Solar-wind ventilation to enhance the cabinet dryer performance for medicinal herbs and horticultural products

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Abstract: This paper presents the design, construction and performance evaluation of a mixed-mode solar cabinet dryer (SCD) for medicinal herbs and horticultural products. Solar- wind ventilation system is used to enhance the cabinet dryer performance. The solar cabinet is equipped with a vertical blackened solar chimney and a flat plate solar collector to enhance buoyancy force. The chimney is provided with suction axial fan that can rotate smoothly by wind power. The performance of SCD was evaluated without load (empty) and with load (potato chips and peppermint). After performing various standardized pretreatments, products were dried separately under open sun, SCD and electric oven. Results of parametric studies indicated that, highest drying air temperature was achieved at 60° collector tilt angle followed by 30°, when the dehydration system tracked the sun. The developed SCD exhibited sufficient ability to dry the chips and peppermint reasonably to a safe moisture level within 9-10 and 5-6 hrs (≈1 clear sunny day), respectively. The best chips colour was achieved at 15 s frying time. All the fried chips and dried peppermint were well accepted by the panelists. The SCD ensures a superior quality of the dried products. In terms of electricity requirement, frying time, health conscious and utilization of solar energy, the enhanced SCD is considered a suitable method for drying potato chips as well as peppermint.

Keywords: solar cabinet, solar collector, windmill, drying, chips, peppermint

Citation: Mohamed A. Eltawil, Said E. AbouZaher, and Wagdy Z. El-Hadad. 2012. Solar- wind ventilation to enhance the cabinet dryer performance for medicinal herbs and horticultural products. Agric Eng Int: CIGR Journal, 14(4): 56−74.

1 Introduction

The domestic demand for energy substantially exceeds supply and the gap is not new, hence increasing its magnitude is alarming. In recent years, the public has become more concerned about the rapid depletion and escalating cost of the finite fossil fuels. These concerns have focused worldwide attention to the potential of harnessing the sun's power in new and varied form to meet society's growing energy needs.

Egypt lies within the subtropical region. The annual daily average of solar radiation on horizontal plane in Egypt is about 8 kWh m^{-2} day^{-1}. While, the average solar radiation during winter is about 7 kW hm^{-2} day^{-1}, and the measured annual daily sunshine duration amounts to approximately 11 hrs (Moharam, 1993).

Solar drying of agricultural products in enclosed structures is an attractive way of lowering post-harvest losses and poor quality associated with traditional sun-drying methods (Bena and Fuller, 2002; Chen et al., 2005; Sacilik et al., 2006). Natural convection solar crop dryers are reported to perform poorly due to low ventilation in the dryers, especially the direct-mode type with no air preheating device (Ekechukwu, 1999b). However, investigations on chimneys suggest that heated chimneys can improve the ventilation in a room (Chen et al., 2003; Ekechukwu and Norton, 1997; Eltawil and Imara, 2005; Ferreira et al., 2008).

The artificial driers produce an improved quality of

Received date: 2011-10-29 **Accepted date:** 2012-08-30

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dried products as the velocity and the temperature of the drying air can be controlled, but they also consume a significant amount of energy to heat and move the air-flow resulting in higher capital and operational costs of those driers (Janjai et al., 2009; Ferreira et al., 2008).

Solar dryer are classified in a variety of ways (Leon et al., 2002; Tripathy and Kumar, 2009a). A most often used classification is: direct type or natural convection solar dryers; indirect type dryers; and forced circulation type dryers.

In direct dryer the solar radiation is absorbed directly by the product intended to be dried. The hot air supply is provided through solar collectors which are employed in the drying unit in which the product is directly irradiated by solar energy through transparent sheet covering the east and west sides of the chamber. One of the disadvantages of this system is poor quality of product processed which may causes black surface on the product due to the direct solar radiation on the product.

In indirect solar dryer, the solar radiation gained by the system is utilized to heat the air which flows through the product to be dried. The air is normally heated by the converted thermal energy from absorbed solar radiation from separate solar collector. In this mode of operation, the sides of the drying chamber are insulated in order to prevent solar radiation and at the same time decrease the heat loss through the sides.

In the natural convection solar dryer design, the heated air flow is induced by thermal gradient. It's sometimes called passive dryer because of the natural movement of heated air. Effect of solar dryer may be enhanced by the addition of chimney in which exiting air is heated even more.

The forced convection dryer, is design in such a way that air is forced through a solar collector and the product bed by a fan or a blower, normally referred to as active dryer. Forced circulation dryers usually lead to faster drying rate, higher airflow rates and better control of hot air temperature. Dryer can be designed to meet different capacities depending on the user needs and availability of the open space.

In fact, the operation of these dryers is primarily based on the principle of natural or forced air circulation mode. Comparative tests on these basic designs suggested that the mixed-mode natural convection solar crop-dryer is potentially the most effective and it appears to be particularly promising in tropical humid areas where climatic conditions favour sun drying of agricultural products (Zaman and Bala, 1989; Garba et al., 1990).

To dry various agricultural products at farm level, natural convection solar dryers are preferred over forced convection solar dryers because of non-availability of, or erratic power supply in villages. For large scale drying applications, a large number of direct, indirect, and natural circulation solar dryers have been developed (Singh et al., 2004).

The development of solar-powered assisted-convection cabinet-type dryers has been reported by Farkas and Meszaros (1999). Boughali et al. (2009) constructed and investigated a new specific prototype of an indirect active hybrid solar–electrical dryer for agricultural products. The study was done in a somewhat high range of mass flow rate between 0.04 and 0.08 kg m^{-2} s^{-1}, a range not properly investigated by most researchers. Experimental tests with and without load were performed in winter season in order to study the thermal behavior of the dryer and the effect of high air mass flow on the collector and system drying efficiency. Many different thin layer mathematical drying models were investigated.

In last few years, a considerable interest among researchers has been noticed in the design, development and testing of various types of solar dryer like direct, greenhouse, indirect and mixedmode (Farhat et al., 2004; Leon et al., 2002; Saleh and Badran, 2009; Sethi and Arora, 2009; Singh et al., 2006; Sreekumar et al., 2008; Tripathy and Kumar, 2009b). 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). Most of the solar dryers developed so far are designed for specific agricultural products or class of products. Selection of a solar dryer for drying a particular agricultural product is determined by the drying characteristics of the product, quality requirements and economic considerations (Leon et al., 2002; Sodha and Chandra, 1994). The operational parameters that significantly influence the performance of a dryer are drying air characteristics (such as drying air temperature, humidity and airflow rate); product variables (product throughput, initial and final moisture contents, product size and size distribution); and dryer variables (width, length, height or diameter of the dryer, number of passes and dryer configuration); dryer material characteristics (type and colour of the collector plate, type and dimensions of glazing material, and the type and nature of internal surfaces of the dryer).

Solar energy can be very effective for crops and medicinal herbs because it is natural and provides low grade heat, which is good for drying at low temperatures and high flow rates. In addition, the intermittent nature of solar radiation will not affect the drying performance at low temperatures. Even the energy stored in the product itself may help in removing excess moisture during that period.

Potato crisps are very popular fried snacks. Their characteristic crispy texture is one of the most important quality indicators of the finished product. Developed during frying, it is mainly dependent on the quality of raw material and also on the parameters of technological processing (Kita, 2002). Frying temperature and oil type have a recognized effect on the final potato crisp product. Lowering frying temperature may help in avoiding some harmful characteristics such as the formation of acrylamides, known to be potential carcinogenic substances (Gertz and Klostermann, 2002; Grob et al., 2003).

Peppermint oil is one of the most popular and widely used essential oils, mostly because of its main components menthol and menthone. Peppermint oil is used for flavoring pharmaceuticals and oral preparations. Therefore, the proper procedure in conservation peppermint by dehydration plays an important role to keep its properties.

This study has been devoted to develop, design and construct a solar-wind ventilation system (mixed mode) to enhance the performance of cabinet dryer for small scale farms. The solar cabinet dryer (SCD) was equipped with solar chimney and flat plate collector. The solar chimney was provided with an axial suction fan that can rotate smoothly by wind power. The performance of developed SCD was evaluated without load and with load (Medicinal herbs and horticultural products). The quality of solar and mechanical (oven) dried products was also compared.

2 Materials and methods

2.1 Theoretical analysis

The energy balance of the solar collector is obtained by equating the total heat gained per unit time to the total heat lost per unit time as in Equation (1) (Abed Gatea, 2010):

$$I_T \ A_c = E_u + E_{cond.L} + E_{conv.L} + E_R + E_{R.L} \quad (1)$$

where, I_T: the total radiation incident per unit time on the absorber's surface, W/m^2; A_c: the collector area, m^2; E_u: the useful energy collected by the air per unit time, W; $E_{cond.L}$: the energy conduction losses from the absorber per unit time, W; $E_{conv.L}$: the energy convective losses from the absorber per unit time, W; E_R: the energy long wave re-radiation from the absorber per unit time, W; $E_{R.L}$: the energy reflection losses from the absorber per unit time, W.

The collector area (A_c) required for drying batch amount M_{sd} (kg-dry basis) of the agricultural product may be expressed as in Equation (2) (Purohit and Kandpal, 2005):

$$A_c = \left(\frac{M_{sd}}{t\ I\ \eta_d}\right)\left[\left\{\left(\frac{1-M_{cf}}{1-M_{ci}}\right)C_{pr}\left(T_{fs}-T_{amb}\right)\right\} * \left\{1+\left(t-1\right)\zeta\right\} + \left\{\frac{M_{ci}-M_{cf}}{1-M_{ci}}\right\}h_{fg}\right] \quad (2)$$

In Equation (2), M_{ci} and M_{cf} respectively represent the initial and final moisture contents (in fraction- wet basis) of the product to be dried, C_{pr} is the specific heat of raw product (in MJ kg^{-1} ℃$^{-1}$), T_{amb} is the ambient temperature (℃), T_{fs} is the drying temperature (℃) and h_{fg} is the latent heat of vaporization of water (in MJ/kg), t is the time required (in days) for drying of a single batch of the product. I represent the average daily solar radiation available during the harvesting period (in MJ/m^2) and η_d the overall thermal efficiency of the solar dryer (in fraction).

When there is no sunshine, the temperature inside the drying chamber of a solar dryer may often decrease due to thermal losses and reach values much below the drying temperature of the product. Therefore, some thermal energy will be required for sensibly heating of the agricultural product to its drying temperature on subsequent days specially during winter season. It is assumed that, on other days of drying, a fraction ζ of the sensible heat requirement of the agricultural product on the first day is required to raise the temperature to the drying temperature. In addition, the total incident radiation flux I_T, on a tilted surface (Equation (3)) as given by Sukhatme (1996) was employed.

$$I_T = I_b R_b + I_d R_d + (I_b + I_d) R_r \tag{3}$$

where, I_b is the hourly beam radiation; I_d the hourly diffuse radiation; R_b the tilted factor for beam radiation; R_d the tilted factor for diffuse radiation; and R_r the tilted factor for reflected radiation. Further, the three heat loss terms $E_{cond.L}$, $E_{conv.L}$ and E_R are usually combined into one-term (E_L), i.e.,

$$E_L = E_{cond.L} + E_{conv.L} + E_R \tag{4}$$

If τ is the transmittance of the top glazing and I_T is the total solar radiation incident on the top surface, therefore,

$$I A_c = \tau I_T A_c \tag{5}$$

The reflected energy from the absorber is given by the expression:

$$E_{R.L} = \rho \tau I_T A_c \tag{6}$$

where, ρ is the reflection coefficient of the absorber. Substitution of Equations (4), (5) and (6) in Equation (1), yields:

$$\tau I_T A_c = E_u + E_L + \rho \tau I_T A_c$$

or $$E_u = \tau I_T A_c (1 - \rho) - E_L$$

Solar absorptance (α) of absorber $=1 - \rho$

Hence,

$$E_u = \alpha \tau I_T A_c - E_L \tag{7}$$

Since E_L is composed of different conduction, convection and radiation parts, therefore, it is presented as follows:

$$E_L = U_L A_c (T_{coll} - T_{amb.}) \tag{8}$$

where, U_L is the overall heat transfer coefficient of the absorber (W m^{-2} K^{-1}); T_{coll} is the temperature of the collector's absorber (K); and T_{amb} is the ambient air temperature (K).

Substitution of Equation (8) in Equation (7), then the useful energy gained by the collector is expressed as:

$$E_u = \alpha \tau I_T A_c - U_L A_c (T_{coll} - T_{amb}) \tag{9}$$

Therefore, the energy per unit area (E_{ua}) of the collector is

$$E_{ua} = \alpha \tau I_T - U_L (T_{coll} - T_{amb}) \tag{10}$$

If the heated air leaving the collector is at collector temperature, the energy gained per unit time by the air E_g is:

$$E_g = \dot{m}_a C_{Pa} (T_{coll} - T_{amb}) \tag{11}$$

where, $\dot{m}_a$ is the mass of air leaving the dryer per unit time (kg/s); C_{Pa} is the specific heat of air at constant pressure (kJ kg^{-1} K^{-1}); U_L is the overall heat transfer coefficient of the absorber (W m^{-2} K^{-1}); T_{coll} is the temperature of the collector's absorber (K); and T_{amb} is the ambient air temperature (K).

The ratio of actual useful energy gained of a collector (Equation (9)) to the useful energy gained by the air (Equation (11)) is known as the collector heat removal factor, F_R. Therefore,

$$F_R = \frac{\dot{m}_a C_{pa} (T_{coll} - T_{amb})}{A_c[\alpha\tau I_T - U_L (T_{coll} - T_{amb})]} \tag{12}$$

or

$$E_g = A_c F_R [(\alpha \tau) I_T - U_L (T_{coll} - T_{amb.})] \tag{13}$$

The instantaneous collection efficiency is defined by Sukhatme (1996):

$$\eta_c = \frac{Useful\ heat\ gain}{Radiation\ incident\ on\ the\ collector} = \frac{E_g}{A_c I_T} \tag{14}$$

2.1.1 Energy balance equation for the drying process

The minimum useful energy required for drying (UE_d) unit amount of an agricultural product (in MJ/kg) can be estimated as the sum of the useful energy required for sensible heating of the product (q_{sens}) and the useful energy required for evaporation of moisture in the product (q_{evap}), i.e. (Pallav et al., 2006):

$$UE_d = q_{sens} + q_{evap} = \left[\left\{ \left(\frac{1 - M_{cf}}{1 - M_{ci}} \right) C_p \left(T_{fs} - T_{amb} \right) \right\} x \left\{ 1 + (t-1)\zeta \right\} \right] + \left\{ \frac{M_{ci} - M_{cf}}{1 - M_{ci}} \right\} h_{fg} \tag{15}$$

Energy balance of water evaporation can be used to estimate the total energy required for drying a given quantity of food (Youcef-Ali, et al. 2001).

$$m_w L_v = m_a C_p (T_{fs1} - T_{fs2}) \tag{16}$$

where, m_w is the mass of water evaporated from the food item (kg); m_a is the mass of drying air (kg); T_{fs1} and T_{fs2} are the initial and final temperatures of the drying air respectively (K); T_{pr} is the surface temperature of the product (℃); C_p is the specific heat of air at constant pressure (kJ kg^{-1} K^{-1}) and L_v the latent heat of vaporization = 4.1868 (597 – 0.56 (T_{pr} + 273)) (kJ kg^{-1}) (Youcef-Ali, et al. 2001).

The mass of water evaporated (m_w) is calculated from Equation(17):

$$m_w = \frac{m_i(M_i - M_e)}{100 - M_e} \quad (17)$$

where, m_i is the initial mass of the food item (kg); M_i is the initial moisture content (% d.b.) and M_e is the equilibrium moisture content (% d. b.).

The equilibrium moisture content based on the dry mass of the potato is proposed by McLaughlin and Magee (1998), it depends on the moisture content of the product as well as the drying temperature

$$\begin{aligned} M_e = {} & (10.169e^{0.0108T_{fs}}\, 0.724e^{0.0025T_{fs}}\, 0.18054e^{-0.022T_{fs}} a_w) / \\ & [(1 - 0.724e^{0.0025T_{fs}} a_w) x (1 - 0.724e^{0.0025T_{fs}} a_w + \\ & 10.169e^{0.0108T_{fs}}\, 0.724e^{0.0025T_{fs}} a_w)] \end{aligned} \quad (18)$$

The specific heat of the product (Cp_{pr}) can be estimated (in J kg^{-1}K^{-1}) from Equation (19) (Wang and Brennan, 1993):

$$Cp_{pr} = 4186\ (0.406 + 0.00146T_{fs} + 0.203M - 0.0249M^2) \quad (19)$$

where, a_w is the water activity and T_{fs} is the temperature of drying air (℃).

2.1.1.1 The water activity

Water activity (a_w) is of great importance for food preservation as it is a measure and a criterion of microorganism growth and probably toxin release, of enzymatic and nonenzymatic browning development, etc. For every food or agricultural product there exists an activity limit below which microorganisms stop growing. Water in food and agricultural crops, is in the form of a solution which contains salts, sugars, carbohydrates, proteins, etc., which at constant temperature are in thermodynamic equilibrium. The water activity is then given by the following equation (Belessiotis and Delyannis, 2011):

$$a_w = (p_w/p^*_w)_T \approx \varphi \quad (20)$$

where, p_w is the partial pressure of water solution and p^*_w is partial pressure of pure water, at the same temperature; φ is the relative humidity of the material at the same temperature.

2.2 Experimental site

The experiments were carried out in the premises of Agricultural Engineering Department, Faculty of Agriculture, Kafrelsheikh University, Kafr El-Sheikh Province, which lies at latitude 31.07°N and longitude 30.57°E.

2.3 Description of passive solar cabinet dryer

The design concept of the solar cabinet dryer is to collect the solar energy through a solar collector and direct radiation into the cabinet. The energy is used to heat up a mass of air and then pass it through a drying chamber by natural convection. Hence the heat supplied to the product is by direct and indirect absorption of solar radiation. The solar dryer was developed, constructed and assembled as shown in Figure 1. The dryer consist of the following components: solar cabinet, flat plate solar collector, air vents and dryer stands.

2. 3.1 Solar cabinet

The solar cabinet dryer consisted of drying chamber, drying trays, transparent glass cover, and a chimney having a suction axial fan which can be operated by wind power. A wooden drying chamber of 2.0 cm thickness × 100 cm width × 150 cm length (at the bottom) was constructed. The height of the dryer was 100 cm from back side and 30 cm from front side. The back side of the drying chamber had a set of two shallow perforated trays made of 0.5 cm mesh stainless steel wire screen arranged one above the other. The drying trays can be removed or inserted into the drying chamber (for loading and evacuating the fresh and dried materials) through the cabinet back side which was sealed tightly during the drying process.

The vertical distance between the two trays is 40 cm and the height of each tray is 5 cm. The locations of uppermost and lower trays in the dryer are 20 and 60 cm from the top of the cabinet, respectively. The loading capacity of cabinet trays is about 5 kg of fresh peeled

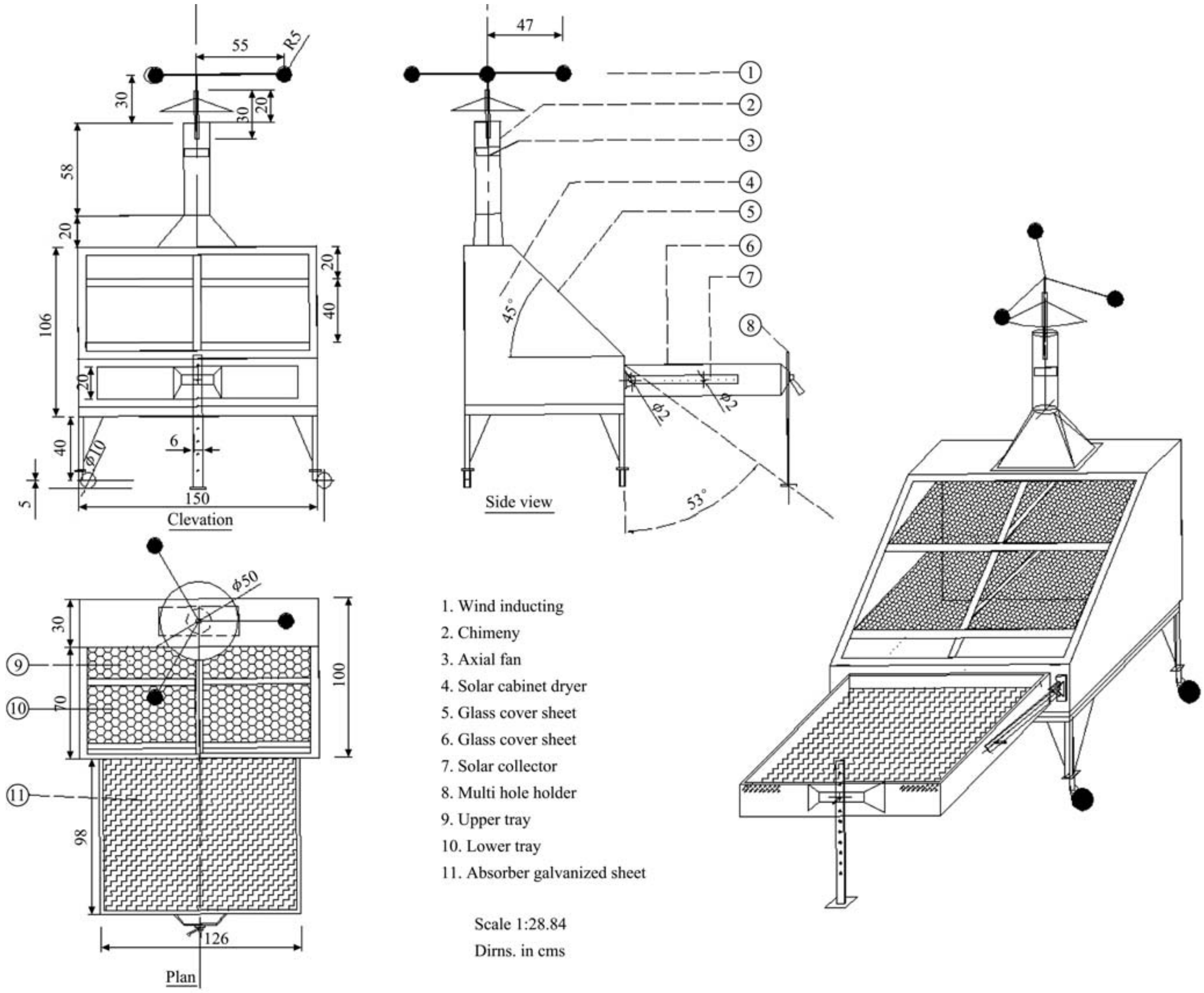

Figure 1 Schematic diagram of the developed solar cabinet dryer (SCD)

potato slices. The exterior and interior surfaces of the dryer are blackened. The bottom and interior walls are covered by aluminum foil. The front of the drying chamber is covered with a 5 cm thick glass sheet which was fixed in a wooden frame at an angle of 45º on the horizontal. The cabinet drying chamber attached from the front side at the bottom (plenum chamber) to a flat plate solar collector.

Part of solar radiation falling on the cabinet front glazing enters into the drying chamber and helps in further increase of the crop temperature directly. Thus the dryer works as a mixed mode type (direct and indirect solar drying systems).

2.3.2 Solar chimney

A vertical solar chimney, cylindrical in shape with 98 cm height and 15 cm diameter was connected to the top of the cabinet drying chamber in order to facilitate and control the convection flow of air. The chimney was made from galvanized iron and painted with black matte to maintain a higher temperature inside the solar chimney. This makes the chimney air less dense and increase the flow of air up the whole structure (natural convection). The solar chimney was provided with an axial fan (suction effect) that can rotate smoothly by wind power, therefore enhances the outlet air flow rate (forced convection). A mini-windmill was used to operate the suction fan which fixed on vertical steel shaft of 1 cm diameter located at the middle of chimney. The windmill consisted of three stainless steel hollow cups of 10 cm diameter each which light in weight and fixed on the top of steel shaft. The cups rotate horizontally on a vertical pivot shaft making a rotor diameter of 115 cm. To avoid entry of dust and rain water to the drying cabin, the chimney was covered from top with metal lid in the form of an inverted parabola and a 50 cm wide. Some ball and footstep bearings were used to reduce frictional resistance. The suction fan rotates directly by rotating the shaft with the help of wind draft. The chimney details are shown in Figure 1.

2.3.3 Flat plate solar collector

A flat plate solar collector was connected to the dryer from the front side. The collector is rectangular in shape, and its gross dimensions are 1.30 m long, 1.0 m wide and 2 mm thick for the absorber plate, with a net upper surface area of 1.3 m^2. The solar collector made from galvanized corrugated sheet, painted with matt black paint and insulated from back side with 10 cm wood shavings. To reduce the reflection of radiation and reduce heat losses by convection, the top of the collector was made of one layer colourless glass sheet of 5 mm thick, 1.30 m long and 1.00 m wide. A gap of about 10 cm between the glass cover and the absorber plate forms the air passage. The air intake into the collector is through 25 holes circular in shape of 10 mm each made through the collector front side casing. The collector hot air passed through a rectangular opening of 10 cm × 100 cm to the cabinet. The collector is supported by a movable multi-hole stand for obtaining the desired optimum tilt angle during the months of the year (0° to 75°).

The solar cabinet drying chamber and solar collector were mounted on a movable frame (trolley). The cabinet orientation and collector tilt angle can be adjusted manually, hence the impact of insolation can be judged.

2.4 Operation of the dryer

The heated air coming from solar collector is ducted to the solar cabinet drying chamber from the bottom and strikes the first tray and losses its heat to the crop. The air then transfers its sensible heat to the product on the second (upper) tray and finally leaves at the top of the cabinet under the natural circulation mode. Part of solar radiation falling on the cabinet front glazing enters into the drying chamber and helps in further increasing the crop temperature directly. The airflow rate can be enhanced during the dehydration process, by using the suction axial fan that works with help of ambient natural wind. Thus the dryer works as mixed mode type.

Drying of the product takes about one clear sunny day or even less. The drying of the product was done in batch mode and can be processed in the semi-continuous mode. Drying starts at 9:00 am and terminated at 6:00 pm or when the reduction in weight of samples had almost ceased. Drying data were monitored using three labeled samples, which were individually weighed and positioned at the center and the two sides of each tray.

2.5 Performance evaluation

To evaluate the developed SCD performance, the fabricated complete sets were placed outdoors in the real environmental conditions. Experimental runs were performed to judge the system. The dehydration process inside the developed SCD depends on total aperture area of the cabinet and solar collector, insolation, ambient temperature, ambient relative humidity, wind velocity, etc. It was intended to study the performance of the SCD throughout the day light time corresponding to weather conditions.

The developed SCD was tested without load (empty) and with load under the following parameters: The entire system was oriented to face south or track the sun during the tests at three tilt angles of solar collector namely 0°, 30° and 60°. In case of tracking, the system was oriented towards east (from 9:00 to 12:00), south (from 12:00 to 14:00) and west (from 14:00 to 18:00) directions. One horticultural product represented by Diamont potato tubers (Solanum tuberosum) and one medicinal herb represented by peppermint namely mentha virdis were used to evaluate the system.

2.6 Measurements

All measurements were recorded at an interval of one hour if there is no other statement.

Instantaneous insolation (W/m^2) was measured with a thermoelectric pyranometer (identification No. 8-S-1-2, Make of TWC Tokyo, 100 mV/cal cm^{-2} min^{-1} output, and total accuracy of ± 5%). It was set horizontally (S_h), on the same plane of cabinet dryer glass (S_{cab}) and solar collector (S_{coll}). The readings were taken with the help of Unit-T multimeter, Model DT830B in terms of mV.

For monitoring the environment inside the SCD, the temperatures (℃) were measured with the help of muti-channel switch, copper-constantan thermocouple

(T-type) and digital temperature indicators. The temperatures were recorded at different locations as follow: ambient air temperature, T_{amb} (collector input); absorber temperature, T_{abs}; collector glass, T_{cg}; collector outlet, $T_{coll.\ exit}$ (solar cabinet input); bottom of the solar cabinet, $T_{d.bottom}$; air below lower tray, T_{tray1} (average of three points); air below upper tray, T_{tray2} (average of three points); solar cabinet temperature, T_{dryer} (average of T_{tray1} and T_{tray2}) and solar cabinet exit, T_{exit}. Copper-constantan thermocouples covered with cotton cloth were used to measure wet bulb temperatures. The ambient dry and wet bulb temperatures were measured under shade to avoid the effect of direct solar radiation. Also, wet bulb temperature was measured at the outlet of the cabinet dryer. All the thermocouples were calibrated at the freezing and boiling points of water with the help of a mercury thermometer.

The measured dry and wet bulb temperatures with the help of psychrometric relationship were used to calculate the relative humidity values as follow (Albright, 1990): ambient air, $RH_{amb.}$ (Entering the solar collector); air entering the lower tray, RH_{tray1}; air entering the upper tray, RH_{tray2} and outlet of the solar cabinet dryer structure, RH_{cab}.

A Japanese type hot-wire anemomaster (Model 24-6111) ranged from 0 to 50 m/s with a precision of 0.1 m/s was used to measure wind velocity (m/s).

Initial and final mass, and mass changes of potato and peppermint tested samples at one hour interval for different experimental stages were measured by a laboratory electronic balance. The balance capacity was 1 kg with resolution of 0.01 g. Samples of approximately 20 ± 2 g (potato slices and peppermint) were taken every 1 hour interval and dried in an electric air convection oven at about 70 ±1℃ until a constant mass to determine the moisture content and dry matter. The moisture content was calculated on both wet and dry bases (ASAE, 1991; Ghadge, et al., 1989).

2.6.1 Dehydration measurement:

The percentage of moisture contents on the wet (M) and dry (X) basis are represented as:

$$M = \frac{W_o - W_d}{W_o} \times 100\% \qquad (21)$$

$$X = \frac{W_o - W_d}{W_d} \times 100\% \qquad (22)$$

The moisture contents on the wet and dry bases are inter-related according to the following equations:

$$M = 1 - \left[\frac{1}{(X+1)}\right] \qquad (23)$$

$$X = \left[\frac{1}{(1-M)}\right] - 1 \qquad (24)$$

The instantaneous moisture contents (wet and dry bases) at any given time were calculated according to the following equations (Ekechukwu, 1999b):

$$X_t = \left[\frac{(X_o+1)\,W_o}{W_t}\right] - 1 \qquad (25)$$

$$M_t = 1 - \left[\frac{(1-M_o)\,W_o}{W_t}\right] \qquad (26)$$

where, X_o is the initial moisture content (decimal, dry basis); M_o is the initial moisture content (decimal, wet basis); X_t is the moisture content at time t (decimal, dry basis); M_t is the moisture content at time t (decimal, wet basis); W_o is the initial weight of undried product (kg); W_d is the final weight of dried product (kg) and W_t is the weight of product at time t (kg).

The collected moisture data were used to plot graphs of moisture content versus drying time based on the theory of thin layer drying. The drying rate (dX/dt) was taken to be approximately proportional to the difference in moisture content between the product being dried and equilibrium moisture content at the drying air state, as given by Equation (27) (Boughali et al., 2009; Omid et al., 2006):

$$\frac{dX}{dt} = \frac{X_{t+\Delta t} - X_t}{\Delta t} \qquad (27)$$

where, X_t is moisture content at time t; $X_{t+\Delta t}$ is moisture content at time $t+\Delta t$ and Δt is time of successive measurements.

Dehydration ratio (DR) was calculated as ratio of weight of material kept for dehydration to the weight of dehydrated material.

2.7 Preparation of samples and pretreatment

The required quantity of freshly harvested potato cultivar (Diamont) was procured and used as an experimental material. The potatoes were cleaned then bruised, blemished and other defective potatoes were removed. The tubers were manually peeled and sliced in an industrial slicer into 1.2 ± 0.1 mm and treated as follows:

i) Control: Blanching the potato slices in plain boiling water for 4 min + dipping in cold water.

ii) Treat. A: Blanching the potato slices in plain boiling water containing 0.5% common salt for 4 min + dipping in cold water.

iii) Treat. B: Blanching the potato slices in plain boiling water for 4 min + dipping in 1% sodium meta-bi-sulphite for 10 min (0.5 kg solution/kg of slices).

iv) Treat. C: Washing the slices trice in plain water + blanching the slices in plain boiling water for 4 min + dipping in cold water.

The pretreated slices were thoroughly mixed to ensure uniformity of sampling and hot air dried using the developed SCD. All dried slices were kept in transparent polyethylene plastic sacks and tightly closed to avoid rehydration before frying.

Another set was dried using an electric oven to study the effect of pretreatments on quality of potato tubers. While, in case of peppermint, another set was dried under the natural open sun and compared to the SCD.

2.8 Chips frying process and overall acceptability

The potential merits of solar drying as compared to open sun drying include (i) improved product quality, (ii) reduced wastage of products, (iii) reduction in the drying time, and consequently, (iv) free land available for some more days, etc.

For the assessment of chip colour, the dried slices were fried in refined cottonseed oil at 180±1℃ (Marwaha and Kang, 1994) for four different frying times (15, 30, 45 and 60 s). The fried slices were laid out on paper towels before packaging. Grading of chip colour is accomplished by comparing chip appearance to the ten code chip colour chart. The lightest color is 1 with the darkest being 10, and scores of ≤ 7 considered acceptable. Data were collected and the effect of frying time on the crisp colour was then figured out. The texture of potato chips was evaluated using hardness taster (Kiya Seisakusho. Ltd. Tokyo, Japan).

The individual organoleptic characteristics, namely colour, texture, taste, flavour, and appearance provided an effective indication of the varied impact of various pretreatments and drying conditions. Thus to secure an overall view of acceptability, all the individual characteristics was summed up and their mean values were compared for each pretreatment and drying method.

2.9 Chemical analysis

Freshly potatoes and dried slices were analysed for different chemical parameters viz. total sugars and reducing sugars which estimated as per the procedure given by Somogyi (1952). Non reducing sugars were calculated by subtracting reducing sugars from total sugars. Starch was determined by anthrone reagent method (Thimmaiah, 1999).

The chemical analysis was performed on both fresh and dried peppermint samples in order to determine the essential oil according to the method described in Aflatuni (2005). While, chlorophyll A and chlorophyll B contents were determined according to Lichtenthaler (1987) using aqueous Me_2CO (80%).

Data analyses were carried out using MS Excel. Analysis of variance and least significant difference tests were conducted to test significance among variables means.

3 Results and discussion

3.1 Hourly performance of the solar cabinet dryer (SCD)

3.1.1 Test at no load

Figures 2-7 show the temperature and relative humidity variation of empty mixed mode SCD as affected by ambient conditions with respect to zonal time of the day, at different orientations and tilt angles. Observations show that the temperature of air leaving the SCD and solar collector increases as the day progresses peaks at around noon and afternoon due to transient effect of heat and thereafter decreases.

The analysis of recorded data indicated that, the air temperature at the SCD output changed significantly with ambient conditions. Generally, all treatments gave the cabinet daily average temperature in the range of 59.9℃ to 72.5℃ as shown in Table 1. It should be noted that the above mentioned range of temperature was recorded for empty SCD, while this range may be come down under load due to moist air. This range of temperature can be used for drying horticulture products as well as medicinal herbs, since they required dehydration temperature in the same range. However, the highest temperature of the drying air was achieved at 60° followed by 30° tilt angle, when the dehydration system tracked the sun. Therefore, the tilt angle of 60° with tracking the sun was used for testing the system under load (potato slices and peppermint).

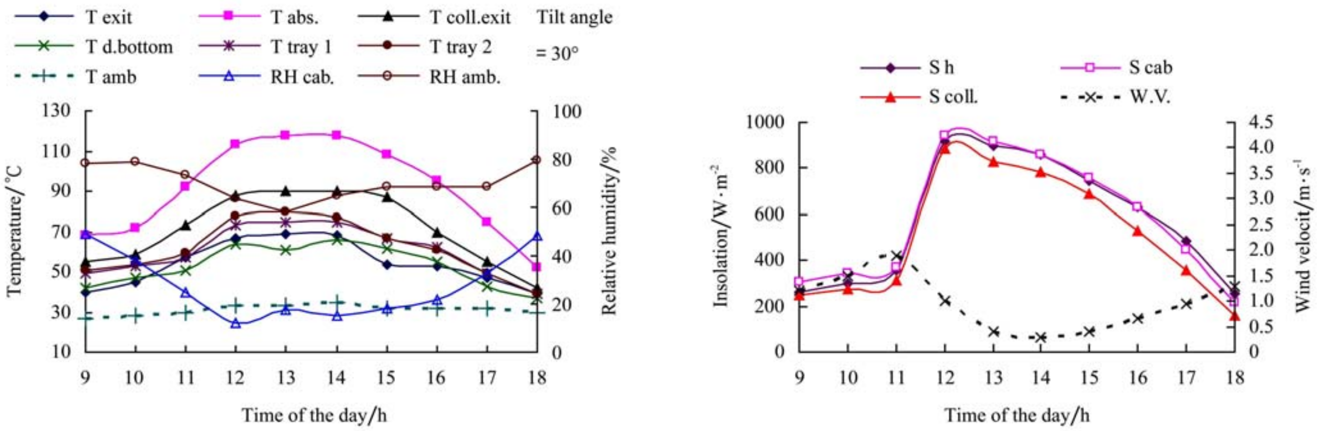

Figure 2 Effect of ambient conditions on temperature and relative humidity of empty SCD versus zonal time of the day when the system was due south at 30° collector tilt angle

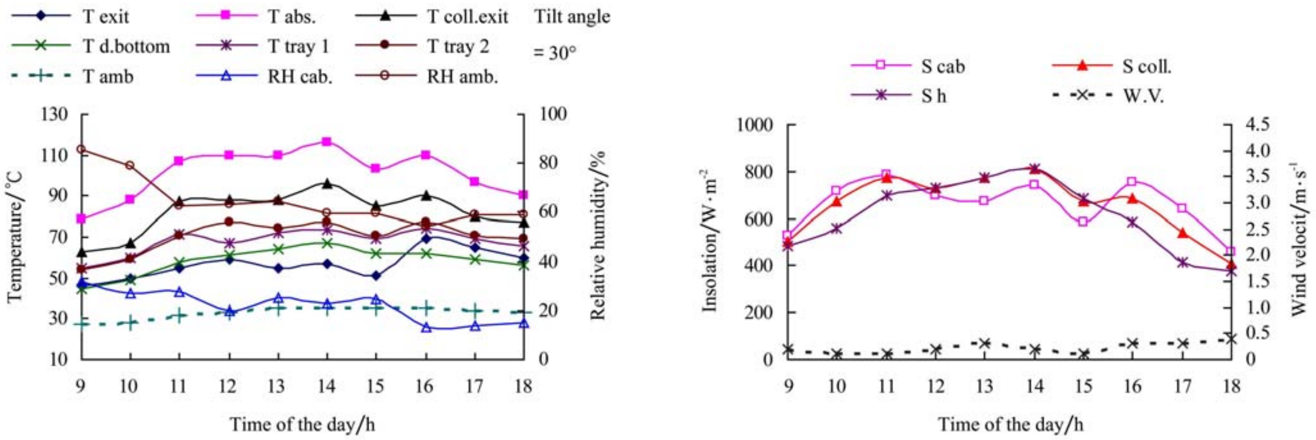

Figure 3 Effect of ambient conditions on temperature and relative humidity of empty SCD versus zonal time of the day when the system tracked the sun at 30° collector tilt angle

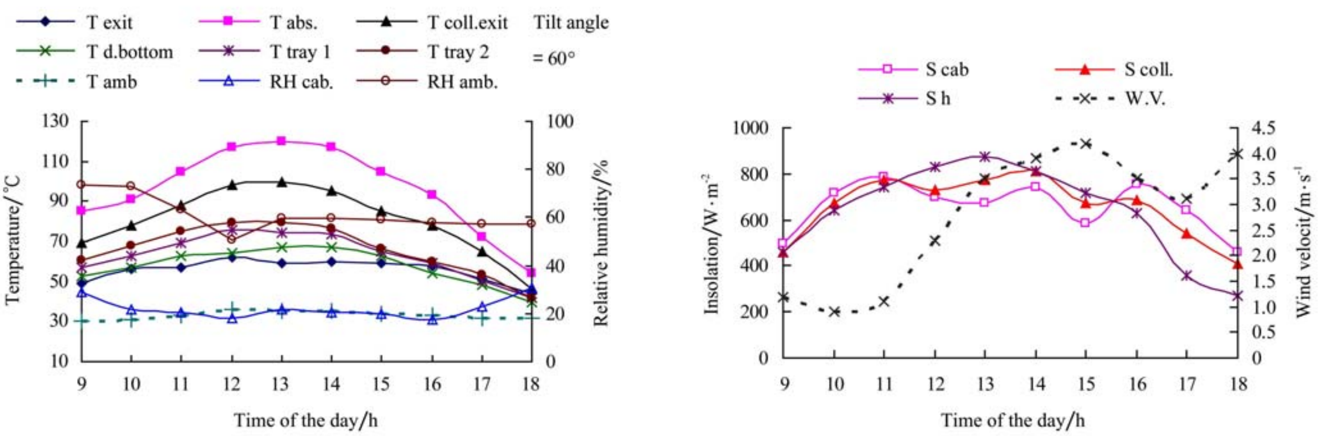

Figure 4 Effect of ambient conditions on temperature and relative humidity of empty SCD versus zonal time of the day when the system was due south at 60° collector tilt angle

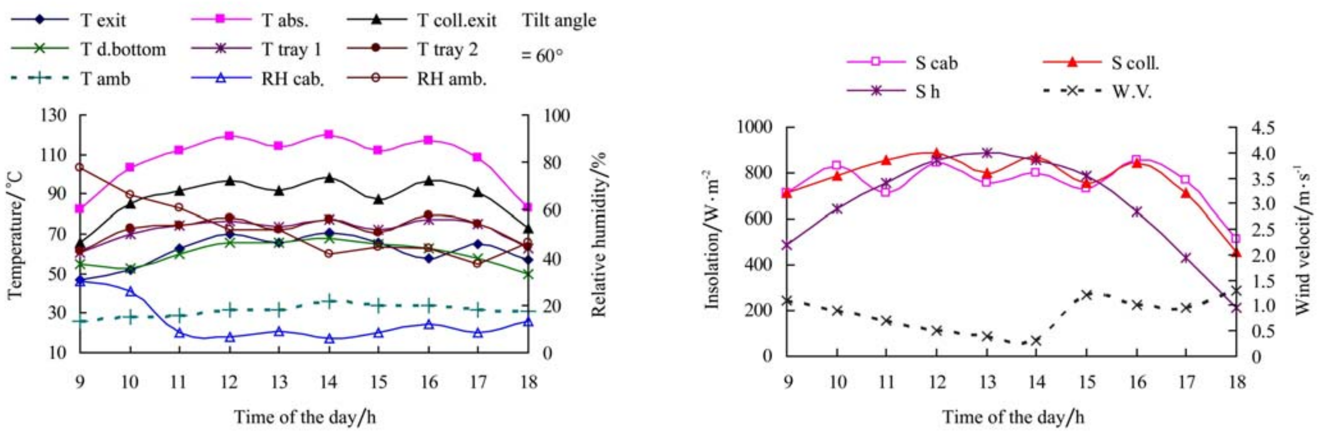

Figure 5 Effect of ambient conditions on temperature and relative humidity of empty SCD versus zonal time of the day when the system tracked the sun at 60° collector tilt angle

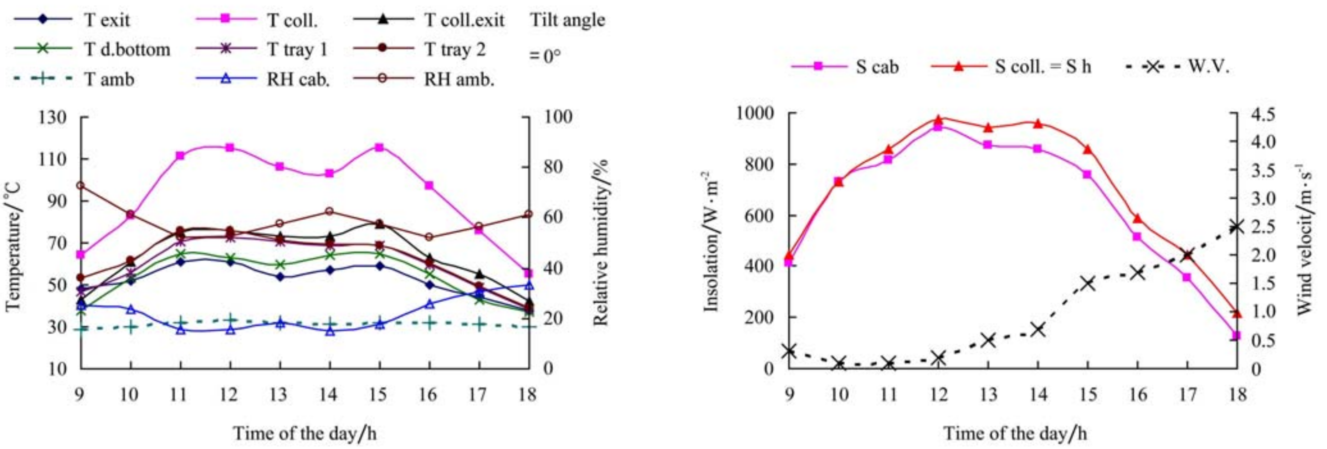

Figure 6 Effect of ambient conditions on temperature and relative humidity of empty SCD versus zonal time of the day when the system was due south at 0° collector tilt angle

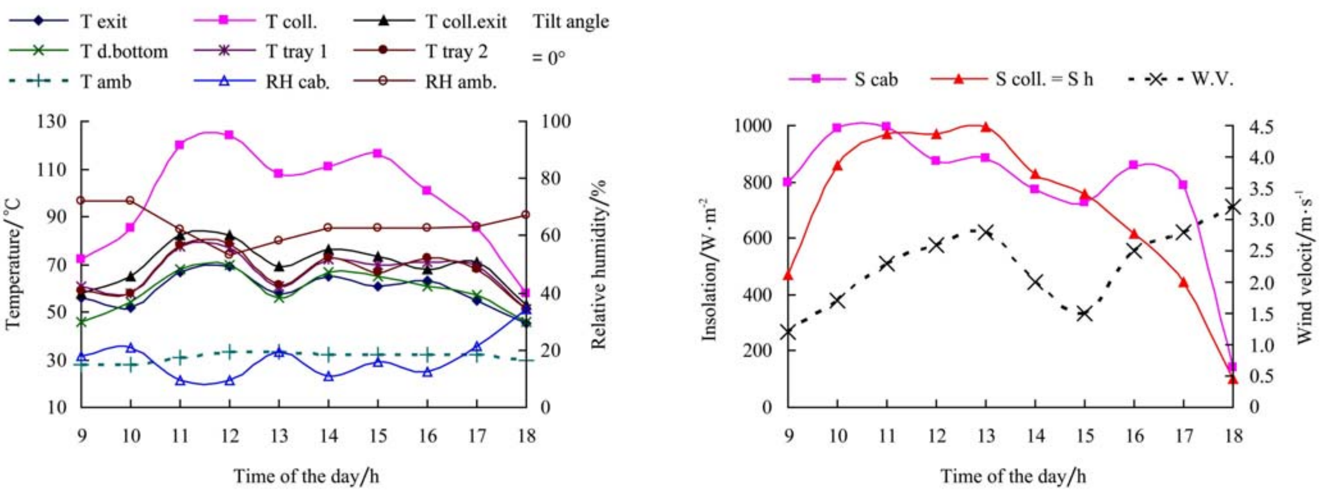

Figure 7 Effect of ambient conditions on temperature and relative humidity of empty SCD versus zonal time of the day when the system tracked the sun at 0° collector tilt angle

Table 1 Daily average and standard deviation of different measured parameters for the empty mixed mode dehydration system as affected by ambient conditions during experimentations

Conditions		T_{exit}	RH_{cab}	$T_{abs.}$	$T_{coll.exit}$	$T_{d.bottom}$	T_{tray1}	T_{tray2}	T_{amb}	RH_{amb}	S_h	S_{cab}	$S_{coll.}$	$W.V.$
0 tilt angle & due South	Average	52.4	22.1	92.5	64.0	54.3	59.9	62.5	31.2	58.6	700.0	638.6	700.0	1.0
	St.D.	7.6	6.6	21.7	13.6	11.2	12.1	12.1	1.2	6.2	264.6	269.3	638.0	0.9
0 tilt angle & tracking the sun	Average	59.1	17.2	98.0	69.7	59.0	66.7	66.6	25.3	63.58	701.0	782.8	701.0	2.3
	St.D.	7.4	7.6	22.1	9.4	8.7	8.7	9.2	0.8	5.83	291.6	241.5	291.6	0.6
30 tilt angle & due South	Average	53.9	27.8	91.1	70.9	52.8	60.0	61.5	26.5	70.1	570.3	577.7	506.3	1.0
	St.D.	11.3	13.6	23.4	17.5	10.3	12.4	13.7	1.4	7.3	271.3	275.2	271.0	0.5
30 tilt angle & tracking the sun	Average	56.7	22.2	101.0	82.1	58.3	67.8	70.0	27.2	64.6	612.2	658.9	656.8	0.2
	St.D.	7.0	6.5	12.0	10.4	6.8	6.1	7.8	1.9	9.8	151.4	105.4	131.5	0.1
60 tilt angle & due South	Average	55.5	22.2	95.9	80.2	57.6	62.9	66.1	26.6	61.0	633.2	655.5	652.8	2.8
	St.D.	5.7	4.3	21.4	16.8	8.9	11.1	18.6	4.0	11.7	32.6	16.9	21.0	1.3
60 tilt angle & tracking the sun	Average	61.5	12.8	107.0	87.8	60.4	72.0	72.5	23.3	52.2	654.3	752.9	768.6	0.8
	St.D.	7.8	8.3	13.9	10.7	6.2	5.9	5.9	1.2	12.5	220.5	98.8	125.6	0.3

At no load, the variation of temperature inside the SCD was measured at three locations in each tray and at the bottom of the cabinet. It was found that the upper tray (tray 2) receives slightly more thermal energy input as compared to lower tray (tray 1). This may be attributed to the direct effect of insolation on the air coming form the collector and lower tray. The maximum daily average temperature goes high as 72.5℃ and 72.0℃ for upper and lower trays, respectively when the system tracked the sun at 60º collector tilt angle.

The temperature of cabinet trays was varied close to each other, and the maximum variation was about 3.2℃ when the system was due south at 60º collector tilt angle. It should be mentioned that, this result was reached at highest recorded ambient wind velocity (daily average of 2.8 m/s), which may affect the incoming air to the collector due to increase the airflow rate.

The increase in SCD temperature would arise due to high insolation heating, low wind velocity with the consequent low heat transfer from the dehydration system to the surrounding air. For this reason, minimum cabinet temperatures were recorded in the mornings when the system has not yet been heated up, while maximum temperatures were recorded around noon. Also, it should be mentioned that, the ambient wind velocity as an input parameter has affected significantly the gained thermal effect of SCD.

During tested days, the variation of daily average relative humidity of air leaving the SCD ranged from 12.8% to 27.8%, while daily average ambient relative humidity ranged from 52.2% to 70.1%. Since increasing air temperature leads to reduce air relative, therefore the hot air has the ability to carry out more moisture content from the loaded product during the dehydration process. As shown in Figures 2-7, the relative humidity at the SCD outlet was significantly lower than the ambient relative humidity.

Also, it was found that, the relative humidity of air leaving the SCD is proportional to the collector temperature, ambient temperature, cabinet temperature and ambient relative humidity. The daily average insolation on the cabinet and collector aperture surfaces was increased with about 11.6% and 14.5%, respectively when the dehydration system tracked the sun at 60° collector tilt angle.

The following conditions were recorded for the developed SCD under test when the dehydration system was due south and tracked the sun (Table 2). It is clear that the best performance of the dehydration system was achieved with tracking the sun.

Table 2 Monitored conditions when the empty dehydration system was under test

System due South	System tracking the sun
$27 \le T_{amb.} \le 36$	$26 \le T_{amb.} \le 36$
$42 \le T_{coll.\ exit} \le 100$	$53 \le T_{coll.\ exit} \le 98$
$38 \le T_{exit} \le 69$	$45 \le T_{exit} \le 71$
$52 \le T_{abs.} \le 120$	$58 \le T_{abs.} \le 124$
$30 \le T_{cg} \le 70$	$29 \le T_{cg} \le 70$
$50.5 \le RH_{amb.} \le 79.6$	$37.6 \le RH_{amb.} \le 85.32$
$0 \le \theta \le 60$	$0 \le \theta \le 60$
$157.1 \le S_{coll.} \le 971.43$	$100 \le S_{coll.} \le 996$
$128.57 \le S_{cab.} \le 942.9$	$142.86 \le S_{cab.} \le 995$
$0.1 \le WV \le 4.2$	$0.1 \le WV \le 3.2$

3.1.2 Test with load

Testing of the SCD was done in batch mixed mode forced convection powered by relevant ambient wind velocity using pre-treated potato slices and peppermint, when the system tracked the sun at 60° collector tilt angle. In case of potato slices, the experiments were started at 09:00 am and terminated at 19:00 and 17:00 for SCD and electric oven drying, respectively. In case of peppermint, the experiments were started at 09:00 am and terminated at 15:00, 17:00 and 13:00 for SCD, open sun drying and electric oven drying, respectively.

The initial moisture content on wet basis (dry basis) of fresh potato slices (without pre-treatment) was 81.97% (454.76%), while it was 83.35% (500.46%), 82.7% (479.02%), 83.59% (509.42%) and 83.7% (513.64%) for pre-treatments control, A, B and C, respectively. This difference in initial moisture content means that, fresh potato slices absorbed moisture during the pretreatments process. The initial moisture content on wet basis (dry basis) of fresh peppermint was 78.6% (367%).

Figure 8 shows the effect of ambient conditions on the SCD temperature, relative humidity and pretreated potato slices moisture content versus solar drying time, when system tracked the sun. Generally, the recorded moisture content of pretreated samples decreased with the advance of drying time and reached almost constant values at the end of solar drying time. The drying rate was very low after 16:00, since most of the pretreatments slices reached constant weight.

Results presented in Figure 8 indicated that, temperature of lower tray 1 varied from 36.0℃. to 64.5℃, upper tray 2 ranged from 37.5℃. to 68.0℃, collector exit ranged from 39℃. to 84℃ and ambient ranged from 25℃. to 32℃. The average maximum maintained temperature inside the SCD was exceeded the ambient temperature with about 106.2% in the experimental day under load. Relative humidity of air entering lower tray ranged from 15.6% to 65.12%, upper tray ranged from 16.8% to 68.45% while ambient air ranged from 46.16% to 84.70%.

Insolation was varied from 50.80 to 828.57; 65.7 to 842.86 and from 60.5 to 857.14 W/m^2 on horizontal surface, cabinet surface and collector surface, respectively.

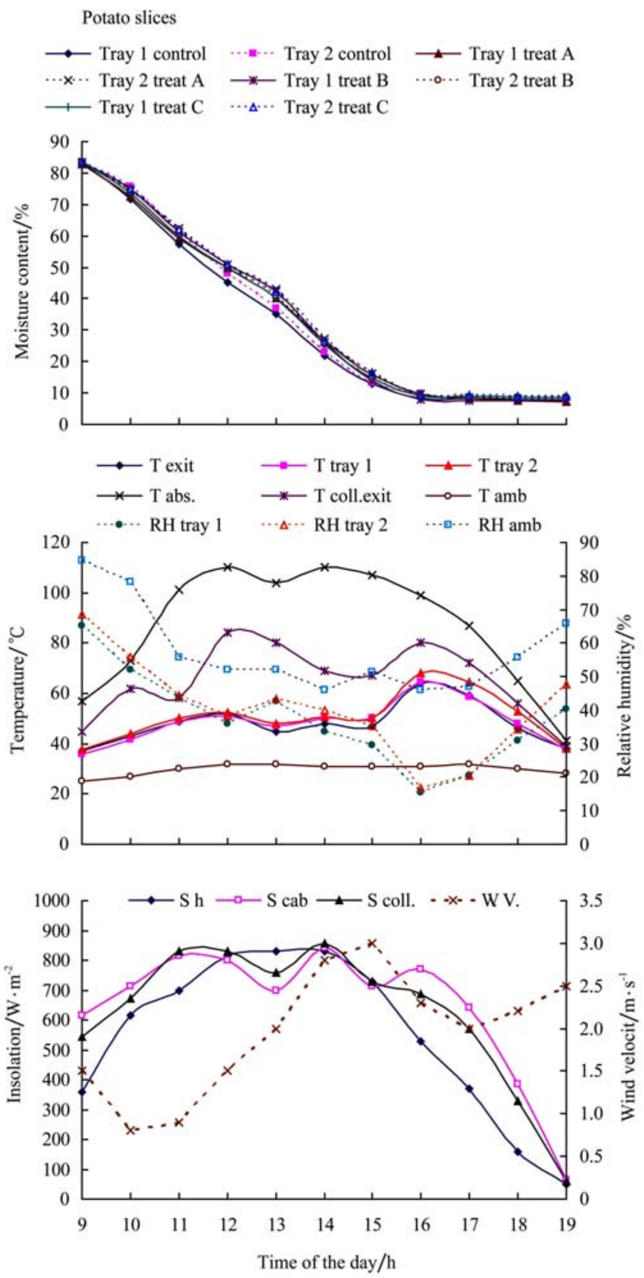

Figure 8 Variation of pretreated potato slices moisture content, dryer temperature and relative humidity versus solar drying time as affected by ambient conditions under mixed mode forced convection when the system tracked the sun with 60° collector tilt angle

Ambient wind velocity ranged form 0.8 to 3.0 m/s with an average of 1.95 m/s. As shown in figure, ambient wind velocity had a significant effect on the temperature and humidity that maintained inside the SCD as well as solar collector. Increasing wind velocity leads to increase airflow rate (forced convection) inside the SCD.

It should be mentioned that, the higher temperature and higher humidity was recorded for the air that flow towards the upper tray as compared to the lower tray. The predominant effect on the dehydration process was for the higher temperature. This result reflects in the depression of moisture content of potato slices for the upper tray as compared to the lower one.

Final moisture contents (FMCs) of pretreated potato slices for the lower tray (upper tray) were 7.90% (8.28%), 7.2% (7.6%), 7.52% (8.44%) and 8.76% (9.0%) for treatments of control, A, B and C, respectively, in case of SCD. While, for electric oven drying the FMCs were 6.7%., 7.1%., 7.3%, and 7.6% with respect to treatments of control, A, B and C, respectively. The FMCs of different pre-treated potato slices and peppermint with respect to drying time in case of oven drying (70 ±1℃ at room temperature) are shown in Figure 9.

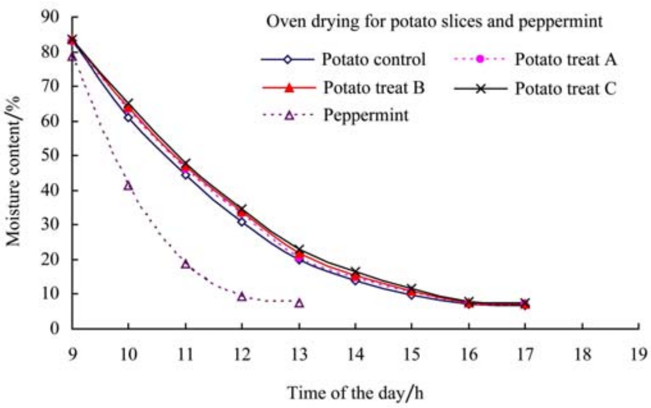

Figure 9 Variation of pretreated potato slices and peppermint moisture content versus drying time in case of electric oven drying method

The FMCs of peppermint were 7.81%, 8.50%, 10.40%, and 7.57% for lower tray, upper tray, open sun drying and electric oven drying, respectively as shown in Figure 9 and Figure 10.

During the dehydration process of pre-treated potato slices, the total loss of moisture varied between 90.92% to 91.96% and 89.39% to 91.05% for electric oven drying and SCD, respectively.

While, in case of peppermint the total loss of moisture ranged from 89.2% to 90.1% for SCD and 90% for electric oven drying. It is also seen that the SCD accelerates the drying process of peppermint as compared to the open sun drying. The daily average temperature of the solar cabinet drying air was about 53℃, while the average ambient air was about 29.8℃ during these experiments.

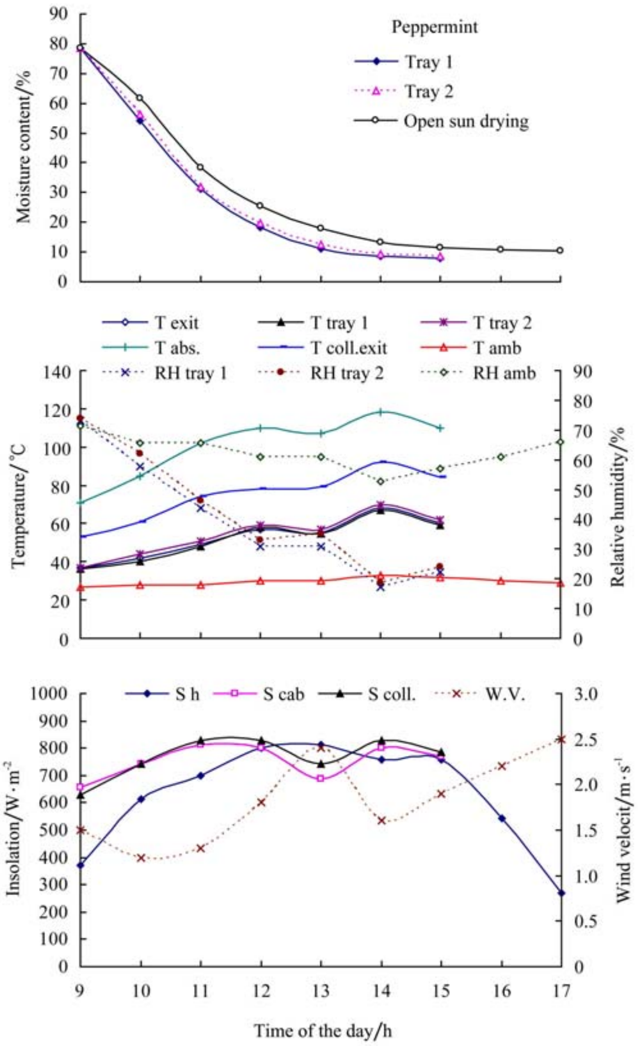

Figure 10 Effect of drying methods (mixed mode forced convection and open sun drying) and ambient conditions on peppermint moisture content, dryer temperature and relative humidity versus solar drying time when the system tracked the sun with 60° collector tilt angle

Figure 10 illustrates the variations of peppermint moisture content vs. drying time for the first and second trays as well as open sun drying. From the results of Figure 10, it is clear that the samples of the peppermint on first and second trays achieved their equilibrium moisture contents between hours 14:00 and 15:00, while for open sun drying it reaches the hour 17:00.

In case of SCD, the highest drying rate was observed at the first tray from the bottom, while the lowest drying rate was found at the top tray. But the final moisture content of the dried products was very close to each other as shown in the figures. This may be attributed to, when the hot air moves through the loaded trays, it losses heat and gains moisture from the product. In the same time the direct insolation fall on the cabinet aperture causes an increase in drying air temperature that flow towards upper tray.

On the basis of the results of Figures 8 and 10, it may be concluded that the present system can be used for drying pretreated potato slices in 7–9 hrs and peppermint in 6 hrs. It is clear from the curves of Figures 8, 9 and 10 that the moisture content of the samples decreases exponentially with drying time. At the initial high moisture content the interstitial water readily migrates to the surface by capillary forces. The water is redistributed into the capillary tubes by moisture diffusion in the product, probably from its centre with higher moisture level to its drier outer surface. Once the water reaches the product surface, it is evaporated by the diffusion phenomenon. The drying is, therefore, enhanced by an increase in the temperature gain of the drying air. At the lower moisture content of the product, there is higher resistance to the migration of the water to the surface, hence, the drying rate is slower. Similar curves are reported in the literature in the drying of medicinal herbs, grains and cocoa beans (Fagunwa et al., 2009; Gbaha et al., 2007; Müller et al., 1989; Sampaio et al., 2007).

Due to limited variation of drying rate between lower and upper trays, the average values were considered. Regression analysis was conducted to describe the relationship between moisture content of potato slices and peppermint with respect to drying time (t in hours), taking moisture content (MC, %) as the dependent variable when the dehydration system tracked the sun at 60° collector tilt angle. The regression equation obtained was as follows:

$$MC, \% = a * \exp [b * t] \tag{28}$$

The values of regression coefficients a, b, and r^2 corresponding to each equation for different pre-treated potato slices and peppermint are presented in Table 3.

3.1.2.1 Dehydration ratio

In case of SCD, the dehydration ratios of pretreated potato slices were 5.52%, 5.36%, 5.61% and 5.59% for control, treatment A, treatment B and treatment C, respectively. While, for oven drying method, the dehydration ratios were 5.6%, 5.37%, 5.65% and 5.67% with respect to control, treatment A, treatment B and treatment C, respectively.

Table 3 Regression coefficients of pre-treated potato slices and peppermint during the dehydration process

Crop/herb	Conditions*	Regression coefficients and r^2	Pre-treatments Control	A	B	C
potato slices	SCD	a^{**}	1135	1113.3	1294.6	1088.8
		b^{**}	-0.2792	-0.2719	-0.2858	-0.2705
		r^2	0.95	0.95	0.94	0.94
	Electric \oven drying	a^{**}	1778.5	1721.5	1696.8	1615.7
		b^{**}	-0.3406	-0.3348	-0.331	-0.3247
		r^2	0.99	0.99	0.99	0.99
Peppermint (without pretreatments)	SCD	a^{**}	2905.8	-	-	-
		b^{**}	-0.4082	-	-	-
		r^2	0.97	-	-	-
	Open sun drying	a^{**}	784.58	-	-	-
		b^{**}	-0.2734	-	-	-
		r^2	0.93	-	-	-
	Electric oven drying	a^{**}	18985	-	-	-
		b^{**}	-0.6176	-	-	-
		r^2	0.97	-	-	-

Note: * Drying method; ** Regression coefficients (Equation (28)).

The dehydration ratios of peppermint were 4.29%, 4.19% and 4.32% for SCD, open sun drying and electric oven drying, respectively.

3.2 Drying quality and overall acceptability

Table 4 shows the effect of various pretreatments and drying conditions on some chemical analysis of potato chips. While the effect of pretreatment and drying conditions was found to be significant on starch and reducing sugar, it was non-significant for non-reducing sugar contents. The differences noted in the values were due to the effect of various pretreatments on the extent of leaching. Tubers with high value of dry matter gave chips with higher overall acceptances than tubers with less dry matter content. All the individual characteristics were summed up and their mean values were compared for each pretreatment and drying method as shown in Table 5.

There was no difference in the flavour and colour of the solar and electric oven dried potato slices in case of treatment A as shown in Table 5. The best chips colour was achieved with 15 s frying time.

Table 4 Effect of various pretreatments and drying conditions on starch, reducing sugar and non-reducing sugar contents of potato chips (*Diamont*)

Item	Pretreatment	Fresh pretreated samples	SCD	Electric oven drying
Starch, % of fresh weight	Control	21.4 ± 0.02	14.8 ± 0.01	13.15 ± 0.01
	Treat. A	21.9 ± 0.02	15.1 ± 0.01	14.0 ± 0.00
	Treat. B	19.3 ± 0.03	14.90 ± 0.02	12.8 ± 0.01
	Treat. C	17.5 ± 0.02	12.7 ± 0.01	12.0 ± 0.01
Reducing sugar, % dry basis	Control	0.750 ± 0.002	0.325 ± 0.001	0.312 ± 0.001
	Treat. A	0.774 ± 0.003	0.330 ± 0.001	0.318 ± 0.001
	Treat. B	0.644 ± 0.001	0.317 ± 0.001	0.311 ± 0.001
	Treat. C	0.569 ± 0.002	0.296 ± 0.001	0.291 ± 0.001
Non-reducing sugar, % dry basis	Control	1.90 ± 0.003	0.770 ± 0.001	0.768 ± 0.002
	Treat. A	1.95 ± 0.001	0.830 ± 0.002	0.826 ± 0.001
	Treat. B	1.86 ± 0.002	0.700 ± 0.001	0.693 ± 0.001
	Treat. C	1.72 ± 0.003	0.640 ± 0.001	0.637 ± 0.001

Table 5 Effect of pretreatments on chipping colour of solar dried potato slices (*Diamont*)*

Frying time /s	Pretreatments of potato slices				Electric oven
	Control	Treat. A	Treat. B	Treat. C	
15	2	1	2	2	1
30	2	2	3	3	2
45	4	3	4	4	3
60	5	4	5	6	4

Note: *Chip colour on scale 1-10 where 1 is white and 10 the dark brown colour.

Electric oven dried samples obtained slightly higher score comparing with solar cabinet dried ones (Figure 11). Among various pretreatments, the highest score was obtained by common salt-treated samples (8.9-9.1) followed by those treated with sodium meta-bi-sulphite (8.5-8.8), control (7.4-7.6) and water washing (8.6-7.0). The trend of results obtained is in agreement with Goyal and Bhargava (1999). Blanching in hot water for about 4 min has significantly improved the over all qualities of chips hence tuber slices must be blanching prior to frying to prepare quality chips. In case of potato processing, blanching is used to inactivate peroxides, to improve the texture, color and, to some extent, the flavor of final product.

Table 6 shows the average values of chemical analysis of fresh and dried peppermint. The economic importance of peppermint cultivation relies solely on essential oil yield and quality. Preference of SCD in keeping the quality of dried peppermint close to the fresh herbs is very clear as shown in Table 6.

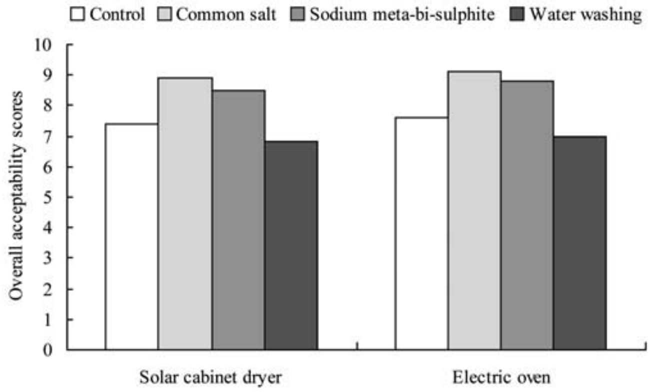

Figure 11 Effect of pretreatments and drying conditions on overall acceptability of potato chips

Table 6 Chemical analysis of fresh and dried peppermint (*Mentha virdis*)

Drying method	Essential oil /%	Chlorophyll /mg g^{-1}	
		(A)	(B)
Fresh peppermint	2.53 ± 0.03	9.79 ± 0.02	5.76 ± 0.01
Solar cabinet dryer (SCD)	1.46 ± 0.01	7.13 ± 0.01	3.44 ± 0.01
Open sun drying	1.03 ± 0.02	5.67 ± 0.02	2.98 ± 0.03
Electric oven drying	0.75 ± 0.02	3.18 ± 0.03	1.35 ± 0.02

In all the tested attributes, the solar cabinet dried samples compared favourably with the sun-dried samples. The qualities of both the solar cabinet dried and electric oven dried sample are within the acceptable level of the panelist.

In passive drying system, the low air flow rates generate high temperatures on the exit of the collector (drying temperature), sometimes able to exceed that of deterioration of horticulture and medicinal herbs (about 70℃), in particular, when the sun is at its Zennith. Therefore, the developed system was equipped with suction axial flow fan fixed in the chimney, which generate air flow rates, high enough to get suitable drying temperature.

It should be noted that, the dried samples obtained by SCD were stored in air tight polyethylene bags for 9 months without any significant changes in their physiochemical characteristics (unpublished data, which will be published in another article in the near future).

4 Conclusions

The purpose of the present investigation was devoted to the development, design, construction and performance evaluation of a mixed mode solar cabinet dryer for small scale farms. The solar cabinet performance was enhanced by using solar-wind ventilation system represented by solar collector and mini-wind turbine. A modest attempt to develop a simple framework to facilitate a comparison of enhanced solar cabinet drying feasibility as against electric oven and open sun drying has been made. Results of the present study indicated that in relation to drying time and physiochemical quality of the potato slices, the electric oven stands first, followed by solar cabinet dryer. For peppermint, solar cabinet dryer stands first, followed by open sun drying.

Due to shortage or frequent electricity failure and non- electrification of rural areas, solar cabinet dryer provides a suitable alternative for drying potato chips, and medicinal herbs. It can be concluded that, among pretreatments of potato chips, the use of common salt was observed to be the best. The solar cabinet dryer performed satisfactorily in drying freshly potato chips and peppermint within one clear sunny day.

Nomenclature

a, b regression coefficients

a_w water activity (-)

C_{Pa} specific heat of air at constant pressure (kJ kg^{-1} K^{-1})

C_P specific heat of air (J kg^{-1} K^{-1})

C_{pr} specific heat of raw product (MJ kg^{-1} ℃$^{-1}$)

DR dehydration ratio

$E_{cond.L}$ energy conduction losses from the absorber per unit time (W)

$E_{conv.L}$ energy convective losses from the absorber per unit time (W)

E_R energy long wave re-radiation from the absorber per unit time (W)

$E_{R.L}$ energy reflection losses from the absorber per unit time (W)

E_u useful energy collected by the air per unit time (W)

FMCs final moisture contents

h_{fg} latent heat of vaporization of water (MJ/kg)

I average daily solar radiation availability (MJ/m^2)

I_T total radiation incident per unit time on the absorber's surface (W/m^2)

L_v latent heat of vaporization = 4.186 (597 – 0.56 (T_{pr} + 273) (kJ/ kg)

M moisture content of product at time t (kg water kg^{-1} dry basis)

M_0 initial moisture content (%)

$\dot{m}_a$ mass of air leaving the dryer per unit time (kg/s)

m_a mass of drying air (kg)

MC moisture content (%)

M_{cf} final moisture content of the product on wet basis (in fraction)

M_{ci} initial moisture content of the product on wet basis (in fraction)

M_e equilibrium moisture content (% d.b.)

m_i initial mass of the food item (kg)

M_i initial moisture content (% d.b.)

M_{sd} per batch drying capacity of solar dryer (kg)

M_t the instantaneous moisture content at any time

m_w mass of water evaporated from the food item (kg)

p_w partial water pressure (Pa)

p^*_w partial water pressure (Pa)

$RH_{amb.}$ relative humidity for ambient air (%)

$RH_{cab.}$ relative humidity for air leaving the cabinet (%)

s time measured in seconds

$S_{cab.}$ insolation on the solar cabinet glass cover (W/m^2)

SCD solar cabinet dryer

S_{coll} insolation on the solar collector surface (W/m^2)

S_h insolation on the horizontal plane (W/m^2)

t time required for drying of a single batch of the product (in days)

T_{amb} ambient air temperature (K)

$T_{abs.}$ absorber sheet temperature (℃)

T_{amb} ambient air temperature (℃)

$T_{amb.}$ ambient air temperature (℃)

T_{cab} average air temperature for the solar cabinet dryer (℃)

T_{cg} collector glass temperature (℃)

T_{coll} temperature of the collector's absorber (K)

$T_{coll.\ exit}$ solar collector air temperature at the exit (℃)

T_{dryer} solar cabinet air temperature (℃)

T_{fs} temperature of drying air (℃)

T_{fs} dry temperature of drying air (℃)

T_{fs1} , T_{fs2} initial and final temperatures of the drying air respectively (K)

T_{pr} surface temperature of the product (℃)

U_L overall heat transfer coefficient of the absorber (W m^{-2} K^{-1})

W_0 initial weight of dried product (kg)

W_t weight of product to be dried at any time (kg)

WV ambient wind velocity (m/s)

Greek letters

θ tilt angle of solar collector, degree

τ the transmittance of the top glazing

ζ fraction of the sensible heating requirement of the product on the first day that is required for sensible heating on other days of drying

η_d overall thermal efficiency of the solar dryer (in fraction)

ρ reflection coefficient of the absorber

φ relative humidity (%)

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