

An indirect skin emissivity measurement in the infrared thermal range through reflection of a CO₂ laser beam

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Recibido el 7 de mayo de 2009; aceptado el 25 de septiembre de 2009

An indirect procedure to measure human skin emissivity is proposed. This procedure uses a 10.6 μm CO₂ laser, to project a controlled energy on the skin, and a power meter to measure the projected, reflected, emitted and background energies. To eliminate the effects of background radiation, two power measurements are taken: one of the skin and background emission and another that includes the skin emission itself, the background radiation, as well as the reflection of the laser beam by the skin. Those two measurements are subtracted to obtain the reflected energy and, with this, the corresponding reflectivity of the skin. With such subtraction, background and other sources of noise are eliminated, and using the Kirchhoff law the emissivity is calculated. The emissivity values obtained with this procedure were corroborated using a theoretical blackbody. Both methods give practically the same values, which validates our procedure. In addition, our values are in accordance with those previously reported by other researchers, but our procedure is simpler, faster and innocuous. An additional contribution of this work is the analysis of the way the skin reflects the infrared radiation, in the mid range. It was found that the reflection of the skin is more specular than Lambertian, for the wavelength that was used in this work.

Keywords: Skin emissivity; skin reflection; skin reflectivity; emissivity without blackbody; Lambertian surfaces.

En el presente trabajo se propone un procedimiento indirecto para medir la emisividad de la piel humana. Este procedimiento usa un láser de CO₂ de 10.6 μm para proyectar una energía controlada sobre la piel, y un radiómetro para medir las energías proyectadas, reflejadas, emitidas y de fondo. Para eliminar la influencia de la radiación de fondo, se toman dos lecturas con el radiómetro: una que incluye la energía de la piel y la emisión de fondo y otra inmediatamente después que incluye la energía de la piel, la radiación de fondo, y la reflexión de la piel. Se obtiene la diferencia de esas dos mediciones para obtener la energía reflejada y, con esto, la reflectividad correspondiente de la piel. Al obtener la diferencia, la radiación de fondo y otras fuentes de ruido se eliminan, y usando la ley de Kirchhoff la emisividad es calculada. Los valores de emisividad obtenidos con este procedimiento fueron corroborados con el método directo usando un cuerpo negro teórico. Ambos métodos arrojan prácticamente los mismos valores, lo cual valida nuestro procedimiento. Adicionalmente nuestros resultados están acordes con aquellos obtenidos por otros investigadores, pero nuestro procedimiento es más simple, más rápido e inocuo. Una aportación adicional de este trabajo, es el análisis de la forma en que la piel refleja la radiación infrarroja en el rango medio. Se encontró que la reflexión de piel en esta longitud de onda es más especular que Lambertiana.

Descriptores: Emisividad de la piel; energía de la piel; reflectividad de la piel; emisividad sin cuerpo negro; superficies Lambertianas.

PACS: 78.20.Ci; 06.20.Jr; 92C50

1. Introduction

Characterization of surfaces like the human skin with optical devices in the thermal infrared range is strongly influenced by the emissivity of such surfaces, since emissivity is a measure of surface radiation (and absorption) efficiency [1]. For example, skin temperature may be incorrectly varied or mistakenly recorded, when non-contact thermometers or IR cameras are used, due to erroneous emissivity considerations [2-5]. Madding has emphasized the fact that measurement of temperatures or temperature differences with thermography is not possible without a precise knowledge of the target emissivity [2].

Human skin emissivity depends on many parameters: temperature, moisture, fat, contamination, and roughness especially on the spectral range considered for the measurement [4,6-9].

Emissivity measurements can be done directly or indirectly [3,10,11]. The most common and preferred direct method uses the ratio of the energy emitted by the body under

study to the energy emitted by a blackbody at the same temperature. In spite of the simplicity of this procedure, a blackbody represents many practical disadvantages that limit the accuracy of the corresponding measurements [12-14]. The most important inconvenience may be the differences between any practical blackbody and the ideal blackbody.

Indirect methods avoid using a blackbody and apply equations such as the Kirchhoff law. In such methods a given energy is projected on a surface and, considering the transmitted, reflected, and absorbed energies, the emissivity can be computed through previous computations of transmissivity, reflectivity, and absorptivity [15-20]. Most researchers have preferred indirect methods that make use of the Kirchhoff law [15-20], but others have used techniques based on periodic radiometry [4,10], which involve multifrequency modulation of the front-side temperature of the sample and consideration of two measurements that yield a two-equation system that, in turn, enables one to compute emissivity [10,15].

Steketee [7] used an original setup based on a monochromator and a selector serving as sensor of the energies emitted by the skin, and a rudimentary blackbody as reference. He reported a skin emissivity of 0.98 ± 0.01 in the range from $3 \mu\text{m}$ to $14 \mu\text{m}$, concluding that skin pigmentation does not affect that value, a statement supported by Jones and Plassmann [21].

Togawa [15] estimated the skin emissivity based on reflectivity measurements upon a transient modulated stepwise change in ambient temperature, using two hoods at different temperatures which were switched by a relatively hazardous mechanism. He reported a skin emissivity on the back of the hand of 0.972 ± 0.004 for $8 \mu\text{m}$ to $14 \mu\text{m}$.

Togawa and Saito [22], using the same setup, but with an infrared camera instead of a radiometer, acquired images to compute the changes of energy before and immediately after switching the hoods. From those images, an emissivity measurement was done. However, the obtained emissivity images and the thermal parameter that they defined contained significant amounts of noise.

Although most researchers have obtained values of skin emissivity similar to ours, we think that our procedure is simpler, easier and faster to apply, allowing for the analysis of the emissivity behavior for specific wavelengths, or within a wide wavelength range with the simplicity of only changing the "illumination" source.

Given that non-invasive procedures for medical diagnosis using infrared thermography have become common practice [22-26], we considered it convenient to propose a new procedure for indirect emissivity measurements, which permits reliable measurements at specific wavelengths. To corroborate the results obtained with the proposed method, the human skin emissivity was computed using the direct method through the theoretical calculation of the ratio between the energy coming from the skin and the energy emitted by a blackbody at the same temperature.

2. Theory

The human skin in thermodynamic equilibrium at a given temperature T emits radiation in all directions into a given hemisphere [9,27]. This radiation is affected by its emissivity (ε), since emissivity is part of the superficial properties of a body which within the infrared thermal range depends on temperature and on superficial characteristics such as moisture level, roughness, and the presence of fat [4,15,22,28].

Human skin radiance, or observed intensity, in the infrared thermal wavelength range ($8 \mu\text{m}$ - $14 \mu\text{m}$) is not a function of direction [23]. That is, skin behavior is similar to a Lambertian radiator [27,29]. However, when the skin is acting as a reflector its behavior is not completely Lambertian. The skin shows a rather specular behavior, as will be shown below.

As already mentioned, emissivity can be measured directly or indirectly. An indirect measurement can be made using the Kirchhoff equation, when a controlled energy is

projected on the skin, allowing for the computation of the reflected, transmitted, and absorbed energies. Considering that the non-absorbed energy falling on the skin can only be reflected (because transmission is not possible due to the thickness and properties of the human skin and neighboring tissues), and that, in this case, the absorption is mathematically equal to the emissivity [3,8,9]; once reflectivity (ρ) has been calculated using the amount of reflected energy ($M_{reflected}$) and the amount of projected energy ($M_{projected}$) through the equation

$$\rho = \frac{M_{reflected}}{M_{projected}}. \quad (1)$$

The emissivity can be obtained applying Kirchhoff's law, which for surfaces like the human skin is given by

$$\varepsilon = 1 - \rho. \quad (2)$$

With the aforementioned procedure, the emissivity of the skin can be computed for any wavelength of interest as long as the required source to "illuminate" the skin is available. For a specific wavelength, a laser beam is probably the best option.

On the other hand, the direct skin emissivity measurement is commonly made by calculating the rate of the energies emitted by the skin [$M_{skin}(\lambda)$] and by a blackbody [$M_{BB}(\lambda)$] [1,8,9,28], both being at the same temperature. Then, the hemispherical spectral emissivity of the skin in terms of the involved wavelength $\varepsilon(\lambda)$ is given by

$$\varepsilon(\lambda) = \frac{M_{skin}(\lambda)}{M_{BB}(\lambda)}, \quad (3)$$

and the total hemispherical emissivity can be obtained with the equation

$$\varepsilon = \frac{M_{skin}}{\sigma T^4}, \quad (4)$$

where σ is Boltzmann's constant and T is the temperature of the skin.

In practice, $M_{BB}(\lambda)$ is recorded directly from a blackbody; however it is possible to compute the equivalent blackbody energy using Planck's equation for the same characteristics of the skin, spectral wavelength range, and responsivity of the detector used, as follows:

$$M_{BB}(\lambda, T) = r \cdot \frac{C_1}{\lambda^5} \left(\frac{1}{e^{\frac{c_2}{\lambda T}} - 1} \right) \left[\frac{W}{m^2 \cdot \mu\text{m} \cdot sr} \right], \quad (5)$$

where

$$c_1 = 2\pi hc^2 = 3.7418 \times 10^{16} \text{ W/m}^2 \mu\text{m}$$

and

$$c_2 = \frac{hc}{k} = 1.4388 \times 10^2 \mu\text{m} \cdot K;$$

T is the temperature of the skin, r is the detector responsivity

In addition to correctly calculate M_{skin} it is necessary to take into account the solid angle subtended by the skin area

and the detector area to then integrate this energy in the hemisphere where the energy is emitted (due to the Lambertian behavior of the skin as emitter).

On the other hand, to correctly calculate $M_{reflected}$, considering the partial specular behavior of the skin when acting as reflector in the middle range of the infrared (as corroborated in this work), it is necessary to consider the part of the hemisphere where the energy is being reflected.

Finally, to calculate the energy (E) from digital images, in terms of gray levels, the discrete form of the following equation can be used [3]:

$$E = \int \int_{-\infty}^{\infty} E = I^2(x, y) dx dy, \quad (6)$$

where I represents the intensity (or grey level) of the image and (x, y) represents the position of a given pixel.

3. Materials and methods

The proposed procedure was tested with the participation of 32 volunteers who were previously informed about the conditions and safety of the test. They were instructed not to apply any kind of substance (creams, lotions, etc.) on the skin of the back of their hands.

To measure the skin temperatures of the participants, a Fluke 52II thermometer (Fluke Corporation Everett, Washington), with a type K thermocouple, and a Fluke 68 IR thermometer (Fluke Corporation Everett, Washington) were used, both with a resolution of 0.1°C .

A $10.6 \mu\text{m}$ Synard CO_2 laser (Synard Inc. 4600, Campus Place Mukilteo, WA, 98275, USA) was used to project a controlled amount of energy on the skin of the back of the hands of the participants for less than 3 seconds. The energy reaching the skin was maintained at 350 mW and measured with a Field Master Coherent power meter (Coherent Inc. 5100 Patrick Henry Drive Santa Clara, CA 95054 USA), which has a detecting area of 2.84 cm^2 , and is sensitive from $0.3 \mu\text{m}$ to $10.6 \mu\text{m}$. The optical setup used is shown in Fig. 1.

The distance from the laser to the hand was 3.5 m. An adjustable shutter was used to control the time of exposition. The distance from the skin surface to the detector was 4 cm. The hand of each participant was positioned so as to form an angle of 70° with respect to the incident beam, and the detector surface formed an angle of 140° , also with respect to the incident beam. With those settings a maximum of reflected energy was captured.

To determine the positions of the hand and the detector in such a way as to capture the maximum reflected energy, the rotary setup shown in Fig. 2 was used. To analyze the behavior of the reflected energy by the skin we used a SATIR infrared camera, model S280 (Guangzhou SAT Infrared Technology Co., LTD, PR, China), sensitive between $8 \mu\text{m}$ and $14 \mu\text{m}$, with a spatial resolution of 1.3 mrad, and thermal sensitivity of 80 mK at 30°C . The camera was set as follows:

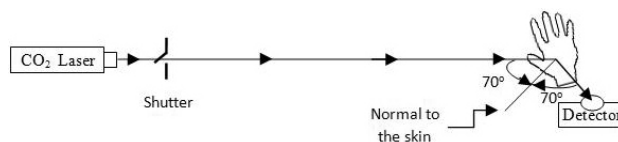


FIGURE 1. Diagram of the experimental setup used to measure the skin emissivity.



FIGURE 2. Experimental setup used to analyze the behavior of the skin reflection.

emissivity at 1.0, temperature level 34°C , $\text{spam} \pm 16^{\circ}\text{C}$, ambient temperature at 22°C , and work temperature range from -40 to 160°C .

For the analysis of the reflection of the infrared laser by the skin, the angle between the camera and the skin surface was varied from 20 to 180° (in steps of 10°) while the laser beam was projected forming an angle of 70° with respect to the skin surface. To eliminate the effects of background and other noise sources, two images were taken for each angle: First, an image including the skin and background energies was acquired. Immediately after the first image was acquired, a laser beam was projected on the skin and a second image, including the skin, background and reflected energies was acquired. These two images were then subtracted so that the resulting image contained only the reflected energy in terms of gray levels, which was calculated using Eq. (6).

Several tests were needed to determine an appropriate level for the intensity of the laser beam to avoid damage of the skin and, at the same time, to obtain useful data. It was found that a beam of 350 mW, applied during three seconds, was necessary to obtain a good reading in the radiometer, however if a more sensitive sensor is used this energy can be reduced. For example, using an infrared camera as a sensor for the setup of Fig. 2, less than 30 mW can be adequate. However, in that case image calibration is required.

In summary, the proposed procedure to measure the skin reflection and thus the skin emissivity consisted of two measurements with a radiometer. As mentioned in the previous description, the first measurement that included the skin and background energies was done as described in Fig. 1, but

without the laser beam. Immediately after the first measurement, the laser beam was projected on the skin and the second measurement was done, again, as described in Fig. 1. This time, the measurement included the skin, background, and reflected energies. It is clear that the difference of those two measurements includes only the energy reflected by the skin. So, knowing the amount of energy that was projected on the skin, it is possible to calculate the reflectivity using Eq. (1), and in turn the corresponding emissivity with Eq. (2).

4. Results

Once infrared images were acquired using the setup shown in Fig. 2, and the Eq. (6) was used to calculate the corresponding energies. Then, energies in gray levels were normalized. As can be seen in Fig. 3, the magnitudes of the energies reflected by the skin are a function of the angle of incidence. In Fig. 3, it is clearly shown that the maximum reflection of the skin occurs at 70° , which corresponds to the angle of reflection of a specular surface, since the angle of incidence is precisely the same. This finding was used for the final adjustments of the setup shown in Fig. 1.

TABLE I. Energies and emissivities measured and calculated.

Participant	Energies of the skin (mW)	Energies of blackbody (mW)	Emissivities obtained by definition	Reflected energies (mW)	Emissivities computed with Kirchhoff
1	6.571	6.725	0.977	6.56	0.981
2	11.499	11.894	0.967	6.56	0.981
3	8.214	8.478	0.969	11.48	0.967
4	9.857	10.034	0.982	8.20	0.977
5	9.857	9.995	0.986	6.56	0.981
6	10.514	10.634	0.989	6.56	0.981
7	9.857	10.034	0.982	9.84	0.972
8	9.857	10.019	0.984	3.28	0.991
9	8.214	8.346	0.984	8.20	0.977
10	8.214	8.397	0.978	8.20	0.977
11	6.571	6.774	0.970	16.40	0.953
12	8.214	8.565	0.959	11.48	0.967
13	13.142	13.261	0.991	3.28	0.991
14	6.571	6.782	0.969	9.84	0.972
15	3.286	3.405	0.965	9.84	0.972
16	9.857	10.006	0.985	9.84	0.972
17	6.571	6.776	0.969	6.56	0.981
18	6.571	6.776	0.970	6.56	0.981
19	8.214	8.417	0.976	4.92	0.986
20	6.571	6.683	0.983	3.28	0.991
21	4.928	5.002	0.985	14.76	0.958
22	4.928	5.043	0.977	14.76	0.958
23	9.857	10.003	0.985	11.48	0.967
24	9.857	9.998	0.986	9.84	0.972
25	8.214	8.346	0.984	8.20	0.977
26	11.499	11.601	0.991	6.56	0.981
27	9.857	10.119	0.974	8.20	0.977
28	11.499	11.779	0.976	8.20	0.977
29	8.214	8.508	0.966	6.56	0.981
30	6.571	6.813	0.965	6.56	0.981
31	8.214	8.314	0.988	6.56	0.981
32	6.571	6.807	0.965	8.20	0.977

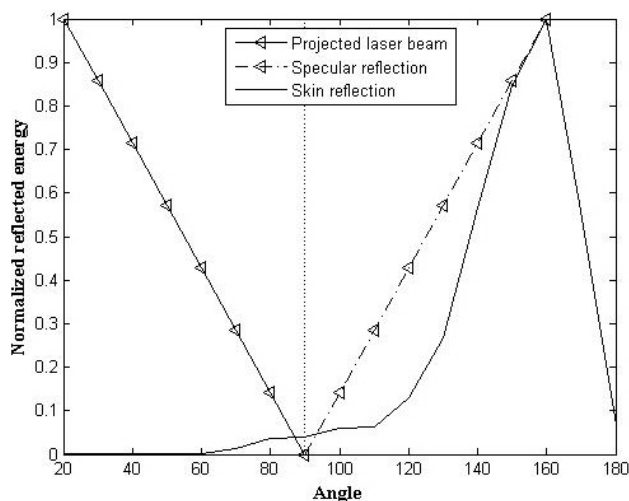


FIGURE 3. Skin reflection vs. angle.

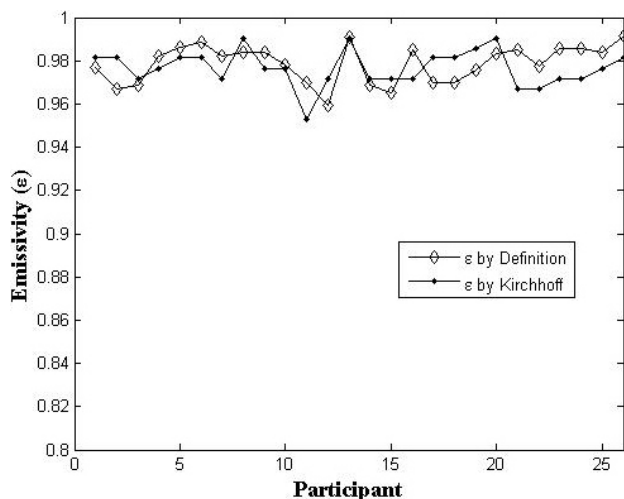


FIGURE 4. Emissivities obtained with the two methods.

Once the maximum reflection angle was determined, the reflected energies by the skins of all participants were measured as described. The obtained values are shown in Table I labeled as *Reflected energies*. Considering that the projected energy was 350 mW, the corresponding reflectivities were calculated using Eq. (1). With those values of reflectivity the corresponding emissivities were calculated using Eq. (2). Such values are also shown in Table I labeled as *Emissivity computed with Kirchhoff*.

The values given in the second column of Table I, as “*Energies of the skin*,” are the energies emitted by the skin of each

participant that were measured with the power meter. The theoretical “*Energies of blackbody*” calculated at the measured temperatures of the skin, using the same wavelength range, and taking into account the characteristics of the detector are given in the third column of Table I. The resulting emissivities obtained with Eq. (3) are shown in Table I as “*Emissivity obtained by definition*”.

A comparative plot of the emissivity values obtained using the two methods (values from Table I) is shown in Fig. 4. As can be seen, both procedures yield very similar emissivity values.

5. Discussion

All of our measurements of skin emissivity were corroborated through theoretical calculations. Our procedure produced an average skin emissivity of 0.976 ± 0.006 , while the direct method using the theoretical blackbody model gave an average skin emissivity of 0.978 ± 0.008 , which are very similar. The corresponding standard deviations (0.008 for the indirect method and 0.006 for the direct method) indicate that variability due to individual skin properties is minimal at $10.6 \mu\text{m}$, which is in accordance with the conclusions of Togawa [15,26,27], and Stekete [7].

Considering what is mentioned in the related literature, that skin emissivity is practically constant in the range from $8 \mu\text{m}$ to $14 \mu\text{m}$ [7,15,22,26,27] (which is the interval that we used with the direct method), it seems to be that using a laser at $10.6 \mu\text{m}$ is enough to measure the skin emissivity for this infrared thermal range.

Togawa [15] estimated that skin emissivity in the back of the hand (where we also did our measurements) was 0.972 ± 0.004 , between $8 \mu\text{m}$ and $14 \mu\text{m}$, which is very close to what we obtained.

6. Conclusions

With the procedure proposed in this work, the need for an extremely controlled environment is eliminated, and measurements of skin emissivity at specific wavelengths are easily achieved.

It was shown that, at $10.6 \mu\text{m}$, the maximum reflection in the human skin occurs at the same angle of specular reflection.

The results given by our procedure are in accordance with those given by the traditional blackbody procedure to compute emissivity.

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