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Testing method for thermal performance based rating of various solar dryer designs

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Abstract

A generalized methodology is developed for thermal testing of various solar dryer designs operated for natural and forced air flow conditions. The steady state mathematical model based on heat balance concept of solar dryer without load is applied to identify the dimensionless parameter called no-load performance index (NLPI). Laboratory models of direct (cabinet), indirect and mixed mode solar dryer are designed and constructed to perform steady state thermal tests for natural and forced air circulation. The dryers with no-load are operated with air passage between absorber plate and glass cover for the range of 300–800 W/m^2 and 0.009–0.026 kg/s of absorbed thermal energy and air mass flow rate respectively under indoor simulation conditions. The present study reveals that the forced convection operated dryer provides higher NLPI in contrast to that of natural convection. The comparative performance analysis of dryers indicates that the mixed mode dryer exhibits maximum value of NLPI followed by indirect and cabinet ones for both natural and forced air circulation. It is also found that for any dryer operating at given air flow condition, almost invariable NLPI values have been obtained for a wide range of absorbed energy and ambient air temperature data, thus facilitating performance comparison between different dryer designs on equitable basis. The results of statistical analysis showing low standard errors of mean further demonstrate good consistency in NLPI values for various dryer designs. The uncertainty in NLPI due to error in measurement of several parameters by instruments ranges from 0.79 to 1.96% for various dryer designs operated under different conditions.

Keywords: Solar dryer; No-load thermal testing; Performance index; Statistical analysis; Uncertainty estimation

1. Introduction

The use of solar energy in drying applications is becoming an important and viable alternative since it decreases consumption of conventional energy by 27–80% at an average solar collector system efficiency of 40% (Arata et al., 1993). In addition, it can easily provide low temperature heating required for food drying applications (Mahapatra and Imre, 1990). In recent past, a considerable interest among researchers has been noticed in the design, development and testing of various types of solar dryer like direct (Singh et al., 2006; Saleh and Badran, 2009), greenhouse (Farhat et al., 2004; Sethi and Arora, 2009), indirect (El-Sebaii et al., 2002; Sreekumar et al., 2008) and mixed-mode (Tripathy and Kumar, 2009). Several researchers presented an overview of various designs, details of construction and operational principles of wide variety of practically realised solar assisted dryer systems (Ekechukwu and Norton, 1999; Murthy, 2009). However, these dryer systems can be broadly grouped into three major types as direct, indirect and mixed mode, depending on arrangement of system components and mode of solar heat utilization (Leon et al., 2002). In fact, the operation of these dryers is primarily based on the principle of natural or forced air circulation mode.

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Nomenclature

A	cross-sectional absorber area (m^2)
C_p	specific heat of air (J/kg K)
E	confidence interval
h_{cfg}	convective heat transfer coefficient from hot air to glass cover of collector–dryer assembly (W/m^2 K)
h_{cga}	convective heat transfer coefficient from glass cover to ambient air of collector–dryer assembly (W/m^2 K)
h_{cpf}	convective heat transfer coefficient from absorber plate to hot air of collector–dryer assembly (W/m^2 K)
h_{rga}	radiative heat transfer coefficient from glass cover to ambient air of collector–dryer assembly (W/m^2 K)
h_{rpg}	radiative heat transfer coefficient from absorber plate to glass cover of collector–dryer assembly (W/m^2 K)
K_b	conductivity of insulation (W/mK)
k	conductivity of air (W/mK)
L_b	thickness of insulation (m)
L	characteristic length (m)
$\dot{m}$	air mass flow rate (kg/s)
N	number of observations
Nu	Nusselt number
S	flux absorbed in the absorbed plate (W/m^2)
s	standard error of mean
SD	standard deviation
$\overline{T}_p$	average temperature of absorber plate of collector–dryer plate assembly (°C)
$\overline{T}_g$	average temperature of glass cover of collector–dryer assembly (°C)
$\overline{T}_f$	average temperature of hot air of collector–dryer assembly (°C)
$\overline{T}_{fo}$	average temperature of hot air at dryer outlet (°C)
$\overline{T}_{fi}$	average temperature of air at collector inlet (°C)
T_{am}	temperature of ambient air (°C)
U_b	bottom-loss coefficient of collector–dryer assembly (W/m^2 K)
$\bar{x}$	arithmetic mean

Greek symbols

ε_p	emissivity of absorber plate
ε_g	emissivity of glass cover
σ	Stefan–Boltzmann's constant (5.67×10^{-8} W/m^2 K^4)

Since the performance of any solar energy system strongly depends on climatic variables, it therefore becomes imperative to evolve a test method that can take into account the influence of these variables for thermal performance evaluation on equitable basis. The thermal test procedures for standardization of selective solar equipments namely, solar domestic water heaters, solar cookers etc., have already been developed and adopted in many countries including India for performance evaluation (ASHRAE, 1986; IS, 1991; ISO, 1993; IS, 2000). For solar water and air heaters, ASHRAE (1986) recommended the instantaneous efficiency test for measuring thermal performance characterised by $F_R(\tau\alpha)$ and F_RU_L under steady state condition. Vaishya et al. (1985) developed a test procedure based on outdoor experiments for thermal performance evaluation of a box-type solar cooker with no-load. In the study, the ratio of solar radiation intensity on a horizontal surface to temperature difference between absorber plate and ambient air at the stagnation condition is used as a test parameter. Mullick et al. (1987) identified two figures of merit namely F_1 and F_2 characterising the thermal tests on box-type solar cooker with no-load and load conditions respectively. These tests were later adopted by Bureau of Indian Standards (IS, 2000). Similarly, for thermal testing of paraboloid concentrator solar cooker, the design parameters $F'U_L$ and $F'\eta_o$ are proposed under load conditions (Mullick et al., 1991).

Recently, some attempts have been made to investigate the effect of solar chimney on solar dryer thermal performance. Afriyie et al. (2011) developed mathematical models to simulate the ventilation in relation to design of chimney dependent solar crop dryer under no-load conditions. The results of investigations reveal that inlet-exit area ratio, drying chamber roof inclination and chimney height are the critical parameters to achieve maximum air flow inside the dryer. In another study, Ferreira et al. (2008) investigated the technical feasibility of solar chimney in drying of different food products and found significant variation in temperature (increase) and relative humidity (reduction) of flowing air compared to the ambient air conditions. For thermal performance comparison of dryer designs, Leon et al. (2002) reviewed several existing test procedures reported in the literature and suggested some test guidelines with respect to certain parameters namely, maximum drying temperature, first day drying efficiency etc. in proposed comprehensive evaluation procedure. However, the study could not recommend any thermal test that takes into account the influence of climatic variables on these parameters. Recently, thermal tests on solar dryers with no-load and load have been reported in literature identifying two parameters namely-overall heat loss coefficient, U_L and drying efficiency, η_d respectively. The determination of U_L is based on the maximum temperature of various components such as plate,