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MEASUREMENT OF HEAT TRANSFER WITH AN INFRARED CAMERA*

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Abstract—In the present paper the application of an infrared camera to heat-transfer measurements in a hypersonic wind tunnel is described. The technique is closely related to the one using temperature sensitive paints or melting coatings. The main advantages of the present method are: (1) it is easy to apply as the model surface need not be treated with paint etc.; (2) the same model can be used again, as soon as it has cooled down; (3) smooth model surface; (4) good accuracy of the temperature measurement. Results are given for heat-transfer measurements on a paraboloid at $M = 7$ and compared with other measurements. Good agreement is found.

NOMENCLATURE

a, thermal diffusivity, $k/\rho c$;
c, specific heat of wall material;
c_p, specific heat of air;
D, diameter of model;
d, diameter of spot focused on detector;
h, α/k;
k, thermal conductivity;
L, distance between camera and object;
M, Mach number;
R, radius of sphere;
Re, Reynolds number, $\rho_\infty u_\infty D/\mu_\infty$;
St, Stanton number, equation (1);
s, distance along surface (see Fig. 2);
T, temperature;
t, time;
u, velocity;
X, thickness of wall.

Greek symbols
α, heat-transfer coefficient;
μ, viscosity;
ρ, density.

Subscripts
i, initial temperature;
r, recovery temperature;
∞, conditions in free stream.

1. INTRODUCTION

HEAT-TRANSFER rates to aerodynamic shapes are often measured in wind tunnels. Usually, the model is suddenly exposed to the flow and the increase of the wall temperature is measured. If the physical properties and the dimensions of the wall are known, the equation for heat conduction in solids can be used to determine a relation between the heat-transfer rate and the measured wall temperature history. This relation is simplified if uniform temperature throughout the (thin) wall can be assumed or if the conditions at the rear face of the (thick) wall can be neglected. In the first case thermocouples are usually used to measure the temperature of the wall and in the second case thin film resistance elements are useful. In both cases, the instrumentation of a model is time consuming and expensive.

In many cases it is desirable to obtain a quick survey of the distribution of heat-transfer rates on complicated shapes and moderate accuracy can be tolerated. Other methods of temperature measurement have therefore been developed. The use of paints that change colour at certain

* Thermovision, manufactured by AGA, Lidingö 1, Sweden.

temperatures has been described. See [1–3] and reference list in [4]. As pointed out in [4] the temperature at which the paints change colour depends upon the rate of change of the temperature, upon the pressure and in some cases also on the humidity absorbed by the paints. It is therefore usual to calibrate the whole technique with experiments on hemispheres for which the results are known.

The method suggested in [4] uses thin opaque coatings that melt at given temperatures and become clear liquids. In this case care has to be taken that the liquid does not flow along the surface with risk for accumulations that disturb the flow.

In the present paper the use of an infrared camera is described. The optical system of the camera contains an oscillating mirror and a rotating prism. It scans the object sixteen times per second. An InSb (indium–antimony) detector transfers the incident infrared radiation into an electric signal. On a special oscilloscope this signal is displayed as a picture (as in a television-set) and can be photographed. Temperature differences of 0·1 degC can be distinguished. As isothermals can be marked on the picture the instrument can be used to obtain quantitative data. As the motion of an isothermal is determined, the method works in principle in the same way as the paints described above and the difficulties encountered when relating the measured temperature increases with heat-transfer rates are the same in both cases.

In the present paper the application of the instrument to heat-transfer measurements in a hypersonic wind tunnel will be described and a simple solution for the window problem is given.

2. DESCRIPTION OF THE INFRARED CAMERA

As the camera was described in Swedish [5] and as it has been modified since then, a short description of the principle will be given here. A picture of the camera is shown in Fig. 1. An image of the field of view is formed by a spherical mirror with a 200-mm dia. A plane oscillating mirror and a rotating prism scan the field of view at high speed. They focus the infrared radiation from a small surface element of the field of view on a InSb detector. The detector converts the radiation signal into an electrical signal which is used to modulate the intensity of the beam in an oscilloscope. The vertical beam in the oscilloscope tube is synchronized with the position of the oscillating mirror in the optical system and the horizontal position is synchronized with the rotating prism. Each point in the optical field of view is therefore transformed into a corresponding point on the oscilloscope screen, the intensity of the beam being a function of the infrared radiation. A picture on the oscilloscope screen shows therefore the field of view with the warm parts bright and the cold ones dark. It is made up of 100 lines with an optical resolution of about 100 elements per line.

The InSb detector is cooled with liquid nitrogen and utilizes a wave length band between 2 and $5{\cdot}4 \times 10^{-6}$ m.

If quantitative results are needed, a certain level of infrared radiation focused on the detector can be marked on the oscilloscope screen. In the moment the signal reaches this preset level, the instrument adjusts the beam to maximum intensity, indicating the isothermal as a bright (or dark) line on the screen. The relation between the temperature of an object and the radiation focused on the detector depends on the emissivity of the surface of the object and on the losses of the intensity in the optical system. A calibration of the actual arrangement is therefore necessary. In the present case a thermocouple embedded in the wall was used.

If heat-transfer data have to be determined the position of an isothermal must be known as a function of time. This can be recorded with a 16 mm movie camera synchronized with the oscilloscope. The position can then be measured on the pictures.

In principle it is possible to use the video signal (the signal consisting of the picture signal

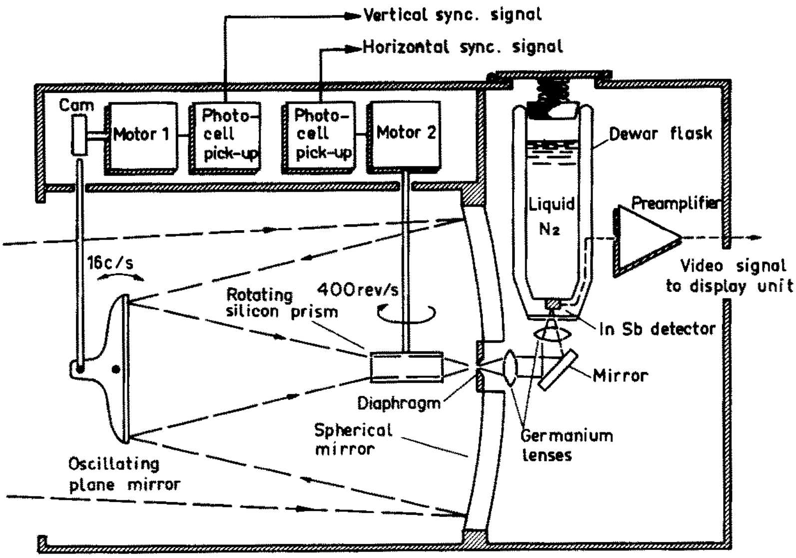

FIG. 1. Drawing of camera unit.

and the synchronizing signal) itself for the data reduction. This has the advantage that the detour over the optical system is avoided but needs, on the other hand, some development of additional electronic equipment before the data can be handled by a computer.

3. EXPERIMENTS AND DISCUSSION OF THE RESULTS

The experiments were conducted at $M = 7$ in a hypersonic blowdown tunnel with 12 bar stagnation pressure, about 600°K stagnation temperature and a test section diameter of 200 mm. The model investigated was a paraboloid. This shape was chosen as accurate measurements and theoretical predictions are available (see [6]). The model was cast with the technique described in [3]. General purpose RTV silicone rubber (Eccosil 4855, manufactured by Emerson & Cuming) was used and the geometry of the model is shown in Fig. 2. The model was mounted on an injection device which injected the model into the established flow field in about 0·05 s.

The following problems were encountered when using Thermovision.

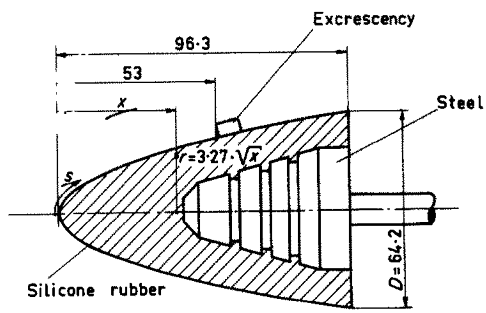

FIG. 2. Design of model (all dimensions in mm).

1. The windows of the tunnel were the main problem, as neither glass nor quartz can be used for the wave lengths for which the detector is sensitive. The simple arrangement shown in Fig. 3 worked very well. A thin plastic foil* is supported by a perforated force-carrying metal sheet. As the sheet is far away from the focal plane it only decreases the intensity without interfering with the optical quality of the picture. In the present case the foil had to support a pressure difference of about 1 bar. Holes of 8-mm

* Cryovac XL (0·025 mm thick), Åkerlund & Rausing AB, Postfack, Lund 1.

dia. were used. No difficulties due to heating of the foil were encountered, as the foil was far away from the hot jet boundary.

2. In a tunnel with hot parts, another effect must be observed. The intensity of the radiation falling on the detector is a combination of the energy radiated by the surface element itself and of the energy reflected by it. If the model is surrounded by hot parts, this reflected energy can be a considerable fraction of the energy emitted, even if the emissivity of most surfaces is close to unity for the actual wave lengths.

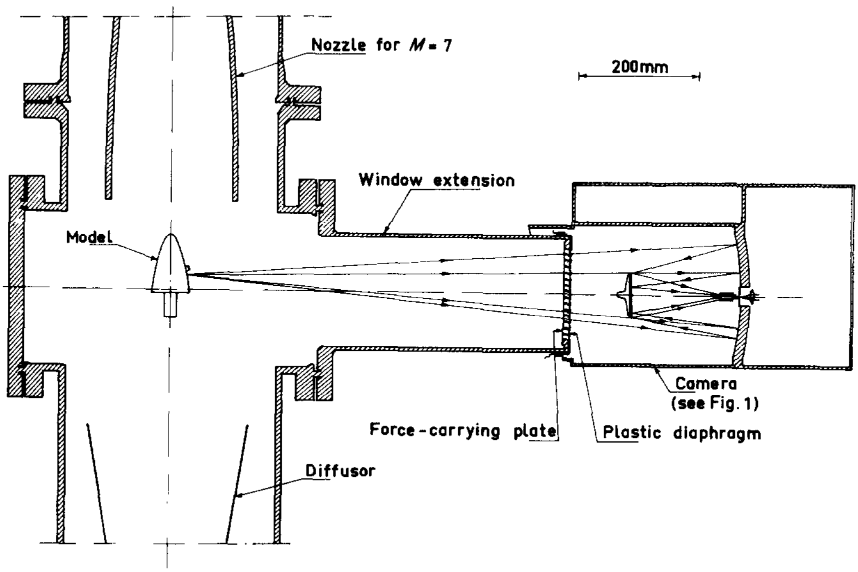

FIG. 3. Experimental arrangement.

In the present case the error introduced by this effect was negligible even after a running time of the tunnel of 2 min. This was checked by measuring the apparent model temperature with and without a cold radiation shield between the model and the hot parts.

3. With an ideal arrangement the shape and the location of the model are indicated by the isothermal between the hot parts of the model and the cold background. However, when an attempt was made to measure the location of the isothermal on the model some difficulties were encountered locating the position of the model on the picture. A typical set of pictures is shown in Fig. 4. The closed curve near the right side of the picture is formed by the isothermal across the model and the isothermal between the hot model and the cold background (see also Fig. 5). The curves on the left part of the picture are due to the hot regions formed on and around the excrescency. It is observed that the tip of the model seems to move relative to the edge of the picture and that the shape of the isothermal between the hot model and the cold background differs from the shape of the model shown in the first frame. This is due to the following effect. As explained in Section 2 the radiation of a surface element is focused on the detector and transformed into an electrical signal. Due to the optical arrangement this surface element can be considerably bigger (relative to the field of view) than the beam on the oscilloscope screen. In parts where the temperature distribution on the model and on the background is highly curved the average intensity (averaged over the surface element) will differ from the intensity radiated from the center of the element, and the spot on the screen indicating the isothermal will be

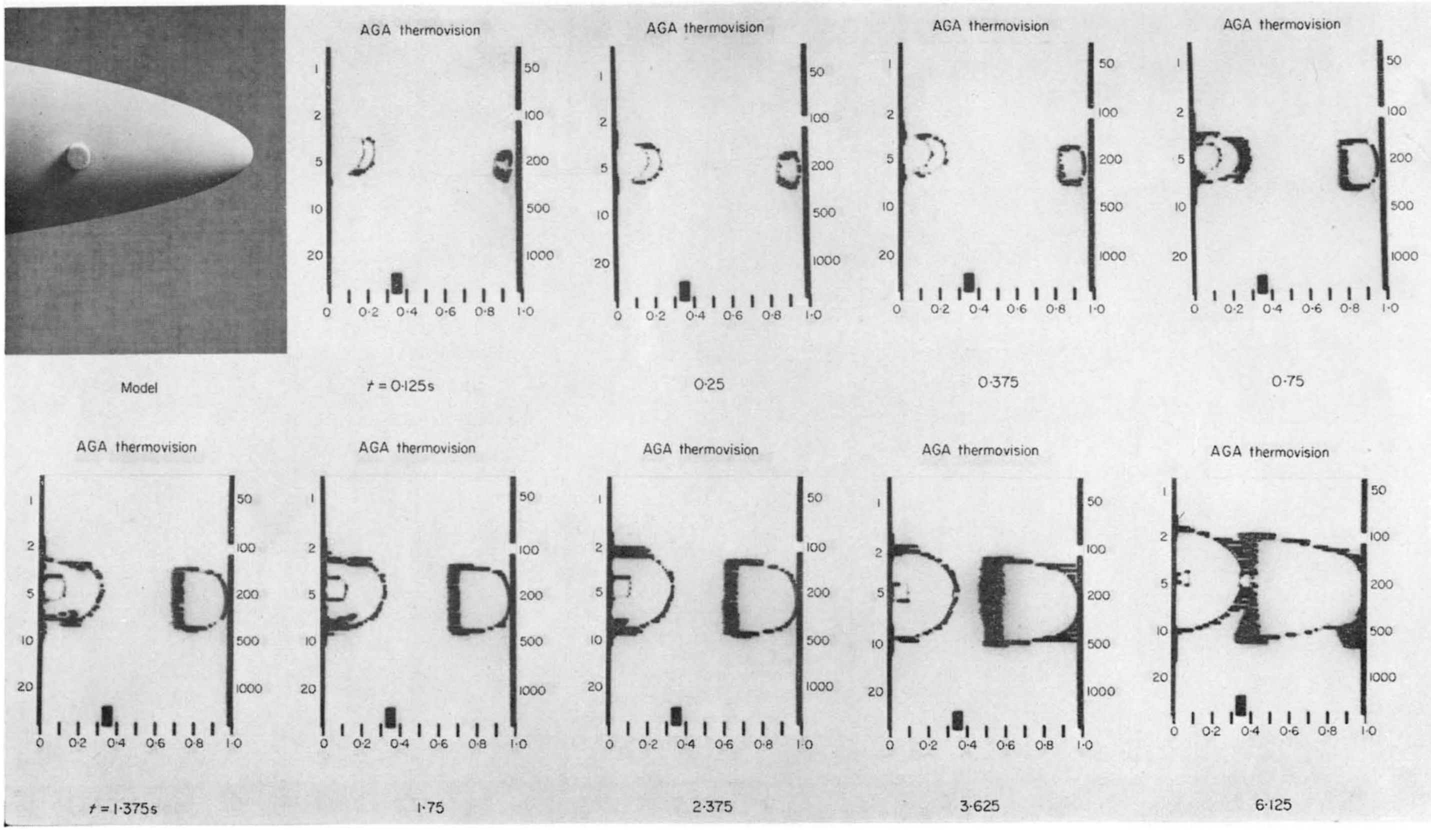

FIG 4. Picture of model and isothermals (to same scale).

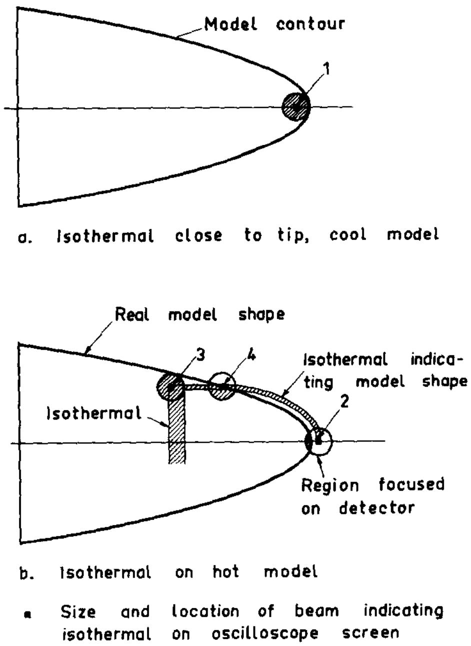

FIG. 5. Indicated location of isothermal, cold background.

displaced. This effect is most severe if the field of view contains parts of the hot model and of the cold background as demonstrated in Fig. 5. In the upper part, the temperature of the model tip is slightly bigger than the temperature indicated by the isothermal. The detector receives maximum intensity if the surface element indicated is viewed. The first isothermal will therefore appear in point 1. If the tip is very hot as in the lower part of Fig. 5 the small surface element sectioned will radiate enough energy and the isothermal will appear in point 2. In the same way the long horizontal isothermal adjacent to point 3 can be explained as the sectioned parts of the field of view in points 3 and 4 radiate essentially the same energy.

For the data reduction the size of the surface element viewed must therefore be known. It was measured by observing with the instrument two parallel hot wires. The beam was scanned normal to the direction of the wires. The video signal from the camera was directly fed into an oscilloscope. The intensity of the radiation focused on the detector was thus directly displayed as a function of the distance normal to the wires. With this intensity distribution the size of the observed surface element was determined. As expected, it depends on the distance of the element from the focal plane. This relation is shown in Fig. 6. For the experiment the camera was focused on the small excrescency on the model surface (see Fig. 2). Therefore, the centerline of the model was about 30 mm out of focus giving a diameter of the spot of about 8 mm. With this value the location of the model contour in Fig. 4 was determined and the location of the isothermal relative to the model could thus be determined.

As temperatures far below usual model temperatures can be measured, the present instrument is more sensitive than necessary. It should therefore be possible to decrease the size of the diaphragm in the camera (see Fig. 1) thus decreasing the distance between the model contour and the corresponding isothermal.

With the location of the isothermal known as a function of time the data reduction schemes described in [1–4] can be used to determine the heat-transfer rates. The present results were determined by comparing the measured temperature increase with the results predicted by the heat-conduction equation applied to a semi-infinite plane wall (see e.g. [4]). The initial temperature was determined with a thermocouple embedded in the wall close to the surface. A considerable error can be introduced into the result by the uncertainty of the physical properties of the wall material. The following values were used in the present case:

$$a = k/\rho c = 1{\cdot}4 \times 10^{-7}\ \mathrm{m^2/s},$$

$$k = 0{\cdot}29\ \mathrm{W/m\ ^\circ C}.$$

The figure for a is given in [3] and the figure for k is given by manufacturers of similar materials. With these figures the Stanton numbers shown in Fig. 7 were determined. They are defined in the usual way as

$$St = \frac{\alpha}{\rho_\infty u_\infty c_p}. \qquad (1)$$

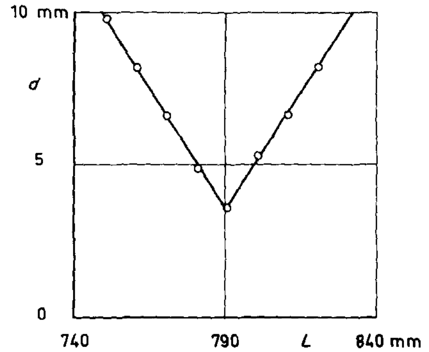

FIG. 6. Diameter of region focused on detector as function of distance from camera. Camera focused for $L = 790$ mm.

The good agreement between the two methods indicates a common source of error. At least parts of it are probably due to the uncertainty in a and k. If $a = 10^{-7}$ m^2/s is used, a figure mentioned in [7], the discrepancy is greatly reduced.

Another source of error that is difficult to take into account is the non-uniform wall temperature. This effect is minimized if isothermals close to the starting temperature are measured. In Fig. 7 no systematic variation of the Stanton number with the temperature of

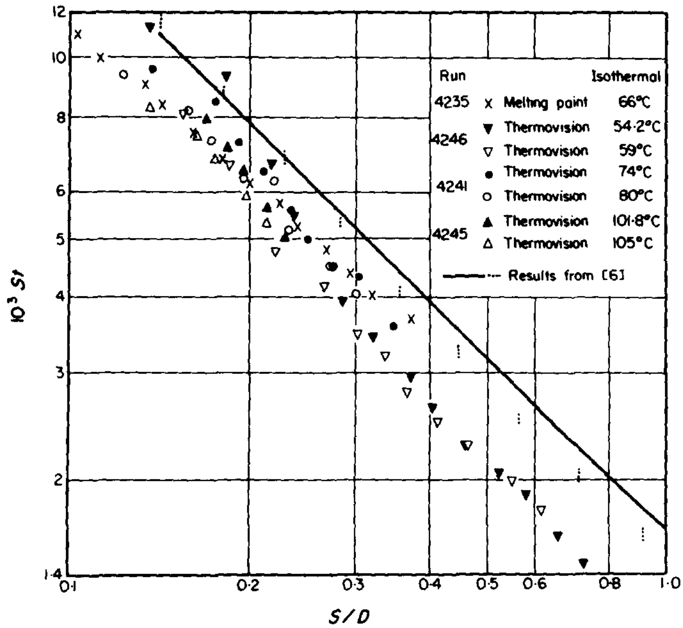

FIG. 7. Comparison of Stanton numbers determined with thermocouples, melting paint and Thermovision, $M = 7{\cdot}1$, $Re = 3{\cdot}2 \times 10^5$.

The results determined with the coating* that melts at 66°C agree very well with the Thermovision results. Both are about 30 per cent below the results from [6] which were reduced to the present conditions with the assumption $St \sim Re^{-0.5}$.

the isothermal can be seen which indicates that this effect is small.

If the heat-transfer coefficient α and the recovery temperature T_r are constant and if the physical properties of the wall material are independent of the temperature, the surface temperature of a semi-infinite plane wall is given by

$$\frac{T - T_i}{T_r - T_i} = 1 - \exp(-h^2 at)\operatorname{erfc}[h\sqrt{(at)}]. \quad (2)$$

* Tempilaq, manufactured by Tempil Corporation, 132 West 22nd Street, New York 11.

A convenient graph for the data reduction with equation (2) is given in [4].

During the initial part of the heating period the same relation can be used for a wall with a finite thickness X. If the backface of the wall is insulated α is overestimated by neglecting the effect of the finite wall thickness. The error is shown in Fig. 8. In the same figure the increase of the surface temperature is shown. It is seen that for big hX most of the temperature rise can be used for the data reduction without introducing large errors.

If the wall is supported by a metal core, the boundary condition at the backface of the wall is changed. In most practical cases α will be underestimated and Fig. 8 can only be used to indicate whether the wall thickness is critical or not.

4. CONCLUSIONS

In the present paper the use of an infrared camera for heat-transfer experiments in a hypersonic tunnel is described.

The method can be used to get a quick survey over the heat-transfer distribution on complicated shapes.

The accuracy is comparable to similar methods using temperature sensitive paint or melting coatings, but the present method is ideal if a great number of runs have to be performed, as the model need not be repainted between the runs.

With the present arrangement the isothermals are displayed on an oscilloscope screen but in principle it is possible to use the electric output signal directly and to reduce the data on a computer.

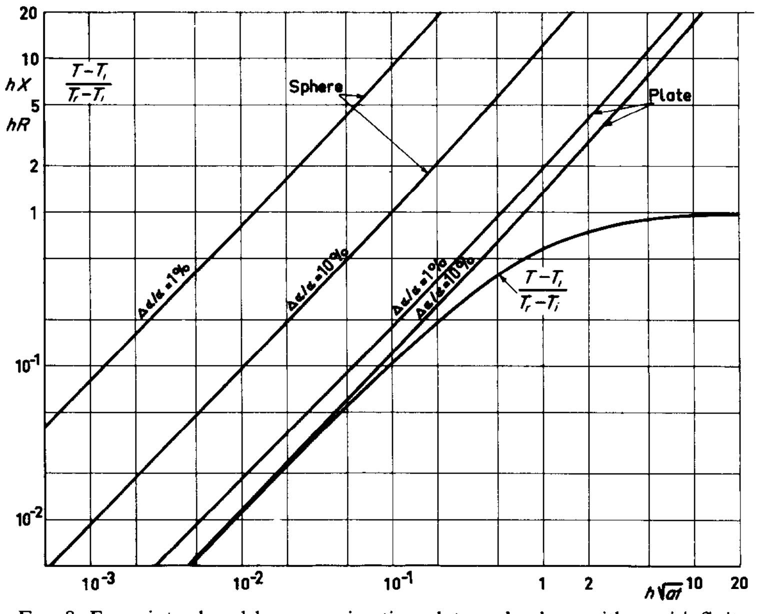

FIG. 8. Error introduced by approximating plate and sphere with semi-infinite plate.

The curves for the sphere were obtained by comparing results for a sphere with radius R with a plate with infinite thickness. They indicate therefore the range in which equation (2) can be used also for a sphere.

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Résumé—Dans cet article, on décrit l'application d'un appareil photographique infrarouge aux mesures du transport de chaleur dans une soufflerie hypersonique. La technique est reliée étroitement à celle qui utilise des peintures thermosensibles ou des revêtements fusibles. Les avantages principaux de la méthode actuelle sont : (1) la facilité d'emploi car la surface du modèle n'a pas besoin d'être recouverte de peinture, etc. ; (2) le même modèle peut être réemployé, aussitôt qu'il est refroidi ; (3) la surface du modèle est lisse ; (4) une bonne précision de la mesure de la température. On donne les résultats pour les mesures du transport de chaleur sur un paraboloïde à $M = 7$ et on les compare avec d'autres mesures. Un bon accord a été trouvé.

Zusammenfassung—Es wird hier die Anwendung einer Infrarot-Kamera auf Wärmeübergangsmessungen in einem Hyperschall Windkanal beschrieben. Die Technik ist eng verwandt mit jener der temperaturempfindlichen Farben oder schmelzenden Überzüge. Die Hauptvorteile der hier verwendeten Methode sind: (1) Leichte Anwendung, da die Modelloberflächen nicht mit Farbe behandelt werden müssen; (2) Dasselbe Modell kann nach Abkühlung wieder verwendet werden; (3) Glatte Modelloberflächen; (4) Gute Genauigkeit der Temperaturmessung. Ergebnisse werden für Wärmeübergangsmessungen an einem Paraboloid bei $M = 7$ wiedergegeben und mit anderen Messungen verglichen. Es ergab sich gute Übereinstimmung.

Аннотация—В данной статье описывается применение инфракрасной камеры для измерения теплообмена в гиперзвуковой аэродинамической трубе. Этот метод тесно связан с методом, в котором используются температуро чувствительные краски или плавящиеся покрытия. Основные преимущества данного метода состоят в следующем : (1) Метод прост в употреблении, так как не нужно обрабатывать краской поверхность модели и т.д., (2) эту же модель можно использовать вновь после её охлаждения, (3) гладкая поверхность модели, (4) хорошая точность в измерении температуры. Результаты приведены для измерения теплообмена на параболоиде при $M = 7$ и сравниваются с другими данными. Найдено хорошее соответствие.