Thermal scanning of curved surfaces

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SUMMARY. A **model based upon a dielectric interface has previously been used to describe the angular dependence of the emissivity, which is an important factor in the interpretation of anatomical thermograms.**

Previous experimental results have suggested that this model may not be generally applicable to clinical thermography. It is shown that if a term is included in this theory to describe the reflection of background radiation, it comes into closer agreement with experimental measurements. The magnitudes of other factors affecting the visibility of hot spots on curved surfaces are also considered.

Key **words:** infra-red **scanning, emissivity, curved surfaces, hot spots visibility.**

INTRODUCTION

The clinical application of thermography depends upon the ability to visualize hot areas on the skin. A scan is made of the infra-red radiation emitted by each part of the subject and a picture of the temperature distribution built up from this. The dependence of the skin emissivity upon the viewing angle of the emitting surface is an important factor in the interpretation of the thermograms from curved anatomical surfaces, but there is still some controversy about the magnitude of this effect and its consequent clinical importance. A model based upon a dielectric interface [5] indicated that the apparent temperature of a surface fell considerably when the angle between the normal and the direction of observation was greater than 65°, but, experimental measurements [2] suggested that such a decrease did not occur until an angle of' 85°. The validity of applying a theory modelled upon a smooth dielectric surface to skin is, therefore, in doubt.

THEORETICAL CONSIDERATIONS

In the previous work the reflection of background radiation from the oblique surfaces was not taken into account, and this would tend to compensate for any decrease in emitted radiation from oblique surfaces.

The dependence of the surface emissivity $\varepsilon_{\phi\lambda}$ for wavelength λ upon the viewing angle ϕ[5] is given by

$$\varepsilon_{\phi\lambda} = 1 - \frac{\sin^2(\phi-\chi)}{2\sin^2(\phi+\chi)}\left[1 + \frac{\cos^2(\phi+\chi)}{\cos^2(\phi-\chi)}\right] \quad (1)$$

and the reflectivity

$$\rho_{\phi\lambda} = 1 - \varepsilon_{\phi\lambda} \quad (2)$$

Consider the effect of this upon the radiation emitted and reflected from a surface, as shown in Graph 1.

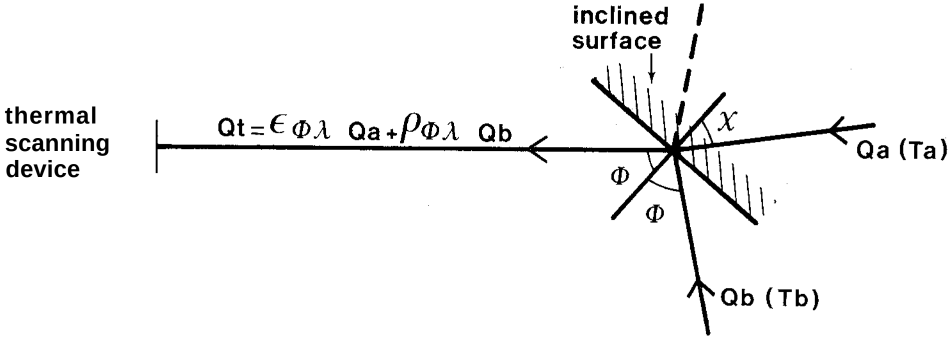
The radiant emittance for a grey body at temperature T, written in terms of Planck's radiation law is

$$\varepsilon_{\phi\lambda}\, Q_{A\lambda} = \varepsilon_{\phi\lambda}\, C_1 \lambda^{-5} \exp\left[-(C_2/\lambda T) - 1\right] \quad (3)$$

where C_1 and C_2 are constants. Now the level of radiation in a cavity resembles that emitted from a black body at the same temperature. So if the room in which the thermographic examination takes place is regarded as a cavity at temperature T_B, the level of radiation can be written as

$$Q_{B\lambda} = C_1 \lambda^{-5} \exp\left[-(C_2/\lambda T_B) - 1\right] \quad (4)$$

and the amount of radiation reflected from the surface being examined will be $\rho_{\phi\lambda}\, Q_{B\lambda}$. Thus, the total amount of radiation being emitted and reflected from a surface at angle ϕ will be



Graph 1. Detection of the radiation emitted and reflected from an inclined surface.

$$Q_{T\phi\lambda} = C_1 \lambda^{-5} \exp[-(C_2/\lambda T_B) - 1]\,[1 + \varepsilon_{\phi\lambda}(\exp[C_2/\lambda(1/T_B - 1/T)] - 1)] \quad (5)$$

The ratio of the amounts of radiation coming from similar surface at angle ϕ and at normal incidence will be

$$\frac{Q_{T\phi\lambda}}{Q_{T0\lambda}} = \frac{1+\varepsilon_{\phi\lambda}(\exp[C_2/\lambda(1/T_B - 1/T)] - 1)}{1+\varepsilon_{0\lambda}(\exp[C_2/\lambda(1/T_B - 1/T)] - 1)} \quad (6)$$

The scanner has no means of discriminating between emitted and reflected radiation or or between surfaces of different emissivities, so the radiation will be interpreted as emission from identical surfaces at temperatures T'_ϕ and T'_0, given by application of equation (3).

$$\frac{Q_{T\phi\lambda}}{Q_{T0\lambda}} = \frac{\varepsilon_\lambda\, C_1\lambda^{-5} \exp[(-C_2/\lambda T'_\phi) - 1]}{\varepsilon_\lambda\, C_1\lambda^{-5} \exp[(-C_2/\lambda T'_0) - 1]} = \exp[C_2/\lambda(1/T'_0 - 1/T'_\phi)] \quad (7)$$

Equating equations (6) and (7), and taking the logarithms, an expression for the fall in temperature with surface angle ϕ can be derived.

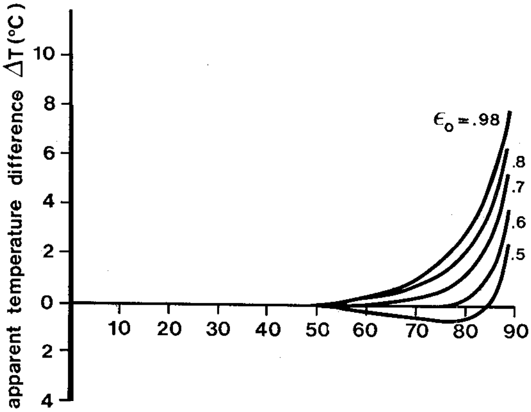
$$\Delta T = T'_0 - T'_\phi = \frac{T'_0 T'_\phi}{C_2} \lambda \ln \left[\frac{1+\varepsilon_{\lambda\phi}(\exp[C_2/\lambda(1/T_B - 1/T)] - 1)}{1+\varepsilon_{\lambda 0}(\exp[C_2/\lambda(1/T_B - 1/T)] - 1)}\right] \quad (8)$$

Values for this angular temperature degradation were computed with $C_2 = 1.4388$ cm° K, $T = 303°$ K $T_B = 293°$ K and $\lambda = 5\mu m$ for a selection of emissivity values. Initial calculations were made with $T'_0 T'_\phi = T^2$ and the approximate value for ΔT used to set $T'_0 T_\phi = T(T - \Delta T)$ in the final result. The curves illustrating the variation of ΔT with angle (Graph 2A), calculated from equation (8), show that the increase in the reflected radiation does tend to mask the fall in the emitted radiation. The apparent temperature of a surface at an angle of 75” is 2°C less than that at normal incidence, whereas if the reflected radiation were not present a similar fall in temperature would occur at an angle of 60” (Graph 2B).

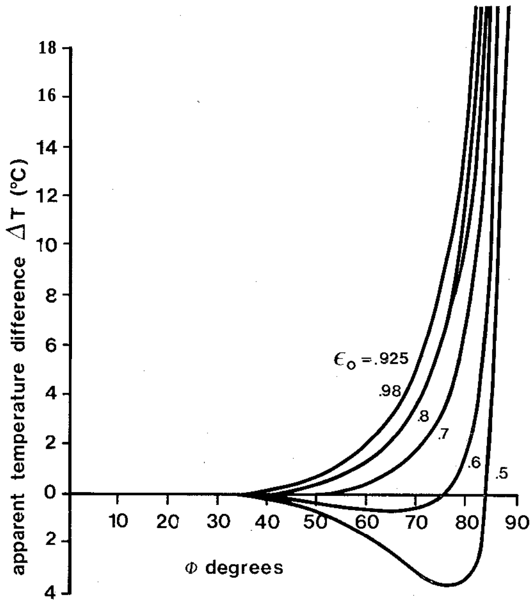
EXPERIMENTAL INVESTIGATION

To test the theory a flat-walled metal container with its outer surface coated with Leyland matt black paint was filled with water maintained at 41°C in a room at temperature 22°C. A black box was constructed around the apparatus to eliminate stray reflections and one surface of the container was positioned in the centre of the field of view at a distance of 40 cm from a modified Rank * Thermograph, which has an indium antimonide detector crystal sensitive over the 2 to 5.5µm wavelength range. The surface was then viewed normally and at angular increments and the apparent temperature levels recorded. The experimental results for ΔT agree fairly well with the theoretical curve plotted from equation (8) using values of $\lambda = 5\mu m$ and $\varepsilon = 0.93$ (Graph 3), so that the model does appear to be generally applicable to dielectric surfaces. The value of the emissivity was derived from the mean of measurements made on a number of matt black paints,' and the use of a single value for the wavelength λ does not create

* Rank Precision Industries, Brentford, Middlesex.

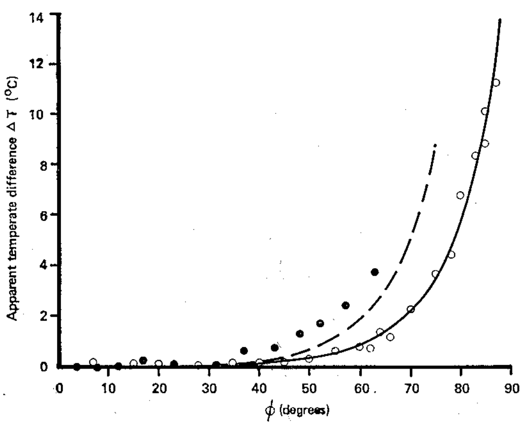


Graph 2A



Graph 2B

Graph 2. Curves showing the decrease in apparent temperature as a function of the angle of inclination of the surface ø, calculated for surfaces at a temperature of 303 °K in an environment at (A) 293 °K and (B) 0 °K.



Graph 3. Results for the decrease in apparent temperature with angle of inclination ø for a flat surface (0) and a cylinder (•); both at a temperature of 41 °C and in an environment at 22 °C and with surface emissivities of 0.93. The solid line is the theoretical curve for a flat surface, and the dashed line takes into account the variation in the viewing angle of the cylinder surface across the scanning field.

a serious error, for the angle ϕ at which the apparent temperature begins to fall rapidly varies by less than 1° for wavelengths in the range 2-5.5μm.

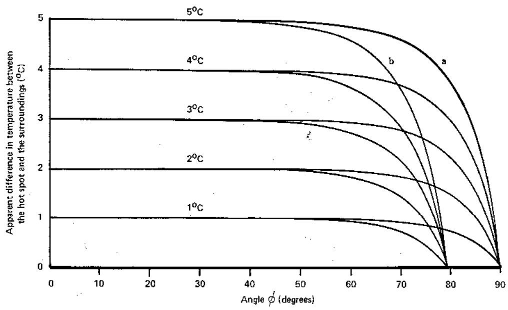
The apparent temperature of a hot spot will be determined largely by the amount of radiation emitted, but (Graph 2B) gives a false impression of the angle at which the visibility will begin to decline. The important factor here is the difference in temperature between the hot spot and its surroundings, both of which will appear to be cooler. To demonstrate this the apparent difference in temperature between hot spots of 1-5° and a background of 30°C which corresponds roughly to skin temperature, were computed for wavelength $\lambda = 5\mu m$., and an emissivity $\varepsilon =$ 0.98. In vivo measurements of the emissivity of human skin [6] suggest that the normal emissivity lies in the range $0.98 < \varepsilon_{n} < 1.00$ for wavelengths between 2 and 5.4μm., and a mean value of 0.975 over the wavelength range 4-18μn. was derived from measurements made on different physiological and pathological condition.4 The results (Graph 4), show that the magnitude of the hot spot does not begin to fall until the inclination of the surface is 70" and is only seriously degraded above 80°.

EMISSION FROM CURVED SURFACES

A flat plate bears little relationship to an anatomical surface, so to gain a better understanding of the effects in operation with curved surfaces, a cylindrical metal container of diameter 22 cm was used. The surface was coated with alternate vertical stripes of black and white matt paint with different emissivities which were 1.8 cm wide. The fall in the apparent temperature of the black strips with angle ϕ, observed when a single picture was taken of the container filled with water at 41°C occurred at a much lower angle than for the flat surface (Graph 3). The additional effects which come into operation are:

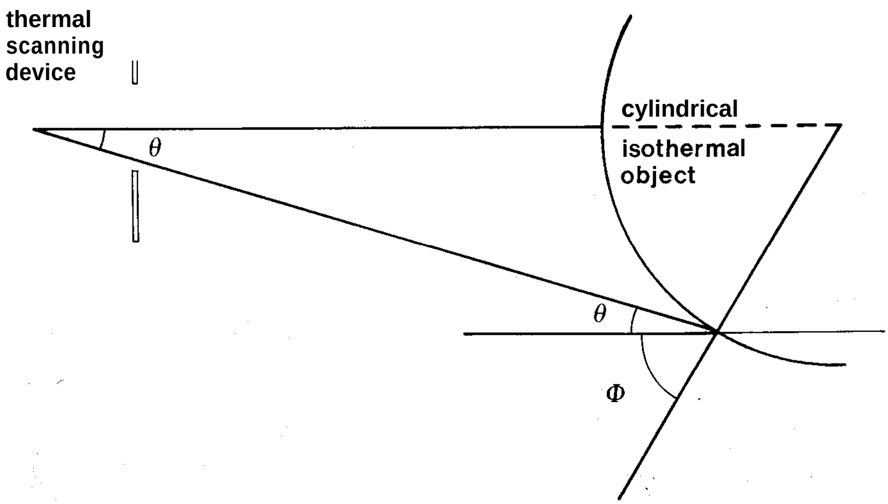
1. ϕ only represents the angle from which a surface is viewed if it lies in the centre of the field of view of the scanner (graph. 5). Surface towards the outside of the picture are inclined at a greater angle $\phi+\Theta$ to the actual direction of observation. This accounts for about half of the discrepancy between the results for the curved and flat surfaces (graph. 3). In the clinical situation the angle Θ would be about 10° for a point on the outer edge of a patient, so that the visibility of a spot in such a position would fall rapidly for $\phi > 70°$ (Graph 4).

2. As the angle of the surface increases, the width of the strips seen by the detector decreases. The picture is built up by the scanning of a point detector across the field, and the apparent temperature will only increase to a new level at a rate determined by the time constant of the detector and the associated electronic circuitry. When the scanner passes



Graph 4. The decrease in visibility with angle ø of hot spots of various magnitudes on a flat surface (a) in the centre and (b) on the edge of the field of view.

$T=30\,°C$, $T_B=20\,°C$,
$\varepsilon=0.98$, $\lambda=5\mu m$ and $\theta=10.6°$,



Graph 5. Detection of radiation off the axis of the scanner.

the front edge of a hot strip the signal will start to rise and after passing the rear edge it will start to fall again. As the width of the strips seen by the detector decreases at the larger angles of inclination, the time to scan across one strip will fall below the response time of the system, causing a further reduction in the apparent temperature of a hot spot. It has been shown that the apparent temperature of objects extending for less than one fiftieth part of the field of view is seriously degraded,3 which would mean that the apparent temperature of the 1.8 cm wide strips would be affected at angles greater than 60°. In the clinical situation a 2 cm hot spot would not be visible on outer surfaces of the body inclined at more than 60° to the direction of observation.

3. Another possible source of temperature degradation is the limited depth of focus available. This is difficult to quantify, but provided the system is focussed before use it should not be a serious drawback.

CONCLUSION

The predicted decrease in the radiation emitted from an inclined surface at larger viewing angles is partially masked by an increase in the amount of radiation reflected from the surroundings. Inclusion of this term brings the theory into close agreement with the experimental results for a plane surface, and shows that the apparent temperature of an object will only fall significantly when the angle of inclination $\phi > 75°$, for a surface with an emissivity of 0.98 similar to that of human skin. The visibility of a hot spot is determined by the intensity of the emitted radiation which begins to fall when ϕ is about 65°, and because the apparent temperature of both the hot spot and its surroundings decrease at similar rates, the temperature difference is only seriously degraded for $\phi > 80°$. However, the resolution of detail on surfaces inclined at angles greater than 75° is too poor to be clinically useful. In addition surfaces on the edge of the field of view are inclined at larger angles to the detector and this may decrease the actual angle at which surface detail is visible by a further 10”. Nevertheless, provided that oblique views are taken in thermographic examinations, the natural curvature of the anatomical surface should not prove a serious obstacle to the detection of thermal abnormalities.

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