Int J Thermophys (2010) 31:2295–2304
DOI 10.1007/s10765-010-0877-7

Thermophysical Properties of Plant Leaves and Their Influence on the Environment Temperature

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Received: 9 March 2010 / Accepted: 8 November 2010 / Published online: 21 November 2010

Abstract It is known that the thermal properties of a material influence the temperature around it. Once heated, the rate at which a material transfers the absorbed heat into the surroundings is determined by the thermal effusivity (or thermal inertia) of the material, and it depends on the well-known thermal properties, thermal conductivity, and specific heat capacity. Since a direct measurement of these properties is rather difficult for thin biological specimens such as plant leaves, a photothermal technique is used to measure the thermal effusivity, thermal diffusivity, thermal conductivity, and specific heat capacity for a few representative species of plant leaves. Measurements have been carried out on fresh as well as dry leaves to estimate the differences in their properties. Thermal properties of plant leaves are compared with the corresponding properties of two materials abundant in the environment and discussed. The influence of thermal properties, particularly the thermal effusivity and specific heat capacity, of plant leaves on controlling the temperature of the environment around them is discussed.

Keywords Environment temperature · Photothermal technique · Plant leaves · Specific heat · Thermal conductivity · Thermal effusivity

1 Introduction

The amount of vegetation present at a location has a significant influence in determining the temperature of the local environment. Since the largest part of any vegetation is plant leaves, the influence of vegetation on the environment temperature is primarily

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due to leaves. Leaves are the principal organs in plants in which photosynthesis, transpiration, and food manufacturing occur. Useful information about the morphological and physiological status of growing plants is also provided by leaves. Leaf characteristics such as size, shape, thickness, venation, surface nature, water content, photosynthetic, anatomical properties, etc., vary considerably among different species of plants.

In general, the presence of a high density of vegetation or leaves results in a cooler environment, particularly in tropical regions. However, it is rather difficult to measure this temperature reduction for the following two reasons:

(i) The reduction in temperature just due to this is rather small, perhaps of the order of 0.1 °C.
(ii) Movement of air surrounding the leaves due to wind smears out the temperature difference, which is already small.

We could measure a temperature difference of up to 0.5 °C between a location inside thick vegetation and a nearby location away from vegetation.

The thermal properties of plant leaves, which control the temperature of their environment is the subject of discussion in this article. It is known that heat transfer between a plant and its environment is essentially through the following three processes: (1) conduction and convection due to direct contact with air, (2) evaporation of water in the form of latent heat, and (3) heat loss through radiation [1]. Though heat transfer from plants to the environment, which is determined by thermal properties of leaves, is a very old problem, new results still continue to appear on this subject [2]. We try to look at this issue from a new angle and analyze it from the point of view of the thermal effusivity or thermal inertia, which is the inverse of the thermal impedance, for plant leaves.

The important thermal properties of interest for any material are its specific heat capacity and thermal conductivity. Two other thermal properties, which are not so obvious, are the thermal diffusivity and thermal effusivity of the material. The thermal diffusivity by definition is a measure of the speed with which thermal energy spreads out through the material and has units of $m^2 \cdot s^{-1}$. The thermal diffusivity α is related to the thermal conductivity λ through the relation,

$$\alpha = \frac{\lambda}{\rho C_p} \tag{1}$$

where ρ is the density and C_p is the specific heat capacity of the medium. The thermal effusivity or thermal inertia is inversely proportional to the thermal impedance, which essentially determines the magnitude of the thermal wave at the sample surface [3]. The value of the thermal effusivity for a material determines the time taken by the material, once heated to a temperature, to reach thermal equilibrium with the environment. The lower the value of the thermal effusivity for a sample, the higher is its surface temperature. Correspondingly, a sample with a low thermal effusivity, once heated to a temperature, will take a longer time to reach the temperature of the environment compared to a sample with a high thermal effusivity heated to the same temperature. The thermal effusivity e is related to other thermal properties through the relation,

$$e = \sqrt{\lambda \rho C_p} \tag{2}$$

and has units of $\mathrm{W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}}$.

In general, it is rather difficult to measure thermal properties of thin biological materials such as plant leaves. Measurement of thermal properties such as thermal conductivity and specific heat involves heating the sample, which leads to changes in properties and damage of the sample. A survey reveals that only a few results on the thermal properties of plant leaves have appeared in the literature. The thermal emissivity of plant leaves in moving air was measured way back in 1905 [4]. The thermal conductivities of several species of leaves were measured by placing the samples between two silver plates of differing temperatures and measuring the time required to boil-off a constant volume of a liquid [5]. A few other measurements of the thermal conductivity of different plant leaves have also appeared in the literature [6–8]. Most of these measurements have reported only the thermal-conductivity values for leaves. These measurements have reported values of the thermal conductivity in the range from $0.2\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ to $0.5\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ for different species of plant leaves. Although a few papers reporting the thermal conductivity of leaves have appeared in the literature, fewer studies on the specific heat or thermal diffusivity could be found [9]. On the other hand, no direct measurements of the thermal effusivity could be found in the literature. Although one can evaluate the thermal effusivity from the thermal conductivity and specific heat, the method is not direct and has limitations. So far nobody has reported either the computed or the measured values of the thermal effusivity for plant leaves and discussed the consequence of their values on the environment temperature.

In this article, we report the results of our measurements of all the above four thermal parameters for a few selected species of plant leaves using the photopyroelectric (PPE) technique [10]. The PPE technique is essentially a photothermal technique in which the sample is optically heated with an intensity modulated beam of light. Since the optical input power required in this technique for the generation of the PPE signal is comparatively small (of the order of a few mW), the inherent temperature rise in the sample is very small (typically a few mK), and so soft biological samples such as leaves do not undergo any change in properties or incur damage in the reasonably short period of time (typically less than an hour) required for measurement. From this point of view, the PPE technique is ideally suited for the measurement of thermal properties of plant leaves. Moreover, the technique enables one to determine all the four thermal transport properties, thermal diffusivity, thermal effusivity, thermal conductivity, and specific heat capacity, simultaneously in one measurement.

A description of the experimental technique, the results obtained on a few selected species of plant leaves, and a discussion of the results are given in the following sections. We have made the measurements on fresh as well as dry leaves so as to bring out differences in their thermal properties. Results on the difference in thermal properties between fresh and dry leaves are presented for the first time and discussed.

2 Experimental Method

We have measured all the four thermal properties of interest, thermal diffusivity α, thermal effusivity e, thermal conductivity λ, and specific heat capacity C_p, for seven species of plant leaves employing an improved photopyroelectric (PPE) technique [10]. The seven plant species selected for this study do not have any special significance. Our interest is to report the order of magnitude of the above thermal properties, particularly the thermal effusivity, for fresh plant leaves and discuss their influence on controlling the temperature of their environment. The corresponding properties for all these plant leaves in the dry form have also been measured to determine the difference in the values of the above thermal properties. Fresh (green) as well as dry (naturally dry, collected from the plant) leaves have been cut to a circular shape of a diameter of about 5 mm and their thickness measured with a micrometer. All the fresh leaf samples have been subjected to PPE experimentation within 1 h of removal from the plants to ensure that they are fresh with their natural properties. The mass densities of all the samples have been determined by measuring the mass of a known volume of the leaf.

The PPE technique is a fairly established one to measure thermal properties of materials [10–12]. The PPE effect is based on the use of a pyroelectric film transducer to detect the periodic temperature rise in a sample when it is irradiated by an intensity modulated beam of light. The sample configuration in a back detection PPE experiment is shown in Fig. 1. The modulated radiation absorbed by the sample at its surface gets converted into thermal waves, which propagate through the sample and are detected by the pyroelectric detector. The temperature variations sensed by the detector give rise to an electrical current, which is proportional to the rate of change of the average heat content, given by

$$i_{\mathrm{d}} = PA\left(\frac{\partial\theta(t)}{\partial t}\right) \tag{3}$$

where P is the pyroelectric coefficient of the detector and A is its area. $\theta(t)$ is the spatially averaged temperature variation over the thickness of the detector L_{d}, and is given by

$$\theta(t) = \left(\frac{1}{L_{\mathrm{d}}}\right)\int_{0}^{L_{\mathrm{d}}} \theta(x,t)\,\mathrm{d}x \tag{4}$$

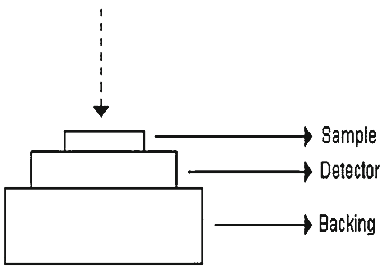

Fig. 1 Sample configuration of back detection photopyroelectric (PPE) experiment

One can draw an electrical equivalent circuit for this configuration and obtain expressions for the output signal amplitude and phase. These expressions are considerably simplified if one assumes physically realistic boundary conditions. Assuming that the sample and the pyroelectric detector are thermally thick, with their thermal diffusion lengths (defined mathematically as $\sqrt{\alpha/\pi f}$ where α is the thermal diffusivity and f is the modulation frequency) smaller than their physical thicknesses, one can obtain the following expressions for the PPE signal amplitude and phase at the output of the detector [10]:

$$V(f,T) = \frac{I_0 \eta_s A R_d}{L_d\left[1+(f/f_c)^2\right]^{1/2}} \frac{P(T)}{\rho_d(T)C_{pd}(T)} x \frac{\exp\left[-(\pi f/\alpha_s)^{1/2} L_s\right]}{e_s(T)/e_d(T)+1} \tag{5}$$

$$\varphi(f,T) = -\tan^{-1}(f/f_c) - \left(\frac{\pi f}{\alpha_s(T)}\right)^{1/2} L_s \tag{6}$$

Here f is the modulation frequency of light, T is the temperature, I_0 is the intensity of the radiation falling on the sample, η_s is a constant for a sample, R_d is the detector leakage resistance, and f_c is the critical frequency at which the sample goes from a thermally thin to a thermally thick regime. L, ρ, and C_p are the thickness, density, and specific heat capacity for the medium with subscripts d and s standing for detector and sample, respectively.

The detector used in the present experiments is a PVDF film of thickness 28 µm, coated on both sides with Ni–Cr alloy. The pyroelectric coefficient of the film is $P = 30 \times 10^{-10}\ \mathrm{C \cdot cm^2 \cdot K^{-1}}$ at room temperature. The parameter $P(T)/[P_d(T)C_{pd}(T)]$ for the detector has been determined by measuring the PPE amplitude and phase at a fixed frequency as a function of temperature from 25 °C to 50 °C in a calibration run.

From Eqs. 5 and 6 it is clear that the thermal diffusivity α_s of the sample can be determined from the variation of phase with frequency of the PPE signal. Fitting the experimental PPE phase curve with Eq. 6 yields α_s. Substitution of α_s into the amplitude expression gives the thermal effusivity e_s of the sample. From these, the thermal conductivity and heat capacity can be obtained from the following relations:

$$k_s(T) = e_s(T)\,[\alpha_s(T)]^{1/2} \tag{7}$$

$$C_{ps}(T) = \frac{e_s(T)}{\rho_s(T)\,[\alpha_s(\mathrm{T})]^{1/2}} \tag{8}$$

A temperature calibration of the PPE detector is necessary as all the parameters in Eqs. 5 and 6 are temperature dependent. The experimental setup and technique have been tested and calibrated with reference materials such as copper ($\alpha = 1.12 \times 10^{-4}\ \mathrm{m^2 \cdot s^{-1}}$) and polymer nylon ($\alpha = 1.26 \times 10^{-7}\ \mathrm{m^2 \cdot s^{-1}}$) with widely different thermal-diffusivity values.

The sample-detector-backing configuration was carefully aligned and mounted in a specially designed chamber with an optical window so that light from a laser source can fall directly on the sample. Good thermal contact between the sample and detector was ensured by applying a very thin layer of a heat sink compound between them.

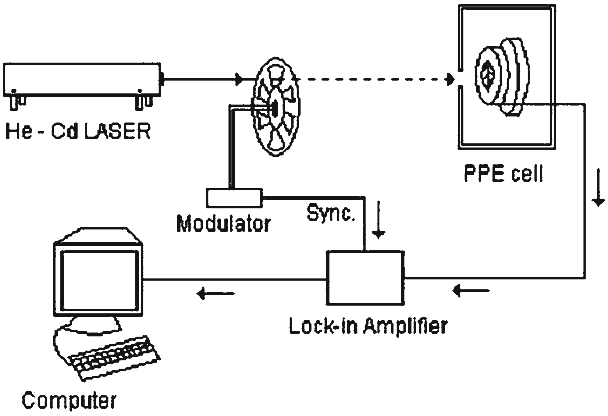

Fig. 2 Block diagram of a PPE experimental setup

A photopyroelectric spectrometer of the type shown in Fig. 2 was used for the PPE measurements.

In the experiment one measures the variations of the PPE amplitude and phase with modulation frequency. One such set of variations for fresh as well as dry leaves of one species of plant leaves is shown in Fig. 3. Similar variations have been obtained for other plant leaves. From these curves the characteristic frequency f_c for each sample is determined as the frequency at which a peak in amplitude is obtained. These values of f_c along with other known quantities are substituted in Eq. 6 to evaluate α_s. This is substituted, along with other known quantities, in Eq. 5 to evaluate e_s. These values of α_s and e_s are then substituted in Eqs. 7 and 8 to obtain k_s and C_{ps}.

3 Results and Discussion

The thermal properties of interest for the selected seven species of fresh plant leaves and the corresponding dry leaves are tabulated in Table 1. The values for dry leaves are given in parentheses below the respective values for fresh leaves. The thermal properties of water are also tabulated in the table for comparison.

In general, fresh as well as dry leaves have a specific heat capacity comparable to that of water (4186 $J \cdot kg^{-1} \cdot K^{-1}$). However, there are variations in the values between species, from 1287 $J \cdot kg^{-1} \cdot K^{-1}$ to 2267 $J \cdot kg^{-1} \cdot K^{-1}$ for fresh leaves and from 1514 $J \cdot kg^{-1} \cdot K^{-1}$ to 5174 $J \cdot kg^{-1} \cdot K^{-1}$ for dry leaves. The value of the specific heat capacity depends on the water content, fiber content, and other organic constituents in the leaf. It may be noted that as leaves get dry, their specific heat capacity increases for the majority of the species, but decreases for one species selected by us. As water and organic liquid constituents are lost and leaves get dry, only dry fiber and other non-volatile constituents remain, which tend to affect the specific heat capacity values.

The thermal conductivity and thermal diffusivity are closely related quantities, both representing the efficiency with which heat energy is transported through the medium.

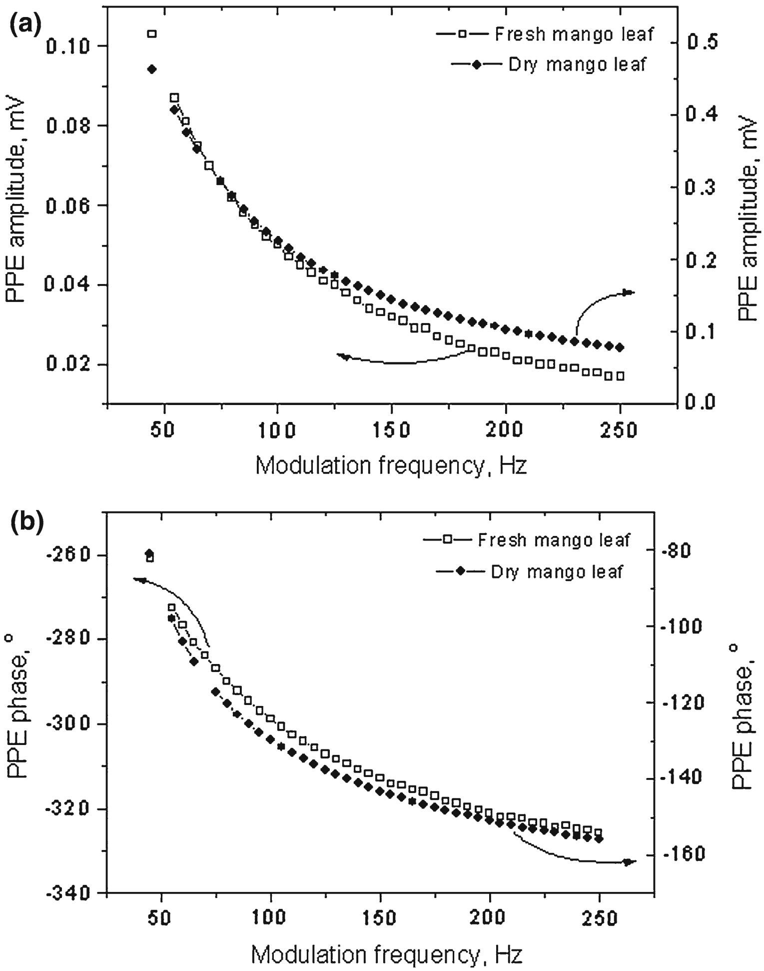

Fig. 3 (a) Variation of PPE amplitude with frequency for mango leaf (fresh and dry) and (b) variation of PPE phase with frequency for mango leaf (fresh and dry)

It should be noted that both fresh and dry leaves have a thermal conductivity lower than that of water ($0.60\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$). As the leaves get dry, the change in thermal conductivity is not predictable. It decreases for four species of leaves, but increases for three. The values of the thermal diffusivity are controlled by the values of the specific heat capacity and thermal conductivity. So, no systematic variation in the values of the thermal diffusivity as leaves get dry can be found.

In general, it can be seen that the thermal effusivity of fresh plant leaves is much smaller than for other materials on the surface of the earth. For example, the thermal effusivity of water is about $1600\,\mathrm{W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}}$, which on the average, is about more than double the value for fresh plant leaves tabulated in Table 1. Sand, which is another material abundant on the surface of the earth, has a thermal effusivity of about $1400\,\mathrm{W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}}$. The comparatively low values of the thermal effusivity for

Table 1 Thermal properties of seven species of plant leaves

Trade name of the plant species	Botanical name of the plant species	Thickness of the leaf sample (10^{-3} m)	Density ρ ($kg \cdot m^{-3}$)	Thermal effusivity e ($W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}$)	Thermal diffusivity α (10^{-6} $m^2 \cdot s^{-1}$)	Thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$)	Specific heat capacity C_p ($J \cdot kg^{-1} \cdot K^{-1}$)
Aangili (Aini)	Artocarpus	0.28 ± 0.02	631 ± 20	716 ± 12	0.49 ± 0.05	(0.50 ± 0.04	1637 ± 38
	Hirsutus	(0.27 ± 0.02)	(408 ± 14)	(624 ± 10)	(0.29 ± 0.03)	(0.33 ± 0.02)	(2868 ± 68)
Jackfruit	Artocarpus	0.33 ± 0.03	650 ± 18	720 ± 17	0.24 ± 0.06	0.36 ± 0.03	2252 ± 53
	Heterophyllus	(0.29 ± 0.02)	(450 ± 25)	(634 ± 11)	(0.38 ± 0.04)	(0.39 ± 0.03)	(2287 ± 66)
Cinnamon	Cinnamomum	0.20 ± 0.01	687 ± 15	688 ± 12	0.19 ± 0.04	0.30 ± 0.02	2267 ± 65
	Verum	(0.20 ± 0.01)	(468 ± 20)	(666 ± 12)	(0.16 ± 0.02)	(0.27 ± 0.02)	(3586 ± 85)
Mango	Mangifera	0.21 ± 0.01	879 ± 31	730 ± 31	0.13 ± 0.01	0.27 ± 0.02	2263 ± 94
	Indica	(0.20 ± 0.01)	(747 ± 21)	(685 ± 12)	(0.35 ± 0.04)	(0.41 ± 0.03)	(1545 ± 45)
Coconut	Cocos	0.32 ± 0.02	918 ± 21	750 ± 18	0.42 ± 0.04	0.45 ± 0.04	1287 ± 30
	Nucifera	(0.32 ± 0.03)	(558±23)	(636 ± 11)	(0.58 ± 0.05)	(0.48 ± 0.04)	(1514 ± 36)
Teak	Tectona	0.20 ± 0.01	475 ± 20	675 ± 16	0.40 ± 0.04	0.43 ± 0.03	2232 ± 52
	Grandis	(0.20 ± 0.01)	(336±15)	(601 ± 10)	(0.12 ± 0.01)	(0.21 ± 0.02)	(5174 ± 123)
Jaiphal (Jathi)	Myristica	0.24 ± 0.02	866 ± 20	728 ± 20	0.47 ± 0.04	0.49 ± 0.04	1255 ± 29
	Fragrans	(0.18 ± 0.01)	(537 ± 30)	(673 ± 12)	(0.21 ± 0.02)	(0.31 ± 0.02)	(2724 ± 65)
Water (for comparison)	–	–	1000	1600	0.14	0.6	4186

Values in *parentheses* are the respective values for dry leaves plant leaves signify that they, once heated to a higher temperature, retain the heat absorbed by them for a longer time. They effuse out the absorbed heat rather slowly without transferring the absorbed heat to the environment, thus helping to keep the environment around them cooler. At the same time, one has to realize that the specific heat capacity of plant leaves (see Table 1) is comparatively high and is comparable to water or sand on the surface of the earth. This means that a high amount of input heat energy is required to raise the temperature of plant leaves, which is comparable to sea water or sand. In other words, with low values for the thermal effusivity and high values for the specific heat capacity, plant leaves act as efficient heat sinks, which help to keep the environment cooler. Obviously, plants use up this energy for various biochemical processes in them. Environmental cooling brought about by vegetation is particularly relevant to tropical regions of the earth.

As is evident from Table 1, all the four thermal properties have wide variations for their values between plant species. For example, the thermal effusivity varies from $675\,\mathrm{W}\cdot\mathrm{s}^{1/2}\cdot\mathrm{m}^{-2}\cdot\mathrm{K}^{-1}$ for teak leaf to $750\,\mathrm{W}\cdot\mathrm{s}^{1/2}\cdot\mathrm{m}^{-2}\cdot\mathrm{K}^{-1}$ for coconut leaf. This range of variation in the thermal effusivity has a correspondence with the thickness of these leaves. A teak leaf has a thickness of about 0.2 mm, whereas a coconut leaf has a thickness of about 0.32 mm. A careful analysis shows that the variations in thermal properties have a correspondence to physical properties of the leaf species.

From Table 1, one can also notice that the values of the thermal effusivity decrease by about 10 % as leaves get dry. However, this decrease is not very significant when the values are compared with the corresponding values for water or sand. So we can notice that irrespective of whether plant leaves are fresh or dry, they posses comparatively low thermal effusivity.

The photopyroelectric technique, which is basically an optical technique, is used for the present measurements. Since the sample is heated optically, the actual temperature rise inside the sample is very small, of the order of a few mK. So the sample does not undergo any thermal shock or any temperature rise that can damage biological cells and tissues during the time taken for experimentation. So the PPE technique is ideally suited for the measurement of the thermal properties of biological samples such as leaves.

4 Conclusions

All the four important thermal properties, thermal conductivity, specific heat capacity, thermal diffusivity, and thermal effusivity, of a few species of fresh and dry plant leaves have been measured and reported for the first time. Obviously, different plant leaves have different thermal properties depending on the species. In general, fresh plant leaves have the following ranges for their thermal properties. The ranges of values given in parentheses are for dry leaves.

Mass density: $475\ \mathrm{kg}\cdot\mathrm{m}^{-3}$ to $918\ \mathrm{kg}\cdot\mathrm{m}^{-3}$($336\ \mathrm{kg}\cdot\mathrm{m}^{-3}$ to $747\ \mathrm{kg}\cdot\mathrm{m}^{-3}$)

Specific heat: $1255\ \mathrm{J}\cdot\mathrm{kg}^{-1}\cdot\mathrm{K}^{-1}$ to $2267\ \mathrm{J}\cdot\mathrm{kg}^{-1}\cdot\mathrm{K}^{-1}$($1514\ \mathrm{J}\cdot\mathrm{kg}^{-1}\cdot\mathrm{K}^{-1}$ to $5174\ \mathrm{J}\cdot\mathrm{kg}^{-1}\cdot\mathrm{K}^{-1}$)

Thermal conductivity: $0.27\,\mathrm{W}\cdot\mathrm{m}^{-1}\cdot\mathrm{K}^{-1}$ to $0.50\,\mathrm{W}\cdot\mathrm{m}^{-1}\cdot\mathrm{K}^{-1}$($0.21\,\mathrm{W}\cdot\mathrm{m}^{-1}\cdot\mathrm{K}^{-1}$ to $0.48\ \mathrm{W}\cdot\mathrm{m}^{-1}\cdot\mathrm{K}^{-1}$)

Thermal diffusivity: $0.13 \times 10^{-6}\,\mathrm{m}^2 \cdot \mathrm{s}^{-1}$ to $0.49 \times 10^{-6}\mathrm{m}^2 \cdot \mathrm{s}^{-1}$($0.12 \times 10^{-6}\,\mathrm{m}^2 \cdot \mathrm{s}^{-1}$ to $0.58 \times 10^{-6}\,\mathrm{m}^2 \cdot \mathrm{s}^{-1}$)

Thermal effusivity: $675\ \mathrm{W} \cdot \mathrm{s}^{1/2} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}$ to $750\ \mathrm{W} \cdot \mathrm{s}^{1/2} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}$($601\ \mathrm{W} \cdot \mathrm{s}^{1/2} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}$ to $685\ \mathrm{W} \cdot \mathrm{s}^{1/2} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}$)

It should be noted that fresh plant leaves have a much lower thermal effusivity than other materials, such as water or sand, present on the surface of the earth. The thermal effusivity of plant leaves is about $700\ \mathrm{W} \cdot \mathrm{s}^{1/2} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}$, whereas it is about $1600\ \mathrm{W} \cdot \mathrm{s}^{1/2} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}$ for sea water and about $1400\ \mathrm{W} \cdot \mathrm{s}^{1/2} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}$ for sand. It is a well known fact that vegetation helps to cool the environment. The results of our measurements of the thermal effusivity and specific heat capacity of plant leaves explain the above fact in terms of the low value of the thermal effusivity (or a high value of the thermal impedance) and a high value for the specific heat capacity for plant leaves.

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