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Theoretical and experimental study of solar thermal performance of different greenhouse cladding materials

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Abstract

A theoretical nongray rigorous model was constructed to study the radiative heat transfer through different greenhouse covering materials by using Radiation Element Method by Ray Emission Model (REM^2). This model was applied to find the difference in thermal performances performed by greenhouses that were covered with different claddings such as silica glass, Polyvinylchloride (PVC) and Low Density Polyethylene (LDPE) materials. By utilizing the wide-range spectral radiative properties (0.22–25 μm) for these materials and taking into account the absorption and emission within the covering material, precise estimations of greenhouse temperatures have been achieved. Moreover, differences in greenhouse (enclosures) temperatures have been confirmed between the semi-transparent plastic films and opaque glass. In addition, outdoor experiments were conducted to measure how much heat can be trapped inside the three identical rectangular enclosures covered by the above mentioned materials. Enclosure inside air, ground surface and cover temperatures' measurement showed a good agreement with the calculated ones by using the rigorous model.

Keywords: Greenhouse effect; Radiation trapping; Thermal performance; Nongray; Glass; Plastic

1. Introduction

Earth is subjected to solar radiation in every single day. Small portion of the solar radiation is absorbed and reflected by stratosphere and troposphere. The rest of this radiation reaches the earth surface and contributes in heating it up. This natural phenomenon is followed by re-emission of longwave infrared (IR) radiation from the earth surface back to the atmosphere. This reemitted longwave radiation will be absorbed by the atmospheric components such as clouds and the natural and manmade greenhouse gases (Ramanathan et al., 1989). Therefore, in a global scale, the heat is retained in the atmosphere and, thus, the earth surface temperature rises. This phenomenon is widely known as the "atmospheric effect".

On the other hand, in a smaller scale, an agricultural greenhouse is constructed to provide appropriate microclimate conditions for plant growth and crop production. The greenhouses are normally covered with transparent materials to the solar radiation such as glass or plastic film

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Nomenclature

$A^R_{i,\lambda}$	effective area (m^2)
$F^A_{j,i}$	absorption view factor from element j to element i (–)
$F^D_{j,i}$	diffuse reflection view factor (–)
$F^E_{j,i}$	extension view factor (–)
G_i	incident irradiance on the radiative element ($W\,m^2$)
h	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
I	radiation intensity ($W\,m^{-2}\,\mu m^{-1}\,sr^{-1}$)
k	imaginary part of index of refraction (–)
n	real part of index of refraction (–)
Q_J	heat transfer rate of diffuse radiosity (W)
Q_T	heat transfer rate of emissive power (W)
Q_X	heat transfer rate of heat generation (W)
$\dot{q}_r$	total radiative heat flux ($W\,m^{-2}$)
q_X	heat flux of surface element or divergence of heat flux for volume element
q	mode of heat flux ($W\,m^{-2}$)
T	temperature (K)
Nu_L	Nusselt number (–)
Ra_L	Rayleigh number (–)
Pr	Prandtl number (–)
H	enclosure air thickness (m)
L	enclosure length (m)
g	gravitational acceleration ($9.81\,ms^{-2}$)

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κ	absorption coefficient (m^{-1})
β	extinction coefficient (m^{-1})
β_a	air volumetric thermal expansion coefficient (K^{-1})
α	thermal diffusivity ($m^2\,s^{-1}$)
v	kinematic viscosity ($m^2\,s^{-1}$)
Λ	thermal conductivity of air ($W\,m^{-1}\,K^{-1}$)
ω	single scattering albedo (–)
ω^D	diffuse reflectivity of surface element or albedo of volume element (–)
ω^S	specular reflectivity (–)
σ	Stefan–Boltzmann constant ($5.670 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$)
τ	surface tilt angle from horizontal (°)
τ^*	critical tilt angle (°)
φ	latitude angle (°)
δ	solar declination angle (°)
ψ	hour angle (°)
ζ	solar zenith angle (°)
θ^i	solar incident angle on a tilted surface (°)
γ	surface azimuth angle measured from north (°)
ε	emissivity (–)
μ	direction cosine of the polar angle
ϕ	scattering phase function (sr^{-1})

Subscripts

b	black body
c	greenhouse cover
p	black soil surface
i	element i
j	element j
λ	spectral value
s	heat flux sensor surface
∞	ambient air
in	inside greenhouse cover surface
out	outside greenhouse cover surface
$cond$	conduction mode of heat flux
rad	radiation mode of heat flux
$conv$	convection mode of heat flux

(Giacomelli and Roberts, 1993; Spanomitsios, 2001; Ting and Giacomelli, 1987). The temperature inside a greenhouse is increased due to two main physical reasons. The first reason is called the "heat trapping" which is basically the trapping of IR radiation by the greenhouse covering material. Similar to "atmospheric effect" phenomena, the greenhouse covering material can be highly transmitted to shortwave radiation and absorbing the reemitted longwave radiation from the warm soil surface, etc. For this reason, the heat is built up inside the greenhouse system by what it is called "greenhouse effect". The second cause is that the greenhouse structure is an "enclosed" space (Hasson, 1990; Kumar and Tiwari, 2006; Mastalerz, 1977). The greenhouse is constructed to be an enclosure that helps to inhibit the convective heat loss by the outer ambient environment.

Although there is a world-wide understanding about the "greenhouse effect", there is still a debate on whether there is major influence by this phenomenon on the temperature of the earth surface. This debate has started by experiment conducted by the physicist Wood (1909). Wood had drawn the attention to the fact that the radiation "trapping" might not contribute in rising up the temperature even though he had not intensely gone into the matter. Other studies suggested that the elevated temperature observed under glass cannot be traced to the spectral absorptivity of the glass (Lee, 1973).

The thermal performances of different greenhouse materials were theoretically estimated in some studies. Based on infrared transmission properties of greenhouse materials, Hanson (1963) has estimated the protection index by different greenhouse covering materials against nocturnal IR radiation. Hanson realized that window glass had the highest heat protection (93%) and polyethylene film had the lowest (26%). Blaga (1978) has reported the differences of some efficient plastics which are commonly used in glazing