Energy and Buildings 43 (2011) 1740–1747

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Energy partition and conversion of solar and thermal radiation into sensible and latent heat in a greenhouse under arid conditions

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ARTICLE INFO

Article history:
Received 26 October 2010
Received in revised form 20 February 2011
Accepted 18 March 2011

Keywords:
Radiation flux
Energy balance
Heat factors
Greenhouses
Arid regions

ABSTRACT

For a greenhouse thermal analysis, it is essential to know the energy partition and the amount of solar and thermal radiation converted into sensible and latent heat in the greenhouse. Factors that are frequently needed are: efficiency of utilization of incident solar radiation (π), and sensible and latent heat factors (η and δ). Previous studies considered these factors as constant parameters. However, they depend on the environmental conditions inside and outside the greenhouse, plants and soil characteristics, and structure, orientation and location of the greenhouse. Moreover, these factors have not yet been evaluated under the arid climatic conditions of the Arabian Peninsula.

In this study, simple energy balance equations were applied to investigate π, η and δ; energy partitioning among the greenhouse components; and conversion of solar and thermal radiation into sensible and latent heat. For this study, we used an evaporatively cooled, planted greenhouse with a floor area of 48 m^2. The parameters required for the analysis were measured on a sunny, hot summer day. The results showed that value of π was almost constant (≅0.75); whereas the values of η and δ strongly depended on the net radiation over the canopy (R_{na}); and could be represented by exponential decay functions of R_{na}.

At a plant density corresponding to a leaf area index (*LAI*) of 3 and an integrated incident solar energy of 27.7 $MJ\,m^{-2}\,d^{-1}$, the solar and thermal radiation utilized by the greenhouse components were 20.7 $MJ\,m^{-2}\,d^{-1}$ and 3.74 $MJ\,m^{-2}\,d^{-1}$, respectively. About 71% of the utilized radiation was converted to sensible heat and 29% was converted to latent heat absorbed by the inside air. Contributions of the floor, cover and plant surfaces on the sensible heat of the inside air were 38.6%, 48.2% and 13.2%, respectively.

1. Introduction

In the Arabian Peninsula, because of its arid climate, scarce water resources and poor-quality of land resources, is not well suited for crop production. As a results, the use of greenhouses for crops production is rapidly increasing. However, achieving favorable environment in the greenhouses under hot and sunny summer conditions has become one of the major challenges still facing designers and growers. Crop productivity depends on the environment and more specifically on the thermal performance of the greenhouse system. The latter is usually predicted by using mathematical models, with proper assumptions, aided by some environmental parameters measured outside and inside the greenhouse. Evaluation of the thermal performance of a greenhouse requires an understanding of the energy exchanges among its components (i.e., the cover, plants, soil and inside air) and the amounts of solar and thermal radiation that are converted into sensible and latent heat. Previous studies have used three parameters to quantify the efficiency of utilization and the amount of solar and thermal radiation converted into sensible and latent heat in the greenhouse:

(a) Evaporation coefficient (δ), is also defined as the evaporation efficiency, or latent heat factor, which estimates the fraction of the transmitted global solar radiation (S_i) that is taken up by evapo-transpiration in the greenhouse. Based on this definition, several values for δ were reported in the range from 0.22 to 0.5 [1–3]. However, it is better to define δ as the ratio of latent heat to the net solar and thermal radiation above the plant canopy (R_{na}). Based on this definition, the value of δ was in the range of about 0.25–1.25 during the maximum radiation load at solar noon [4].
(b) Solar radiation heating factor (η), is also defined as the sensible heat factor, which estimates the fraction of S_i that is transformed to sensible heat contributing to the greenhouse air temperature increases. Several values of η were reported in the range between 0.1 and 0.7 [1–6].

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doi:10.1016/j.enbuild.2011.03.017

Nomenclature

Alphabetic symbols

D	heat flux conducted into the soil ($W\,m^{-2}$)
ET	evapo-transpiration rate of plant and pot's soil surface ($kg\,m^{-2}\,s^{-1}$)
H	sensible heat flux in the greenhouse ($W\,m^{-2}$)
h	enthalpy of moist air ($kJ\,kg^{-1}$)
LAI	leaf area index (surface area of plant leaves per unit area of floor) (–)
L_{n1}, L_{n2}	net thermal radiation fluxes above and below the plant layer ($W\,m^{-2}$)
$\dot{m}_a$	ventilation rate of the greenhouse air ($kg\,s^{-1}$)
Q_L	sensible heat flux exchanges between inside and outside the greenhouse ($W\,m^{-2}$)
Q_{c-a}	convective heat exchanges between the cover and inside air ($W\,m^{-2}$)
Q_{p-a}	convective heat exchanges between the plant and inside air ($W\,m^{-2}$)
Q_{s-a}	convective heat exchanges between the floor and inside air ($W\,m^{-2}$)
RH	relative humidity of air (%)
$R_\uparrow$, $R_\downarrow$	upward and downward effective reflectance of the combined cover–plant system(–)
R_{na}, R_{nb}	net (solar and thermal) radiation above and below the plants ($W\,m^{-2}$)
R_{np}, R_{ns}	net (solar and thermal) radiation absorbed by the plant layer and floor ($W\,m^{-2}$)
S_i	global solar radiation flux transmitted into the greenhouse ($W\,m^{-2}$)
S_L	solar energy lost to outside the greenhouse ($W\,m^{-2}$)
S_{n1}, S_{n2}	net solar radiation fluxes above and below the plants ($W\,m^{-2}$)
S_o	global solar radiation flux outside the greenhouse ($W\,m^{-2}$)
T_d	dry bulb temperature of air (°C)
T_w	wet bulb temperature of air (°C)
$T_\uparrow$, $T_\downarrow$	upward and downward effective transmittances of the combined cover–plant system (–)
U	overall heat transmission coefficient of the greenhouse cover ($W\,m^{-2}\,°C^{-1}$)

Greek symbols

δ	latent heat factor (–)
η	sensible heat factor (–)
λ	latent heat due to vaporization of water ($J\,kg^{-1}$)
π	solar radiation utilization efficiency (–)
ρ_C	reflectance of the greenhouse cover to global solar radiation (–)
ρ_∞	effective reflectance of the plant layer to global solar radiation (–)
ρ_s	reflectance of the floor surface to global solar radiation (–)
τ_c	transmittance of the greenhouse cover to global solar radiation (–)
τ_p	effective transmittance of the plant layer to global solar radiation (–)
ψ	cover-to-floor surface area ratio (–)
ξ	fraction of the incident solar radiation that is lost to outside the greenhouse (–)

Subscripts

c	condition of the cooled air exiting the wet pad (°C)
e	condition of the exhausted air from the greenhouse (°C)
f	condition of air exiting the fans (°C)
m	the mean condition of air inside the greenhouse (°C)
o	condition of air outside the greenhouse (°C)

The δ factor has been used in the ASAE standard (1999) to simply define the sensible heat balance of the greenhouse air [4] as:

$$(1-\delta)S_i = U(T_{dm} - T_{do}) + \dot{m}_a Cp_a (T_{de} - T_{do}) \quad (1)$$

where T_{dm}, T_{do} and T_{de} are the mean dry bulb temperatures of the inside air, outside air and air exhausted from the greenhouse, respectively. U is the overall heat loss coefficient of the greenhouse cover and $\dot{m}_a$ is the mass flow rate of the ventilated air. In Eq. (1) the transmitted solar radiation (S_i) was assumed to be completely transformed into sensible and latent heat added to the greenhouse air, which means $\delta + \eta = 1$. However, Eq. (1) is valid only when the greenhouse floor soil is covered with a dense canopy, in which case the soil heat flux (D) is expected to be minor and can be neglected. In addition, a portion of the transformed sensible heat is lost to outside the greenhouse, which means T_{dm} is always higher than T_{do}. Accordingly, Eq. (1) is not suitable for a greenhouse without plants or a greenhouse that has a thin canopy or a greenhouse that uses a cooling system during hot summer conditions ($T_{dm} < T_{do}$).

(c) Efficiency of utilization (π), which is an estimate of the fraction of the outside global solar radiation (S_o) that was utilized by the greenhouse system. Under steady state condition, π is also defined as the incident solar radiation minus the solar radiation lost to outside the greenhouse ($S_o - S_L$) divided by S_o. Several values of π were reported in the range between 0.32 and 0.79 [1,7–11].

In fact, the factors π, δ and η are no longer adjusted constants; they change with the time of the day and depend on several parameters such as: solar and thermal radiative properties of the greenhouse components, soil surface conditions, plant characteristics, greenhouse configuration, location and its orientation, ventilation rate, the presence of evaporative cooling in the greenhouse and the environmental conditions inside and outside the greenhouse. Therefore, several values for each factor (i.e., π, δ and η) are given in the literature.

A survey of previous studies that estimated these factors revealed that: (i) The conduction heat flux into the greenhouse soil (D) was often neglected as in Eq. (1). (ii) The contribution of thermal radiation to the greenhouse thermal balance and its effects on the values of π, δ and η were neglected. (iii) The transmitted solar radiation into the greenhouse (S_i) was assumed to be completely utilized by the greenhouse components; however, the fraction of S_o that is lost to outside the greenhouse (S_L) was neglected. (iv) The net radiation above the canopy (R_{na}) was assumed to be absorbed completely by plants and then released as sensible and latent heat (H and λET) to the inside air. However, this assumption is valid only when the greenhouse includes a dense canopy that covers the floor soil. (v) In some instances η was evaluated by determining the convective heat transfer from the greenhouse components to the inside air using Newton's law of cooling. This method depends on the convective coefficients between these components and the inside air. These coefficients were derived mainly from in situ measurements, and thus several correlations for each convective coefficient