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Methods for determining the temperature of a plastic net under solar and thermal radiation conditions

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ABSTRACT

To determine the energy transfer through a plastic net-covered structure, the temperature of the net (T_n) is an essential parameter. The perforated nature of nets and the effects of solar and thermal radiation, during the daytimes, make it is impossible to measure T_n correctly by using most types of thermometer. Therefore, $\boldsymbol{T_n}$ has never been theoretically estimated or experimentally measured in the presence of solar and thermal radiation.

In this study, T_n was simulated by determining the emissive power of the net (E_n) and the net emittance (ε_n). To determine E_n and ε_n, the net was tacked onto a wooden frame; thermal radiation balance was applied below and above the net surfaces and above the substrate underneath the frame. The downward and upward thermal radiation fluxes were measured below and above the net to be used in the simulation. A simple measuring method was proposed to predict T_n using a thermocouple junction of 0.3 mm in diameter (copper constantan, type-T) inserted into the net texture. The measured values of T_n were in agreement with those predicted by the simulation. The mean absolute difference between the measured and the simulated values of T_n ranged from 0.75 °C to 1.9 °C for all the nets tested.

For nets with low porosity, the inserted junction should keep exposing to the surrounding environment. However, for nets with high porosity, the inserted junction should be shielded from radiation to improve measurements in the correct direction.

1. Introduction

To protect plants against intensive solar radiation in hot and sunny regions, and in order to reduce the construction cost of greenhouses and to provide complete natural ventilation in summer, many farmers worldwide are using full-scale net houses. The net houses use low cost plastic shading nets as covering materials instead of polyethylene or glass sheets. In addition, plastic nets have many economical and environmental advantages over plastic films [1–4]. A perforated net acts as a barrier between the plants and the ambient environment thus, protecting a crop from the frost in winter and sun spots in summer [5]. In order to investigate the heating or cooling load and the ventilation rate in the net houses, the energy balance needs to be analyzed. The surface temperature of the net cover T_n is an essential parameter needed for such energy analysis.

Computational fluid dynamic (CFD) has been used to determine the temperature and air velocity profiles in greenhouses [6–10], and may also be useful for investigating the air flow pattern and temperature profile in net houses. In such studies, CFD simulations often require T_n to specify boundary conditions. In net houses, as in greenhouses, T_n can be calculated by simulation modeling of the energy transfer. In the theoretical models, a set of equations is needed to describe the energy balance of the net cover and the other components inside the net house (*i.e.* inside air, floor soil and plants). However, complex analysis and much computation effort are needed to predict T_n simultaneously with the temperatures of the other components. Moreover, modeling includes different approaches and assumptions regarding the dynamic nature of the environment in the net house that may affect the accuracy of the predicted values of T_n. Searches of the literature failed to find either a computational method to determine T_n precisely or a measuring technique for T_n. Measuring T_n is difficult because it is difficult to fix a temperature probe to the net surface (*i.e.*, flexible) properly. Thus, the applicability of inserting a thermocouple junction into the net texture for measuring T_n needs to be examined under solar and thermal radiation conditions.

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Nomenclature

Symbols

D_{MA}	mean absolute difference, °C
E_{MA}	mean absolute error, °C
E_n	emissive power of the net, W m^{-2}
E_w	emissive power of the substrate, W m^{-2}
L_1	sky downward thermal irradiance, W m^{-2}
L_2	upward thermal radiation flux over the net surface, W m^{-2}
L_3	downward thermal radiation flux below the net surface, W m^{-2}
L_4	upward thermal radiation flux below the net surface, W m^{-2}
T_a	ambient air temperature, °C.
T_n	temperature of the net, K
T_w	substrate temperature, K
S_{n1}	net solar radiation flux over the net, W m^{-2}
S_{n2}	net solar radiation flux below the net, W m^{-2}
S_i	incident solar radiation flux over the net, W m^{-2}
ΔT_R	temperature correction factor due to radiation effect on the thermocouple junction, °C

Greek symbols

α_n	total absorptance of the net to long-wave (thermal) radiation
ϕ	porosity of the net
ε_n	total hemispherical emittance of the net
ε_w	total hemispherical emittance of the substrate
ρ_n	total hemispherical reflectance of the net to long-wave (thermal) radiation
ρ_w	total hemispherical reflectance of the substrate to long-wave (thermal) radiation
σ	Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
τ_n	total transmittance of the net to long-wave (thermal) radiation

In previous studies a bare thermocouple junction (0.3 mm in diameter) had been used to measure glass surface temperature under day time conditions [11,12]. It was found that solar and thermal radiation have a significant effect on the junction temperature, resulting in an overestimation of the measured temperature, while the air currents around the junction up to 5 m s^{-1} had no significant effect [12]. Thus, a correction factor was provided to exclude the effect of solar and thermal radiation on the thermocouple measurements. The correction factors (ΔT_R) in °C should be subtracted from the thermocouple reading; ΔT_R as a function of the incident solar radiation flux (S_i) is given by [12] as.

$$\Delta T_R = A + B(1.0 - e^{CS_i}) \tag{1}$$

where $A=-0.22$, $B=5.11$ and $C=-0.0024$. Eq. (1) can be applied for greenhouse covers or any other substrates having homogeneous surfaces.

Infra-red (IR) thermometers work well with homogeneous surfaces such as glass or plastic films that do not transmit thermal radiation. However, in the case of plastic nets (perforated surfaces) IR thermometers cannot measure T_n correctly because they detect thermal radiation ($\lambda > 3$ μm) emitted not only from the net surface but also from surrounding objects and sky. An easy and inexpensive method to measure the net temperature is to use a thermocouple junction which is more popular and cheaper than other measuring instruments.

Accordingly, the objectives of this study were to: (i) Measure the net temperature (T_n) by using a thermocouple junction. (ii) Develop an algorithm (thermal radiation balance) aided with measured input parameters (i.e., downward and upward thermal radiation fluxes) to simulate the values of T_n correctly under natural conditions of solar and thermal radiation. Thermal radiation exchange only was considered to simulate T_n; however, convection exchanges as well as energy balance of the net are beyond the scope of this study. The simulated values of T_n will be considered as a reference to validate the proposed measuring methods. (iii) Develop a correction factor, if necessary, for correcting the measured temperature by using the thermocouple. Because the thermal radiation exchanges with the net strongly depends on color and porosity, nets with different colors and porosities (white, beige, green and dark green) were selected for the study.

2. Materials and methods

2.1. Shading net materials

Manufacturers usually designate a net by the net color followed by the nominal shading power (%). For example, white-50 means the net is white and it blocks 50% of the incident solar radiation. The selected nets for the experiments were made from high-density polyethylene (HDPE); their textures are colored and opaque to transmit solar and thermal radiation. In previous studies [13,14], the porosities (ϕ) of these nets were measured with an image processing method. The porosities of the selected nets were: white-50, $\phi=0.28$; green-50, $\phi=0.51$; beige-80, $\phi=0.12$; and dark-green-80, $\phi=0.21$ [13,14]. To show the different structures of the net textures, scanned photos were magnified several time and illustrated in Fig. 1. Description of the net textures are: white-50 is longitudinal interlaced threads like woven robs (2 mm, diameter) held by wires (1 mm, diameter); green-50 is also longitudinal interlaced threads (1.75 mm, diameter) held by wires (1 mm, diameter); beige-80 is longitudinal strips (1.2 mm thick; 2 mm width) held by interlaced strips; and dark green-80 is knitted wires (1 mm, diameter) performed irregular openings.

2.2. Measuring the required parameters

To theoretically and experimentally investigate the net temperature (T_n), experiments were conducted on clear sunny days under solar and thermal irradiance on the roof of the building of the Agricultural Research and Experiment Station at King Saud University (Riyadh, Saudi Arabia, 46° 47′ E, longitude and 24° 39′ N, latitude). Each net sample was tested during a 24-h period (from 6 am to 6 am of the next day) from April 3 to June 11, 2012. A wooden frame was constructed for the experiment (Fig. 2), its base was covered with black cloth having an emissivity (ε_w) of 0.93 and its sidewalls and top were hollow. The frame was 1.5 m width × 2 m length × 0.5 m height. Layout dimensions and locations of the instruments used to measure the required parameters are illustrated, not to scale, in Fig. 2. The frame in Fig. 2 was oriented longitudinally in the E–W direction and mounted horizontally at 1 m above the roof of the building. Un-stretched net samples were tacked onto the frame, draped and fixed on the frame upper sides. Horizontal bars were mounted 0.25 m above and below the center of the frame (Fig. 2) to support the albedometers and