International Journal of Thermophysics, Vol. 10, No. 2, 1989

Emittance of Bare Soil[1]

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The emittance of soils depends upon the moisture content, the porosity of the soil, the soil surface roughness, and the mineralogical properties of the soil particles. An attempt has been made to model the spectral emittance of soils in terms of these characteristics using deterministic and stochastic methods. For the general case of moist soil one must consider the fact that soil is basically a three-component system of air, water, and organic or inorganic material. For practical analysis using remote measurements one usually does not have knowledge of the relative amounts of each component. Thus, a stochastic model which specifies the emittance as functions of the statistics of the individual constituents seems to be the most reasonable practical approach for the analysis of soils. We have developed a stochastic model to represent the soil emittance in terms of probability distribution functions of the soil components. Also presented is a formula for soil emittance in terms of moisture content.

KEY WORDS: emittance; moisture content; radiation properties; soils.

1. INTRODUCTION

For naturally occurring materials such as soils, it is quite difficult to determine the basic optical and thermal properties. Even if one could systematically collect samples from specific, geographic areas, the sample would not necessarily be representative of the material in that region. There are too many factors involved which preclude our detailed knowledge of the pertinent optical and thermal data. In light of this complexity it seems that one should consider the statistical approach in order to ascertain meaningful properties of natural substances. Soil characteristics can be expressed in terms of means, variances, covariances, and probability distribution func-

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[1] Paper presented at the Tenth Symposium on Thermophysical Properties, June 20–23, 1988, Gaithersburg, Maryland, U.S.A.

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0195-928X/89/0300-0527$06.00/0

tions for emittances and other thermophysical properties rather than in terms of specific values. Therefore, a statistical or stochastic approach combined with some deterministic features seems justified.

2. SOIL COMPONENTS

2.1. *N*-Component Theory

Soil is a complex substance. It contains both organic and inorganic matter with various amounts of moisture and air. One approach in the analysis of soil emittance is to express the spectral-directional emittance as a weighted sum over all components. Thus,

$$\varepsilon(\hat{\Omega}, \lambda) = \sum_{i=1}^{N} X_i \varepsilon_i(\hat{\Omega}, \lambda) \tag{1}$$

where the weight factors sum to unity, and the $\varepsilon_i(\hat{\Omega}, \lambda)$ are the spectral-directional emittances for each of the components. For example, $\varepsilon_1(\hat{\Omega}, \lambda)$ could be the emittance of iron oxide, $\varepsilon_2(\hat{\Omega}, \lambda)$ the emittance of some organic matter, etc. Furthermore, let us assume that the emittances of the components are known, that is, they are the deterministic parameters in the analysis. What is *not* known, however, are the relative amounts of each component. The weight factors are unknown but one should be able to obtain reasonably reliable data on their statistics from soil surveys. Thus, we will assume that the X_i variables are stochastic, for which we do know their means and variances.

It is well known in statistics that if one has the sum of N random variables the probability distribution function (pdf) for the sum is given by the convolution of the individual pdf's of the components, i.e.,

$$p_\varepsilon(\varepsilon) = \frac{1}{\varepsilon_1} p_{x_1}\left(\frac{x}{\varepsilon_1}\right) * \frac{1}{\varepsilon_2} p_{x_2}\left(\frac{x}{\varepsilon_2}\right) * \cdots * \frac{1}{\varepsilon_N} p_{x_N}\left(\frac{x}{\varepsilon_N}\right) \tag{2}$$

It should be noted here that for simplicity, we assume that the individual components are uncorrelated.

The general prescription for solving this problem is straightforward; one merely calculates the Fourier transform of each component pdf, forms the product, and then takes the inverse Fourier transform to obtain the pdf of the composite distribution. Thus,

$$p_\varepsilon(\varepsilon) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\omega\varepsilon} \prod_{k=1}^{N} \Phi_{x_k}(\omega)\, d\omega \tag{3}$$

where $\Phi_x(\omega)$ is the Fourier transform of the kth distribution. If we take the beta distribution with the parameters m and n, then a transform $\Phi_x(\omega)$ is the following:

$$\Phi_x(\omega) = \frac{\Gamma(m+n)}{\Gamma(m)} \sum_{l=0}^{\infty} \frac{i^l \Gamma(l+m)}{l!\,\Gamma(l+m+n)} \omega^1 \tag{4}$$

It is immediately apparent that this procedure leads to mathematical difficulties. One would have to form the product of N functions such as those of Eq. (4) and then take the inverse transform. This is a formidable undertaking even if one uses a computer. The difficulty arises because we are taking the Fourier transform of a distribution function with finite limits. If we were to use, say, a Gaussian or a gamma distribution function, the mathematical difficulty would be eliminated. Unfortunately, we cannot use the distribution functions with infinite limits because they are not representative of emittances or reflectances which range from zero to one. It might seem as though one could use the Gaussian function and cut off the "tail" of the distribution to approximate the representation of emittance. However, that procedure is not valid because there would most likely be soil components with mean emittances near one and an arbitrary cutoff of the distribution would lead to considerable error.

2.2. Two-Component Model

Another approach which seems more fruitful is to consider a two-component system in which we assume that the emittances of the dry soil and the water are given by the beta distribution function.

$$f(x) = \frac{\Gamma(m+n)}{\Gamma(m)\,\Gamma(n)} x^{m-1}(1-x)^{n-1} \tag{5}$$

Of course the exponents do not have to be integers. Let us now write the emittance of damp soil as

$$\varepsilon = (1-S)\,\varepsilon_s + S\varepsilon_w \tag{6}$$

where ε_s is the emissivity of dry soil, ε_w is the emissivity of water, and S is the saturation. The last quantity is defined as

$$S = \frac{V_w}{V_w + V_a} \tag{7}$$

where V_w is the volume of water and V_a is the volume of air in some total volume V of soil that contains dry soil, water, and air. The saturation varies between zero and one. If we represent the dry soil by a beta distribution with exponents m and n, and water with exponents p and q, then the composite distribution function of damp soil is

$$f_\varepsilon(\varepsilon) = \frac{1}{S(1-S)} \int_a^b f_{\varepsilon_s}\left(\frac{\varepsilon - t}{1-S}\right) f_{\varepsilon_w}\left(\frac{t}{S}\right) dt \tag{8}$$

where the limits a and b are determined by examining the magnitude of S with respect to the emittance ε. The composite distribution is

$$f_\varepsilon(\varepsilon) = C \int_a^b z^{p-1}(x-z)^{m-1}\,(1-z)^{q-1}\,(y+z-1)^{n-1}\,dz \tag{9}$$

with

$$C = \frac{\Gamma(m+n)\,\Gamma(p+q)}{\Gamma(m)\,\Gamma(n)\,\Gamma(p)\,\Gamma(q)}\,\frac{S^{m+n-2}}{(1-S)^{m+n-1}} \tag{10}$$

and

$$x = \frac{\varepsilon}{S}; \qquad y = \frac{1-\varepsilon}{S}; \qquad z = \frac{t}{S} \tag{11}$$

where x, y, and z are finite for all values of S between 0 and 1. For exponents other than integers the integral in Eq. (9) must be performed numerically. Even for relatively small values of m, n, p, and q, it is quite a task to evaluate the integral. We illustrate the distribution functions for the simple case when $m=5$, $n=3$, $p=3$, and $q=2$ in Fig. 1 for $S=0$, and in Fig. 2 for $S=0.1$, 0.2, and 0.3.

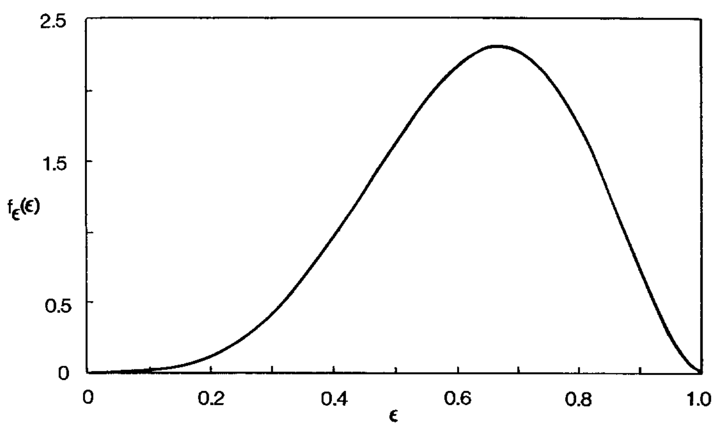

Fig. 1. Composite distribution function, expressed by Eq. (8), for soil with zero saturation.

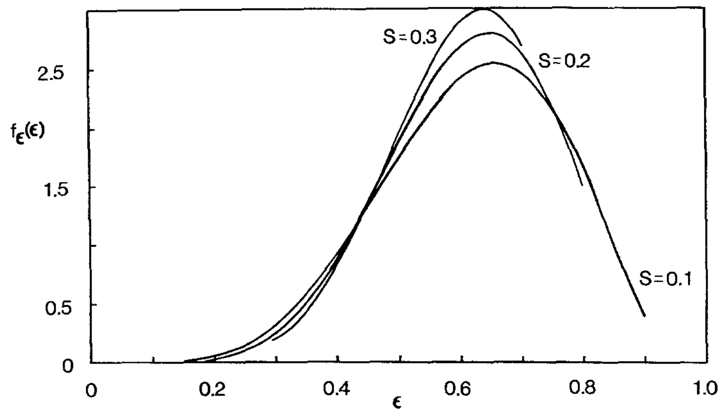

Fig. 2. Composite distribution function, expressed by Eq. (8), for soil with three levels of saturation.

3. SOIL MOISTURE

As given by Swain and Davis [1] the emittance of soil increases with an increase in the moisture content, at least in the visible and infrared parts of the spectrum. Soil moisture is difficult to define in terms of its stratification within the soil. A brief, light rain may wet the surface and subsequently cause a pronounced change in the emittance which is primarily a surface feature. A heavy rain will allow water to penetrate to the lower part of the soil and give a high measure of soil moisture, whereas in reality the moisture that affects the surface emittance could be negligible, as a result of evapotranspiration and wind evaporation.

As pointed out by Hoffer and Johannsen [2], kaolinite clay, bentonite, and muscovite have strong water absorption bands even when only 0.1% moisture exists. This fact indicates that the strongly bound water in clay-like soils has a strong influence on reflectance and emittance. As a result, sandy soils have little of the bound water that is present in clay soils and the sandy soils therefore produce fairly uniform reflectance or emittance curves without the obvious water absorption bands.

Shockley et al. [3] provide data on the influence of soil moisture and bulk density parameters on reflectance of soils in the infrared region from 1.4 to 5.0 μm. Soil samples were also measured by Bowers and Hanks [4] and the results show that the surface moisture content, organic material, and particulate size strongly affect the reflectance. We have taken their data for a wavelength of 2.25 μm and calculated the emittance from the reflectances. The results are depicted as a function of soil moisture by the solid curve in Fig. 3. The data seem to follow a linear relationship for small S but clearly deviate as the emittance increases to the water emittance as S

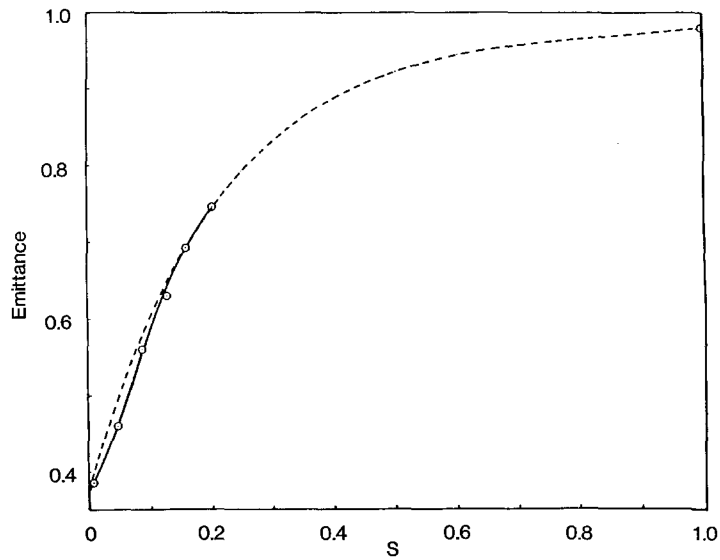

Fig. 3. Emittance of Newtonia silt loam as a function of soil moisture at a wavelength of 2.25 μm according to data from Bowers and Hanks [4] (solid curve) and a curve (dashed) to pass through the points $S=0$, 0.202, and 1.0.

approaches one. We have generated a simple curve to pass through the data points for $S=0$, 0.202, and 1.0, i.e.,

$$\varepsilon(S)=\varepsilon_w\left[\frac{1-e^{-kS}}{1-e^{-k}}\right]-\varepsilon_s\left[\frac{e^{-k}-e^{-kS}}{1-e^{-k}}\right] \tag{12}$$

where $\varepsilon_w=0.98$, $\varepsilon_s=0.375$, and $k=4.616$. Using these numbers we obtain the equation

$$\varepsilon(S)=0.98605-0.61105e^{-4.616S} \tag{13}$$

The equation indicates that soil emittances follow an exponential law for moisture. We suggest that experiments be performed on soil emittance and reflectance to validate this simple model. It must be realized, however, that the emittance, at least in the infrared region, is highly dependent upon conditions in the first few millimeters of the soil. Thus, any soil moisture measurement must take into consideration the probable variation in soil moisture with depth.

4. CONCLUSIONS

It has been demonstrated that one can express the spectral emittance of soils using a stochastic representation of the moisture content. The beta function representation for the distribution function for emittance is useful because emittances vary between zero and unity. Given the statistics of soil samples, one can then generate realistic distribution functions for the spectral emittance. We have also developed a scaling relation for the spectral emittance of soils explicitly in terms of the saturation and compared the model calculations to experimental data. The results clearly indicate the dependence of infrared soil thermal emittance on soil saturation levels. Further analysis should lead to similar expressions of emittances as a function of moisture content for other spectral regions.

ACKNOWLEDGMENT

The author wishes to acknowledge the support of this work by the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

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Printed in Belgium