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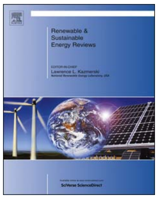

A review on thermal models for greenhouse dryers

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ABSTRACT

This review paper appraisal the previous work on the thermal modeling of greenhouse drying systems. Thermal modeling plays a significant role in ideal design and development of the greenhouse dryer. It is also very useful tool in optimizing the drying parameters to enhance the performance of greenhouse drying systems under various modes of operation. The crop and greenhouse room air temperature, relative humidity inside greenhouse, drying rate, drying kinetics and drying potential can be estimated precisely from thermal modeling. This piece of work is a comprehensive review of various thermal modeling done by researchers for greenhouse drying systems. The greenhouse dryer can be designed for a given mass of crop as well as location of installation from energy balance equations. This review will be valuable and appropriate for further development of energy efficient greenhouse drying systems.

1. Introduction

Greenhouse effect is a process of warming the earth's environment by the trapping the outgoing long wavelength solar radiation. The air is transparent for incoming short wavelength solar radiation and further it falls upon the earth's surface where it gets absorbed. The surface of the earth emits solar radiation back in the form of infrared radiation (long wavelength solar radiation). Infrared rays are absorbed by atmospheric gases like carbon dioxide, methane, nitrous oxide and water vapor. The trapping of infrared radiation by the atmospheric gases and earth surface, increases the temperature of the surrounding. This fact is known as the greenhouse effect [1–3].

A greenhouse system is an enclosed structure of transparent medium (glass/polyethylene/ polycarbonate sheet) which is largely transparent for incoming short wavelength solar radiation. The system traps the long-wavelength radiation to create a favorable micro-climate. Some applications of the greenhouse system are; crop cultivation, poultry, aquaculture, soil solarisation, and crop drying. Greenhouse drying is one of the oldest process of crop preservation and utilized throughout the world [4–6]. It involves heat and mass transfer phenomenon. The heat energy supplied to the product is utilized in two steps. In the first step, product temperature increases in the form of sensible heat and in the second step, the moisture present in product vaporizes through the provision of the latent heat of vaporization [7,8]. The greenhouse dryer offers controlled environment in terms of relative humidity and temperature, which is more favorable for the crop drying, therefore, shortening the drying time [8,9]. The design of greenhouse system involves following major steps [1,9,10]:

- To select exact location (latitude) and orientation for greenhouse system installation.
- To select proper shape and size according to the nature of the crop and quantity to be dried.
- To write energy balance equations for different components in terms of solar fraction, solar radiation, ambient air temperature, wind velocity and heat transfer coefficient.
- To write energy balance equation to obtain the greenhouse room air temperature for a given climatic condition and design parameters.

A system of partial differential equations for heat and mass transfer has been developed for solar greenhouse dryer thermal modeling [11,12]. Thermal models are developed with assumptions for predicting the performance of the greenhouse dryers under natural and forced convection modes of operation [13,14]. A thermal model was introduced to estimate the air temperature inside the greenhouse on the basis of ambient conditions [15,16]. An optimal model is developed for alfalfa drying by considering the differences in drying behavior between stems and leaves of alfalfa, and temperature and mass balances of the

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Nomenclature

α_{cp}	absorptivity
σ	Stefan Boltzmann's constant (W/m^2 K^4)
β	coefficient of volumetric expansion of humid GHD air (1/°C)
γ_{rm}	relative humidity air (%)
λ	latent heat of vaporization (J/kg)
μ	dynamic viscosity of humid air (kg/m)
ρ	density of humid air (kg/m^3)
τ_c	transmissivity
A_{cp}	area of the cover material (m^2)
A_f	area of the concrete floor (m^2)
A_{in}	cross-section area of the air inlet (m^2)
A_{out}	cross-section area of the air outlet (m^2)
A_p	area of the product (m^2)
a_w	water activity
B	parameter of thin layer drying model
C	specific heat (J/kg °C)
C_d	coefficient of diffusivity
C_1	labor cost for construction of dryer (USD)
C	annual cost of the system (USD)
C_m	material cost of dryer (USD)
C_{pa}	specific heat of air (J/kg K)
C_{pc}	specific heat of cover material (J/kg K)
C_{pf}	specific heat of floor (J/kg K)
C_{pl}	specific heat of liquid (J/kg K)
C_{pp}	specific heat of product (J/kg K)
C_{pv}	specific heat of water vapor (J/kg K)
C_T	total capital cost of dryer (USD)
d_m	dry mass in the crop (kg/kg of the crop)
e	root mean square of percent deviation
F_n	fraction of solar radiation
f (t)	time-dependent derivative
F_p	fraction of solar radiation falling on the product (decimal)
g	acceleration due to gravity (m/s^2)
H	humidity ratio of air inside the dryer (kg/kg)
H_{in}	humidity ratio of air entering the dryer (kg/kg)
H_{out}	humidity ratio of the outlet air of the dryer (kg/kg)
h_{cvt}	convective heat transfer coefficient of crop (W/m^2 °C)
$h_{cvt,c\text{-}a}$	convective heat transfer between the cover and the air (W/m^2 K)
$h_{r,c\text{-}s}$	radiative heat transfer between the cover and the sky (W/m^2 K)
$h_{cvt,f\text{-}a}$	convective heat transfer between the floor cover and the air (W/m^2 K)
$h_{cvt,p\text{-}a}$	convective heat transfer between the product and the air (W/m^2 K)
$h_{r,p\text{-}c}$	radiative heat transfer between the product and the cover (W/m^2 K)
h_w	convective heat transfer between the cover and the ambient (W/m^2 K)
$h_{D,f\text{-}g}$	conductive heat transfer between the underground and floor (W/m^2 K)
I_i	solar intensity on greenhouse wall/roof (W/m^2)
I_t	incident solar radiation (W/m^2)
k_c	thermal conductivity of insulation material (W/m K)
k_a	thermal conductivity of air (W/m K)
k_f	thermal conductivity of floor material (W/m K)
L_p	latent heat of vaporization of moisture from product (J/kg)
M	moisture content of product (db, decimal)
M_{dry}	amount of dried product per year (kg)
M_e	equilibrium moisture content of product (db, decimal)
M_f	amount of fresh product per year (kg)
M_o	initial moisture content of product (db, decimal)
M_p	moisture content of dry product (db, decimal)
m	mass (kg)
m_a	mass of air inside the dryer (kg)
m_c	mass of the cover (kg)
m_{ev}	moisture evaporated (kg)
m_f	mass of concrete floor (kg)
m_p	mass of product (kg)
N	life span of the dryer (year)
Nu	Nusselt Number for GHD air
Pr	Prandtl Number for GHD air
P(T)	partial vapor pressure at temperature T (N/m^2)
ΔP	difference in partial pressure (N/m^2)
Q_e	rate of heat utilized to evaporate moisture (J/m^2 s)
R	coefficient for linear expression of partial pressure
Re	Reynolds number (e)
Rh	relative humidity (decimal)
T	time (s)
T_a	air temperature in the dryer (K)
T_{am}	ambient temperature (K)
T_c	canopy temperature (K)
T_f	floor temperature (K)
T_g	ground temperature (K)
T_{in}	temperature of the inlet air of the dryer (K)
T_p	temperature of product (K)
T_{out}	temperature of the outlet air of the dryer (K)
T_s	sky temperature (K)
U_c	overall heat loss coefficient from the cover to ambient air (W/m^2 K)
U_i	overall heat loss (W/m^2 °C)
V	volume of the drying chamber (m^3)
V_a	air speed in the dryer (m/s)
V_{in}	inlet airflow rate (m^3/s)
V_{out}	outlet airflow rate (m^3/s)
V_w	wind speed (m/s)
v_{in}	inlet air speed (m/s)
v_{out}	outlet air speed (m/s)
W	width of the dryer floor (m)
W_m	X_m/X_{m0} dimensionless water content
X	Characteristic constant
X_m	water content (kg water/kg dry matter)
Z	drying cost (USD/kg)

drying air. The complete model is employed to estimate the dynamic optimal operation for alfalfa thin layer drying [17]. The operation of the solar tunnel dryer for pineapple slices drying under Bangladesh climatic conditions was studied. The proximate analysis indicated that the dried pineapple was a good quality product for human consumption [18]. Mathematical models were introduced to analyze the thermal behavior of solar cabinet dryer to predict the hourly variation of crop temperature and the rate of moisture evaporation under constant and falling drying rates [19,20]. Energy balance equation based simulation code was developed to predict the moisture ratio and crop temperature with respect to drying time for carrots and apple slices in a solar greenhouse dryer [21]. The solar heat collection characteristics of a fiber reinforced plastic greenhouse drying were observed and a mathematical model was proven to predict the greenhouse air temperature on the basis of ambient conditions [22]. An analytical study was performed in two cases of forced convection greenhouse dryers. A linear function between the solar radiation and the greenhouse temperature was observed by considering the greenhouse as a solar