Experimental and theoretical performances of a solar assisted dehumidification drying system for heat sensitive products

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Abstract

Problem statement: In most countries, conventional hot air drying method is commonly used for drying heat sensitive products. Although the method is simple and cheap, however the conventional hot air dryers are still not suitable to dry them because of resulting in low product quality. Approach: Solar assisted dehumidification drying system is suitable for drying 'heat sensitive' products like Centella Asiatica L because of drying process is conducted at low air temperature and low relative humidity. The main components of the drying system consist of a solar collector, an energy storage tank, an auxiliary heater, two blowers, two adsorber columns, two water-air heat exchanger, two water circulating pumps, a drying chamber and other ancillary equipment. A computer program was developed in MATLAB software to predict the performance of the drying system. The predicted results are compared with those obtained from experimental results. The performance is indicated by Pick up efficiency (η_P), Coefficient of Performance (COP) and Solar Fraction (SF). Results: The maximum values of the pickup efficiency (η_P), solar fraction (SF) and coefficient of performance (COP), obtained from the predicted and measured data are as follows (93% and 97%), (0.34 and 0.3) and (69.3% and 70.5%), respectively with initial and final wet basis moisture content of Centella Asiatica L 88% and 15%, respectively at an air velocity is 3.25 m/s. Conclusion: Good agreement was found between predicted results and experimental results.

Key words: Heat sensitive products, Centella Asiatica L, low drying temperature, performance of solar drying system

Introduction

Drying is one of the traditional methods for preservation of foods or other heat sensitive and biologically active products. The main purpose of drying is to reduce the moisture content to such a level where spoilage due to the various reactions is minimized (Szentmarjay et al., 1996). Additionally, drying of foods or other heat sensitive, biologically active products is intended to improve stability, decrease shipping weights and costs and minimize packing requirement (Ruiz et al., 2008).

Centella Asiatica L belong to the family of umbrelliferae is commonly found in parts of India, Asia and The Middle East. It is also known as 'Daun Pegaga' in Malaysia, 'Luei Gong Gen' or 'Tung Chain' in China, 'Vallarai' in Tamil Nadu (India) and 'Daun Kaki Kuda' in Indonesia (Somchit et al., 2004). *Centella Asiatica* L is a traditional herbal medicine has been used in Asia for hundreds of years (Guangtao and Xiuyang, 2008). It contains pentacyclic triterpenes, mainly asiatic acid, asiaticoside, madecassic acid and madecassoside (Inamdar et al., 1996). It is has been used for improving memory, treating mental fatigue, anxiety, and eczema (Goh et al., 1995), curing leukorrhea and toxic fever (Kan, 1986), antitumor (Babu et al., 1995), antiproliferative (Yoshida et al., 2005), antigenotoxic (Siddique et al., 2007), anti-inflammatory, anticancer, antioxidation and anxiolytic (Kumar and Gupta, 2002; Gnanapragasam et al., 2007).

Centella Asiatica L contains a high level of moisture content (85%-90% wet basis). Therefore, after harvesting its must be dried as soon as possible to prevent the expected contamination by rodents, birds, insects, dust and dirt. In the drying process, beside removal of water, there are other important considerations like the drying time, operation cost, and quality of dried product and performance of drying system. The quality of the dried product is greatly influenced by drying conditions (Kilic, 2009).

In most countries, conventional hot air drying method is commonly used for drying foods or other heat sensitive and biologically active products. Although the method is simple and cheap, however the conventional hot air dryers is still not suitable to dry them because the evaporative capacity and drying time depends on the drying air temperature. The high drying air temperature may remove the important ingredients, which causes color reactions and degradation of the product resulting in low product quality (Steele et al., 1969; Overhults et al., 1975; Rojanasaroj et al., 1976; White et al., 1976; Ting et al., 1980; Teeboonma et al., 2003; Attanasio et al, 2004; Fennell et al., 2004; Luangmalawat et at., 2008). The low product quality may have adverse economic effects on domestic and international markets value of the product (Beltagy et al., 2007).

Based on researches undertaken by several researchers such as Doymaz and Pala (2002) dried red pepper at 60^{o}C; Demir et al. (2004) dried bay leaves at 60^{o}C; Alibas (2007) dried nettle leaves at above 50^{o}C; Arabhosseini et al. (2007) dried Tarragon leaves at 60^{o}C; Correia et al. (2009) dried chestnut fruit at 60^{o}C-70^{o}C; Hii et al. (2009) dried cocoa at 60^{o}C; Katsube et al. (2009) dried mulberry leaves. They have proven that heat sensitive materials dried by using hot air dryer experience quality degradation. Therefore, low temperature drying technologies must be applied with high evaporative capacity and short drying time to minimize quality degradation of the products. Its can be done either by the use of heat pump dryers or desiccant dryers (Gurtas Seyhan and Evranuz, 2000; Chua et al., 2003). In these systems, the evaporative capacity or drying time depends on the humidity of air whereby the lower its humidity, the higher will be its evaporative capacity.

The water vapor in the air can be removed or dehumidified by using dehumidifiers like evaporator, desiccant materials for heat pump dryers and desiccant dryers, respectively.

Some researchers have been comparing various drying agricultural produce by using heat pump dryer with conventional hot air dryers such as Filho et al. (1997) drieds fruids and roots; Soponronnarit et al. (1998) dried papaya; Gurtas Seyhan and Evranus (2000) dried Mushroom. It was found that the color and aroma qualities of dried agricultural products using heat pumps were better than those products using conventional hot air dryers. However, dehumidification of the process air can be achieved when the evaporator surface temperature is lower than the dew point temperature of the process air at the evaporator inlet (Fatouh, 2006).

There are few agriculture products that use desiccant drying method such as Aldis et al. (1980) drieds corn; Tomlinson et al. (1981) dried fruits; Miller (1985) dried vegetables. Thoruwa et al. (1996) employed a stationary desiccant bed to a solar dryer during the daytime and used it for extending the drying process the night time. Riyad and Jacques (2001) integrated a fixed silica gel bed to a solar dryer and found a shortened drying period was required, from 55 to 44 h, for drying apricots. Gurtas Seyhan and Evranus (2000) found that using low temperature (20, 30, and 40^{o}C) coupling with silica gel for drying heat sensitive products, such as mushrooms, can effectively decrease the Maillard browning reaction rate. Madhiyanon et al. (2007) found that coconut drying time and drying rate use a desiccant dehumidification system faster and higher than a pure hot air drying system. However, No work on experimental performance of solar drying system which employed solid desiccant dehumidification has been reported.

The purposes of this study are to compare the experimental and theoretical performances of a solar assisted dehumidification drying system. The performance of this drying system is indicated by Pick up efficiency (η_P), Coefficient of Performance (COP) and Solar Fraction (SF). A computer program developed in MATLAB software to calculate the performance of the drying system.

Description of solar- assisted dehumidification drying system: A schematic diagram of the solar assisted dehumidification drying system is shown in Fig 1. The main components of the drying system consist of a solar collector, an energy storage tank, an auxiliary heater, two blowers, two adsorber columns, two water-air heat exchanger, two water circulating pumps, a drying chamber and other ancillary equipment. The solar collectors used were 60-evacuated heat pipes tube arranged in parallel with total area of 6 m^2. The area of absorber in tube each individual was 0.1 m^2, and distance between the tubes was 7.1 cm. The pump electrical capacity was 0.1 kW and was used to circulate water from the water tank to the solar collectors. The water tank with diameter of 45 cm and height of 85 cm was made from stainless steel and insulated using glass wool and foam rubber. Two units of cross flow type heat exchanger have been used. This system has two adsorber columns with dimension of 25 cm (width) x 25 cm (length) x 100 cm (height). The columns were filled up with silica gel to a height of 85 cm. The drying chamber was of the cabinet type with the size of 1.0 m (width) x 1.0 m (length) x 2.5 m (height). The chamber contains the drying trays with adjustable racks to place the *Centella Asiatica* L. The dry air from the adsorber column entered the drying chamber at the bottom and exit through an air vent at the top. The dry air was circulated by using blower with electrical capacity of 0.75 kW. Water in the heat storage tank is recirculated in the solar collector by the heat collection pump and this recirculation eventually raises the water temperature in the tank. Since the water in the storage tank is utilized for both the regeneration of the absorbent at a higher temperature and the drying process at a lower temperature, a temperature level of about 70°C-80°C is required. If the solar collector could not raise the water temperature up to this level, then the auxiliary heater is used to supplement the heat energy required to do so. The hot water is first used to produce hot air in the hot water-air heat exchanger for regeneration of adsorbents in one adsober column, and to warm dehumidified air from the other adsorber column in the warm water–air heat exchanger for drying in the drying chamber by manipulation of the two three-way valves. Fresh air for both regeneration and adsorption/drying is drawn in by the two blowers.

The adsorbents are packed in two adsorber columns so that air dehumidification could run continuously by simultaneous bed regeneration and adsorption in alternate bed as follows. Regeneration of adsorbents in the adsorber column (B) is carried out by heating the air drawn in by the air blower (B) in the hot water-air heat exchanger (B) and passing the hot air into the adsorber column (B) so that moisture is desorbed and removed from the adsorbents into the atmosphere. At the same time, drying is carried out in the drying chamber by heating the air drawn in by the blower (A) that is dehumidified by adsorber column (A) in the warm water-air heat exchanger (A) and passing the warm dehumidified air into the drying chamber. When the adsorbents in the adsorber column (A) are saturated with moisture and the regenerated adsorbents in the other adsorber column (B) are fully regenerated, then the regeneration process is switched to the saturated adsorber column (A) and the adsorption process is switched to the another adsorber column (B) by manipulation of the two three-way valves.

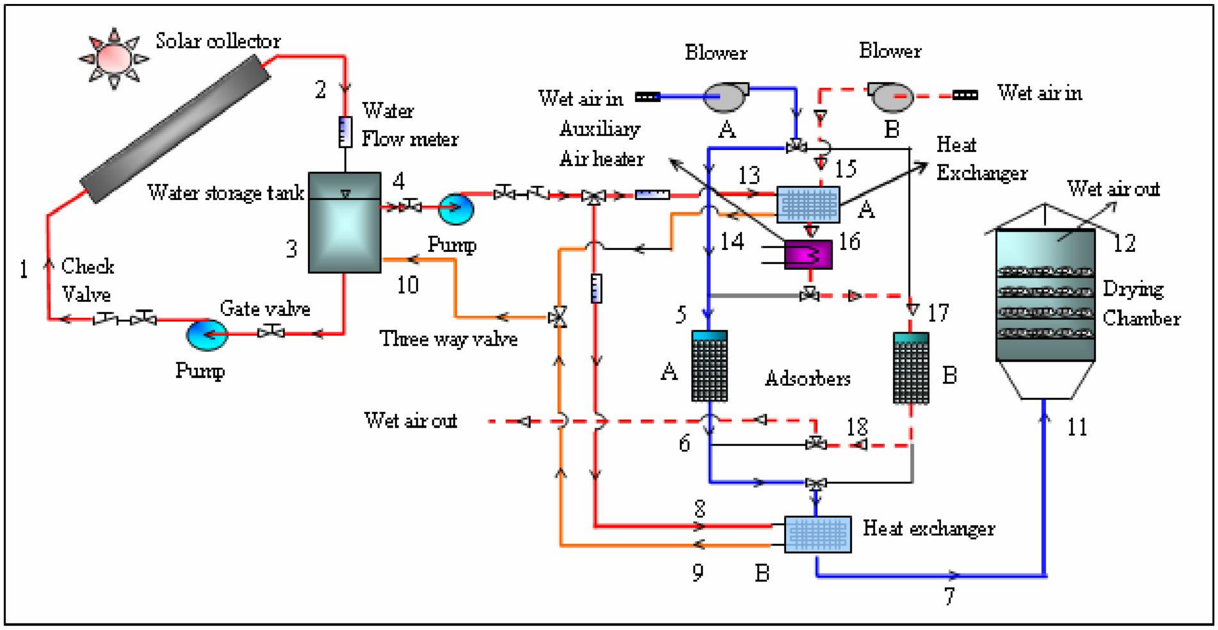

Figure1. Schematic diagram of the solar assisted dehumidification drying system

Theoretical background: The solar assisted dehumidification drying system consist of a solar collector, an energy storage tank, an auxiliary heater, two adsorber columns, two water-air heat exchanger, and drying chamber. This system has three processes, dehumidification process, regeneration process, and batch drying process as shown in Fig 1. The mass balance and energy balance equations for each component are expressed as follows:

a. The solar collector: Arcuri et al. (1995) presented an expression to describe the performance of a solar evacuated tube collector by an energy balance involving energy gain and thermal and optic losses as follows:

$$\dot{Q}_U = F_R\left((\tau\alpha)A_{Ct}I_T - \frac{(T_1 - T_a)}{R_{et}}\right) \tag{1}$$

The useful energy $\dot{Q}_U$ collected by the water in term its temperature rise is also written as:

$$\dot{Q}_U = \dot{m}_{WC}C_{PW}(T_2 - T_1) \tag{2}$$

$$T_2 = T_1 + \frac{\dot{Q}_U}{\dot{m}_{WC}C_{PW}} \tag{3}$$

The instantaneous efficiency of the solar evacuated tube collector η_C is defined as the ratio of the rate of useful energy supplied by collector $\dot{Q}_U$ to the rate of incident solar energy in its area A_{Ct} :

$$\eta_C = \frac{\dot{Q}_U}{A_{Ct}I_T} = F_R\left((\tau\alpha) - \frac{(T_1 - T_a)}{R_{et}A_{Ct}I_T}\right) \tag{4}$$

$$\eta_C = \frac{\dot{m}_{WC} C_{PW} \left(T_2 - T_1\right)}{A_{Ct} I_T} \tag{5}$$

b. Adsorber column

For dehumidification process: Dehumidification is the process of removal of water vapour from moist air using a desiccant (silica gel). The mass balance equations of adsorber column for dehumidification process can be written as follow:

Product (dry matter of silica gel):

$$W_{SGi} = W_{SGt} = W_{SG} \tag{6}$$

Air: $$\dot{G}_{a5} = \dot{G}_{a6} = \dot{G}_a \tag{7}$$

Water: $$\dot{G}w_5 + \left(X_{SGt} - X_{SGi}\right)\frac{W_{SG}}{\Delta t} = \dot{G}w_6 \tag{8}$$

Where:

$$Y_5 = \frac{\dot{G}_{W5}}{\dot{G}_{a5}}, \quad Y_6 = \frac{\dot{G}_{W6}}{\dot{G}_{a6}} \tag{9}$$

Rearranging the above equation gives the outlet air absolute humidity of adsorber column as follow:

$$Y_6 = Y_5 - \left(X_{SGt} - X_{SGi}\right)\frac{W_{SG}}{\dot{G}a\Delta t} \tag{10}$$

The dehumidification rate can be determined using equation as follow:

$$R_{dh} = \left(X_{SGt} - X_{SGi}\right)\frac{W_{SG}}{\Delta t} \tag{11}$$

The energy balance equation for dehumidification process can be written as follow:

$$\dot{Q}_5 = \dot{Q}_6 + \dot{Q}_D + \dot{Q}_{SG} + \dot{Q}_{LAC} \tag{12}$$

Where:

$$\dot{Q}_5 = \dot{G}_a h_5 \tag{13}$$

$$\dot{Q}_6 = \dot{G}_a h_6 \tag{14}$$

$$h_6 = C_{Pa} T_6 + Y_6 \left(h_{fg} + C_{PV} T_6\right) \tag{15}$$

$$\dot{Q}_{SG} = \rho_{SG} V_{SG} \left(C_{SG} + X_{SG} C_W\right) \partial T_{SG} / \partial t \tag{16}$$

$$\dot{Q}_{LAC} = \dot{G}_a q_{LAC} \tag{17}$$

$$\dot{Q}_D = -R_{dh}\left(C_{PW} T_W + h_{SG}\right) \tag{18}$$

Where h_{SG} is the isothermal differential heat of sorption of water on silica gel and this energy can be determined from the following correlation (Biswas et al., 1984):

$$h_{SG} = -1079 X_{SG} + 2745\, kJ/kg \tag{19}$$

Rearranging the above equation gives the outlet air temperature of adsorber column as follow:

$$T_6 = \frac{\dot{Q}_5 - \dot{Q}_D - \dot{Q}_{SG} - \dot{Q}_{LAC} - \left(h_{fg} \dot{G}a Y_6\right)}{\dot{G}a\left(C_{pa} + \left(C_{PV} Y_6\right)\right)} \tag{20}$$

The heat rate received by the air in the absorber column is given by:

$$\dot{Q}_{dh} = \dot{G}_a C_{pa} \left(T_6 - T_5\right) \tag{21}$$

For regeneration process: The regeneration process is the drying of the desiccant (silica gel) using hot air so that it can be used again for dehumidification. The mass balance equations of adsorber column for regeneration process can be written as follow:

Product (dry matter of silica gel):

$$W_{SGi} = W_{SGt} = W_{SG} \tag{22}$$

Air: $$\dot{G}_{a17} = \dot{G}_{a18} = \dot{G}_a \tag{23}$$

Water: $$\dot{G}w_{17} + \left(X_{SGi} - X_{SGt}\right)\frac{W_{SG}}{\Delta t} = \dot{G}w_{18} \tag{24}$$

Where:

$$Y_{17} = \frac{\dot{G}_{W17}}{\dot{G}_{a17}}, \quad Y_{18} = \frac{\dot{G}_{W18}}{\dot{G}_{a18}} \tag{25}$$

Rearranging the above equation gives the outlet air absolute humidity of adsorber column as follow:

$$Y_{18} = Y_{17} + \left(X_{SGi} - X_{SGt}\right)\frac{W_{SG}}{\dot{G}a\Delta t} \tag{26}$$

The regeneration rate can be determined using equation as follow:

$$R_{rg} = \left(X_{SGi} - X_{SGt}\right)\frac{W_{SG}}{\Delta t} \tag{27}$$

The energy balance equation for regeneration process can be written as follow:

$$\dot{Q}_{17} = \dot{Q}_{18} + \dot{Q}_D + \dot{Q}_{SG} + \dot{Q}_{LAC} \tag{24}$$

Where:

$$\dot{Q}_{17} = \dot{G}_a h_{17} \quad (28)$$

$$\dot{Q}_{18} = \dot{G}_a h_{18} \quad (29)$$

$$\dot{Q}_D = R_{rg}\left(C_{PW} T_W + h_{SG}\right) \quad (30)$$

$$h_{18} = C_{Pa} T_{18} + Y_{18}\left(h_{fg} + C_{PV} T_{18}\right) \quad (31)$$

Rearranging the above equation gives the outlet air temperature of adsorption column as follow:

$$T_{18} = \frac{\dot{Q}_{17} - \dot{Q}_D - \dot{Q}_{SG} - \dot{Q}_{LAC} - \left(h_{fg}\dot{G}aY_{18}\right)}{\dot{G}a\left(C_{pa} + \left(C_{PV}Y_{18}\right)\right)} \quad (32)$$

Heat rate required for regeneration process can be determined using equation as follow:

$$\dot{Q}_{rg} = \dot{G}_a C_{pa}\left(T_{17} - T_{18}\right) \quad (33)$$

c. Drying chamber

For drying process: Drying is the process of removal of water vapour from the heat sensitive product (*Centella Asiatica* L). The mass balance equations of drying chamber for drying process can be written as follow:

Product (dry matter of *Centella Asiatica* L):

$$W_{CAi} = W_{CAt} = W_{CA} \quad (34)$$

Air:

$$\dot{G}_{a11} = \dot{G}_{a12} = \dot{G}_a \quad (35)$$

Water:

$$\dot{G}w_{11} + \left(X_{CAi} - X_{CAt}\right)\frac{W_{CA}}{\Delta t} = \dot{G}w_{12} \quad (36)$$

Where:

$$Y_{11} = \frac{\dot{G}_{W11}}{\dot{G}_{a11}}, \quad Y_{12} = \frac{\dot{G}_{W12}}{\dot{G}_{a12}} \quad (37)$$

Rearranging the above equation gives the outlet air absolute humidity of drying chamber as follow:

$$Y_{12} = Y_{11} + \left(X_{CAi} - X_{CAt}\right)\frac{W_{CA}}{\dot{G}a\Delta t} \quad (38)$$

The moisture content of *Centella Asiatica* L is predicted with the help of modified Page's model given as:

$$XR = \frac{X_{CAt} - X_{CAe}}{X_{CAi} - X_{CAe}} = \exp\left(-\left(kt\right)^n\right) \quad (39)$$

$$X_{CAt} = \exp\left(-\left(kt\right)^n\right)\left(X_{CAi} - X_{CAe}\right) + X_{CAe} \quad (40)$$

The equilibrium moisture content of *Centella Asiatica* L X_{CAe} can be obtained from modified Smith model. This model expressed the relationship between the equilibrium moisture content and relative humidity at a given temperature as:

$$X_{CAe} = A - B \ln T_a - C\ln\left(1 - RH\right) \quad (41)$$

Where A, B and C are empirical constants for a particular product, to be determined from the experimental results.

The energy balance equation of drying chamber for drying process can be written as follow:

$$\dot{Q}_{11} = \dot{Q}_{12} + \dot{Q}_{CA} + \dot{Q}_{LDC} \quad (42)$$

Where:

$$\dot{Q}_{11} = \dot{G}_a h_{11} \quad (43)$$

$$\dot{Q}_{12} = \dot{G}_a h_{12} \quad (44)$$

$$h_{12} = C_{Pa} T_{12} + Y_{12}\left(h_{fg} + C_{PV} T_{12}\right) \quad (45)$$

$$\dot{Q}_{CA} = \rho_{CA} V_{CA}\left(C_{CA} + X_{CA} C_W\right)\partial T_{CA} / \partial t \quad (46)$$

$$\dot{Q}_{LDC} = \dot{G}_a q_{LDC} \quad (47)$$

Rearranging the above equation gives the outlet air temperature of drying chamber as follow:

$$T_{12} = \frac{\dot{Q}_{11} - \dot{Q}_{CA} - \dot{Q}_{LDC} - \left(h_{fg}\dot{G}aY_{12}\right)}{\dot{G}a\left(C_{pa} + \left(C_{PV}Y_{12}\right)\right)} \quad (48)$$

The heat transfer rate due to phase change can be determined using equation as follow:

$$\dot{Q}_{evap} = \dot{G}_a C_{pa}\left(T_{12} - T_{11}\right) \quad (49)$$

$$\dot{Q}_{evap} = \dot{X}_W H_{fg} \quad (50)$$

d. Heat exchangers HE_1 and HE_2: The heat balance for heat exchangers HE_1 and HE_2 gives

$$\dot{m}_{WHE_1} h_{13} + \dot{G}_a h_{15} = \dot{G}_a h_{16} + \dot{m}_{WHE_1} h_{14} \quad (51)$$

$$T_{16} = T_{15} + \varepsilon\left(T_{13} - T_{15}\right) \quad (52)$$

$$\dot{Q}_{HE_1} = \dot{G}_a C_{Pa}\left(T_{16} - T_{15}\right) \quad (53)$$

and

$$\dot{m}_{WHE_2} h_8 + \dot{G}_a h_6 = \dot{G}_a h_7 + \dot{m}_{WHE_2} h_9 \quad (54)$$

$$T_7 = T_6 + \varepsilon\left(T_8 - T_6\right) \quad (55)$$

$$\dot{Q}_{HE_2} = \dot{G}_a C_{Pa}\left(T_7 - T_6\right) \quad (56)$$

e. The auxiliary air heater: The heat balance for the auxiliary air heater gives:

$$\dot{Q}_{HT} + \dot{G}_a h_{16} = \dot{G}_a h_{17} \quad (57)$$

$$\dot{Q}_{HT} = \dot{G}_a C_{Pa} (T_{17} - T_{16}) \quad (58)$$

f. Pump and Blower: The power required by pump and blower to circulate air and water through the system each can be determined as follow:

$$\dot{W}_P = Q_P \Delta P_P \quad (59)$$

$$\dot{W}_B = Q_B \Delta P_B \quad (60)$$

g. Coeficient of performance: The coefficient of performance of drying system is defined as the ratio the latent evaporation heat of the moisture content to be removed and the heat amount to be supplied to the dryer is given by:

$$COP = \frac{\dot{Q}_{evap}}{\dot{Q}_{in}} \quad (61)$$

$$\dot{Q}_{in} = \dot{Q}_U + \dot{Q}_{HT} + \dot{W}_P + \dot{W}_B \quad (62)$$

$$\dot{Q}_U = \dot{Q}_{HE1} + \dot{Q}_{HE2} \quad (63)$$

h. Solar fraction: Solar fraction of the system can be defined as the ratio of the energy obtained from the solar collector to the energy required by the load (Duffie and Beckman, 1991):

$$SF = \frac{\dot{Q}_U}{\dot{Q}_L} \quad (64)$$

i. Pick-up efficiency: This efficiency is more useful for evaluating the actual evaporation of moisture from the heat sensitive product (*Centella Asiatica* L) inside the drying chamber. It is a direct measure of how efficiently the capacity of the (heated) air to absorb moisture is utilized. This is expressed as the ratio of the moisture picked-up by the air in the drying chamber to the theoretical capacity of the air to absorb moisture as follows (Tiris et al., (1995)):

$$\eta_P = \frac{(X_{CAi} - X_{CAt}) W_{CA}}{\dot{G}a \, \Delta t (Y_{DCas} - Y_{DCi})} \quad (65)$$

The values of Y_{DCas} and Y_{DCi} can be directly being obtained from Psychometric chart.

Instrumentation

In order to evaluate the performance of the drying system, measurements of temperatures, humidities, moisture contents, air velocities, static pressures, solar radiation on collector surface and on horizontal, mass and density of *Centella Asiatica* L sample were made during tests conducted. Dry bulb temperatures were measured with type-K thermocouples. Solid-state hygrometers were used to measure humidities at different locations. A hygrometer with type-K thermocouples was also used to measure dry-bulb and wet-bulb temperatures at selected locations in the dryer. These temperatures were used to obtain air humidities from psychometric charts. A turbine flow meter is used to measure the flow rate and velocity of the air. The flow rate of water is measured with the help of a water flow meter. The instantaneous solar radiation has been measured by using the Eppley Pyranometer and mounted near the collector on the plane of the collector. Static pressures were measured periodically by a U-tube micrometer. The moisture measurement in the product has been done with the help of a weighing machine. The power consumption of the system is measured by a wattmeter. The instantaneous outputs from the above measuring sensors were averaged and recorded at 15 min intervals by a multi channel data logger connected to desktop computer. The data stored in the data logger were retrieved at selected interval of 6 to 12 h and finally stored in computer disks for eventual use in data analysis.

Procedure

Fresh *Centella Asiatica* L was bought from the local market and cleaned thoroughly before use. The initial moisture content of the *Centella Asiatica* L sample was 88% wet basis. This sample was placed on a tray in the drying chamber. Weight loss of the sample was recorded every 15 minutes by a weighing machine located inside the drying chamber.

Result and discussion

The drying process of fresh *Centella Asiatica* L with initial weight and initial moisture content of about 3 kg and of 88% wet basis, respectively was conducted in two days and each day was started at 10 am and continued till 4 pm. The *Centella Asiatica* L dried to final weight and final moisture content of about 0.37 kg and 15%, respectively at an air velocity of 3.25 m/s. The performances of solar assisted dehumidification drying system as shown in Figure (2-10).

The variation of solar radiation and ambient relative humidity during experimentation is shown in Fig.2. At the first day a maximum solar intensity of 972 Wm^{-2} was measured and the ambient relative humidity varied between 52% and 78% with an average of about 63%. For the second day a maximum solar intensity of 941 Wm^{-2} was measured and the ambient relative humidity varied between 53% and 78% with an average of about 65%.

Fig.3 shows comparison between predicted and measured inlet and outlet drying chamber air temperatures with time. As seen from the figure the drying chamber inlet air temperature was maximum at noon and was about 50^{o}C, it is observed that at the end of the second day the difference between the drying camber inlet and outlet temperatures is small; this is due to the fact that energy required for evaporation of moisture of the drying material is relatively small. However, good agreement is obtained between the predicted and measured data.

Fig. 4 shows the relative humidity at inlet and outlet drying chamber. As seen from figure the drying chamber inlet air relative humidity was the minimum at noon and it was about 20%. From figures 3-4, it can be stated that the drying condition is suitable for drying heat sensitive product like *Centella Asiatica* L because of drying process conducted at low air temperature and low relative humidity.

Fig.5 shows comparison between predicted and experimental moisture content of *Centella Asiatica* L with time. Its moisture content in drying chamber was reduced from an initial value of 88 % wet basis to the final value of 15 % within 2 days or over drying time of about 12 hours. As seen from the figure, the predicted and experimental moisture content data have good agreement.

Fig.6 shows comparison between predicted and experimental pick up efficiency of drying system with time. The pickup efficiency depends on the evaporation of moisture from the products being dried inside the drying chamber. It can be seen from this figure that the pickup efficiency always declines during drying process, because of moisture content of drying material also decreases. The maximum values of the pickup efficiency, obtained from the predicted and experimental for first day are 93% and 97%, respectively. Whereas for second day are 23% and 29%, respectively. As shown predicted and experimental the pickup efficiency values have same trend with enough agreement.

Fig.7 shows comparison between variations of predicted and experimental energy contributed by solar collector and electric energy respectively for drying *Centella Asiatica* L from initial weigh of 3 kg to final weigh of 0.37 kg over drying time of about 12 hours at an air velocity is 3.25 m/s. It can be seen from this figure that total energy required, obtained from the predicted and experimental are 17276 kJ and 16805 kJ, respectively. Energy contributed by solar energy, obtained from the predicted and experimental are 9251 kJ and 9225 kJ, respectively. As seen from the figure, the predicted and experimental energy contributed by solar collector and electric have good agreement.

Fig. 8 shows comparison between variations of predicted and experimental energy contributed by solar collector and electric energy respectively for regeneration processes. It can be seen from this figure that total energy required, obtained from the predicted and experimental are 37990 kJ and 37797 kJ, respectively. Energy contributed by solar energy, obtained from the predicted and experimental are 19929 kJ and 17736 kJ, respectively. As seen from figure, the predicted and experimental energy contributed by solar collector and electric have good agreement.

Fig.9 shows comparison between variations of predicted and experimental total energy required by dehumidification drying system for drying and regeneration processes. As seen from the figure the energy contributed by electric energy decreased with increase in the energy contributed by solar collector, this stated that less electrical energy required by dehumidification drying system for drying and regeneration processes, respectively. The total energy required, obtained from the predicted and experimental is 48055 kJ and 47609 kJ, respectively, and energy contributed by solar energy, obtained the predicted and experimental are 25954 kJ and 25315 kJ, respectively. Whereas the energy contributed by electric values of 22101 kJ and 22293 kJ are obtained from predicted and experimental, respectively. As seen from the figure, the predicted and experimental energy contributed by solar collector and electric have also good agreement.

Fig.10 shows comparison between predicted and experimental coefficient of performance of the drying system (COP) with time. As seen from the figure the maximum values of coefficient of performance of the drying system, obtained from the predicted and experimental are 0.34 and 0.3, respectively. As shown predicted and experimental COP values have trend with enough agreement.

Fig.11 shows the predicted and measured solar fraction (SF) with time. The solar fraction depends on the instantaneous solar radiation; it can be seen from the figure that the solar fraction increased with the increase solar fraction, because the collector absorbs more energy, which is transferred to the water flowing through the collector. The maximum values of the solar fraction (SF), obtained from the predicted and experimental for first day are 67.7% and 68.9%, respectively. Whereas for second day are 69.3 and 70.5 %, respectively. The correspondence between the predicted and experimental solar fraction (SF) are in satisfactory agreement.

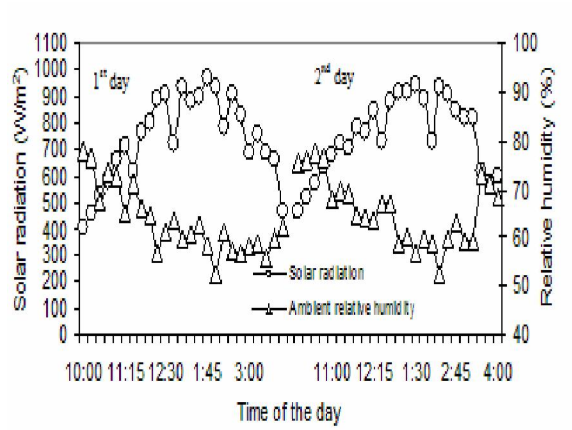

Fig.2. Variations of solar radiation and ambient relative humidity with time.

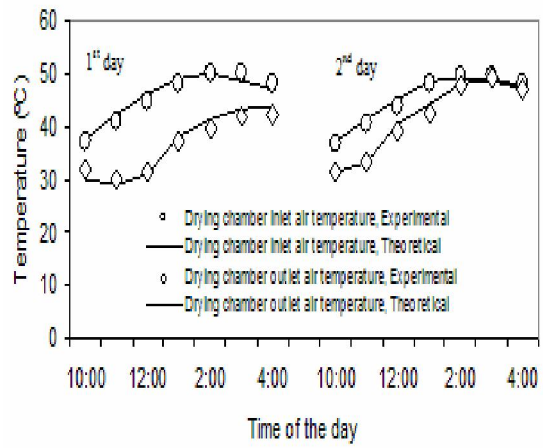

Fig.3. Variations of drying chamber inlet and outlet air temperatures with time.

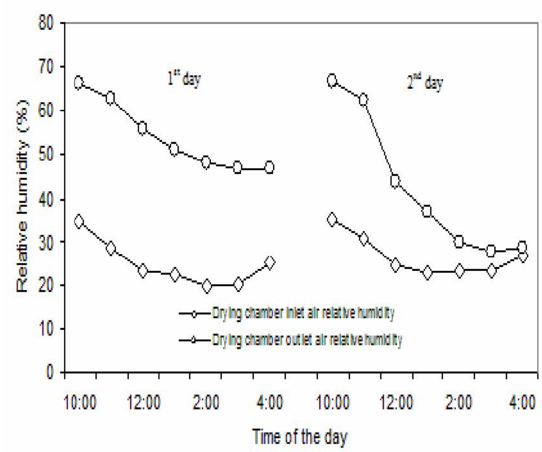

Fig.4. Variations of drying chamber inlet and outlet air relative humidity with time.

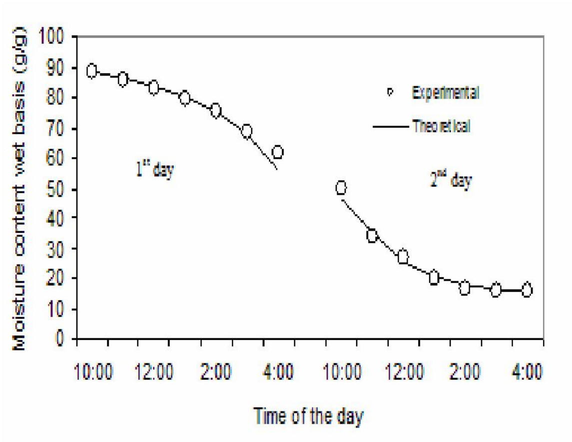

Fig.5. Variations of moisture content of *centella asiatica* L with time.

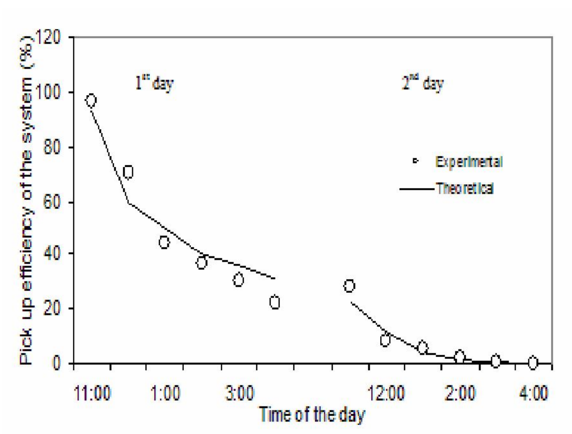

Fig.6. Variations of pick up efficiency of the system with time

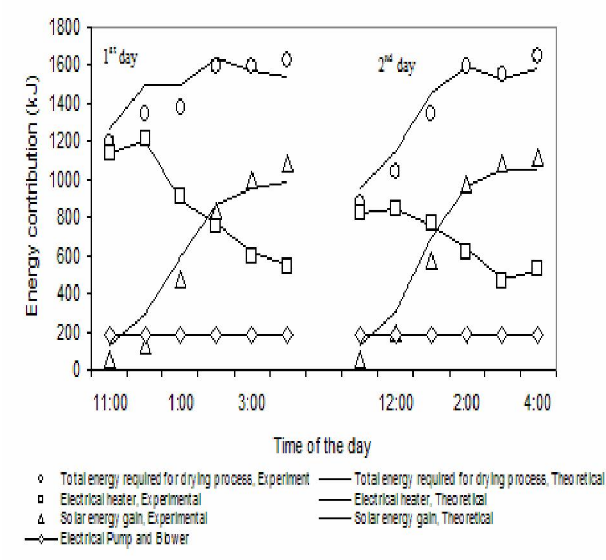

Fig.7. Variations of energy contribution for drying process L with time.

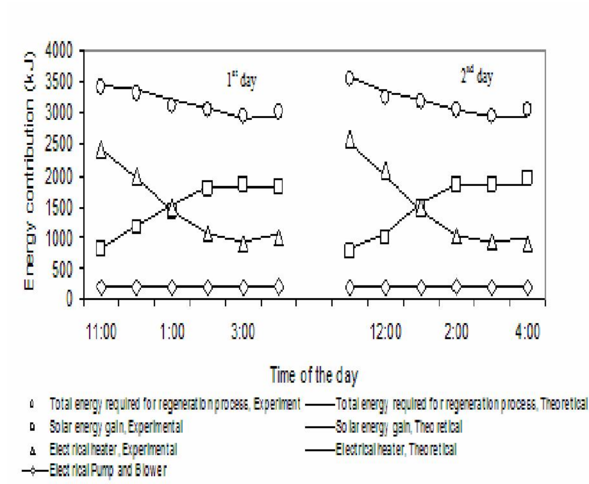

Fig.8. Variations of energy contribution for regeneration process L with time.

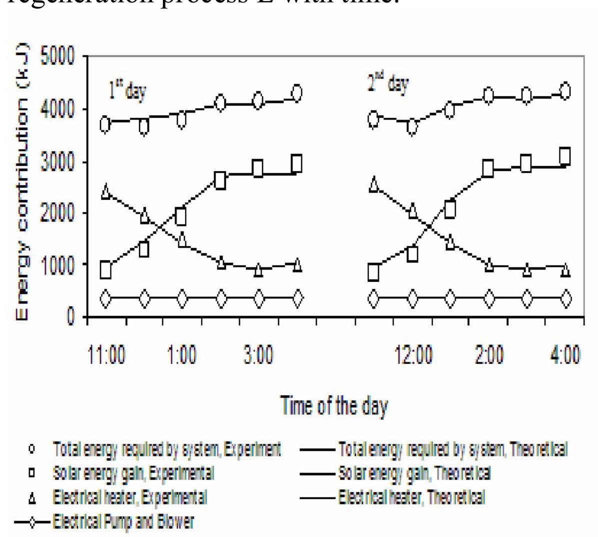

Fig.9. Variations of energy contribution for dehumidification system with time.

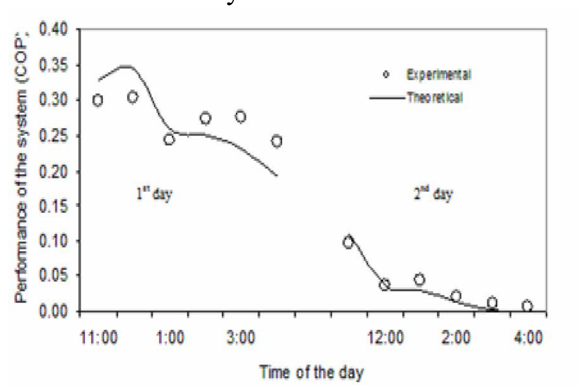

Fig.10. Variations of coefficient of performance of the drying system (COP) with time.

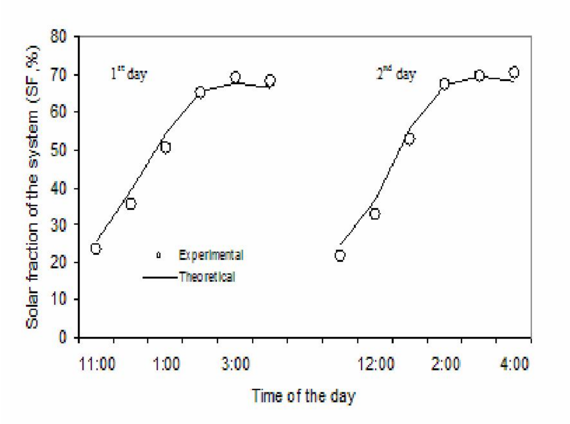

Fig.11. Variations of solar fraction of the drying system (SF) with time.

Conclusions

Performances of a solar assisted dehumidification drying system have been evaluated for drying heat sensitive products (*Centella Asiatica* L). Its performance was investigated both experimentally and theoretically. The maximum values of Pick up efficiency (η_P), coefficient of performance (COP) and solar fraction (SF), obtained from the predicted and measured data are as follows (93% and 97%), (0.34 and 0.3) and (69.3% and 70.5%), respectively with initial and final wet basis moisture content of *Centella Asiatica* L 88% and 15%, respectively at an air velocity is 3.25 m/s. good agreement was found between predicted and experimental results. The solar assisted dehumidification drying system is considered suitable for drying heat sensitive product like *Centella Asiatica* L because drying process was conducted at low air temperature and low relative humidity.

Nomenclature

A_{Ct}	effective area collection of the solar panel (m^2)
COP	coefficient of performance
C	specific heat (kJ/kg°K)
C_{PV}	specific heat of vapor (kJ/kg°K)
C_{PW}	specific heat of moist air (kJ/kg°K)
C_W	specific heat of water (kJ/kg°K)
F_R	heat removal factor of collector
$\dot{G}_a$	mass flow rate of dry air (kg/s)
$\dot{G}_W$	mass flow rate of water (kg/s)
H_{fg}	latent heat of evaporation of water (kJ/kg)
h_{SG}	isothermal differential heat of sorption of water on silica gel (kJ/kg)
I_T	incident solar radiation (W/m^2)
$\dot{m}_{WC}$	water mass flow rate through collector (kg/s)
$\dot{m}_{WHE}$	water mass flow rate through heat exchanger (kg/s)
Q	volumetric flow rate (kg/s)
$\dot{Q}_{CA}$	heat rate used for heating centella asiatica L (W)
$\dot{Q}_D$	heat rate used for dehumidification/regeneration in adsorber column (W)
$\dot{Q}_L$	heat loss rate (W)
$\dot{Q}_{SG}$	heat rate used for heating silica gel (W)
$\dot{Q}_U$	useful energy gain rate of collector (W)
R_{et}	global thermal resistance for a panel of collector towards the outside (°C/W)
R_{dh}	dehumidification rate (kg/s)
R_{rg}	regeneration rate (kg/s)
SF	solar fraction $(\%)$
T	temperature (°C)
T_W	wet bulb temperature (°C)
U_L	total heat loss coefficient (W/m^2°K)
V	volume of material (m^3)
W	mass of dry matter (kg)
X	moisture content dry basis of material (kg water/kg dry matter)
X_{CAe}	equilibrium moisture content dry basis of centella asiatica (kg water/kg dry)
X_{CAi}	initial moisture content dry basis of centella asiatica (kg water/kg dry matter)

X_{CAt}	moisture content dry basis of centella asiatica at any time of drying (kg
XR	moisture ratio
Y	absolute humidity of air (kg water/kg dry air)
Y_{as}	adiabatic saturation humidity of air entering the drying chamber (kg water/kg dry air)

Greeks Symbols

ε	effectiveness of heat exchanger
ρ	bulk density of material (kg/m^3)
η_P	pick up efficiency (%)

Subscripts

a	ambient
AD	adsorber column
CA	*centella asiatica* L
B	blower
DC	drying chamber
dh	dehumidification
HE	heat exchanger
HT	auxiliary air heater
i	initial
P	pump
rg	regeneration
SG	silica gel
t	time (min)

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