Determination of Thermal Radiation Emissivity and Absorptivity of Thermal Screens for Greenhouse

Adeel Rafiq¹, Wook Ho Na², Adnan Rasheed¹, Hyeon Tae Kim³, and Hyun Woo Lee^{1,2,4*}

¹Department of Agricultural Engineering, Kyungpook National University, Daegu 41566, Korea

²Institute of Agricultural Science and Technology, Kyungpook National University, Daegu 41566, Korea

³Dept. of Bio-Industrial Machinery Eng., Gyeongsang National Univ. (Insti. of Agric. & Life Sci.), Jinju 660-701, Korea

⁴Smart Agriculture Innovation Center, Kyungpook National University, Daegu 41566, Korea

Abstract. Greenhouse farmers often use thermal screens to reduce greenhouse heating expenses during the winter, and for shade during hot, sunny days in the summer, as it is an inexpensive solution to temperature control relative to other available options. However, accurate measurements of their emitted and absorbed radiations are important for the selection of suitable screens that offer maximum performance. Material's ability to save energy is highly dependent on these properties. Limited studies have investigated the measurement of these properties under natural conditions, but they are only applicable to materials having partial porosities. In this work, we describe a new radiation balance method for determining emissive power and absorptive capacity, as well as reflectivity, transmissivity and emissivity of materials having complete and partial transparency by using pyrgeometer and net radiometer. In this study, four materials with zero porosity, were tested. The emissivity value of PE, LD-13, LD-15 and PH-20 was 0.439 ± 0.020 , 0.460 ± 0.010 , 0.454 ± 0.004 , and 0.499 ± 0.006 , respectively. All tested samples showed high emitted radiation as compared to absorbed radiation.

Additional key words : image j, net radiometer, pyrgeometer, reflectance

Introduction

During the colder parts of the year, heating is critical to greenhouse production, as it is essential for achieving the prescribed optimum temperature for crop growth (Sethi *et al.*, 2013; Rasheed *et al.*, 2018b). Thus, when designing a greenhouse, careful selection of appropriate material can positively affect the energy requirements and fuel consumption necessary to maintain optimal growth temperatures (Ponce *et al.*, 2014; Marshall, 2016; Rasheed *et al.*, 2018a)

The effort to support a growing energy demand, while simultaneously reducing fossil fuel impacts on the environment, has motivated the scientific community to invest significant time, money, and resources into extensively investigating the application of renewable energy (Adaramola, 2012). As part of that effort, numerous studies have focused on alternative ways to achieve greenhouse heating (Pucar, 2002; Kürklü and Bilgin, 2004; Ghosal and Tiwari, 2006; Abdel-Ghany and Al-Helal, 2011; Joudi and Farhan,

2014). The aim of these studies was minimize greenhouse energy intake by using alternative approaches, such as: increasing shortwave radiation availability inside the greenhouse, reducing energy loss to the outside environment, and increasing the greenhouse's constituent storage ability.

Thermal screens are commonly used in greenhouses to minimize heat loss at night during the winter and to provide adequate shading during the summer (Shukla *et al.*, 2008). Accurate measurement of the screen's longwave radiometric properties are important for selecting an appropriate screen to maintain optimal environmental conditions for plants during the night (Rafiq *et al.*, 2019). These properties can be input into a physical model and used to calculate the amount of saved energy for different screens, thereby permitting a performance comparison between the different screen options.

Spectrophotometers, infrared sensors, and many other instruments are appropriate and available for measuring the properties of simple materials. However, the screen's perforated nature and compositional complexity makes it impractical to use these instruments for accurately measuring the absorbed and emitted radiation (Abdel-Ghany *et al.*, 2015a). To date, no standard technique is available for

*Corresponding author: whlee@knu.ac.kr

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measuring the screens' long-wave properties that can be applied to a diverse array of material types.

This study describes an experimental procedure for determining absorptive and emissive power along with reflectivity, transmissivity and emissivity of energy-saving greenhouse screens. Our method uses simple radiation balance equations and inexpensive radiometers in contrast to complicated procedures and costly scientific equipment. The results of our calculations allow researchers and growers alike to determine whether a material is a good heat insulator or conductor under natural environmental conditions. Such information permits comparison of energy performance between different screens and equips growers with necessary information to make an informed investment choice.

Materials and Methods

1. Material properties and composition

To carry out this experiment, four symmetric materials (identical on both sides) of the same category but with different compositions were selected and tested. The tested materials' properties and nature are presented in Table 1. PhormiTex PHL 20 (PH-20) is an energy saving gable screen. Luxous-1547 D FR (LD-15) combines good heat retaining properties with high light diffusion and transmission. The diffusion brings light to the plants from various directions, reducing overheating of upper areas. The main function of Luxous-1347 D FR (LD-13) is saving energy through maximum light transmission. Polyethylene(PE) is primarily plastic film that is preferred by most

Table 1. Properties of the tested materials

Material	Properties	Weight (g/m ²)	Thickness (mm)	Width of strips (mm)	Composition	Transparency (%)
PH-20		108	0.27	4	100% Polyethylene	80
LD-13		58	0.22	4	100% Polyester	75
LD-15		51	0.18	4	100% Polyester	75
PE		84	0.07	-	100% Polyethylene	100

Fig. 1. Illustration of the experimental structure, units in [m], not to scale.

Table 2. List of equipment and data loggers

Parameter	Unit	Sensors	Range	Data logger
Net long-wave radiation	W/m ²	NR Lite2 Net Radiometer (Kipp and Zonen, Netherlands)	0.2–100 μ m	LR 5041 (Hioki, Japan)
Downward long-wave radiation (L_a)	W/m ²	CGR3 Pyrgeometer (Kipp and Zonen, Netherlands)	4.5–42 μ m	21x Micrologger (Campbell Scientific, Inc. USA)
Downward long-wave radiation (L_c)	W/m ²	IR02 Pyrgeometer (Hukseflux, Netherlands)	4.5–40 μ m	CR300 (Campbell Scientific, Inc. USA)
Temperature/Relative Humidity	°C/ %	Hobo pro v2 U23-002 (Onset, USA)	-40 °C–70 °C 0%–100 %	Hobo pro v2 U23-002 (Onset, USA)
Surface temperature	°C	T-type thermocouple wires	-270 °C–370 °C	Hobo UX120-014M (Onset, USA)

Fig. 2. Ideal drawing of the inward (L_a and L_d) and the outward (L_b and L_c) radiations from the screen.

agricultural growers due to its affordability, flexibility, and easy manufacturing. In this study, polyethylene was used as a standard reference material due to its well-known properties, which are widely reported in the literature. The material, which is transparent and partially porous, was tested to confirm the accuracy of results obtained by our proposed method.

2. Experimental setup

This experiment was conducted on a building roof in order to obtain clear sky radiations. A hollow wooden frame was built, the bottom of which was covered with a black cloth of known radiometric properties ($\tau_b = 0$, $\rho_b = 0.07$, $\varepsilon_b = 0.93$). The frame measurements were $2.4\text{W} \times 2.6\text{L} \times 0.5\text{H}$ m, and the 3D structure enclosed by the frame had a total volume of 3.12m^3 . Fig. 1 depicts the frame dimensions and the equipment positions. One night is required to examine one sample screen and each material was tested from 18:00 to 6:00 o'clock. Downward

longwave radiation (L_a & L_c) was measured with a pyrgeometer, while upward fluxes (L_b & L_d) were computed from the difference between net radiometer and the downward fluxes. Two thermocouple wires, with a very thin diameter, were used to measure the black cloth's surface temperature. All measured parameters were recorded at 10-minute intervals and saved in each parameter's corresponding data logger. Table 2 depicts the list of employed equipment and data loggers.

3. Theory

The outgoing long-wave radiation equation above the screen surface (L_b) for symmetric materials is given below, where L_b is in W/m^2 .

$$L_b = E_s + \rho_s L_a + \tau_s L_d \quad (1)$$

$$L_c = E_s + \tau_s L_a + \rho_s L_d \quad (2)$$

where ρ_s is the screen reflectance, E_s is the screen's emissive power in W/m^2 , τ_s is the screen's transmittance, and L_a is the downward sky radiation in W/m^2 .

The outgoing long-wave radiation equation over the black surface (L_c) and below the screen surface for symmetric materials is given below, where L_c is in W/m^2 .

The reflected portion of incoming long-wave radiation toward the screen, above the black cloth (L_d), depends upon the screen's physical condition. The incoming radiation (L_d) of transparent and semitransparent materials or materials with partial porosities is given below, where L_d is in W/m^2 .

$$L_d = E_b + (\rho_b + \mu) E_s + (\rho_b - \mu) \rho_s L_d + (\rho_b - \mu) \tau_s L_a \quad (3)$$

Where ρ_b is the black cloth's reflectance. E_b is the black cloth's emissive power in W/m^2 , which was determined by Stefan-Boltzmann's law. The emissive power of black can also be calculated using the following equations:

$$E_b = (L_d - L_c * \rho_b) \quad (4)$$

$$E_b = (L_d * \epsilon_b) \quad (5)$$

In the aforementioned equation (3), reflection of all three components (E_s , $\rho_s L_d$, and $\tau_s L_a$) from the black cloth's surface are considered because $\tau_s L_a$ will reach the black cloth's surface, either from porosity or the presence of transparent material in the sample's composition; and $\rho_s L_d$ will reach the black cloth's surface due to the presence of opaque material, e.g., thread. Using the iteration method in Matlab to simultaneously solve the three equations (1, 2 and 3) results in equation (3) causing compatibility issues, even though the number of equations equals the number of unknowns. In order to make these equations compatible to solve simultaneously, micro (μ) $= 10^{-6}$, is subtracted from the reflected portion of $\tau_s L_a$ and $\rho_s L_d$, and added into the reflected portion of E_s in equation (3). μ is the smallest assumed number that can act as tolerance for the black cloth's reflectance (ρ_b). It has no significant effect on the value, but it helps to circumvent the equations' compatibility issue. Subtraction and addition is based on the radiation strength.

The multiple reflections (i.e., ρ_s^2 , ρ_s^3 and ρ_b^2 , ρ_b^3) of thermal radiation between the screen and the black cloth were ignored. No angular interaction between the sample materi-

als and the incident radiation was considered. The absorbed longwave radiation by screen (A_s) can be calculated as:

$$A_s = \alpha_s * (L_a + L_d) \quad (6)$$

Where α_s is the screen's absorption.

4. Transparency measurement

Transparency is defined as the ratio between the non-opaque portion and the total area of a sample's materials. Its measurement is important because it can aid in selecting a suitable pair of equations for the radiative properties' measurement. In this study, the image processing method was used, as it is both fast and accurate. ImageJ software was employed for processing the images, which is a freely accessible source Java image processing program inspired by NIH Image that can compute the area and pixel value statistics of user-defined selections. Furthermore, it can measure distances and angles. For image processing, the first screens were tacked to a small frame (4 cm $\times$ 4 cm) and scanned at 300 dpi resolution with a flatbed scanner (Scanjet 5550c, HP, USA). Scanned images were then converted to black-and-white images by changing the image type to 8-bit and using a bandpass filter. Set scale command was used to adjust the image scale. These steps are essential for real and accurate measurement of the area. Final steps included thresholding and particle analysis of non-opaque areas in the images. After the measurement of empty area, an excel sheet was used to estimate the final value of the materials' transparency.

Results and Discussion

This experiment was conducted under dry and clear sky conditions. Environmental parameters - i.e., air temperature and relative humidity - were also recorded, as previous studies (Cohen and Fuchs, 1999; Abdel-Ghany and Al-Helal, 2012) reported the effect of these parameters on experimental results. Temperature of surrounding air of sample materials was shown in Fig. 3. Highest difference between maximum and minimum value of temperature was recorded for LD-15 and PE which was more than 8°C. Lowest temperature variation was recorded for LD-13 which was about 6.2°C. Fig. 4 clearly depicts that relative humidity gradually increases as night progresses. Even though air temperature and relative humidity varied significantly but these

Fig. 3. Air temperature logged during the analysis for all materials.

Fig. 4. Relative humidity logged during the analysis for all materials.

Fig. 5. Inward (L_a and L_d) and outward (L_b and L_c) radiations for PH-20.

factors showed no impact on the properties.

Fig. 5 demonstrates the incoming and outgoing radiations of PH-20. Downward radiations were directly mea-

sured by a pyrgeometer and upward radiations were calculated using a procedure reported in (Blonquist Jr *et al.*, 2009).

Fig. 6. Reflectivity of all tested materials.

Fig. 7. Emissivity of all tested materials.

Fig. 8. Transmissivity of all tested materials.

Comparison of the tested samples' reflectivity, emissivity, and transmissivity are presented in Figs. 6-8, respectively. PH-20 showed a high reflectance as compared to the other materials. Such materials can reduce temperatures by 1-7°C, as reported by (Hernández-Pérez *et al.*, 2014). PE

results are in good agreement with the values reported by (Gentle *et al.*, 2013). LD-13 and LD-15 have the same structure, but they differ in that LD-13 has shiny surface. Interestingly, both materials exhibited very similar long-wave radiative properties - value differences did not exceed

Table 3. Average values of radiometric properties

Measuring date	Sample material	Average emissivity	S.D.	Average transmissivity	S.D.	Average reflectivity	S.D.
20-21 Nov-2018	PE	0.439	0.020	0.549	0.021	0.168	0.009
27-28 Nov-2018	LD-13	0.460	0.010	0.382	0.034	0.158	0.021
23-24 Feb-2019	LD-15	0.454	0.004	0.378	0.019	0.168	0.014
20-21 April-2019	PH-20	0.499	0.006	0.129	0.025	0.372	0.025

S.D. = Standard deviation

Fig. 9. Emissive power of black cloth during the analysis of LD-15. **Fig. 10.** Emissive power of black cloth during the analysis of PE

2-3% - even though the surfaces had different lusters. All the materials displayed similar emissivity values, except PH-20, which showed 5-6% more emittance than the other materials. Further, the comparison of the average values of radiometric properties with standard deviation is shown in Table 3.

Emitted radiation of any material is usually measured with the Stefan Boltzmann equation, but in this experiment, the black cloth's emissive power was measured via three methods. First method is based on the famous Stefan

Boltzmann equation, which requires surface temperature and emissivity values. The other two methods are specially designed, based on a similar setup to what was used in this study. The second method's output is simply acquired by multiplying incoming radiations (L_d) with 0.93; and the last method is based on radiation balance equation (4). Figs. 9-10 illustrate the black cloth's emissive power for two tested sample screens. Note that the values obtained using newly described methods are very close to the actual measurement by the Stefan Boltzmann equation.

Figs. 11-14 present the absorbed and emitted radiation results from the tested sample materials. These figures clearly show that emitted radiation (2E) was always greater

than absorbed radiation for all the materials. Similar findings were reported by Abdel-Ghany *et al.*, 2015b, despite the fact that they used different materials and different cal-

Fig. 11. Absorbed and emitted radiations by LD-13.

Fig. 12. Absorbed and emitted radiations by LD-15.

Fig. 13. Absorbed and emitted radiations by PE.

Fig. 14. Absorbed and emitted radiations by PH-20.

Fig. 15. Difference between ambient and screen temperature calculated for each sample.

culational methodology. Emitted radiation primarily depends on the material's absolute temperature and emissivity. Sample materials were also exposed to sunlight for an entire day, prior to the actual experiment start time. This received energy would be released from the materials during the night, as longwave radiation. In contrast, absorbed radiation predominantly relies on sky radiation (L_a), radiation coming from black cloth (L_d), and absorptivity and angle of incident radiation. Another factor in this setup that can add or subtract energy to/from the material is convective exchange. In order to clarify the effect of energy exchange between the air and materials, the temperature difference was measured and recorded. Results are shown in Fig. 15. This diagram demonstrates that ambient temperature was always higher than the screen materials' surface temperature. Higher screen and film temperature is clear evidence of energy flow from air to materials.

Conclusion

Experiment was conducted during night time to investigate the material's potential to conserve energy. Radiation balance method was applied in order to get the absorptive and emissive power along with reflectivity, transmissivity and emissivity of energy-saving greenhouse screens by using wide band radiometer. The ability of materials to save energy is dependent on these properties. Based on the results we concluded that PH-20 has greater potential to conserve as it has high reflectance and better absorptive power as compared to other sample materials. Other three tested materials have same potential to absorb energy. LD-13 and LD-15 showed similar properties so they can save energy with equal capacity but less than that of PH-20. The result of PE showed results opposite to PH-20 as it exhibited nearly zero reflectance and high transmission value.

Surly, PE will radiate more energy due to high transmissivity among the tested materials.

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Symbolization

L_b = Outgoing long-wave radiation above the screen surface in W/m^2
 L_c = Outgoing long-wave radiation over the black surface in W/m^2
 L_d = Incoming long-wave radiation toward the screen above the black cloth in W/m^2
 E_b = Emissive power of the black cloth in W/m^2
 E_s = Emissive power of the screen in W/m^2
 τ_s = Transmittance of the screen
 ρ_s = Reflectance of the screen
 ϵ_s = Emittance of the screen
 ρ_b = Reflectance of the black cloth
 PE = Polyethylene

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온실 스크린의 장파복사 방사율 및 흡수율 결정

라피크아딜¹ · 나육호² · 라쉬드아드난¹ · 김현태³ · 이현우^{1,2,4*}

¹경북대학교 농업토목공학과, ²경북대학교 농업과학기술연구소,
³경상대학교 생물산업기계공학과, ⁴경북대학교 스마트농업혁신센터

적 요. 온실에서 겨울철 야간에는 열손실을 줄이기 위한 목적으로, 여름철 주간에는 차광을 위한 목적으로 스크린을 사용하고 있다. 온실의 냉난방 에너지 절감효과에 큰 영향을 미치는 스크린의 장파복사 방사율과 흡수율은 온실에 설치할 적절한 스크린을 선택하는데 있어서 중요한 요소가 되며 이러한 특성값들을 정확하게 측정할 수 있는 방법이 필요하다. 외부 환경조건에서 스크린의 장파복사 특성의 측정과 관련된 연구가 일부 수행된 바 있지만 모든 종류의 스크린에 적용할 수 있는 방법은 아니고 공극이 있는 스크린 자재에만 적용이 가능한 방법이다. 본 연구에서는 순복사계 및 야간복사계를 사용하여 온실 스크린의 장파복사 흡수량과 방사량을 측정하고, 방사율, 흡수율 및 투과율을 결정하는 새로운 방법을 제시하였다. 특성값의 측정은 공극이 0인 4가지 종류의 스크린 자재에 대하여 수행하였다. 모든 자재가 장파복사 방사량이 흡수량보다 높게 나타났다. PE, LD-13, LD-15 and PH-2의 장파복사 방사율은 각각 0.439 ± 0.020 , 0.460 ± 0.010 , 0.454 ± 0.004 , and 0.499 ± 0.006 범위로 나타났다.

추가주제어: 반사율, 순복사계, 야간복사계, 이미지J