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Development of a sustainable methodology for life-cycle performance evaluation of solar dryers

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ABSTRACT

An innovative methodology for the performance evaluation of solar dryers, which considers the total life-cycle (LC) energy effectiveness in present-value terms, has been proposed. In this method, the performance of solar dryers has been defined in terms of a set of performance parameters, called present value performance indicators (PVPIs). By applying the concept of unsteady-state mass and energy balances for solar kilns, and using known diffusion and heat transport equations from drying theory, a mathematical model was constructed and subsequently solved to predict the future thermal energy inflows and outflows as part of the assessment of the performance parameters. In order to illustrate the overall methodology proposed in this study, the model has been applied, as an example, to a case-study greenhouse-type solar kiln (i.e. Oxford) in the context of hardwood drying in Australia. The current methods used for the performance evaluation of solar dryers have also been reviewed, and it was found that the proposed method was likely to overcome the shortcomings and inadequacies of the current practices for assessing the performance of solar dryers. A sensitivity analysis was carried out in order to assess the robustness of the estimated performance indicators against the uncertain parameters.

1. Introduction

The use of solar energy for low-temperature commercial and industrial applications is increasing worldwide and being considered as one of the most promising areas for the utilization of solar energy (Janjai et al., 2011; Prakash and Kumar, 2014). Concerns regarding greenhouse gas (GHG) emissions (related to the rapid depletion of fossil fuels), together with drying being an energy-intensive process, has prompted the development of solar drying systems on an industrial scale (Luna et al., 2009; Pirasteh et al., 2014; Romano et al., 2009; Sharma et al., 2009). However, the development of solar-drying technology, such as large-scale solar drying facilities, must be based on sound knowledge of the energy resource and the anticipated performance of the associated dryer (i.e. kiln) designs over the expected service life (Singh and Kumar, 2012). In the case of solar kilns, the selection process of kilns for a particular application is based on small-scale experimental testing to assess the kiln performance (Hasan and Langrish, 2014a; Langrish et al., 1997). One of the main difficulties for this experimental approach is the involvement of a large number of variables that vary in time and with the geographic location, as mentioned by Langrish et al. (1992) and Thibeault et al. (2010). Moreover, different drying materials have different drying properties (e.g. drying rates) even with the same environmental conditions. This situation makes it problematic to compare the performances between solar dryers of different designs based purely on experimental studies.

Over the last three decades, many numerical and experimental studies, including Aktaş et al. (2009), Jairaj et al. (2009), Romano et al. (2009), and Smitabhindu et al. (2008) for various solar dryers, have been carried out. Most solar dryers were designed for specific drying materials or climatic conditions. The simulation studies were also either type- and site-specific or did not consider long-run performance indicators. Thus, it is necessary to develop a robust methodology/tool that is capable of predicting and comparing the performances between the kiln designs with a range of drying materials, climatic conditions, and geographical locations. This approach may assist kiln manufacturers/designers in improving solar kiln designs and users in selecting appropriate dryers.

Literature reviews of existing performance evaluations for solar dryers reveal that, despite several simulation and experimental studies being carried out, no attempt has been made to develop a standard and robust LC performance evaluation method, so that it can be utilized for performance comparison between the kiln

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Nomenclature

d	discount rate (%)
LC	life-cycle
$DPBP$	discounted payback period (years)
F_v	future value of energy
FCV	future consumption value (J)
FPV	future production value (J)
P_v	present value of energy (J)
$NPVEER$	net present value to embodied energy ratio
IRR	internal rate of return (%)
$MARR$	minimum attractive rate of return (%)
MC	moisture content (kg kg^{-1})
n	time into the kiln service life
E	modulus of elasticity (Pa)
NPV	net present value (J)
Q	radiation energy flow rate (W)
A	surface area (m^2)
I_T	total solar radiation (W m^{-2})
G_{cb}	beam radiation
R_b	ratio of the beam radiation on a tilted surface to that on a horizontal surface
G_{cd}	diffuse radiation (W m^{-2})
h	heat transfer coefficient (W m^2 K^{-1})
k_G	thermal conductivity (W m^{-1} K^{-1})
g	acceleration due to gravity (m s^{-2})
X	timber moisture content (kg kg^{-1})
D	diffusion coefficient (m^2 s^{-1})
D_r	reference diffusion coefficient (m^2 s^{-1})
VR	venting rate (kg s^{-1})
D_E	activation energy (K)
Z	distance through the timber thickness (m)
$NEBCR$	net benefit to loss ratio
$TPCV$	total present consumption value
$TPPV$	net present production value
$TPEL$	total present energy losses
SG	solar gain (W)
CL	convection losses (W)
RL	radiation losses (W)
M	thermal mass (J K^{-1})
T	temperature (K)
Y	air humidity (kg kg^{-1})
E_n	net energy flow rate (W)
W_n	net water flow rate (kg s^{-1})
C	convection heat transfer (W)
TR	thermal radiation heat transfer (W)
SR	solar radiation heat transfer (W)
$Evap$	evaporation rate (kg s^{-1})
$Cond$	condensation rate (kg s^{-1})
T_p	plate temperature (K)
$Hvap$	latent heat of vaporization (J kg^{-1})
WS	water spray rate (kg s^{-1})
LR	leakage rate (kg s^{-1})
PVPI	present value performance indicator

Greek symbols

η_p	pick-up efficiency (%)
η_d	drying efficiency (%)
η_{d1}	first-day drying efficiency (%)
η_{pd}	present drying efficiency (%)
C_p	specific heat capacity of a component (J kg^{-1} K^{-1})
C_{pt}	specific heat capacity of timber (J kg^{-1} K^{-1})
ρ_t	timber density (kg m^{-3})
k	timber thermal conductivity (W m^{-1} K^{-1})
γ	the slope angle (radians)
ρ_g	reflectance of the ground
ε_p	emissivity of the panel
τ	transmissivity of cover
βp	reflectivity of the panel
βc	reflectivity of the cover
ρ_G	density of the air (kg m^{-3})
μ_G	dynamic viscosity of the air (kg m^{-1} s^{-1})
β	thermal expansion coefficient (m m^{-1} K^{-1})

Subscripts

f	floor
air	internal air
nr	north roof
sr	south roof
na	north absorber
sa	south absorber
$intw$	internal walls
$intf$	internal floor
int	internal
w	walls
a	ambient
$extsr$	external south roof
$intsr$	internal south roof
$extnr$	external north roof
$intnr$	internal north roof
$intsa$	internal south absorber
$intna$	internal north absorber

designs in present value terms. This paper first describes the state of the art for evaluating the performance of solar dryers. Based on the shortcomings and inadequacies of the prevailing procedures, a novel method for LC performance analysis of solar dryers has been presented in this paper.

2. State of the art

To assess the performance of different solar dryers, several methods and procedures, including Bucki and Perre (2003), Perré and Turner (2002), Romano et al. (2009), Smitabhindu et al. (2008), and Wan and Langrish (1995), have been reported in the literature. It was found by Chadwick and Langrish (1996) that cyclic drying (solar drying) of wood gave better quality products with a comparatively shorter drying period than continuous drying. The theoretical and experimental studies on the performance of solar kilns for wood drying have been carried out by Khater et al. (2004) and Helwa et al. (2004), respectively. However, these studies were limited in their capacity to consider the variability of the ambient conditions and the likely change in the performance of the kiln over the system life time. Various testing methods and procedures, including the National Bureau of Standards (NBS) in United States, American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), and Federal Association for Solar Energy in Germany, for evaluating the comparative and absolute thermal performance of solar collectors were reviewed in Sodha and Chandra (1994). In these methods, the dryers were evaluated by measuring and comparing certain selected parameters, but no particular procedure was followed in these assessments.

In most of the recently-proposed methodologies for characterizing the performance of solar dryers (Altobelli et al., 2014; López-Vidaña et al., 2013; Singh and Kumar, 2012), parameters, such as the pick-up efficiency (η_p), the drying efficiency (η_d), the