Full Paper

THE DEHYDRATIVE CAPACITY OF SOLAR RICE DRYER FOR RURAL AREAS

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ABSTRACT

A detailed method for determining the dehydrative capacity of solar dryer is presented in this paper. A solar drying system working on the principles of natural heat flow was developed using mainly inexpensive locally available materials to make it relatively affordable. The dryer was evaluated by the dehydrating temperature and relative humidity attained, rate of moisture removal from the food item and its overall dehydrative capacity. The results obtained during the period of test revealed that the dehydrating temperature inside the drying chamber was higher than the ambient temperature by an average of 64% during most hours of the daylight. The dryer was able to reduce the moisture content of the wet rice from 33.0% (dry basis) to 1.4% (dry basis) in 13 hours of effective dehydration time. The system overall dehydrative capacity and drying efficiency during the test period were 0.5 kg/kg.h of atmospheric air and 52.2%, respectively.

Keywords: *Air heater, dehydrative capacity, dryer, rice, solar energy.*

1. INTRODUCTION

The utilization of solar energy as a source of heat has been going on for a long time. The parts of the world lying between 35°N and 35°S which have at least 2000 hours of bright sunshine per year is normally accepted to be suitable for utilization of energy from the sun (Chandra and Oguntuase, 1986). Nigeria satisfies this requirement; hence positive results are expected from solar energy utilization.

Due to unexpected high prices of agricultural products, their preservation is becoming more and more important nowadays. Also food preservation becomes more important in a country like Nigeria where agriculture plays crucial role in providing employment for the majority of the population. Food and energy are the essential factors of the human survivals, so the efforts for greater food production and smaller energy dissipation can undoubtedly provide more peaceful and secure future for mankind (Bolaji, 2003). For Nigerians to produce enough food to feed themselves, they must improve on their method of food production, processing and storage.

In Nigeria, larger proportion of the population lives in the rural area. These people are mainly farmers and they are confronted with the problem of reducing the moisture content of their harvested crops to prevent spoilage during storage (Awachie, 1985). The traditional methods of dehydration employed by these farmers are open air sun drying or natural drying (in shade) without technical aid. These methods take quite a long time and the crops are exposed to infestation and are spoilt before they are needed (Diamante and Munro, 1993). Awachie (1985) has reported that about 50 – 60% of harvested food crops by Nigerian farmers are lost annually due to lack of good preservation methods and post harvest handlings. This figure is disturbingly high, therefore, introduction of solar dryers to the farmers is urgently necessary to reduce crop losses and improve the quality of dried products.

Many researchers (Youcef-Ali et al., 2001; Ozbey and Soylemez, 2005; Yadav and Moon, 2008) have in recent times designed and constructed dryers. Some of these dryers either use electricity or fossil fuel as source of energy. The ever-rising cost of electricity and fossil fuels have kept the operating cost of these dryers rising. Other researchers have worked on solar dryer and now different types of solar dryers are available, such as that by Itodo et al. (2002), Madhlopa et al. (2002), Sacilik et al. (2006), and Zomorodian et al. (2007). Most of these dryers are designed with circulating fan (powered by electricity) and moving parts, which required professional handlings. Since most of the farmers that require these dryers are unlearned and poor, it would be worthwhile for such solar dryers to be simple, affordable and maintenance-free.

Also, several authors (Fath, 1995; Njomo, 1995; Tris et al., 1995; and Ahmad et al., 1996) have reported both theoretical and experimental studies on the optimization of solar air heaters. Most of them considered the pertinent performance indicator to be the collector's thermal efficiency. For a solar air-heater (collector) designed as a component in solar drying system, which consists of collector, drying chamber and chimney, this criterion may not give the correct overall performance of the system. Therefore, it is necessary to report another dryer performance in term of its capacity called "dehydrative capacity" when a solar collector is designed as an integral part of solar drying system. The dehydrative capacity of a solar dryer is the amount of water content in a food item that the dryer can remove per unit mass of atmospheric air flowing through the dryer in a unit time, or dehydrating rate per mass of atmospheric air. It evaluates the overall performance of an entire drying system (Duffie and Beckman, 1991).

Dehydration as a method of preserving farm produce involves the removal of moisture to prevent the development of a favourable environment for the growth of moulds, bacteria and insects that normally cause spoilage. In this study, the variables (such as water activity, relative humidity and humidity ratio) and mechanisms involved in the dehydration processes of food items are considered. Also, the dehydrative capacity of a solar rough-rice dryer for rural application is evaluated.

2. THEORETICAL ANALYSIS

2.1 Dehydrative Capacity of Solar Air-Heater

Air evolution in a solar dryer is represented schematically on a psychrometric chart in Fig. 1. As shown in this figure, air at point 'a' enters the collector where it is heated at a constant pressure. Then, at point '1' it enters the drying enclosure, where it is isenthalpically humidified before leaving the dryer at point '2'. Fournier and Guinebault (1995) defined the water activity (a_w) as the relative humidity of air in equilibrium with the material at the same temperature. If a_w is the water activity of food in the dryer, the maximum dehydrative rate of the product (D) in kg/s is

$$D = \dot{m}_{da}(\omega_{2m} - \omega_a) \quad (1)$$

When air leaves the dryer in equilibrium with the product, $\omega_{2m} = \omega_2$, $\dot{m}_{da} = \dot{m}_{ha}$. Therefore, Eq. (1) becomes

$$D = \dot{m}_{ha}(\omega_2 - \omega_a)$$

The partial vapour pressure in air (P_{va}) is calculated (Jayaraman et al., 1992) as:

$$P_{va} = \frac{\phi_a}{100} P_s(T_a) \quad (2)$$

With

$$\log_{10}[P_s(T_a)] = 27082 - \frac{372544}{T_a} - 516.56\log_{10}(T_a) \quad (3)$$

(Jayaraman et al., 1992)

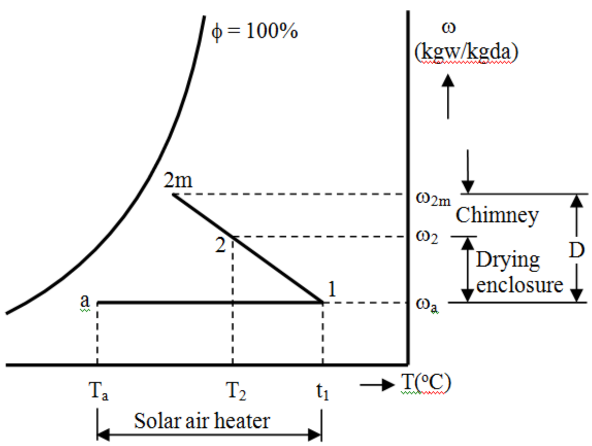

Fig. 1: Schematic representation on a psychrometric chart of the air evolution in a solar dryer

The thermal efficiency (η_c) of the solar collector is calculated from (Duffie and Beckman, 1991):

$$\eta_c = \frac{\dot{m}_{da} C_{pha}(T_1 - T_a)}{A_c I} \quad (4)$$

The corresponding wet bulb temperature (T_w) is determined by solving the following equation (Jayaraman et al., 1992):

$$P_{va} = P_s(T_{w1}) - \frac{C_{pha}(T_1 - T_{w1})[P_a - P_s(T_{w1})]}{0.622 L_v(T_{w2})} \quad (5)$$

With

$$L_v(T_{w1}) = (2.5018)10^6 - (2.378)10^3\, T_{w1} \quad (6)$$

Atmospheric air humidity ratio, ω_a is then determined from (Eastop and McConkey, 1996):

$$\omega_a = 0.622 \frac{P_{va}}{P_a - P_{va}} \quad (7)$$

and then the dryer outlet temperature T_2 is determined by solving the following equation:

$$a_w P_s(T_2) = P_s(T_{w2}) - \frac{C_{pha}(T_2 - T_{w2})[P_a - P_s(T_{w2})]}{0.622 L_v(T_{w2})} \quad (8)$$

In which it is assumed that $T_{w2} = T_{w1}$. The dryer outlet air humidity ratio is then obtained from:

$$\omega_2 = 0.622 \frac{P_{v2}}{P_a - P_{v2}} \quad (9)$$

with

$$P_{v2} = a_w P_s(T_2) \quad (10)$$

Atmospheric air humidity ratio, ω_a is the ratio of mass of water vapour to the mass of dry air in a given volume of atmospheric air:

$$\omega_a = \frac{m_v}{m_{da}} \quad (11)$$

The concept of specific humidity is that if the mass of dry air (m_{da}) is 1kg, then the mass of water vapour (m_v) associated with 1 kg of dry air will be ω_a kg (Eq. 11). Therefore, the total mass of air (m_a) is:

$$m_a = m_{da} + m_v$$

or $$m_a = (1 + \omega_a)\ \text{kg} \quad (12)$$

Finally, the sought dehydrative capacity, D_c is dehydrating rate (Eq. 1) per unit mass of atmospheric air (Eq. 12) and is calculated from:

$$D_c = \frac{\dot{m}_{ha}}{1 + \omega_a}(\omega_2 - \omega_a) \quad (13)$$

2.2 Energy Balance Equation for the Drying Process

The energy balance equation for the drying process is given by Howe (1980) and Bolaji (2005) as:

$$m_w L_v = m_a C_p (T_1 - T_2) \quad (14)$$

The mass of water evaporated is calculated from Eq. 15:

$$m_w = \frac{m_i(M_i - M_e)}{100 - M_e} \quad (15)$$

3. MATERIALS AND METHODS

3.1 Construction of the Solar Rice Dryer

The materials used for the construction of the solar dryer are easily obtainable in the local market. Fig. 2 shows the essential features of the dryer, consisting of solar air heater, drying chamber, drying rack and chimney.

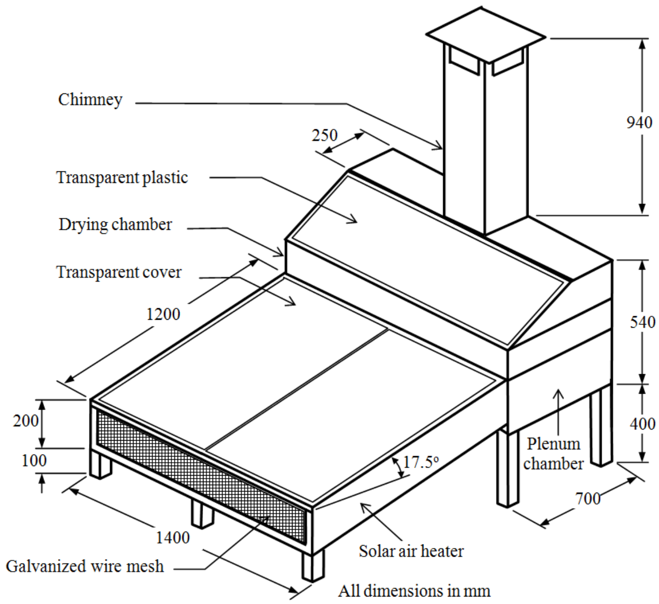

Fig. 2: Solar rice dryer

Solar Air Heater (Collector): The heat absorber (inner box) of the solar air heater was constructed using 2 mm thick aluminium plate. The plate was painted black and was mounted in an outer box built from a well-seasoned wood. Foam material of thermal conductivity of 0.04 W/m.°C was used to insulate the system. In order to reduce the heat flux per unit rise in temperature through the walls to about 1.0 W/m2.°C, a space of 40 mm was provided between the inner box and outer box, which was filled with the insulation material. The solar collector assembly consists of air flow channel enclosed by transparent cover (glazing). The glazing is a single layer of two glass sheets arranged side by side with total surface area of 1.68 m^2. Each sheet is 4 mm thick, has a surface area of 0.84 m^2 and of transmittance (τ) of 0.7 for wave lengths in the rage of 0.2 – 2.0 μm and opaque to wave lengths greater than 4.5 μm. One end of the solar collector has an air inlet vent of area 0.28 m^2, which is covered by a galvanized wire mesh to prevent entrance of rodents, the other end opens to the plenum chamber.

The Drying Chamber: The drying chamber together with the structural frame of the dryer was built from well-seasoned woods of high resistant against termite and atmospheric attacks. The dimensions of the drying chamber are 1400 x 700 x 140 mm. Access door to the drying chamber was provided at the back of the cabinet. This consists of three removable wooden panels made of 13 mm thick plywood, which overlapped each other to prevent air leakages when closed. The top glazing made of transparent plastic sheet on the drying chamber provided additional heating and also served as an inspection port.

The Drying Rack: The drying rack is contained inside the drying chamber and was constructed from a double layer of fine chicken wire mesh which allows drying air to pass through the layer of rice grains, but prevent the grain from falling into the plenum chamber. The depth of the drying rack was estimated to be 100 mm for full capacity of 30 kg of rough rice, so that the resistance to air flow at maximum depth would be minimum. The cross-sectional area of the rack is 0.98 m^2.

The Chimney: It is located to the top of the drying chamber. It has a square cross-section area of 0.0625 m^2 and height of 940 mm, which was estimated by dividing the volumetric air flow by wind speed. It was constructed from galvanized iron sheets and painted matt black to obtain elevated temperatures to improve air flow and increase buoyancy.

The orientation of the Solar Collector: The best stationary orientation is due south in the northern hemisphere and due north in southern hemisphere. Therefore, solar collector (air heater) in this work is oriented facing south and tilted at 17.5° to the horizontal. This is approximately 10° more than the local geographical latitude (Ado-Ekiti a location in Nigeria, 7.5°), which according to Adegoke and Bolaji (2000), is the best recommended orientation for stationary absorber. This inclination is also to allow easy run off of water and enhance air circulation.

3.2 Experimental Analysis

The solar dryer was tested in the month of August, 2004 to evaluate its dehydrative capacity. During the testing period, the air temperatures at collector inlet, collector outlet, plenum chamber, drying chamber, chimney exhaust and ambient were measured by laboratory type mercury bulb thermometers (accuracy ± 0.5°C) at regular interval of one hour between the hours of 08.00 and 18.00. The solar intensity was measured by means of pyranometer placed at an inclination of 17.5° facing south on latitude 7.5°.

The dryer was used to dry local rough rice and the dehydrative capacity was monitored. This was achieved by soaking 20.6 kg of rough rice in water for over 24 hours and the rice was then parboiled according to the local pre-drying preparation, which increased the mass of the rough rice to 27.4 kg. The drying rack was loaded with this wet rice and placed in the drying chamber of the solar dryer. The average depth of rice bed was 40 mm, which gives an initial bulk density of 698 kg/m^3 and the mass of the rice was measured hourly for two days. The dehydrative capacity of the dryer was evaluated using Eqn. 13 and the result is shown in Fig. 8. The system drying efficiency (η_d) is the ratio of the energy required to dehydrate the food item (Eqn. 14) to the energy supplied to the dryer, and is computed from Eqn. 16 (Itodo et al., 2002):

$$\eta_d = \frac{m_w L_v}{A_c I \tau \alpha} \times 100\% \qquad (16)$$

4. RESULTS AND DISCUSSION

The results obtained from dehydration tests are shown in Figs. 3 to 8. Figs. 3 and 4 show diurnal variation of temperatures inside the dryer and solar radiation on latitude 7.5° during the first and second days of dehydration process respectively. The average temperatures in the drying chamber and ambient air were 50.0°C and 30.5°C during the daylight respectively, therefore, the dehydrating temperature inside the drying chamber was higher than the ambient temperature by an average (11 observations) of 19.5°C (64%) during most hours of the daylight. High temperatures were obtained both in the collector and in the drying chamber between 11.00 hour and 15.00 hour, which correspond to the period of high solar radiation (Figs. 3 and 4).

Fig. 5 shows the diurnal variation of the relative humidity of the ambient air and drying chamber. Comparison of this figure with Figs. 3 and 4 shows that the dehydrating processes were enhanced by the heated air at very low humidity. Rice dehydration curves for two days of drying, 18th and 19th August, 2004 are shown in Figs. 6 and 7, and the corresponding dehydration rate versus time plot is shown in Fig. 8. As shown in these figures, effective dehydration occurred between 11.00 hour and 15.00 hour when the relative humidity inside the drying chamber was between 28% and 33%, which corresponds to the period when the chamber reached its maximum temperature of about 65°C during the hottest part of the day (Fig. 4). This illustrates the important influence that dehydrating temperature and relative humidity have on the performance of a solar dryer. The initial mass of wet rough rice was 27.40 kg and the final mass after dehydration was 20.89 kg, which shows that the dryer was able to remove moisture of 6.51 kg in drying time of two days.

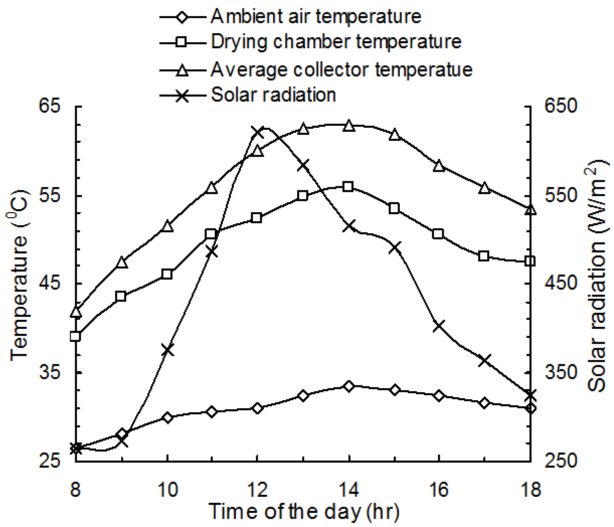

Fig. 3: Diurnal variation of temperature and solar radiation during the 1st day of drying process

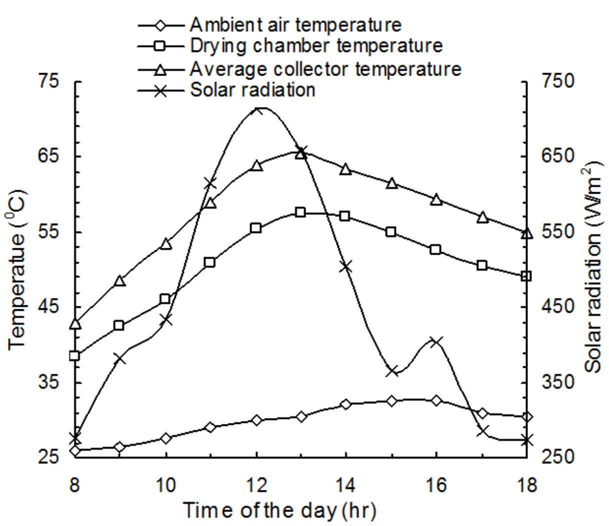

Fig. 4: Diurnal variation of temperature and solar radiation during the 2nd day of drying process

The dryer reduces the moisture content from 33% (dry basis) to 1.4% (dry basis) in 13.00 hours of dyhydration time, that is, a period when the incident solar radiation is appreciable. The dried grains were preserved in a sack bag kept in a well ventilated room for a period of one year without deterioration. The system overall dehydrative capacity and drying efficiency during the test period were found to be 0.5 kg/hr per kg of atmospheric air and 52.2% respectively. These results compare well with the results obtained from other dryers. The results obtained by Bala and Woods (1994) show that their system was able to remove maximum 4.2 kg of moisture from an initial grain mass of 72.4 kg and initial moisture content of 7.8 kg in drying time of two days, with an overall drying efficiency of 20%. Itodo et al. (2002) also obtained an overall drying rate and drying efficiency of 0.03 kg/hr and 10%, respectively, for shelled corn using a forced convective solar crop dryer for rural application in Nigeria.

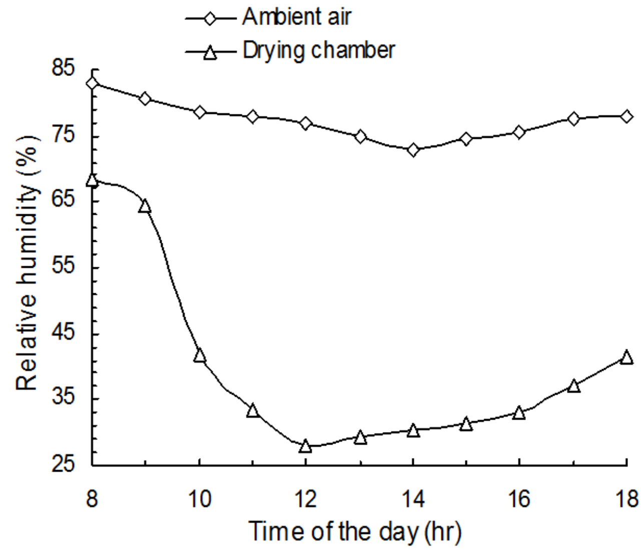

Fig. 5: Diurnal variation of relative humidity of the ambient air and drying chamber

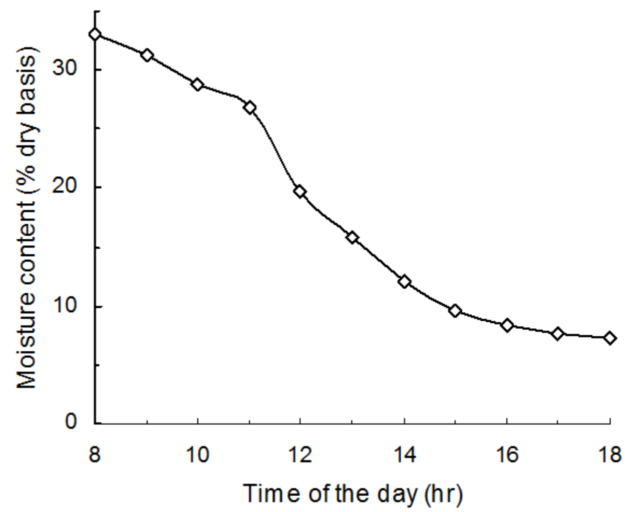

Fig. 6: Dehydration curve for rough rice in the solar dryer for 18th August, 2004

4. CONCLUSION

In this paper, a solar rice dryer was developed with materials that are readily available in the local market. Dehydrative capacity was employed as an index to evaluate the performance of the solar rice dryer. The results obtained from the experimental tests indicated that the dryer is to a large extent effective in dehydrating food items reasonably and rapidly to a safe moisture level. The dehydrating temperature in the drying chamber was higher than the ambient temperature by an average of 19.5°C (64%) during most hours of the daylight. The dehydrating processes were enhanced by the heated air at very low humidity. The maximum dehydration rate occurred between 11.00 hour and 15.00 hour when the relative humidity inside the drying chamber was between 28% and 33%. The dryer was able to reduce the moisture content of the wet rice from 33.0% (dry basis) to 1.4% (dry basis) in 13.00 hours of effective dehydration time and the grains were preserved for a period of one year without deterioration. The system overall dehydrative capacity and drying efficiency during the test period were found to be 0.5 kg/hr per kg of atmospheric air and 52.2% respectively.

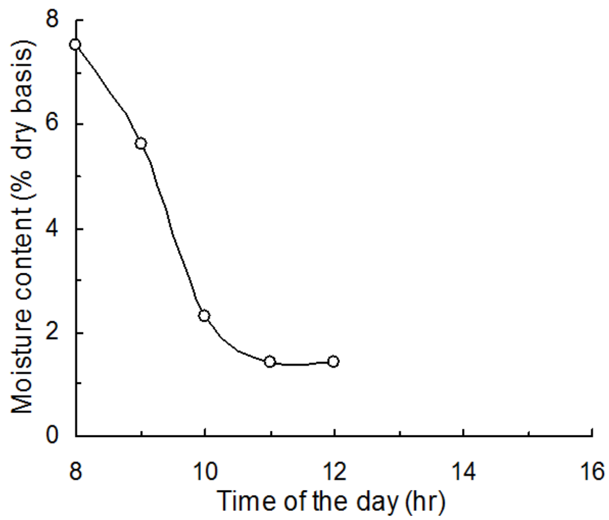

Fig. 7: Dehydration curve for rough rice in the solar dryer for 19th August, 2004

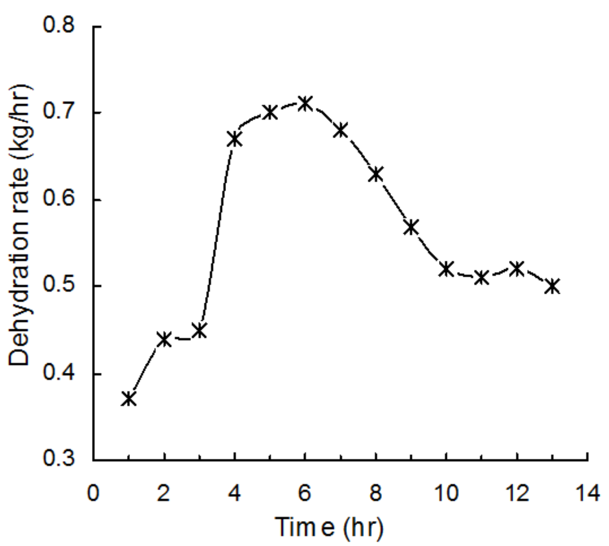

Fig. 8: Dehydration rate for rough rice in the solar dryer

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NOMENCLATURE

A_c – surface area of the collector (m^2)

a_w – water activity defined under materials and methods

C_p – specific heat at constant pressure (kJ/kg.^{0}C)
D – dehydrating rate (kg/s)
D_c – dehydrative capacity (kg/kg.h of atmospheric air)
I – incident solar radiation (W/m^2)
L_v – latent heat of vaporization of water (J/kg)
M – moisture content, decimal dry basis
m – mass (kg)
$\dot{m}$ – mass flow rate (kg/s)
P_s – partial water vapour pressure at saturation (N/m^2)
P_{va} – partial water vapour pressure in the ambient air (N/m^2)
P_a – atmospheric pressure (N/m^2)
t – temperature (^{0}C)

Greek:

α – solar absorptance
ϕ – relative humidity (%)
η – efficiency (%)
ω – humidity ratio (kgw/kgda)
τ – transmittance

Subscripts:

1 – collector outlet
2 – drying chamber outlet
2m – chimney outlet
a – ambient air
c – collector
d – drying
da – dry air
e – equilibrium
ha – humid air
i – initial
w – water or wet bulb