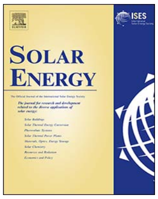
Solar Energy 162 (2018) 620–636

Contents lists available at ScienceDirect

Solar Energy

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



On the design, modelling and analysis of multi-shelf inclined solar cooker-cum-dryer

Manpreet Singh, V.P. Sethi*

Department of Mechanical Engineering, Punjab Agricultural University, Ludhiana 141004, India

ARTICLE INFO

Keywords:
Inclined solar cooker
Solar dryer
Cooker-cum-dryer
Thermal model
Drying model
Techno-economic analysis

ABSTRACT

A novel design of multi-shelf side loading inclined solar cooker-cum-dryer (ISCCD) is designed using single reflector North Facing Booster Mirror (NFBM) to improve the performance of both cooking and drying operations particularly in winter months. Innovative parallelepiped shape vessel (PSV) is designed (having longest inclined south facing wall) to further enhance the performance of ISCCD in cooking mode. Solar radiation capture model by ISCCD is used in developed thermal model for various interactive components such as; glass covers, chamber air, absorber plate, cooking vessel and vessel water while considering the effect of NFBM and experimentally validated at Ludhiana climate (30°N latitude), India. Volume to aperture area ratio along with size of PSV is optimized in such a way that ISCCD with three-shelves is capable of cooking three times more food as compared to the conventional horizontally placed solar cooker (HPSC). Due to optimized vessel design and NFBM effect, ISCCD can be effectively used in extreme winter conditions when maximum temperature during the day hovers around 15–20 °C (on sunny days) at latitudes > 30°N for both cooking as well as drying operation when conventional HPSC and dryer (generally not fitted with booster mirror) do not perform well due to lower solar radiation availability. Stagnation test (first figure of merit F_1) and sensible heat test (second figure of merit F_2) were also computed and compared with HPSC to ascertain the performance of ISCCD. In drying mode, ISCCD was tested for drying gooseberry (*Emblica officinalis*) (local name amla) under natural as well as forced convection modes with and without the effect of NFBM. The Logarithmic drying model was found to be the best fit for drying gooseberry. Techno-economic analysis showed that in cooking mode ISCCD can be used to cook at least one meal per day for a joint family of 10 persons during 280 days in a year and can recover its cost within 65 months if compared with wood burning costs besides having the advantage of being used as an efficient dryer thereby saving the cost of second gadget. In terms of savings in biomass fuel burning, ISCCD can mitigate much higher CO_2 emissions as compared to conventional HPSC.

1. Introduction

Energy is fairly essential, meanwhile life is directly influenced by energy and its consumption. Present cooking fuels are originated from fossil fuels like LPG, kerosene and biomass such as firewood, crop residue and cow dung. These biomass based energy resources still play a vital role in global energy consumption, but due to continuous burning of these fuels adverse affects on environment, human and soil heath are attaining alarming levels particularly in developing countries (Sahin et al., 2007). Solar energy is recognised as one of the most promising future renewable energy source and becoming a viable substitute since it diminishes the utilisation of conventional energy and enhances production adeptness. Solar energy is most commonly employed for solar cooking, water heating and solar drying applications. As cooking is an integral part of every human being, it expends a prime portion of the domestic energy requirement. Under the current scenario, solar cooking is green, clean and environment friendly replacement which precludes global warming due to non-emission of greenhouse gases and also diminishes indoor air pollution besides preventing health problems. Moreover, adequate cooking temperatures in solar cooking devices also help to preserve food nutrients (Muthusivagami et al., 2010).

Numerous designs of solar cookers have been presented by eminent researchers over the last more than half a century. These are classified mainly into three types; (i) box type (ii) focusing type and (iii) advanced or indirect type. Simple structure, easy operation mode and low cost have attracted the attention of researchers towards box-type solar cookers. Various improvements have been incorporated in solar box cookers (SBCs) in order to: (i) increase the thermal performance, energy saving and durability; (ii) decrease the weight, cost and payback period as reported by Mahavar et al. (2011) and Mahavar et al. (2013).

---

* Corresponding author.
E-mail addresses: vpsethi@pau.edu, vpsethi68@yahoo.co.in (V.P. Sethi).

https://doi.org/10.1016/j.solener.2018.01.045
Received 3 October 2017; Received in revised form 4 January 2018; Accepted 15 January 2018

Nomenclature

A_e	edge area, m^2
A_{g1}	area of upper glass cover, m^2
A_{g2}	area of lower glass cover, m^2
A_p	area of absorber plate, m^2
A_v	area of vessel, m^2
F_1	first figure of merit, dimensionless
F_2	second figure of merit, dimensionless
FC	forced convection
$h_{g1\text{-}a}$	convective heat transfer coefficient between upper glass cover and ambient air, (4.5 Wm^{-2} °C^{-1})
$h_{ch\text{-}g2}$	convective heat transfer coefficient between chamber air and lower glass cover, (5.2 Wm^{-2} °C^{-1})
$h_{p\text{-}ch}$	convective heat transfer coefficient between absorber plate and chamber air, (5.4 W m^{-2}°C^{-1})
$h_{v\text{-}ch}$	convective heat transfer coefficient between vessel and chamber air, (5.4 W m^{-2} °C^{-1})
$h_{v\text{-}w}$	convective heat transfer coefficient between vessel and water, (6.0 W m^{-2} °C^{-1})
h_w	wind loss coefficient, (12.0 W m^{-2} °C^{-1})
Ib	beam solar radiation, W m^{-2}
Id	diffuse solar radiation, W m^{-2}
ISCCD	inclined solar cooker-cum-dryer
I_t	total solar radiation incident on the aperture of ISCCD, W m^{-2}
I_h	total solar radiation incident on the aperture of horizontal cooker, W m^{-2}
k	drying rate, gm h^{-1}
K_{in}	thermal conductivity of insulation, Wm^{-1} °C^{-1}
L_{in}	thickness of insulation, m
m_p	moisture evaporated, gm
q_{ab}	heat energy absorbed by the absorber plate of ISCCD, MJ m^{-2}
q_l	heat energy lost, MJ m^{-2}
q_u	useful heat energy, MJ m^{-2}
R_b	conversion factor for beam radiation, dimensionless
$R_{b'}$	conversion factor for reflected beam radiation from north facing booster mirrors, dimensionless
R_d	conversion factor for diffuse radiation, dimensionless
R_r	conversion factor for reflected radiation, dimensionless
T_a	ambient air temperature, °C
T_{g1}	upper glass cover temperature, °C
T_{g2}	lower glass cover temperature, °C
T_{ch}	chamber air temperature, °C
T_v	vessel temperature, °C
T_{pm}	mean plate temperature, °C
T_p	temperature of absorber plate of ISCCD, °C
T_{p1}	temperature of absorber plate of HPSC, °C
T_w	temperature of water in vessel of ISCCD, °C
T_{wo}	temperature of water in vessel of HPSC, °C
T_{v1}	circular vessel's temperature, °C
t	time taken by ISCCD for drying, h
U_b	bottom heat loss coefficient of ISCCD, W m^{-2} °C^{-1}
U_e	edge heat loss coefficient of ISCCD, W m^{-2} °C^{-1}
U_l	overall heat loss coefficient of ISCCD, W m^{-2} °C^{-1}
U_t	top heat loss coefficient of the ISCCD, W m^{-2} °C^{-1}
V_a	velocity of air flowing over glazing of ISCCD, m sec^{-1}
w_i	initial weight of product, gm
w_f	final weight of product, gm

Greek letters

ρm	reflectivity of north facing booster mirror, dimensionless
ρ	reflectivity of ground, dimensionless
β	slope of the ISCCD with horizontal, degrees
β_r	slope of north facing booster mirror with horizontal surface, degrees
ϕ	latitude of selected location, degrees
τ_g	transmissivity of glass, dimensionless
ε_p	emissivity of the absorber plate, dimensionless (0.28)
ε_v	emissivity of the vessel, dimensionless (0.10)
ε_{g1}	emissivity of the upper glass cover, dimensionless (0.35)
ε_{g2}	emissivity of the lower glass cover, dimensionless (0.35)
α_{g1}	absorptivity of upper glass cover, dimensionless (0.17)
α_{g2}	absorptivity of lower glass cover, dimensionless (0.17)
α_p	absorptivity of absorber plate, dimensionless (0.70)
α_v	absorptivity of vessel, dimensionless (0.90)
σ	Stefan-Boltzmann constant, 5.67×10^{-8} W m^{-2} K^4
$\alpha\tau$	absorptivity transmissivity coefficient, dimensionless
η_t	thermal efficiency of solar cooker, dimensionless

Detailed information on the salient features, types, functioning designs of many diversified cookers with theoretical and experimental studies have been described in many review articles such as Doraswami (1994), Lakhar et al. (2010), Muthusivagami et al. (2010), Panwara et al. (2012) and Cuce and Cuce (2013). Saxena et al. (2011) performed a thermodynamic review on box type solar cookers to optimize various major parameters. Harmin et al. (2014) presented a review of research works and studies carried out in the development of solar cooking to focus on diverse box type solar cookers consisting of (i) simple solar box cooker with a tilted absorber-plate, (ii) a double exposure solar cooker and (iii) a novel non-tracking solar box cooker, which is equipped with a fixed asymmetric compound parabolic concentrator (CPC) as booster-reflector and its absorber-plate, is in a form of a step. Hereza et al. (2017) reviewed the principle and classification, parameters influencing the performance of a solar cooker along with energy and exergy analysis. Coccia et al. (2017) designed and tested a high concentration ratio (11.12) solar box cooker prototype to cook food at high temperature (> 200 °C) with good optical efficiency and thermal insulation.

Thermal performance analysis on solar box cookers has been conducted by many researchers such as Grupp et al. (1991), Jubran and Alsaad (1991), Mullick et al. (1997) and Subodh (2004). Funk and Larson (1991) developed a parametric model for prediction of cooking power of a solar cooker depending upon the different controlled and uncontrolled parameters such as solar intercept area, overall heat loss coefficient, absorber plate thermal conductivity, insolation, temperature difference and load distribution. Regression analysis of experimental data was done for obtaining coefficients of each term in the model. Channiwala and Doshi (1989) presented complete procedure to determine the heat loss coefficient of box type solar cookers. Esan (2004) studied the thermal performance of a solar cooker integrated vacuum-tube collector with heat pipes containing different refrigerants. Detailed temperature distributions and their time dependences were measured. The maximum temperature obtained in a pot containing 7 L of edible oil was 175 °C. Also, the cooker was successfully used to cook several foods.

Reddy and Narasimha (2007) tested a double-glass solar cooker to examine the heat flow process and derived a mathematical model. Kurt et al. (2008) predicted the thermal performance parameters using artificial neural network. Kumar et al. (2011) emphasized the need of thermal performance indicators determined through exergy analysis for solar cookers. Sengar et al. (2014) studied the mathematical formalism of energy and distribution pattern in solar hot boxes for global solar radiation capture. Nwosu et al. (2014) introduced an inclined box-type