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A Field Method for Determination of Emissivity with Imaging Radiometers

The method, in which measurement is done on a small hand-warmed sample of the surface under examination and incorporates a determination of ambient radiation, was tested on some emissivities at $\lambda = 5\ \mu$m.

Introduction

Thermal emissivity (by scientific convention properly called emittance) is the ratio of radiant power emitted by a surface to that of a blackbody at identical temperature. A blackbody radiator has emissivity equal to one whereas most natural materials and surfaces (e.g., soils, vegetation, and water) have spectral emissivities that can have much lower values. A knowledge of emissivity is necessary for determination of the absolute surface temperature radiometrically. Field methods of determining emissivity with simple non-

ety of surfaces is encountered in differing natural states, a need exists for a rapid, simple way to determine emissivity in the field. Emissivity values of natural features are desired also in aerial thermal sensing.

In the following a simple and quick method of measuring thermal emissivity of a surface in the field is described that can be used with a portable imaging radiometer that provides a means for sensing relative temperature levels within the image of an object (isotherm detection). The only instrument required besides an imaging radiometer is a thermometer (small probe-type is con-

ABSTRACT: *A simple method is presented for the determination of spectral emissivity (ϵ) in the field that is particularly applicable in thermography related to outdoor environmental work and energy studies. The method requires only a thermometer apart from an imaging radiometer that incorporates an image isotherm function. The measurement is done on a small hand-warmed sample of the surface under examination and incorporates a determination of ambient radiation. It takes a few minutes. The accuracy of the basic method is probably sufficient for common applications in the field but can be improved if signal video recording is available or an analysis of signal decay (cooling) is incorporated. A list is given of preliminary emissivity values determined by the method around $\lambda = 5\ \mu$m for some natural and artificial surfaces. The work was done using an AGA Thermovision T-750.*

imaging radiometers have been published, most recently by Rosenthal (Rosenthal, 1978). Imaging radiometers such as the AGA Thermovision system present new possibilities for determining emissivity because they provide (1) detail resolution, (2) an opportunity to study the dynamics of the often short-lived thermal events, and (3) means for practically simultaneous comparison of thermal states of several features. Because of the increasing use of imaging radiometers, particularly in thermal insulation studies and in environmental research conducted in the field where a great vari-

venient). Two people are necessary for making the measurement, one to read the instrument and the other to handle the object.

The instrument used in this study was an AGA Thermovision 750 System, henceforth referred to as AGA T-750.

Method

The method consists of heating up a sample of the object between the palms of clasped hands to the skin temperature and comparing the apparent

radiances of the skin, at known emissivity, and the object at known (the same as the skin) temperature and of unknown emissivity. The temperature can be measured by a small probe placed either inside the sample in the case of granular or soft materials or against the surface of hard objects. A small sample, e.g., 2 to 3 cm in diameter and 1 to 3 mm deep, is of sufficient size since the observation is done at close range, e.g., at 1-m distance. The temperature inside the hands clasping the object will gradually increase and in a few minutes level off somewhere in the 33 to 37°C range. This signals that the object and the skin are, practically, at the same temperature and measurement can be taken by opening the hands and quickly sighting the object first, because its temperature will fall-off faster than the surrounding skin of the palm. The measurement on the object will be taken within the first second or two, since significant heat losses can occur at the surface when the ambient temperature is more than 10°C below that of the human body. Reading on the surrounding skin does not have to be rushed. Its temperature will also drop upon uncovering but not as much as the object's. Experimentally, it is better to find the drop of the signal of the skin separately for given conditions and apply a correction to the reading. The measuring should be done in shade and out of the wind.

Quick sighting of the object is especially necessary when dealing with highly porous materials that have low thermal inertia such as dry soil, dry organic matter, insulating materials, etc. Care must be taken to maintain the natural state of dryness/wetness of the surface, which can be done, e.g., by placing a piece of aluminum foil between the object surface and the hand to prevent transfer of hand moisture to the surface.

Video taping of the signal eliminates the need for rushing the observations and should lead to an improvement in the accuracy of emissivity determination. However, even if video-recording is not available, the accuracy can still be improved by resorting to surface cooling analysis at a moderate cost of increased observational work. In this case a timed sequence of observations is taken, both on the object and hand surface, and, assuming simple Newtonian cooling, the signal values at zero time are calculated from these observations using statistical data reduction.

Figure 1 shows relative surface cooling (in terms of isotherm readings) of skin and a hand-warmed sample of concrete of three repeated data sets. The data follow an exponential decay. Correlation coefficients (r^2) indicate goodness of fit and experimental control.

EMISSIVITY DETERMINATION

In order to determine the emissivity values the instrument calibration, which gives the relationship between the instrument response to blackbody temperature, must be known. An average calibration curve corresponding to a given generation of detectors is usually supplied by the manufacturer, but when accurate results are desired or when special filters are used the instrument has to be calibrated. A calibration procedure used by this author which was suggested to him by Dr. G. Suits (Suits, 1978) consists in looking through the opening of a blackbody-simulating cavity made of copper sheeting in a two-cone mouth-to-mouth configuration. The blackbody is immersed in an insulated container filled with water at various known temperatures in the range of temperatures encountered during measurement. A calibration curve for the instrument used, an AGA T-750, equipped with a 4.8 μm cut-on filter is shown in Figure 2. The ordinate values, termed the absolute isotherm levels (q), are proportional to radiant power values predicted by Planck's radiation law.

In practice, to achieve optimal temperature discrimination at various thermal ranges, relative isotherm levels (i) are derived first which are then converted into absolute isotherm levels (q)
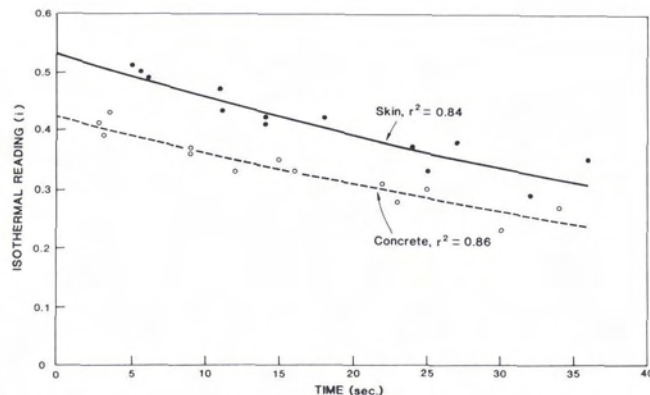

FIG. 1.　Relative cooling of skin and concrete from equal initial temperatures.
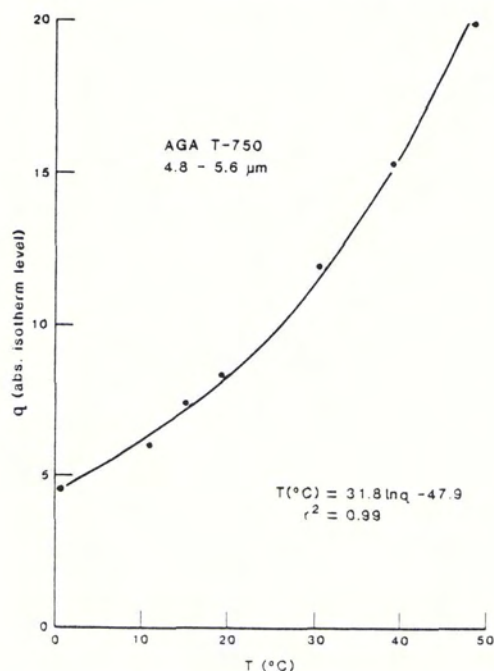
AGA T-750
4.8 - 5.6 μm

$T(°C) = 31.8 \ln q - 47.9$
$r^2 = 0.99$

FIG. 2.   Calibration curve.

through known skin temperatures (T_s), skin emissivity (ϵ_s), and range setting of the instrument.

The formula for emissivity of a surface can be derived from the basic observation equation (Equation 1), valid for any arbitrarily selected isotherm level. The equation recognizes both the emitted and reflected components of the radiation signal, that is,

$$\epsilon_o q_o + (1 - \epsilon_o)q_a = i + c \qquad (1)$$

where q_o and q_a are the absolute isotherm levels for the object surface and ambient radiation, respectively, c is a constant relating to the arbitrarily selected isotherm scale level, and ϵ_o is the object emissivity. The i-values are the isotherm scale readings multiplied by the instrument range used.

Writing Equation 1 for the surface of the skin (subscript s) and object (subscript o) the object emissivity (ϵ_o), remembering that $q_o = q_s$ by design, can be calculated from Equation 2, that is,

$$\epsilon_o = \epsilon_s + \frac{\overline{\Delta i_{os}}}{q_s - q_a} \qquad [2]$$

where Δi_{os} represents the average difference between the isothermal levels for the object and skin, which in turn is the average between the scale readings on the object and skin multiplied by the appropriate instrument range.

In Equation 2 the emissivity of human skin (ϵ_s) is assumed to be known from studies in medicine where thermography has found an important application (e.g., Elam *et al.*, 1963; Watmough and

Oliver, 1968; Steketee, 1973). Although not a full agreement exists among the researchers about its spectral variation, primarily because of the various experimental approaches used to determine it, there is a prevailing evidence that ϵ_s ($\lambda = 5$ μm) = 0.98 and not lower than 0.95 (Nudelman and Patton, 1980). We have attempted to measure palm skin emissivity with the aid of the blackbody reference mentioned earlier but were unable to obtain an accurate value because of the crudeness of our method and instrument instability, although an average of 0.97 was achieved. For the purpose of this paper ϵ_s ($\lambda = 5$ μm) = 0.97 will be used subject to correction of the emissivity values given when a more definite value is found. The value of q_s is derived from the palm temperature at the time of measurement and from calibration. q_a, which relates to ambient radiation, must be determined experimentally. One of the simplest ways consists of "zero-ing" the instrument by sighting liquid N which is used as the coolant for the InSb detector through the dewar opening, and reading q_a directly by sighting the surface of a suitable diffuser-reflector placed on the hand of the assistant in the same orientation as the sample that is being measured. We have found finely crinkled aluminum foil to be a suitable surface for this purpose, because high accuracy for this measurement is not necessary.

ERROR ANALYSIS

Accuracy of the emissivity determination depends on the accuracy of palm skin emissivity as well as on any systematic errors encountered during the measurement. However, the precision of the emissivity determination is, in the main, under the control of the experimenter, because it will depend on the choice of the parameters involved and the instrumentation available. The formal emissivity error variance derived from Equation 2 is given by Equation 3, that is,

$$\text{var}(\epsilon_o) = \text{var}(\epsilon_s) + 2(q_s - q_a)^{-2} \text{var}(i) + (\Delta i)^2 (q_s - q_a)^{-4} [\text{var}(q_s) + \text{var}(q_a)] \qquad [3]$$

It can be seen that, if the difference $(q_s - q_a)$ can be made numerically large, the contribution to the error by the last term in Equation 3 can be safely neglected even though the error in the determination of q_a could be quite large. Var(q_s) will usually be quite small. Practically, this means that for accurate results the ambient temperature should be 10°C or more below the body temperature, which is the usual situation in the field anyway. However, too low an ambient temperature will result in very rapid cooling of the surface upon exposure which might make it impossible to take a reading in time and thus lead to large systematic errors unless a cooling analysis is performed.

The main source of loss of precision will come from reading the isotherm scale on the AGA T-750

instrument as represented by var(i). For this reason, it is recommended to work with as small a range setting as possible, which in turn is possible only if the emissivities of the skin and the object are not too far apart. In my practice I have found that the emissivity between 0.9 and 1.0 can be determined quite accurately using the hand skin method. The accuracy will drop off progressively going to lower emissivities because of increasing values of var(i) due to the larger range settings necessary to accommodate the increasing apparent temperature differences. For practically all natural surfaces this method of using skin as an emissivity reference will be sufficient for $\epsilon_o > 0.80$. For $\epsilon_o < 0.80$ the same hand method can still be used but a lower emissivity reference should be employed. Rather than comparing relative radiances between object and skin, one would compare relative radiances between two objects, one of which will have known emissivity, or the hand could be covered by a lower emissivity material.

Inherent in the value of ϵ_o will be the inaccuracy in the reference emissivity, in our case the skin emissivity.

While the above formal error analysis indicates sources of variation than can be controlled by the experimenter, other sources of systematic errors, not included in Equation 3, could result from, e.g., the difficulty of attaining the condition of temperature equilibrium, the variation in skin temperature and perspiration from place to place, the effect of specular reflection component, and instrument signal drift. Even with great care high accuracy results cannot be expected under field conditions. However, knowledge of emissivity to a high degree of accuracy will rarely be utilized in natural environments because of often high temperature gradients existing within the surfaces being observed.

EMISSIVITIES OF SOME SURFACES NEAR $\lambda = 5\ \mu M$

Table 1 gives spectral emissivity values for some selected natural surfaces that were determined by the described method using an AGA T-750 whose spectral range was restricted by a cut-on filter at $\lambda = 4.8\ \mu m$. While the nominal sensitivity range of the detector extends to about $\lambda = 5.6\ \mu m$, it drops off rapidly toward the end of the range so that the emissivities given can be taken as representative of a narrow spectral band centered at $\lambda = 5\ \mu m$. In this region they represent values applicable to the first channel thermal scanner imagery.

What can be said about the reliability of the values? It can be seen that the standard errors of some emissivities are quite large. These are usually associated with material having low thermal inertia where an obvious difficulty existed with "catching" the initial temperature level as discussed earlier. A rather significant instrumental signal drift prevented carrying out a reliable temperature decay analysis so that the given values represent averages of three to six determinations based on only the initial sample-skin sightings. This, coupled with some uncertainty surrounding the exact value of skin emissivity, leads us to conclude that the given values should be regarded only as preliminary and crude estimates of the true values. More precise and sophisticated instrumentation should yield much improved results.

While the absolute accuracy of the values may be difficult to establish, their relative accuracies (their internal consistency) can be assessed. This can be done in two different ways. One way (Method 1) consists in "palming" two samples at once and observing their initial isotherm levels from which emissivity of one sample can be determined relative to the other by using Equation 2. Another way (Method 2) of verifying the relative magnitudes of emissivity values, which should yield accurate results when the surfaces are good diffusers of radiation, is to resort to measurement of reflectance (ρ) and derive the emissivity from the relationship $\epsilon = 1 - \rho$. This relationship between emissivity and reflectance, known as Kirchhoff's law, holds, theoretically, only under temperature equilibrium, which makes it difficult to exploit under field conditions. However, if two surfaces are perfect diffusers, their relative reflectances can still be determined by irradiating them with a suitable heat source and using the relationship in Equation 4 given in Vlcek (1978); that is,

$$\rho_o = \frac{\Delta i_o}{\Delta i_r} \rho_r \qquad [4]$$

where the subscripts o and r refer to the object and reference, respectively, and Δi represent the isotherm difference readings before and after irradiation. When the surfaces differ in their diffusive properties, considerable errors can result from this method.

To check the internal consistency of the given emissivity values Method (1), and Method (2) within its limitation, was used to compare most of the results presented.

Specific observations can be made about the emissivity values of the materials listed in Table 1. Spectral emissivity of natural materials such as soil appears to depend on the moisture content. As the soil approaches saturation point its emissivity approaches that of water. Sand appears to have higher emissivity than clay at $\lambda = 5\ \mu m$. This can be explained by a high quartz content in sand. Quartz was found to have emissivity practically equal to that of skin ($\epsilon = 0.97$). All dry organic materials containing cellulose fibres such as wood and paper appear to have much lower emissivities than inorganic materials. The cellulose base materials have low heat capacities and thus their emis-

TABLE 1. EMISSIVITIES AT $\lambda = 5 \mu m$ IN 33–37°C RANGE

Material (ω = % moisture content by weight	Origin & surface condition	Emissivity at $\lambda = 5 \mu m$	St. error of emissivity value
Loamy sand	glacio fluvial, forest nursery		
$\omega = 0.1\%$	glacio fluvial, forest nursery	0.94	±0.02
$\omega = 0.5\%$	glacio fluvial, forest nursery	0.95	0.03
$\omega = 1.0\%$	glacio fluvial, forest nursery	0.94	0.03
$\omega = 5.3\%$	glacio fluvial, forest nursery	0.96	0.02
$\omega = 6.0\%$	glacio fluvial, forest nursery	0.96	0.01
$\omega = 6.6\%$	glacio fluvial, forest nursery	0.95	0.03
$\omega = 11.2\%$	glacio fluvial, forest nursery	0.96	0.02
$\omega = 14.8\%$	glacio fluvial, forest nursery	0.96	0.02
$\omega = 21.7\%$	glacio fluvial, forest nursery	0.96	0.01
Clay-silt loam	glacio-lucustine forest nursery		
$\omega = 1.1\%$	glacio-lucustine forest nursery	0.93	0.04
$\omega = 1.3\%$	glacio-lucustine forest nursery	0.94	0.04
$\omega = 4.3\%$	glacio-lucustine forest nursery	0.93	0.02
$\omega = 7.0\%$	glacio-lucustine forest nursery	0.96	0.02
$\omega = 9.7\%$	glacio-lucustine forest nursery	0.93	0.03
$\omega = 14.8\%$	glacio-lucustine forest nursery	0.96	0.01
$\omega = 16.7\%$	glacio-lucustine forest nursery	0.96	0.01
Silt loam	forest nursery		
$\omega = 1.10\%$		0.92	0.02
Organic soil	nursery mixture 50% peat moss	0.89	0.04
Mulch	Cellulose base	0.84	0.04
Limestone	natural surface	0.94	0.02
Siltstone	natural surface	0.94	0.02
Granite	natural surface	0.96	0.02
Quartz	granular, horticultral grade	0.97	0.02
Plywood	commercial, smooth finish, dry	0.82	0.06
Filter paper	chemical (white)	0.94	0.05
Cardboard paper	box	0.84	0.05
White paper	Xerox copy type	0.83	0.05
Wood	polished spruce, dry	0.87	0.02
Wood	varnished	0.90	0.02
Wood paneling	light finish	0.88	0.03
Styrofoam	insulation type	0.60	0.05
Plastic	acrylic, new, shiny surface	0.96	0.02
Plastic	acrylic, sanded, opaque surface	0.93	0.02
Glass	chemical ware	0.96	0.02
Concrete	dry	0.93	0.02
Mortar	dry	0.92	0.02
Brick	masonry	0.90	0.02
Floor tile	asbestos type	0.95	0.02
Tape	electrical, insulating, black	0.96	0.02
Tape	masking	0.90	0.03
Rubber	stopper, black	0.96	0.02
Oil	motor	0.96	0.02
Paint	Krylon, ultra-flat black	0.96	0.01
Sugar	granular	0.96	0.01
Sandpaper	ordinary	0.95	0.03
Poplar leaf	upper side	0.95	0.02
(white poplar)	under side	0.89	0.07
Birch leaf	upper side	0.96	0.02
(white birch)	under side	0.92	0.03
Pine needles	red pine	0.96	0.02

sivities could be underestimated because of the rapid heat loss at the surface during measurement. For the same reason they have also the largest standard error associated with their emissivity values. Styrofoam insulation was found to have the lowest emissivity, $\epsilon = 0.60$. This values should be taken cautiously, (1) because of the previous statement regarding materials with low thermal capacities and (2) because the emissivity value is, in its magnitude, far removed from the reference

(skin) emissivity and results in loss of precision of measurement. The emissivity of living vegetative surfaces seems to approach the emissivity of water but is much lower for hair covered leaves. The pubescent layer acts as an insulator and its emissivity could be underestimated and, also, the hairs have a large content of cellulose.

The overall surprising finding about the emissivity values is that they appear to be quite high. This is either because most natural surfaces have higher emissivities at $\lambda = 5\ \mu m$ or the reference emissivity (skin) is overestimated. Accepting these high values of emissivity at $\lambda = 5\ \mu m$, and coupled with our observation of high sky radiation levels around that range which compensates to a degree for the losses of radiation due to emissivity by increased reflectance, should give better relative temperature values in the 5-μm atmospheric window than in the 10-μm window.

ACKNOWLEDGMENTS

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