Solar drying of fruits, vegetables, spices, medicinal plants and fish: Developments and Potentials

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Abstract:

This paper presents developments and potentials of solar drying technologies for drying of fruits, vegetables, spices, medicinal plants and fish. Previous efforts on solar drying of fruits, vegetables, spices, medicinal plants and fish are critically examined. Recent developments of solar dryers such as solar tunnel dryer, improved version of solar dryer, roof-integrated solar dryer and greenhouse type solar dryer for fruits, vegetables, spices, medicinal plants and fish are also critically examined in terms of drying performance and product quality, and economics in the rural areas of the tropics and subtropics.

Experimental performances of different types of solar dryers such as solar tunnel dryer, improved version of solar tunnel dryer, roof-integrated solar dryer and greenhouse type solar dryers which have demonstrated their potentialities for drying fruits, vegetables, spices, medicinal plants and fish in the tropics and subtropics are addressed.

Simulated performances of solar tunnel dryer, improved version of solar tunnel dryer and roof-integrated solar dryers were assessed for drying fruits, vegetables, spices, medicinal plants and fish. The agreement between the simulated and experimental results was very good. The simulation models developed can be used to provide design data and also for optimal design of the dryer components.

A multilayer neural network approach was used to predict the performance of the solar tunnel drier. Using solar drying data of jackfruit and jackfruit leather, the model was trained using backpropagation algorithm. The prediction of the performance of the drier was found to be excellent after it was adequately trained and can be used to predict the potential of the drier for different locations and can also be used in a predictive optimal control algorithm. Finally, prospects of solar dryers for drying fruits, vegetables, spices, medicinal plants and fish in the tropics and subtropics are discussed.

1. Introduction

Drying is the oldest preservation technique of agricultural products and it is an energy intensive process. High prices and shortages of fossil fuels have increased the emphasis on using alternative renewable energy resources (Muhlbauer, 1986). Drying of agricultural products using renewable energy such as solar energy is environmental friendly and has less environmental impact.

Sun drying is still widely used in many tropical and subtropical countries. Sun drying is the cheapest method, but the quality of the dried products is far below the international standards. Improvement of product quality and reduction of losses can only be achieved by the introduction of suitable drying technologies. However, increase of purchasing power of the farmers and the reflection of the quality in the price of quality dried products are the important prerequisites for acceptance by the farmers and introduction of improved drying technologies. As long as there is no or only slight difference in the price for high and low quality products, the additional expenses for new preservation techniques will never be paid back and the new drying technologies will not be acceptable by the farmers. However, for adoption of the improved technology field level demonstration of the technology and advertisement of the quality dried products are essential. Micro-credit may also be needed and an extension model which is also an extension of the micro-credit approach of Grameen Bank may be adopted. Furthermore, for sustainability of the improved drying technology marketing channels must be established.

Solar drying can be considered as an elaboration of sun drying and is an efficient system of utilizing solar energy (Bala, 1997a & 1998, Zaman and Bala, 1989 and Muhlbauer, 1986). The tropics and subtropics have abundant solar radiation. Natural convection solar dryers do not require power from the electrical grid or fossil fuels. Hence the obvious option for drying would be the natural convection solar dryers. Many studies on natural convection solar drying of agricultural products have been reported (Excell and Kornsakoo, 1978, Excell, 1980, Oosthuizen, 1995, Bala and woods, 1994 & 1995, Sharma et al., 1995). Several designs are available and these are (i) cabinet type solar drier suitable for drying fruits and vegetables (Sharma et.al, 1995), (ii) indirect natural convection solar drier for paddy drying (Oosthuizen, 1995) and mixed mode AIT drier for drying paddy(Excell, 1978). These dryers have been widely tested in the tropical and subtropical countries. Considerable studies on simulation and optimization have also been reported (Bala and Woods, 1994&1995 and Simate, 2003). The success achieved by indirect natural convection solar dryers has been limited, the drying rates achieved to date not having been very satisfactory (Oosthuizen, 1996). Box type solar dryer is suitable for drying of 10 – 15 kg of fruits and vegetables (Sharma et al, 1995). The mixed mode dryer and AIT drier are improvement over the indirect natural convection solar dryer (Bala, 1998). All of these types of dryers have been tested and attempts have been made to extend at the farm levels. But none of these dryers practically exist in the fields in the tropics and subtropics. However, Kenya black box dryer which is a mixed mode solar dryer is claimed to be appropriate for small scale drying (Eckert, 1998). Furthermore, these dryers are not suitable for small scale industrial production of fruits, vegetables, spices, fish and medicinal and herbal plants. These prompted researchers to develop forced convection solar dryers. These dryers are (i) solar tunnel drier (Esper and Mühlbauer, 1993 and Janjai, 2004), (ii) indirect forced convection solar drier (Oosthuizen, 1996), (iii) Greenhouse type solar drier (Janjai, 2004), (iv) Roof integrated solar drier (Janjai, 2004) and (v) Solar assisted dryer (SmitaBhindu, 2004). Numerous tests in the different regions of the tropics and subtropics have shown that fruits, vegetables, cereals, grain, legumes, oil seeds, spices, fish and even meat can be dried properly in the solar tunnel dryer (Muhlbauer *et al*., 1993, El-shiatry *et.al*, 1991, Schirmer, *et.al*, 1996, Esper and Muhlbauer, 1993, 1994 & 1996, Bala, 1997b, 1999a&b, 2000 and 2004, Bala *et.al*, 1997, 1999, 2002 & 2003 and Bala and Mondol 2001).

The purpose of this paper is to present the developments and potentials of solar drying technologies for drying grains, fruits, vegetables, spices, medicinal plants, and fish in the tropics and subtropics and the performance of the solar driers for drying of fruits, vegetables, spices, medicinal plants and fish and also to present simulated performance of the solar tunnel dryer and roof-integrated solar dryer for drying of chilli and neural network prediction of the performance of the solar tunnel drier for drying of jackfruit and jackfruit leather

2. Solar Drying Systems

Different types of solar dryers have been designed, developed and tested in the different regions of the tropics and subtropics. The major two categories of the dryers are natural convection solar dryers and forced convection solar dryers. In the natural convection solar dryers the airflow is established by buoyancy induced airflow while in forced convection solar dryers the airflow is provided by using fan operated either by electricity/solar module or fossil fuel. Now the solar dryer designed and developed for and used in tropics and subtropics are discussed under two headings.

2.1 Natural Convection Solar Drying

Natural convection solar drying has advantages over forced convection solar drying is that it requires lower investment though it is difficult to control drying temperature and the drying rate may be limited. Due to low cost and simple operation and maintenance, natural convection solar drier appears to be the obvious option and popular choice for drying of agricultural products. It is the oldest type of solar dryer and consists of a solar collector with a transparent cover on the top and a drying unit with an opaque cover on the top. These are connected in series (Fig. 1.). In such a dryer, the crop is contained within a cabinet in a relatively thin bed, which completely spans the cabinet. Air, which is heated in a simple flat plate type solar collector, then flows as a result of the buoyancy forces resulting from the temperature differences up through the crop bed thereby producing the drying. The drying rates achieved to date with these dryers have not, generally, been very satisfactory. Oosthuizen (1995) identified part of this failure due to the fact that the dryers have usually not really been matched to the design requirements. Oosthuizen (1995) also discussed the use of a model in the selection of a dryer design that meets a particular set of requirements. Bala and Woods (1994) reported a mathematical model to simulate the indirect natural convection solar drying of rough rice and Bala and Woods (1995) also developed a technique for optimization of natural convection solar dryers.

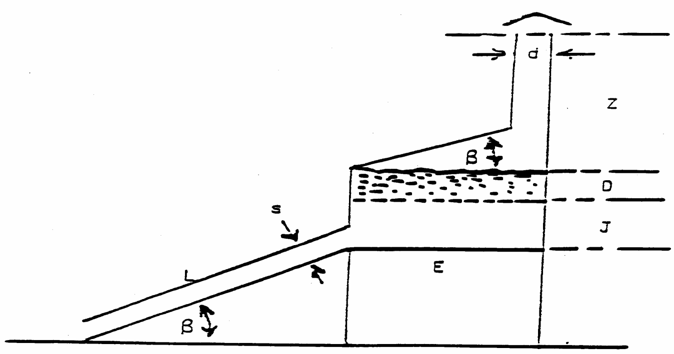

Fig.1. Indirect natural convection solar dryer

The mixed-mode solar dryer consists of a separate solar collector and a drying unit, both having a transparent cover on the top. Solar radiation is received in the collector as well as in the dryer box. Exell and Kornsakoo (1978) developed a simple mixed mode solar dryer designed to provide the rice farmer in South-East-Asia with a cheap and simple but efficient method of drying the wet season harvest. The dryer is shown in Fig. 2 and the solar collector consists of a matt-black substance spread on the ground and provided with transparent top and side covers. The dryer was initially designed with a bed of burnt rice husk as the absorber and clear UV stabilized polyethylene plastic sheet as transparent cover. However, these materials could be substituted with locally available materials such as charcoal, black plastic or black-painted metal sheets, dark-coloured pebbles, etc.

Many studies have been made to develop mixed solar drier (Exell and Kornsakoo, 1978; Simate 2003). The basic concepts involved in computer modeling of such dryers are discussed by Simate (2003). The computer simulation model is combined with the cost of the drier materials and a search technique to find the optimal dimensions of such dryers. This model is based on the concept of optimal design of solar dryers developed by Bala and Woods (1995).

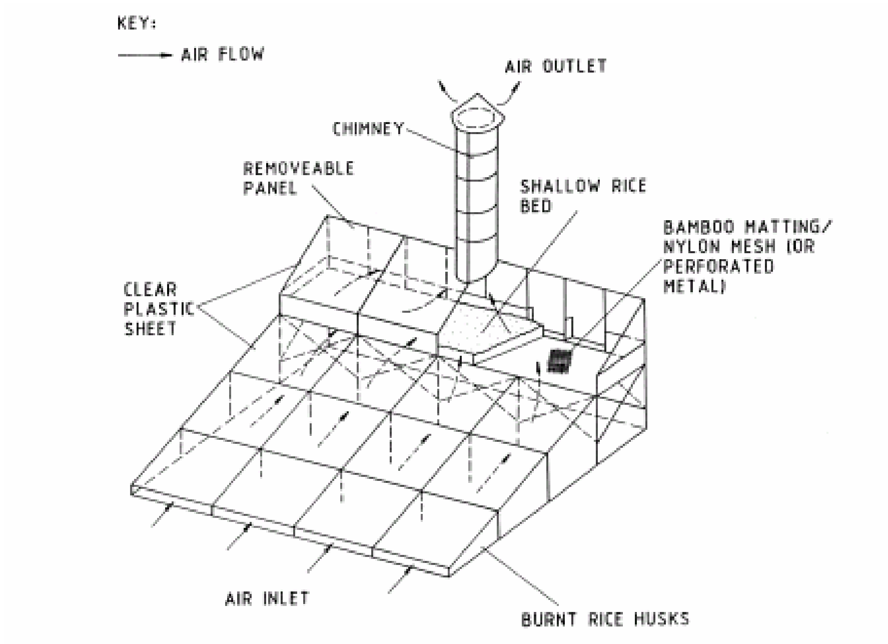

Fig. 2. AIT dryer

2.2 Forced Convection Solar Drying

Solar tunnel dryer was developed at the University of Hohenheim, Germany in the early eighties for small scale production of dried fruits, vegetables, spices, fish etc. This type of dryer has been widely tested and attained economic viability. A low cost version of this drier has been designed at Bangladesh Agricultural University, Mymensingh, Bangladesh and the pictorial view of the dryer under construction is shown in Fig. 3. The drier consists of a flat plate air heating collector, a tunnel drying unit and a small fan to provide the required air flow over the product to be dried. These are connected in series as shown in Fig.4. Both the collector and the drying unit are covered with UV stabilized plastic sheet. Black paint is used as an absorber in the collector. The products to be dried are placed in a thin layer in the tunnel drier. Glass wool is used as insulation material to reduce the heat loss from the drier. The whole system is placed horizontally on a raised platform. The air at required flow rate is provided by two dc fans operated by one photovoltaic module. As the air is passed over the product rather than through the product in the drier, the power requirement to drive a fan is low. To prevent the entry of water inside the drier unit during rain, the cover is fixed like a sloping roof.

The design of the solar tunnel dryer has been further improved and tested by Janjai (2004) at Silpakorn University at Nakhon Pathom in Thailand. The dryer still consists of two parts, namely the solar collector part and the drying part similar to the original version. Instead of using PE plastic sheet, the roof of the new design dryer is made of polycarbonate plates fixed with the side walls of the dryer. The plate has an inclination angle of 5° for the drainage of rain. As loading of products to be dried cannot be done from the top of the dryer, rectangular windows were made at the side wall of the drying part for loading and unloading products. Back insulation was made of high density foam sandwitched between two galvanized metal sheets. A 15 watt-solar cell module was used to power a dc fan for ventilating the dryer. The collector part and the drying part have the area of 1.2×4 m^2 and 1.2×5 m^2, respectively. The schematic diagram of this dryer is shown in Fig.5.

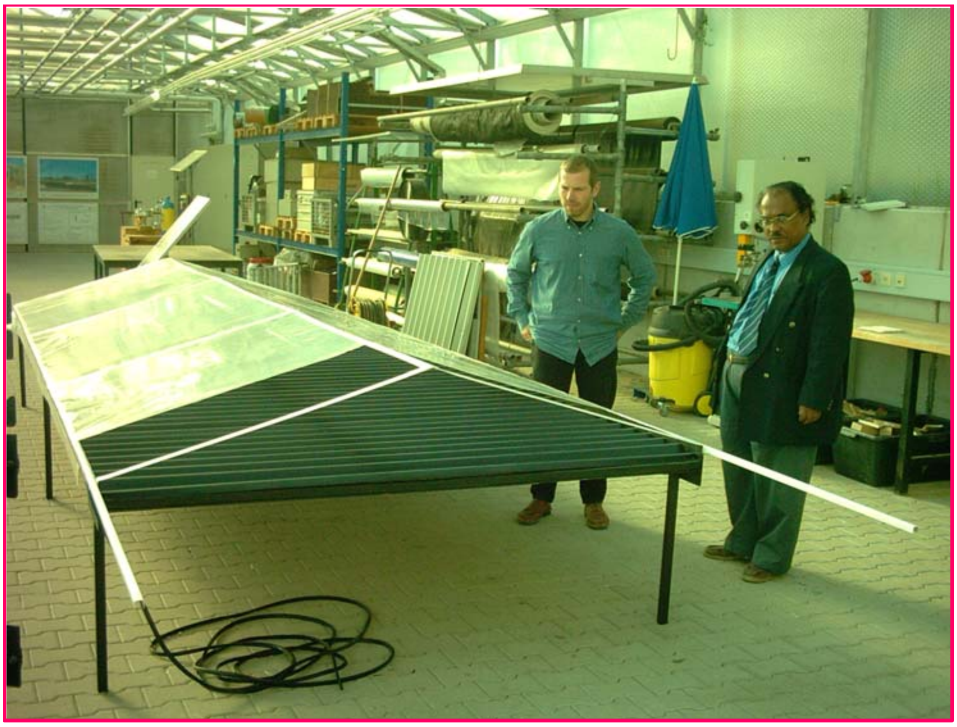

Fig. 3. Pictorial view of the solar tunnel dryer under construction

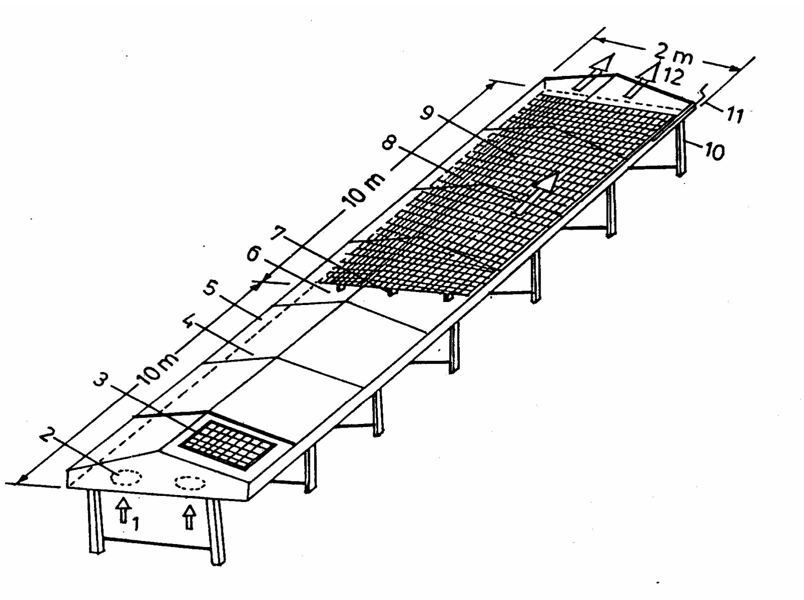

Fig. 4. Solar tunnel drier:

1. air inlet, 2. fan, 3. solar module, 4. solar collector, 5. side metal frame, 6. outlet of the collector, 7. wooden support, 8. plastic net, 9. roof structure for supporting the plastic cover, 10. base structure for supporting the tunnel drier, 11. rolling bar, 12. outlet of the drying tunnel

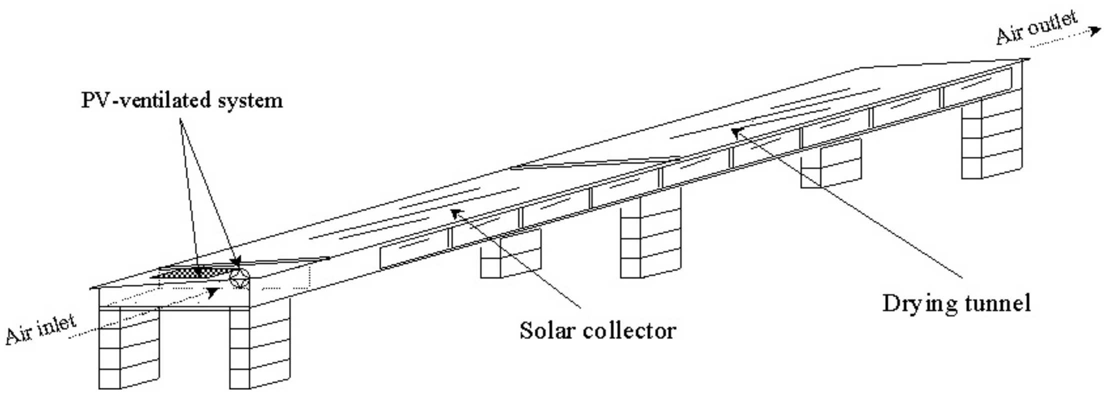

Fig. 5. Schematic diagram of the solar tunnel dryer with polycarbonate cover

A pv-ventilated greenhouse solar dryer was developed at Silpakorn University (Janjai, 2004). The dryer essentially consists of a parabolic shape greenhouse with a black concrete floor with an area of 5.5×8.0 m^2 (Fig. 6.) and the pictorial view of the dryer is shown in Fig. 7. The parabolic shape can withstand well the tropical rain and storm. The roof of the dryer is covered with polycarbonate plates. The floor of the dryer is made of concrete mixed with black powder paint to serve as a basement of the dryer as well as solar radiation absorber. As concrete has relatively high heat capacity, it also functions as a heat storage system for the dryer. In addition, its thermal inertia helps to reduce the variation of the drying air temperature due to the fluctuation of incident solar radiation. Three fans powered by a solar cell module of 53 W are used to ventilate the dryer during day. Another 53 W solar cell is employed to charge a battery for night ventilation. This type of dryer is developed for village scale use in the tropics and subtropics.

The loading capacity of the pv ventilated greenhouse solar dryer is 100-150 kg of fresh chillies. Drying in the pv ventilated greenhouse results in considerable reduction in drying time (50%) and the quality of the dry products is high quality dried products in terms of color and texture. The payback period of the dryer is estimated to be about 3.36 years. This type of solar dryer is suitable for drying applications of value added products where the quality is reflected in price. Several units of this type of dryer have been constructed in Thailand and are being used for drying of chilli, banana and green tea.

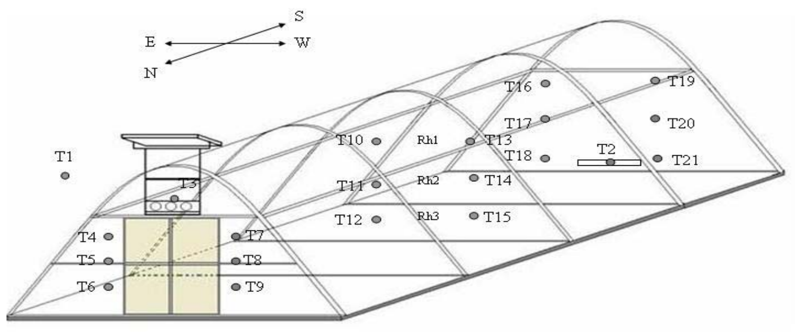

Fig. 6. Schematic diagram of the greenhouse type solar dryer with polycarbonate sheet

The roof-integrated solar dryer consists of a roof-integrated solar collector and a drying bin with an electric motor operated fan to provide the required air flow (Fig.8.). The bin is connected to the middle of the collector through a T- type air duct connection. The roof-integrated collector consists of two arrays of collector: one facing the south and other facing the north with a total area of 108 m^2. These arrays of these collectors also serve as the roof of the building. The roof-integrated collector is essentially an insulated black painted roof serving as an absorber which is covered with a polycarbonate cover.

Fig. 7. Pictorial view of the greenhouse solar dryer

The drying bin is essentially a batch dryer which has a capacity of $1.3 \times 2.4 \times 0.8$ m^3 and it is located inside the building. This building was partitioned into 2 rooms and a space for placing the drying bin. The first room is used for the preparation of the product to be dried and the second for the storage of dried products. Solar radiation passing through the polycarbonate cover heats the absorber. Ambient air is sucked through the collectors and while passing it through the collectors gains heat from the absorber. This heated air is passed through the drying bin.

Field level tests of drying of 200 kg of rosella flower and chilli at Suan Phoeng Educational Park, Ratchaburi, Thailand demonstrated that drying in roof integrated solar dryer results significant reduction in drying time compared to the traditional sun drying method and the dry product is a quality dry product compared to the quality dry products in the markets. This dryer was used to dry rosella flower from a moisture content of 90% (w.b.) and chilli from moisture content of 80% (w.b.) to a moisture content of 18% (w.b.) within 3 days. The payback period of the roof integrated solar dryer is about 5 years.

Roof-integrated solar dryer is costly in terms of capital cost. But the operating cost is extremely low and it is also environment friendly. The roof-integrated solar dryer is suitable for drying applications of value added products where the quality is reflected in price. Although this dryer was installed and tested for demonstration of the drying potential of herbs and spices, it is still being used for production of quality dried products for sale to the visitors of the Suan Phoeng Educational Park. After the successful tests of this dryer at Suan Phoeng Educational Park, this type of dryer has been constructed at Pakxe provice, Lao's Democratic Republic. It is now being used for small scale production of quality dried spices and herbs.

Fig. 8. Roof integrated solar dryer

3. Mathematical Modeling

Mathematical models are useful for predicting performance and optimal designs of solar drying systems. The fundamentals of heat and mass transfer during drying are given in Bala (1997a). The details of heat and mass transfer during drying of chilli in a solar tunnel dryer and roof integrated solar dryer are given in Hossain (2004) and Hossain et al (2005), and Janjai et al. (2006) respectively. Mathematical models to simulate the heat and mass transfer in a solar tunnel drier are discussed below:

Analysis of Collector Performance

Considering an element, dx of collector at a distance, x from the inlet (Fig. 9.), the energy balances on the collector components give the following equations (Bala and Woods, 1994).

Energy Balances on the Plastic Cover

Energy balance on the cover gives the following equations:

$$h_{cam}(T_c - T_{am}) + h_{ca}(T_c - T_a) + h_{rcs}(T_c - T_s) - h_{rpc}(T_p - T_c) = \alpha_{cS}(1 + \tau_{cS}\rho_{pS})E \quad (1)$$

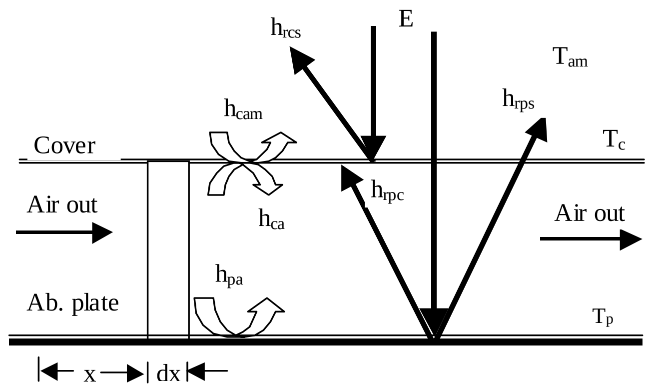

Fig.9. Heat balances in the flat plate solar collector of depth, b

Energy Balances on the Absorber Plate

The following equation gives the energy balance on the absorber plate:

$$h_{pa}(T_p - T_a) + h_{rpc}(T_p - T_c) + h_{rps}(T_p - T_s) = \frac{\tau_{cS}\alpha_{pS}E}{1-(1-\alpha_{pS})\rho_{pS}} \quad (2)$$

Energy Balances on the Air Stream

The following equation gives the energy balances in the air inside the collector.

$$bG_a C_{pa}\frac{dT_a}{dx} = h_{pa}(T_p - T_a) + h_{ca}(T_c - T_a) \quad (3)$$

Analysis of Solar Tunnel Drier Performance

The following system of equations is developed to describe the drying of a product in the solar tunnel drier. Consider an element, dx of drying tunnel at a distance, x from the inlet and the energy balances in the drier components are shown in Fig. 10.

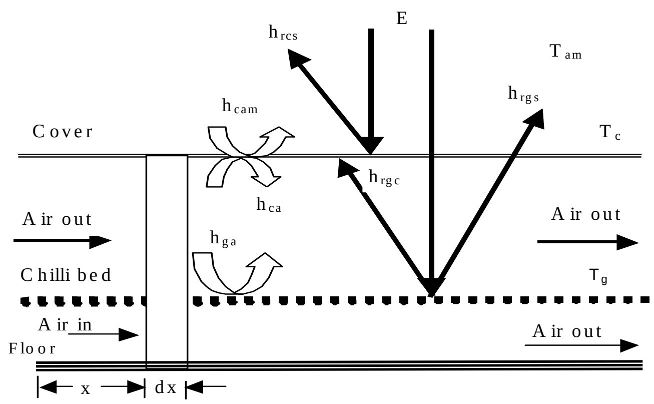

Fig. 10. Energy balances in the solar tunnel drier of depth, b

Energy Balances on the Cover

Heat balance on plastic cover of drying tunnel is same as the cover of collector and the temperature of plastic cover is

$$T_c = \frac{h_{cam}T_{am} + h_{ca}T_a + h_{rcs}T_s + h_{rgc}T_g + \alpha_{cS}(1+\tau_{cS}\rho_{gS})E}{h_{cam} + h_{ca} + h_{rcs} + h_{rgc}} \qquad (4)$$

Energy Balances on the Product

The following energy balance equation is developed for the drying of chilli in the solar tunnel drier.

$$\frac{\partial T_g}{\partial t} = -\frac{\left[-\rho_g z_g (C_v - C_l)\frac{\partial M}{\partial t} + h_{ga} + h_{rgc} + h_{rgs}\right]T_g}{\rho_g z_g (C_{pg} + C_{pw}M)} + \frac{\{\frac{\alpha_{gS}\tau_{cS}}{1-(1-\alpha_{gS})\rho_{gS}}\}E + \rho_g z_g L_g \frac{\partial M}{\partial t} + h_{ga}T_a + h_{rgc}T_c + h_{rgs}T_s}{\rho_g z_g (C_{pg} + C_{pw}M)} \qquad (5)$$

Energy Balances of the Air Stream

Change in enthalpy of air = heat transferred convectively to the product and heat supplied to air in the evaporated moisture.

$$\frac{\partial T_a}{\partial x} = -\frac{(h_{ca} + h_{ga})T_a}{\rho_a z_a V_a (C_{pa} + C_{pv}H)} + \frac{h_{ca}T_c + h_{ga}T_g}{\rho_a z_a V_a (C_{pa} + C_{pv}H)} \qquad (6)$$

Drying Rate Equation

The rate of change of moisture content of a thin layer product inside the dryer can be expressed by an appropriate thin layer drying equation. The Newton equation in differential form is

$$\frac{dM}{dt} = -K(M - M_e) \qquad (7)$$

Mass Balance Equation

The exchange of moisture between the product and the air inside the dryer is given by
Moisture lost by product = moisture gained by air.

$$\rho_g dx(-\frac{\partial M}{\partial t})dt = bG_a(\frac{\partial H}{\partial x})dxdt \quad (8)$$

Eqs. (1) - (8) are solved using numerical techniques.

Neural Network Computing

An independent multilayer ANN model of solar tunnel drier has been developed to represent the drying system of jackfruit bulb and jackfruit leather (Bala et al. 2005). Network of both the models is 4-layered and has large number of simple processing elements, called neurons. The input layer of the model consists of seven neurons which correspond to the seven input variables, and the output layer has one neuron, which represents the final moisture content (FMC) in the model (Fig. 11.)

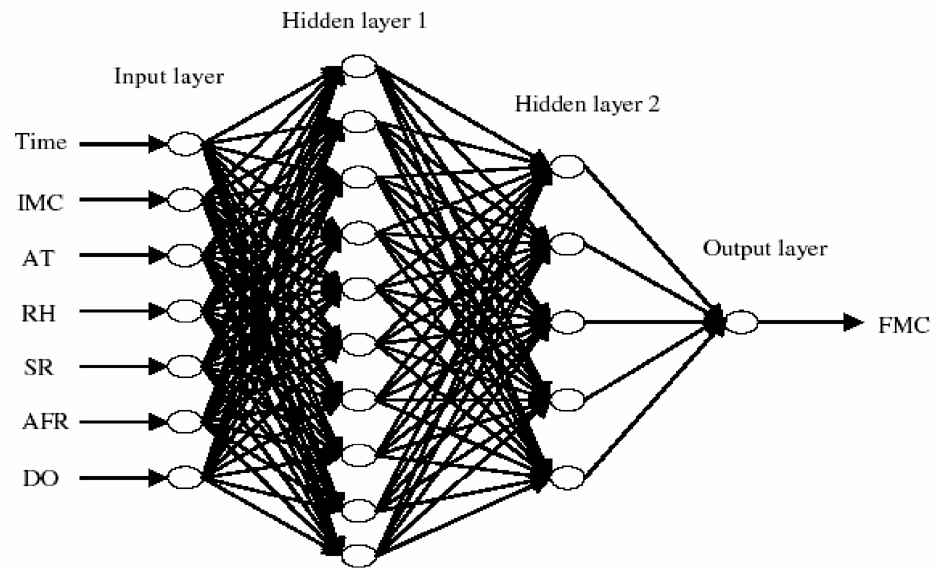

Fig. 11. The structure of the ANN solar tunnel dryer model for drying jackfruit bulb and jackfruit leather

A wide variety of training algorithms has been developed, each with its own strengths and weakness. The ANN drier models are trained by backpropagation algorithm so that application of a set of input would produce the desired set of output. Further details are given in Bala et.al (2005)

4. Results and Discussion

4.1 Experimental results

Large scale field level studies were conducted at Bangladesh Agricultural University, Mymensingh, Bangladesh and Silpakorn University at Nakhon Pathom, Thailand to demonstrate the potentiality of the solar driers for production of high quality solar dried fruits, vegetables, spices, medicinal plants and fish. Some typical results for solar tunnel dryers, greenhouse type solar dryer and roof integrated solar dryer are summarized below:

Dried mango is an excellent snack food and has a demand for both national and international markets. Comparison of the moisture contents of mango in the solar tunnel drier with those obtained by the traditional method for a typical experimental run during drying at Chapai Nawabganj, Bangladesh is shown in Fig.12. The solar tunnel drying required 3 days to dry mango samples from 78.87% to 13.47% as compared to 78.87% to 22.48% in 3 days.

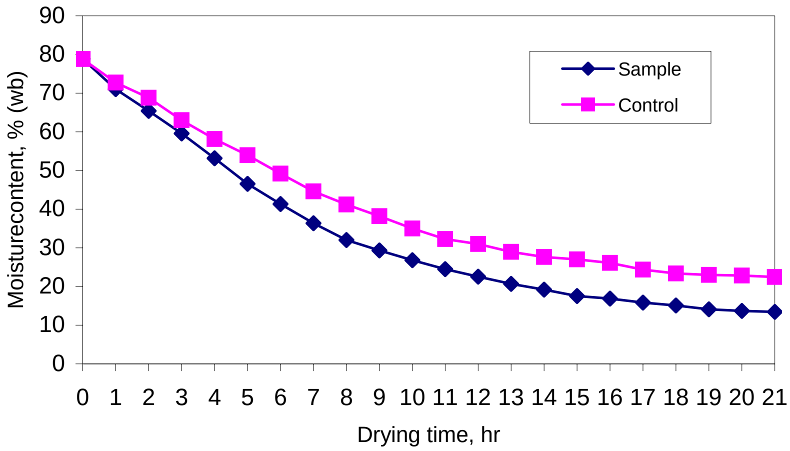

Fig. 12. Variations of moisture content with time for a typical experimental run during solar drying of mango.

Dried pineapple is also an excellent snack food and has a demand for both national and international markets. Comparison of the moisture contents of pineapple in the solar tunnel drier with those obtained by the traditional method for the variety Giant Kew for a typical experimental run during drying at Bangladesh Agricultural University, Mymensingh, Bangladesh is shown in Fig.13. The solar tunnel drying required 3 days to dry pineapple samples from 87.32% to 14.13% as compared to 87.32% to 21.52% in 3 days.

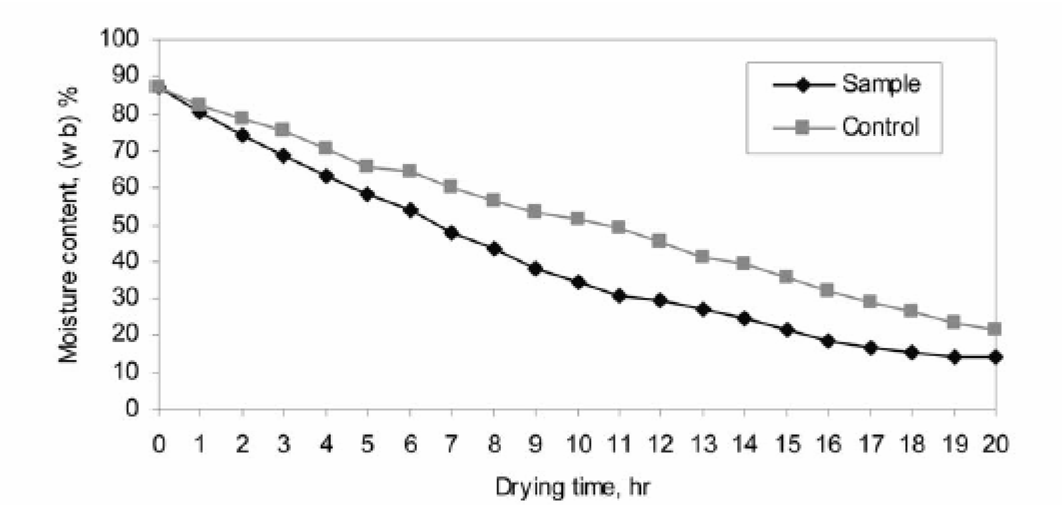

Fig. 13. Variations of moisture content with time for a typical experimental run during solar drying of pineapple.

Mushrooms are edible fungi of commercial importance and their cultivation and consumption have increased substantially due to their nutritional value, delicacy and flavour. But mushrooms are extremely perishable and the shelf life of fresh mushroom is only about 24 hrs at ambient conditions and 7-10 days even with refrigerated storage because of its high moisture content and rich nutrients that spoil easily and quickly. Therefore, mushrooms are usually dried to extend the shelf-life. Hence, these should be consumed or processed promptly after harvest. Comparison of the moisture contents of mushroom in the solar tunnel drier with those obtained by the traditional method for a typical experimental run during drying at Bangladesh Agricultural University at Mymensingh is shown in Fig.14. The moisture content of mushroom reached from 89.41% to 6.14% in 8 hours in the solar tunnel drier and it took 8 hours to dry it from 89.41% to 15% in the traditional method under similar conditions.

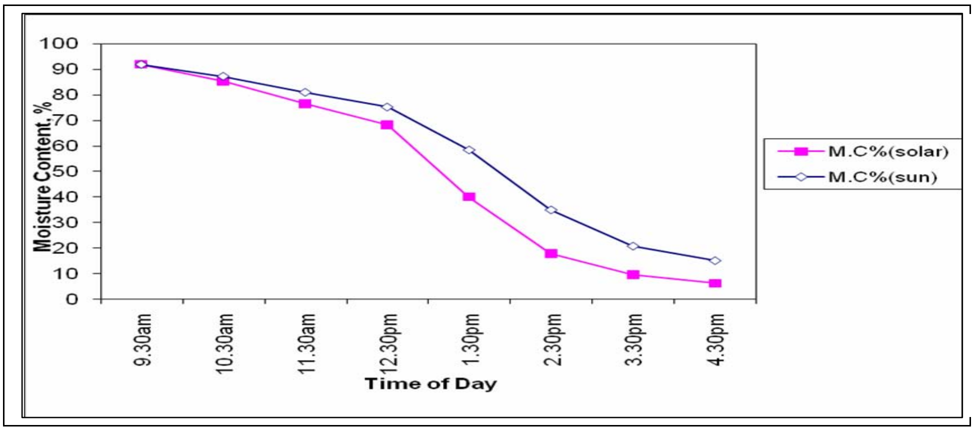

Fig. 14. Variations of moisture content with time for a typical experimental run during solar drying of mushroom.

Chilli is an important spice and a potential cash crop in the world. It is dried for making powder and to store it for both short term and long term storage. Comparison of the moisture contents of chilli inside the greenhouse dryer with those obtained by the traditional sun drying method for a typical experimental run conducted at Silpakorn University is shown in Fig. 15. The moisture contents of chilli at three different locations starting from top to bottom inside the dryer reached to 16.70 % (w.b.), 07.13 % (w.b.) and 01.58 % (w.b.) respectively from 76.96 % (w.b.)

in 27 hours of drying in three days while the moisture content of a similar sample in the traditional method after the same period of drying was 53.78 % (w.b.).

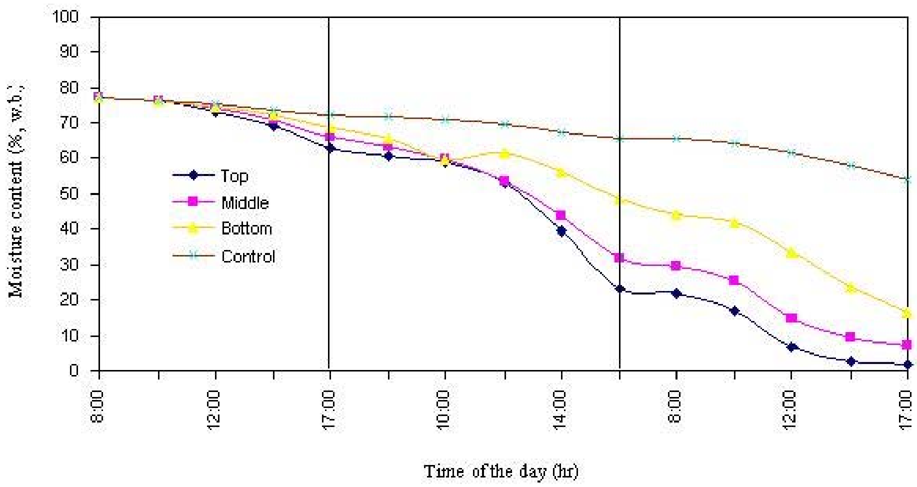

Fig. 15. Comparison of the moisture contents of chilli inside the greenhouse dryer with the traditional sun drying method for a typical experimental run.

Chilli was also dried in a roof integrated solar dryer at Silpakorn University. For a typical clear sky weather condition, the moisture content of the chilli in the drying bin was reduced from an initial value of 80 % (wb) to the final value of 18 % (wb) within 3 days or with an effective drying time of approximately 24 solar hours whereas the moisture content of the sun dried samples was reduced to 53% (wb) during the same drying period as shown in Fig. 16. From Fig. 16, it was observed that the moisture content slowly decreased on the first day and it rapidly decreased on the second day and slowly again on the third day while the moisture content of control sample decreased very slowly in a similar fashion in the second and third and the final moisture content was about 53% (wb).

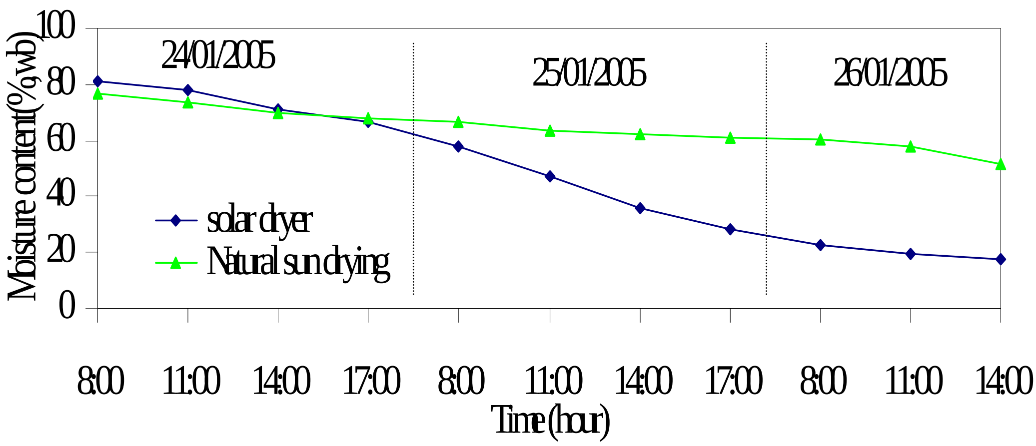

Fig. 16. Comparison of the moisture changes inside roof-integrated solar dryer and open sun drying during drying of chilli

Coffee is one of the most popular drinks all over the world. Coffee beans are needed to dry immediately after harvest to avoid discoloration because of fungi growth. Roasted and powdered coffee beans are used for drinking purposes. Among the drinks coffee usually receives premium for its superior flavor and aroma. Fig.17. shows that the moisture content of coffee reached to 8.3% from 58.36% (w .b.) in 6 days of drying in the solar tunnel drier while it took 6 days to bring down the moisture content in a similar sample to 26.65% in traditional sun drying method.

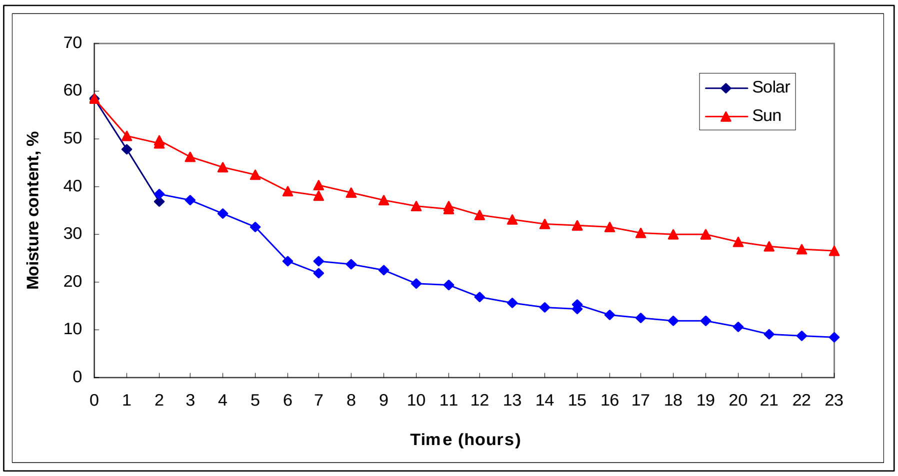

Fig.17. Variation of moisture content with time of day for a typical experimental run during solar drying of coffee.

Vasaka (*Adhatoda vasica* Nees.) is an important medicinal plant in the tropics and subtropics and it cures cough and breathing problem such as asthma. Quality dried vasaka has wide national market and international market for export. The typical drying curves of vasaka dried in the solar dryer and those dried with natural sun drying at Bangladesh Agricultural Research institute, Gazipur are shown as Fig.18. Blanched vasaka was dried to 3% (wb) from 74% (wb) in 6 hours in the hybrid solar drier as compared to 12.5% (wb) from 74% (wb) in the traditional method while non-blanched vasaka was dried to 3% (wb) from 74% (wb) in 8 in the hybrid solar drier as compared to 16% (wb) from 74% (wb) in the traditional method. In solar dryer, it took 6 hours to reduce moisture content of blanched leaves from 74% (wb) to 3% (wb) but for non-blanched samples it took 8 hours to reduce similar moisture contents. There is a significant difference of drying rate between the blanched and non-blanched vasaka as well as between the drying inside the hybrid solar dryer and open sun drying.

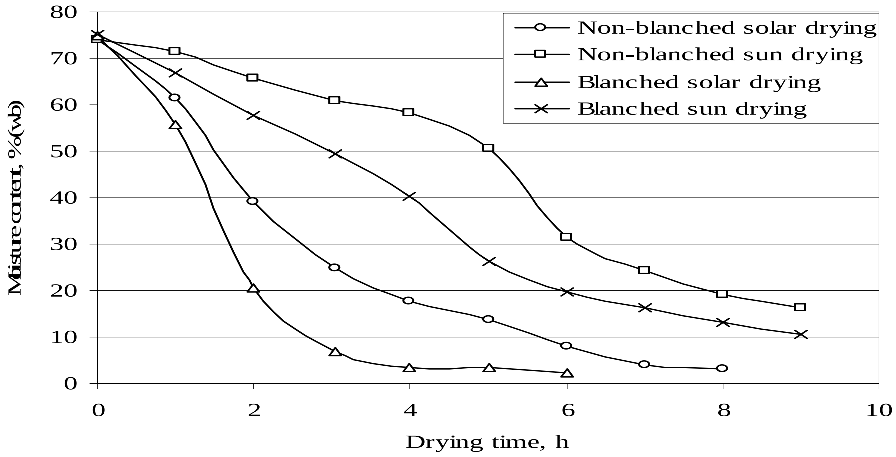

Fig*. 18. Comparison of the moisture changes inside hybrid solar dryer and open sun drying during drying of Vasaka leaves*

Solar tunnel drier has been widely tested in the fields in Bangladesh for drying of fish, marketing channels have been explored and has been introduced with a success. The pictorial view of the dryer is shown in Fig. 19. The typical drying curves of fish dried in the solar tunnel dryer and those dried with natural sun drying at Cox's Bazar, Bangladesh shown are Fig .20. Drying in the solar tunnel drier required 3 days to dry silver jew fish from 71.56% to 14.75% as compared to 71.56% to 23.63% in 3 days in traditional sun drying. There was no difference of drying rate at different positions of solar tunnel dryer.

Fig. 19. Pictorial view of the solar tunnel dryer

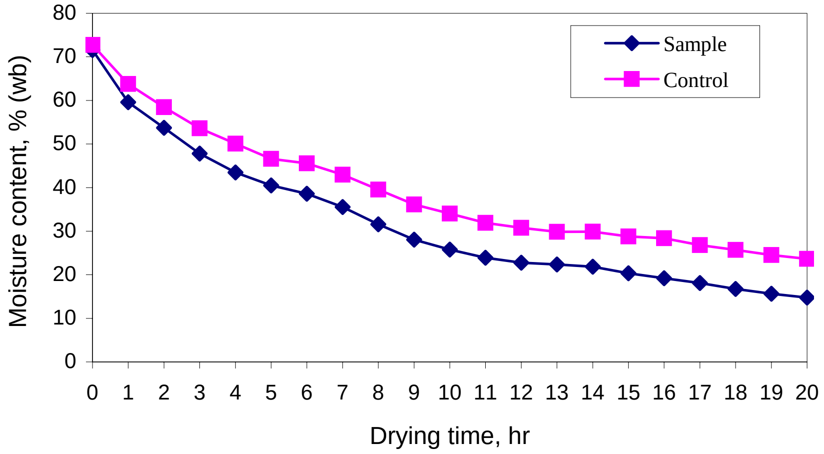

Fig. 20. Variations of moisture content with time for a typical experimental run during solar drying of silver jew fish

In all the cases there was a considerable in reduction in drying time in solar drying using solar drier in comparison to sun drying. The solar dried products were high quality dried products in terms of colour, texture and flavour.

4.2 Simulated results

The model was validated against the experimental data of chilli. The simulated and observed air temperatures along the length of the dryer are shown in Fig. 21. The agreement is good.

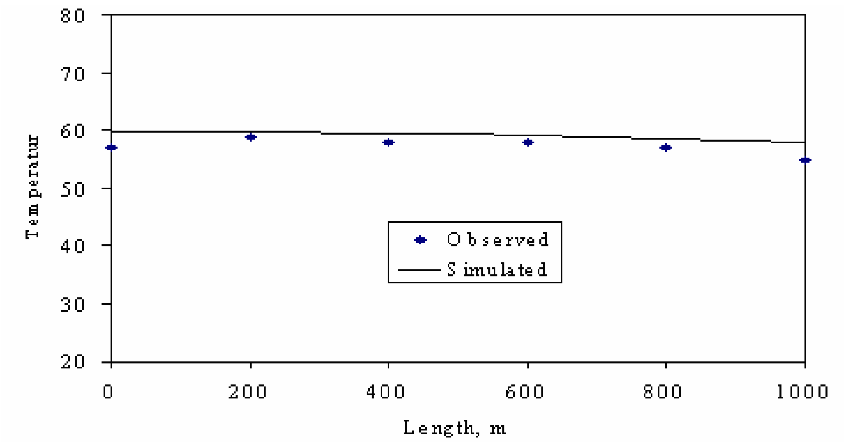

Fig. 21. Observed and simulated air temperature along the length of the dryer

Fig. 22 shows the experimental and simulated moisture content during solar drying of green chilli in a solar tunnel dryer. Good agreement was found between the experimental and simulated moisture contents.

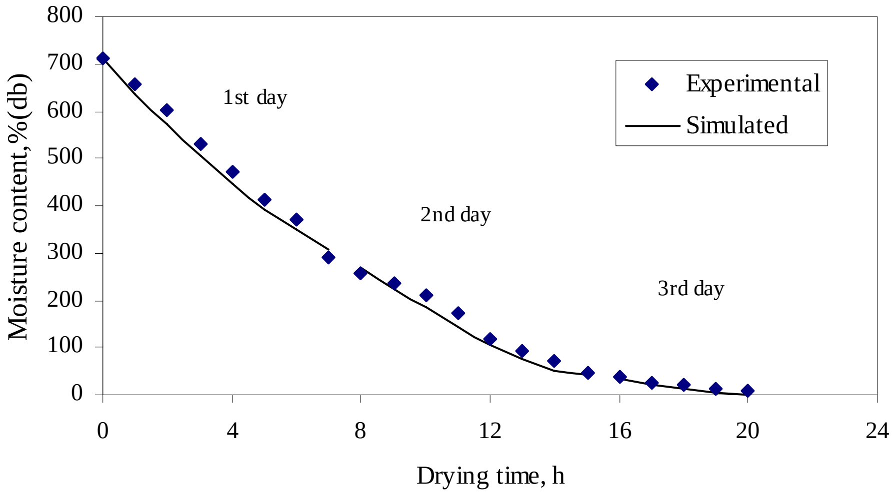

Fig. 22. Experimental and simulated moisture content at the outlet end of drier during drying of green chilli (After Hossain et al 2003)

Fig.23. shows a typical comparison between the predicted and experimental values of the temperatures at the outlet of the collector during drying of chilli in a roof integrated solar dryer at Silpakorn University. The agreement is good. Fig. 24 shows a typical comparison of the predicted and observed moisture contents of chill inside the dryer and the model predicts well the moisture content changes during drying.

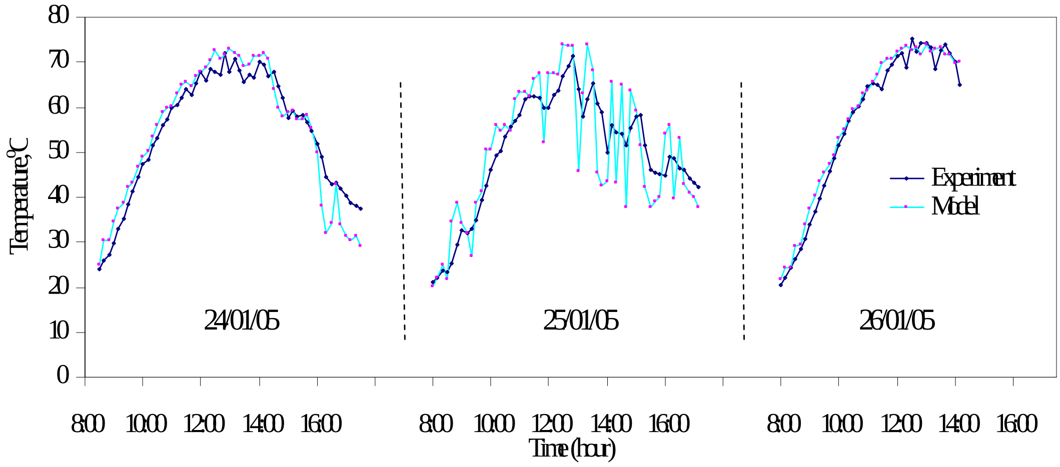

Fig. 23. Predicted and experimental values of the outlet temperature of the roof-integrated collector

4.3 Neural network prediction

Comparison between the observed and neural network prediction of the performance of solar tunnel drier for drying of jack fruit leather is shown in Fig. 25. It is found from Fig. 25 that the agreement between the predicted and observed moisture contents for jackfruit leather is very good. Thus, if the model is adequately trained, it can appropriately represent the solar tunnel drying system for jack fruit leather and can predict the moisture content very well.

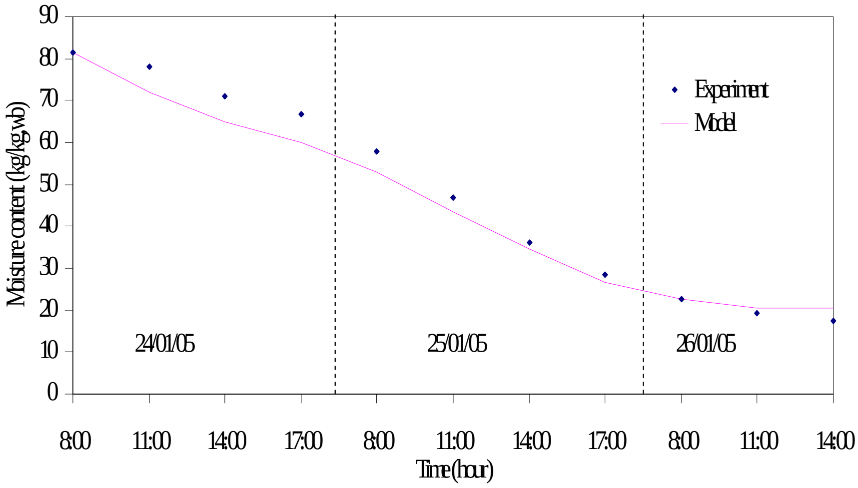

Fig. 24. Predicted and observed values of the moisture content of chilli

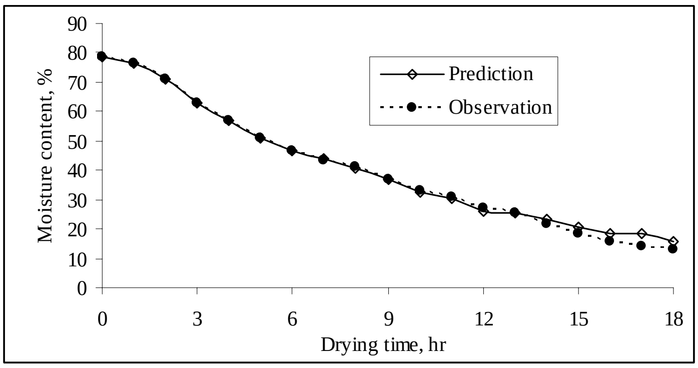

Fig. 25. Variation of predicted moisture content and observed moisture content of jackfruit leather with drying time

4.4 Potentials and Limitations

Field level tests in Bangladesh and Thailand have demonstrated the potentialities of solar tunnel dryer, greenhouse type solar dryer and roof integrated solar dryer for production of quality dried fruits, vegetables, spices, medicinal plants and fish.

Different products to be dried have different maximum permissible drying air temperatures. The drying air temperature for a product must not exceed the maximum permissible drying air temperature. The maximum permissible temperature for production of quality dried pineapple, mango, jackfruit and chilli is 65 °C and that of fish is 52 °C. But for herbal and medicinal plants a maximum temperature of 100°C is recommended for glycoside species, 65°C for mucilage species and 35 to 45°C for essential-oil species. This drying air temperature can be achieved by simply adjusting collector length (in solar tunnel dryer) or air flow rate by changing the number of fans in operation.

The photovoltaic system has the advantage that the temperature of the drying air is automatically controlled by the solar radiation.

Solar tunnel drier with UV stabilized plastic cover requires frequent replacement of the plastic cover. However, this problem can be overcome if solar tunnel drier with polycarbonate cover is used.

In cloudy days the solar tunnel drier can be used for drying since it operates on diffuse solar radiation but the drying rate is significantly reduced.

One major disadvantage of this drier that it does not have any form of back up heating system. But in rainy days the solar tunnel drier can be used if it is integrated with either a biomass furnace or oil or gas burner.

The year round operation of the solar drier for production of different solar dried products would further reduce pay back period and would justify the financial viability of the solar drier as an attractive and reliable alternative to the sun drying in the tropics and subtropics.

Since the drier is PV operated it can be used in the areas where there is no electric grid connection.

The photovoltaic driven solar drier must be optimized for efficient operation.Solar tunnel driers are now in operation in different regions of the tropics and subtropics and the improved versions designed by Janjai (2004) are now in operation in the field in Thailand and Lao's.

Finally solar driers are environmentally sound.

5. Conclusions

Field level tests demonstrated that pv ventilated solar driers are appropriate for production of quality dried fruits, vegetables, spices, herbs and medicinal plants, and fish.

In all the cases the use of solar drier leads to considerable reduction of drying time in comparison to sun drying and the quality of the product dried in the solar drier was of quality dried products as compared to sun dried products. However, the drying time increases with the increase in humidity of the ambient air.

Solar driers are simple in construction and can be constructed using locally available materials by the local craftsman.

The solar drier can be operated by a photovoltaic module independent of electrical grid.

The photovoltaic driven solar driers must be optimized for efficient operation.

The neural network prediction of the model has been found very good and can be used to predict the potential of the drier for different locations and can also be used in a predictive optimal control algorithm.

Nomenclature

C_p	specific heat, kJ/kg ^oK
E	solar radiation, W/m^2
G_a	mass flow rate of air, kg/m^{2}s
H	humidity ratio, kg/kg
K	drying constant, min^{-1}
L_g	latent heat of product, kJ/kg

M	moisture content, % or ratio (db) or (wb)
M_e	equilibrium moisture content, % or ratio (db) or (wb)
M_o	initial moisture content, % or ratio (db) or (wb)
T	temperature, °C
V	air velocity, m/s
b	depth of collector/drier, m
h_c	convective heat transfer coefficient, $W/m^2\ ^oK$
h_r	radiative heat transfer coefficient, $W/m^2\ ^oK$
t	time, min
z	thickness, m

Greek

α	absorbance
ρ	density, kg/m^3
ρ	reflectance
τ	transmittance

Subscripts

a	air
am	ambient
c	collector
e	equilibrium moisture content
g	product
l	liquid
L	long wave
p	absorber plate
s	sky
S	short wave
w	water
v	water vapour

References

Bala, B. K. and Woods, J. L., Simulation of the Indirect Natural Convection Solar Drying of Rough Rice, *Solar Energy* 53(3), 259-266, 1994.

Bala, B. K. and Woods, J. L., Optimization of a Natural Convection Solar Drying System, *Energy*, 20(4), 285-294, 1995.

Bala, B. K., Hossain, M. D. and Mondol, M. R. A., Photovoltaic Based Forced Convection Solar Tunnel Dryer for Pineapple, *Journal of Agricultural Engineering*, 32(4), 23-31, 1997.

Bala, B. K., *Drying and Storage of Cereal Grains*, Oxford & IBH Publishing Co. Pvt. Ltd, India, 1997a.

Bala, B. K., Experimental Investigation of the Performance of the Solar Tunnel Drier for Dying Fish, Final Research Report, Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh, Bangladesh, 1997b.

Bala, B. K., *Solar Drying Systems: Simulation and Optimization*, Agrotech Publishing Academy, India, 1998.

Bala, B. K., Hussain, M. D. and Mondol, M. R. A., Experimental Investigation of Solar Tunnel Drier for Drying of Pineapple, *Journal of the Institution of Engineers, Bangladesh, Agricultural Engineering Division*, 26(4), 37-44, 1999.

Bala, B. K., Adaptive Research on Solar Driers for Drying Mango, Pineapple and Fish, Annual Research Report, Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh, Bangladesh, 1999a.

Bala, B. K., Experimental Investigation of the Performance of the Solar Tunnel Drier for Dying Cabbage, Banana, Jackfruit and Spices, Final Research Report, Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh, Bangladesh, 1999b.

Bala, B. K., Adaptive Research on Solar Driers for Drying Mango, Pineapple and Fish, Annual Research Report, Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh, Bangladesh, 2000.

Bala, B. K. and Mondol, M. R. A., Experimental Investigation on Solar Drying of Fish Using Solar Tunnel Drier, *Drying Technology*, 19(2), 1-10, 2001.

Bala, B. K., Mondol, M. R. A., and Das Choudhury, B. L., Solar Drying of Mango Using Solar Tunnel Drier, *Journal of Agricultural Engineering*, 38(14), 2002.

Bala, B. K., Mondol, M. R. A., Biswas, B. K., Das Choudhury, B. L. and Janjai, S., Solar Drying of Pineapple Using Solar Tunnel Drier, *Renewable Energy*, 28, 183-190, 2003.

Bala, B. K., Experimental Investigation of the Performance of the Solar Tunnel Drier for Drying Jackfruit for Production of Dried Jackfruit and Jackfruit Leather, Annual Research Report, Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh, Bangladesh, 2004.

Bala, B. K., Ashraf, M. A., Uddin, M. A. and Janjai, S., Experimental and Neural Network Prediction of the Performance of a Solar Tunnel Drier for Drying Jack Fruit and Jack Fruit Leather, *Journal of Food Process Engineering,* 28, 552-566, 2005.

Eckert, M. van., Mango drying: A Tree Product Value, and Income Generating Enterprise in Rural Areas, ITFSP Internal Paper # 19, Nairobi, Kenya, 1998.

El-Shiatry, M. A. Müller, J. and Mühlbauer, W., Drying Fruits and Vegetables with Solar Energy in Egypt, *Agricultural Mechanization in Asia, Africa and Latin America*, 22(2), 61-64, 1991.

Esper, A. and Mühlbauer, W., Development and Dissemination of Solar Tunnel Drier, ISES Solar World Congress, Budapest 22, 1993.

Esper, A. and Mühlbauer, W., PV-Driven Solar tunnel Drier, Agricultural Engineering Conference, Bangkok, December 6-9, 1994.

Esper, A. and Mühlbauer, W., Solar Tunnel Dryer for Fruits, *Plant Research and Development*, 44, 61-80, 1996.

Excell, R. H. B. and Kornsakoo, S., A Low Cost Solar Rice Dryer, *Appropriate Technology*, 5(1), 23-24, 1978.

Excell, R. H. B., Basic Design Theory for a Simple Solar Rice Dryer, *Renewable Energy Review Journal*, 1(2), 1-14, 1980.

Hossain, M. A., Forced Convection Solar Drying of Chilli, Ph.D. Thesis, Bangladesh Agricultural University, Mymensingh, 2004.

Hossain, M. A., Bala, B. K. and Woods, J. L., Simulation of Solar Drying of Chilli in Solar Tunnel Drier, *International Journal of Sustainable Energy* ; 24: 143-153, 2005.

Janjai,_S., Srisittipokakun, N. and Bala, B. K. Experimental and modelling performances of a roof integrated solar drying system for drying herbs and spices. Energy, 33, 91–103, 2006

Janjai, S., Personal Communication, Silpakorn University, Nakhon Pathom, Thailand, 2004.

Mühlbauer, W., Esper, A. and Muller, J., Solar Energy in Agriculture, ISES Solar World Congress, Budapest, August 23-27, 1993.

Mühlbauer, W., Present Status of Solar Crop Drying, *Energy in Agriculture*. 5, 121-137, 1986.

Oosthuizen, P. H., The Design of Indirect Solar Rice Dryers, *Journal of Engineering for International Development*, 2(1), 20-27, 1995.

Oosthuizen, P. H., An Experimental Study of Simulated Indirect Solar Rice Dryer Fitted with a Small Fan, *Journal of Engineering for International Development*, 3(1), 22-29, 1996.

Simate, I. N., Optimization of Mixed Mode and Indirect Mode Natural Convection Solar Dryers, *Renewable Energy*. 28, 435-453, 2003.

Sharma, V. K, Colangelo, A. and Spagna, G., Experimental Investigation of different Solar Driers Suitable for Fruits and Vegetable Drying, *Renewable Energy*, 6(4), 413-424, 1995.

Schirmer, P., Janjai, S., Esper, A., Smitabhindu, R. and Mühlbauer, W., Experimental Investigation of the Performance of the Solar Drier for Drying Bananas, *Renewable Energy*, 7(2), 119-129, 1996.

Smitabhindu, R., Personal Communication, Royal Chitralada Project, Bangkok, Thailand, 2004.

Zaman, M.A. and Bala, B.K., Thin Layer Solar Drying of Rough Rice, *Solar Energy*, 42, 167-171, 1989.