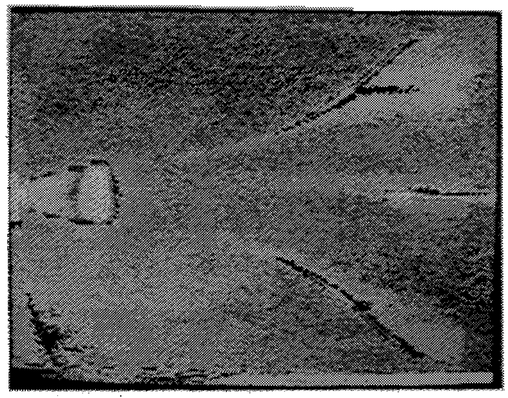

Fig. 12 Infrared view of the leeside of an Orbiter model at zero incidence at Mach 15 in the VKI Longshot intermittent tunnel.

exact, a fast Fourier transform (FFT) should be applied to the signal before each spatial frequency is corrected, followed by an inverse FFT to yield the corrected signal. For the purposes of illustration, the oscillating part of curve 1 in Fig. 9 has been corrected by the MTF at the dominant spatial frequency determined by the spacing of the striations. The result is given as curve 2 in Fig. 9, showing that convective heating rates near reattachment vary by ±20% across the span, a variation that is consistent with the findings of Ginoux.[11]

Obviously, the correction described above for the modulation transfer function in Fig. 9 is too important for the result to be of high quality. However, the problem of spatial resolution may be alleviated by concentrating the total field of view of the IR camera onto a small area of interest, either by means of a commercially available 3X telescope/close-up lens combination or, alternatively, by positioning the camera closer to the model. In either case, it is believed that, for all practical operational distances of the camera, an MTF correction will still be required, but this will be much smaller—on the order of 30%.

Another more general problem related to the measurement of convective heating at highly localized hot spots, which applies to all measurement techniques that make use of the transient variation of the model surface temperature to deduce heat flux, is that the assumption of one-dimensional heat conduction into the model surface breaks down in regions of strong transverse temperature gradients, such as across the span of the ramp in the H-3 experiments, thus considerably complicating the data reduction. This lateral conduction effect may be reduced only by using very short test times and/or highly insulating materials for the test models.

An approximate analytical model has been used to quantify the lateral conduction effect on the heat flux/surface temperature relationship for the case of the streamwise striations discussed above. It assumes a time-invariant sinusoidal variation of the heat flux along the spanwise line of interest. Incorporating this model in the data reduction yields curve 3 of Fig. 9, showing that lateral conduction is not important in the present result. However, the effect of transverse temperature gradients becomes increasingly important with running time, as illustrated by the result of an earlier experiment with much longer running time in Fig. 11.

Use in Intermittent Facilities

Intermittent tunnels are frequently characterized by test times of the order of 1–50 ms, which is less than or roughly equal to the IR camera framing period of 20 ms. For qualitative measurements, useful information on the location of hot spots may, nevertheless, be obtained with the standard mode of operation of the camera. An example is shown in Fig. 12 with a wooden model of the Orbiter vehicle at zero incidence in the test section of the Longshot tunnel. Nose, canopy, and wing/tail leading-edge regions are clearly hotter than other areas; the 'spike' developing downstream of the nose shock/wing shock interaction on the starboard wing is also noted.

A more fundamental result is given in Fig. 13; it shows the spanwise surface temperature distribution across part of the span in the reattachment region of a model similar to that of Fig. 4 tested in Longshot at Mach 15. The presence of streamwise striations is clearly indicated, even though no correction has been applied for the spatial resolution of the IR camera. It is noted that this correction will be about one-half of the correction needed in the H-3 experiments because of the much larger spacing of the striations, whereas the operational distance of the camera was again about 1 m. Furthermore, in intermittent wind tunnels, such as Longshot, generally one-dimensional heat conduction into insulating thick skin models may be safely assumed, due to the very short running times.

However, because of the time variation of the test conditions in Longshot and, consequently, of heat flux, quantification of heat transfer rates requires a numerical technique and, thus, a knowledge of the time rate of change of the surface temperature in function of time.[10] For this purpose, the 20-ms framing period of the IR camera is too slow, and conversion to the 8-kHz line scan mode is needed, so that each 20-ms frame comprises the image of a single line repeated as a function of time.

The capabilities of the line scan mode of operation of the IR camera have been demonstrated in the Longshot tunnel with the Plexiglas flat plate/sharp unswept fin (vertical wedge) model shown in Fig. 14. A line in the streamwise direction, intersecting the wedge on its compression side, was scanned, and the result is shown in the upper part of Fig. 15. The lower part of this figure shows the whole model as viewed by the IR camera in its standard mode of operation and also the line scanned during the test. Qualitatively, the expected temperature distribution along the scanning line was found, showing peak heating in the leading edge and shock/boundary-layer interaction regions.

Quantitatively, the temperature-time trace obtained from the thermogram of Fig. 15, at the location of peak heating

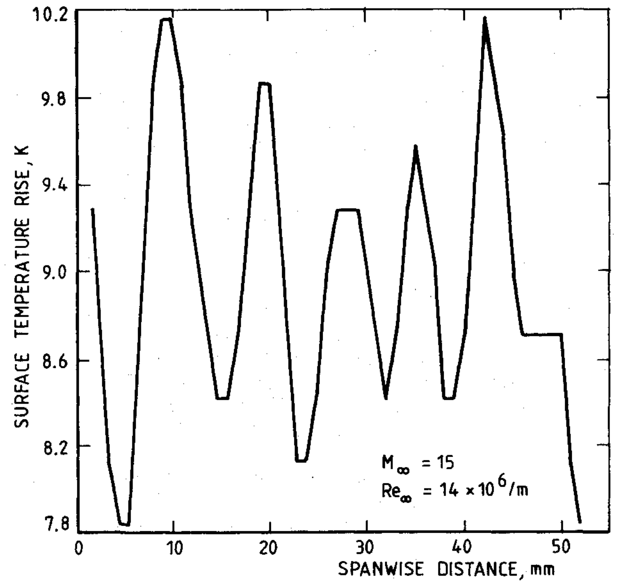

Fig. 13 Instantaneous spanwise surface temperature distribution near reattachment on a two-dimensional flat plate/15-deg ramp model in the VKI Longshot intermittent tunnel.

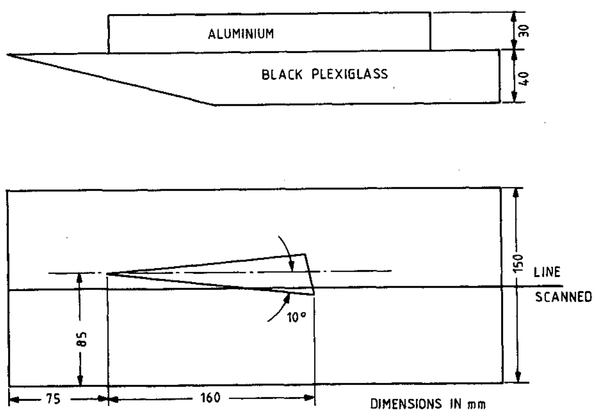

Fig. 14 Infrared flat-plate/vertical wedge model tested in the Longshot tunnel.

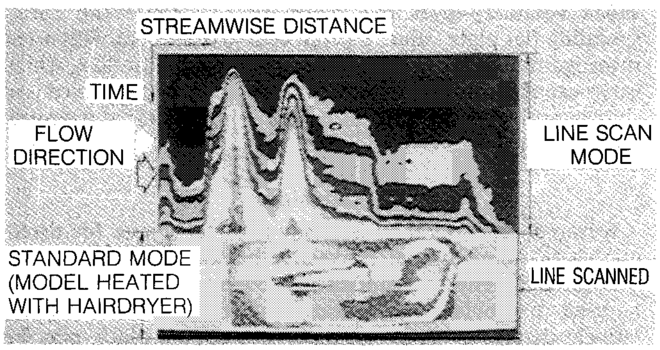

Fig. 15 Infrared thermogram in the 8-kHz line scan mode of a flat-plate/vertical wedge configuration in the VKI Longshot intermittent facility at Mach 15.

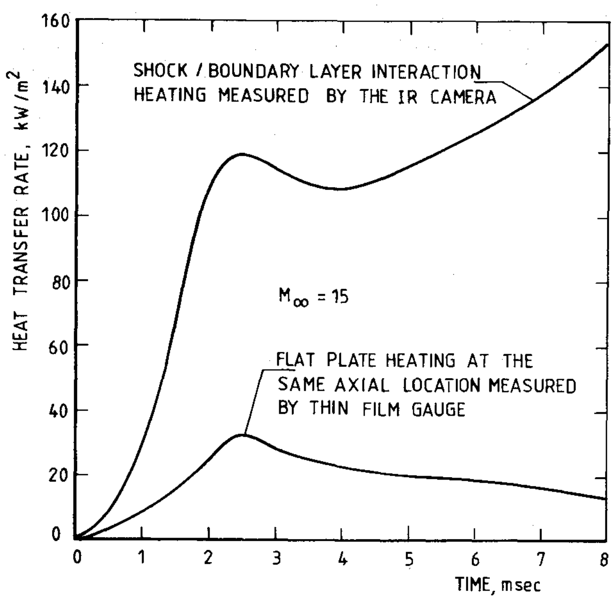

Fig. 16 Time-variation of heat transfer rate of the shock/boundary-layer interaction on a flat-plate/sharp unswept fin model in the VKI Longshot intermittent tunnel.

corresponding to the shock/boundary-layer interaction, was used with a numerical technique[10] to determine the time variation of convective heat flux at this location. The result is shown in Fig. 16, together with the heat flux trace measured by a thin-film gage in another test with a flat plate model at a corresponding axial location and at the same test conditions. The flat plate trace is representative of the decay of heat flux with time in Longshot caused by the decay of the total pressure and temperature. However, this trend is not found in the present infrared result.

Closer examination of Fig. 15 shows a temperature rise also upstream of the model, which is believed to be due to the presence of hot particulate matter eroding away from the high temperature reservoir/throat sections of the nozzle. Further, the infrared emission of these particles is seen to have, with time, an increasingly important effect on the apparent model surface temperature distribution, causing the continuous divergence from the expected evolution of heat flux with time in Fig. 16. There are indications, however, that this phenomenon does not become effective until a few milliseconds after the beginning of the test (Fig. 15), which can be justified by a delayed arrival of the particles in the test section due to their inertia. It is, therefore, conceivable that quantitative heat transfer data may be obtained with the line scan mode of operation of the IR camera during the first few miliseconds of a test. This is supported in a sense by the result of Fig. 16, which shows for the first part of the test a peak heating rate in the shock/boundary-layer interaction of 4-5 times the corresponding flat plate value, a result that is consistent with other investigators.[14] It is noted that the presence of hot dust, which is typical of most intermittent hypersonic facilities, has caused similar problems with the interpretation of infrared measurements in other earlier studies.[15]

Conclusions

Infrared thermography is a powerful technique for determining two-dimensional convective heating maps over complex three-dimensional models in blowdown facilities. It may be used to provide global heat transfer distributions, qualitatively detecting highly localized hot spots, which may be later quantified through a close-up operation.

In intermittent facilities, infrared thermography may clearly be used in a qualitative sense to quickly provide information on the location of hot spots, which will facilitate the positioning of discrete point gauges. For quantitative measurements, the short running time of intermittent tunnels does not pose a limitation, provided the line scan mode of operation is employed at the expense of one of the two dimensions of thermal mapping. The presence of hot particulate matter, however, in the flowfield of most intermittent facilities may be critical in the interpretation of infrared measurements, although the problem could be solved by considering only the first part of a test before the hot particles arrive in the test section. This last point remains to be further explored with simpler models (e.g., flat plate) and by comparison to thin-film measurements.

One of the main advantages of the infrared technique is that it does not require the construction of expensive instrumented models or any special model preparation before each test. The use of the IR camera is relatively simple, particularly so with novel designs employing thermoelectrically cooled sensors that do not require frequent addition of liquid nitrogen. Finally, data reduction is no more complicated than with techniques incorporating thin-film gauges or fast response thermocouples.

Acknowledgment

The Longshot IR thermogram of Fig. 15 was taken by an Inframetrics Model 600 scanning radiometer, in the line scan mode, kindly demonstrated to the authors by the French representatives of the manufacturer Infratek of Clermont-Ferrant, France.

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