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COMPUTATIONAL STUDIES ON PERFORMANCE OF A MIXED MODE SOLAR DRYER WITH THERMAL STORAGE

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ABSTRACT

This paper presents a computational analysis to investigate the performance of a mixed mode solar dryer with thermal energy storage. The dryer incorporates a flat plate solar collector, a greenhouse, packed bed phase change energy storage and drying plenum with crop trays. Here drying is happening within the solar greenhouse. Solar air heater preheats the air that goes through the agro crops kept in trays within the greenhouse. This will increase the drying rate. The drying system works in such a fashion that phase transition material stores the thermal energy throughout sunshine hours and releases the latent and sensible heat after the sun sets, therefore dryer is effectively operative for next five - six hours. This maintains continuity of drying of herbs and crops for their colour and flavour vulnerability. The drying rate within the solar dryer will be much beyond than the open sun drying. The simulation of drying curves shows the increased drying rate with solar dryer.

KEYWORDS: Solar dryer, Solar greenhouse, Flat plate collector, Phase change thermal energy storage.

INTRODUCTION

Energy is the causal agent of economic growth and is significant to the sustenance of a modern economy. In a tropical country like India, most of the energy demands may be met by simple systems which will convert solar power into acceptable forms by correct application of technologies. Solar drying has been considered as one of the foremost promising areas for the use of solar power particularly within the field of food preservation. Open sun drying is the most common methodology utilized in tropical countries for the drying of agricultural product, foodstuff etc. Despite the fact that the method is easy, it suffers from the disadvantages like insect infestation, microbic contamination etc. products dried during this approach are unhealthful and typically unsuitable for human consumption. Therefore, solar dryer is the best alternative solution for all the drawbacks of ancient drying. As compared to natural open drying, solar dryers generate higher temperatures, lower relative humidity, lower product wet content and reduced spoilage throughout the drying process. But the main limitation of the solar dryer is that it works only if the sun is shining. It may be mitigated by storing excess energy throughout the peak time and use it in off-sunshine hours or once the energy accessibility is inadequate.

Aravindh *et al.*[1] explains the different aspects and types of solar drying, parameters involved in the drying process. Visavale[2] explains the drying principles and working principles of different drying techniques. Classification of solar dryer was also incorporated here. Sreekumar *et al.*[3] have studied regarding construction, working and thermal analysis of solar air heater, which is one of the important components of the system. Serm Janjai *et al.*[4] make the study regarding solar greenhouse dryers and made energy balance equations for different components in the greenhouse. Dan Nchelatebe Nkwetta *et al.*[5] explains regarding thermal energy storage using PCM materials which are included in the proposed system. Experimental investigation and economic evaluation of a mixed-mode solar greenhouse dryer for drying of red pepper and grape were done by Aymen ELkhadraoui *et al*[6]. Dilip Jain *et al.*[7] have studied the performance of indirect through pass natural convective solar crop dryer with phase change thermal energy storage. Computer-based analysis of solar dryers can be done with software tools. Habtamu Tkubet Ebuy *et al.*[8] have done an analysis of solar cereal dryer using TRNSYS software. Dai-Chyi Wang *et al.*[9] developed a visual method to test the range of applicability of thin layer drying equations using MATLAB.

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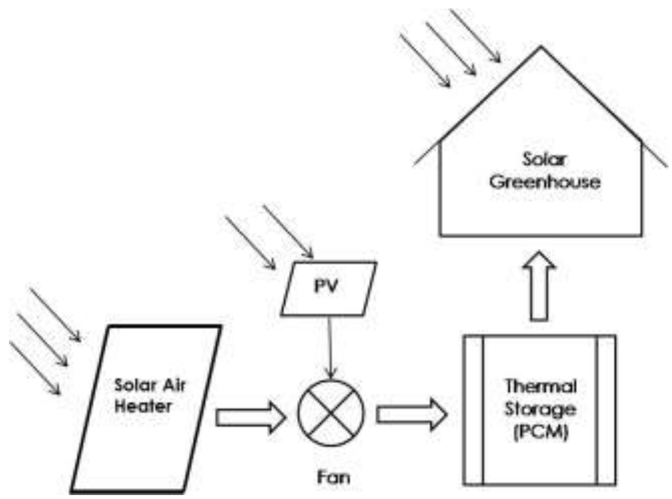
EXPERIMENTAL SET-UP

Experimental set-up of the mixed mode solar dryer with thermal energy storage is the diagram (Fig. 1). In line with the past researches and studies, these dryer systems are often classified into three forms as direct, indirect and mixed mode based on the arrangement of system parts and mode of solar heat utilization.

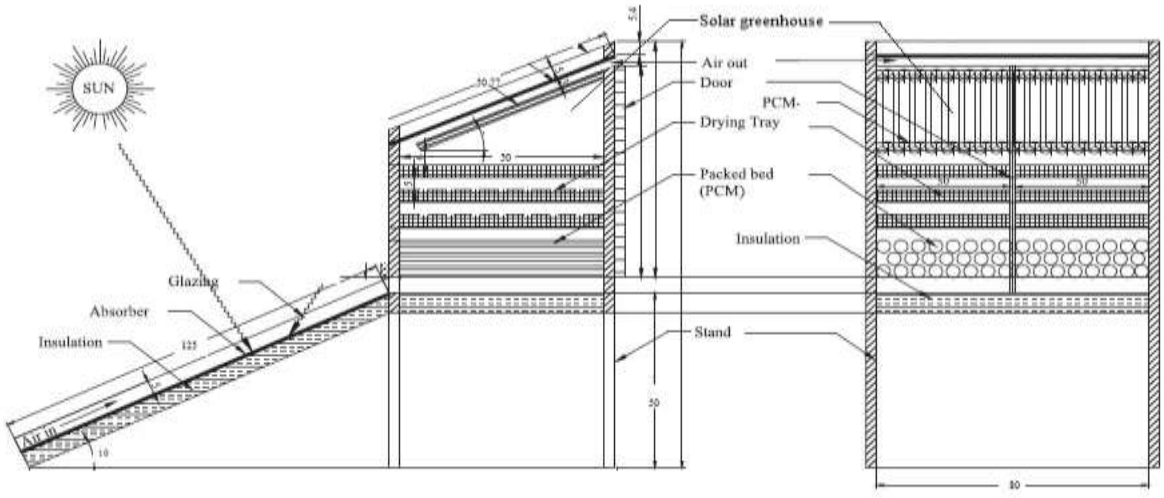
Figure:1



Block diagram of mixed mode solar dryer

A continuous process is needed for drying of crops, till it reaches the desired moisture content that's unattainable with open solar drying after sunshine hours. Thus, for continuous drying, a thermal storage can be used with the solar air heater. A thermal storage unit integrated with the solar air heater is charged throughout the peak sunshine hours and used (discharged) during off-sunshine hours for supplying the hot air to the dryer. Heat storage using phase transition materials is a wise alternative that leads to continuous process throughout the day and night. Development of solar dryer with phase change thermal energy storage can offer continuous and uniform drying of spices and herbs for a higher quality product with reference to color and essential oil. Here the planned system is a mixed mode solar dryer having 3 major components i.e. flat plate collector, greenhouse and PCM thermal storage. Flat plate collector and solar greenhouse represents the mixed mode and PCM packed bed for thermal storage which is assembled as shown in Fig. 2.

Figure:2



Mixed mode solar dryer with PCM storage **[6]**

A 1 m^2 flat plate collector with insulation at base and variable tilt angle goes to attach in front of the drying system as shown in Fig. 2. The collector contains a toughened glass that was placed on the collector at a distance of 0.05 m from the absorber plate. This area in between permits the air to flow within the dryer. The plate will paint with matt finished black color. The air gets heated because it travels from the inlet to the drying system with the absorption of solar radiation on the plate.

A phase change material (PCM) thermal energy storage system is introduced below the greenhouse drying chamber that consists of cylindrical tubes (Fig. 2). The tubes fill with paraffin wax and tightly packed to avoid any outflow. The tubes were placed in a zigzag orientation to store thermal energy. PCM gets liquefied during day time and stores energy within the form of latent and sensible heat. This stored energy is employed throughout the night time for drying crops.

Greenhouse is the drying chamber in this set-up. Agro crops which need drying is kept in trays in different layers. The experimental greenhouse occupies a floor space up to 0.4 m^2, 0.5 m wide, 0.8 m long and 0.5 m high. The greenhouse walls and roof will cover with plexiglass. Provision will be provided for exhaust moist air.

METHODOLOGY

The system is assumed to face towards the noon sun. Because the radiation falls directly on flat plate collector, the glazing prevents thermal losses, ends up in entrapment of radiations. The air heats up and flows through the gap in between absorber plate and glazing and drying set-up can get heated by convection. The natural draught will be created as a result of thermal buoyancy and air starts flowing within the system. The higher temperature of the air is employed in heating and melting of PCM as thermal storage and remaining is passed over to the drying trays kept in the greenhouse, that starts drying the crops throughout sunshine hours. The greenhouse itself acts as a dryer. The wet air from drying trays will move upward and once it'll come in close with the top glazing of the greenhouse, that once more gets heated and facilitate in making a draught as a result of thermal buoyancy and therefore wet laden air are discharged out of the system. Throughout off-sunshine hours the heat stored in PCM is discharged, as the PCM will get solidified, which will release latent heat. This latent heat is used by crops throughout off-sunshine hours to continue drying a minimum of 5-6 hour which will enhance the drying of crops. The fundamental aim of this project is to increase the drying hours, utilise most obtainable energy and prevent microbial and other physiochemical losses because of moisture remained in products.

SIMULATION STUDY

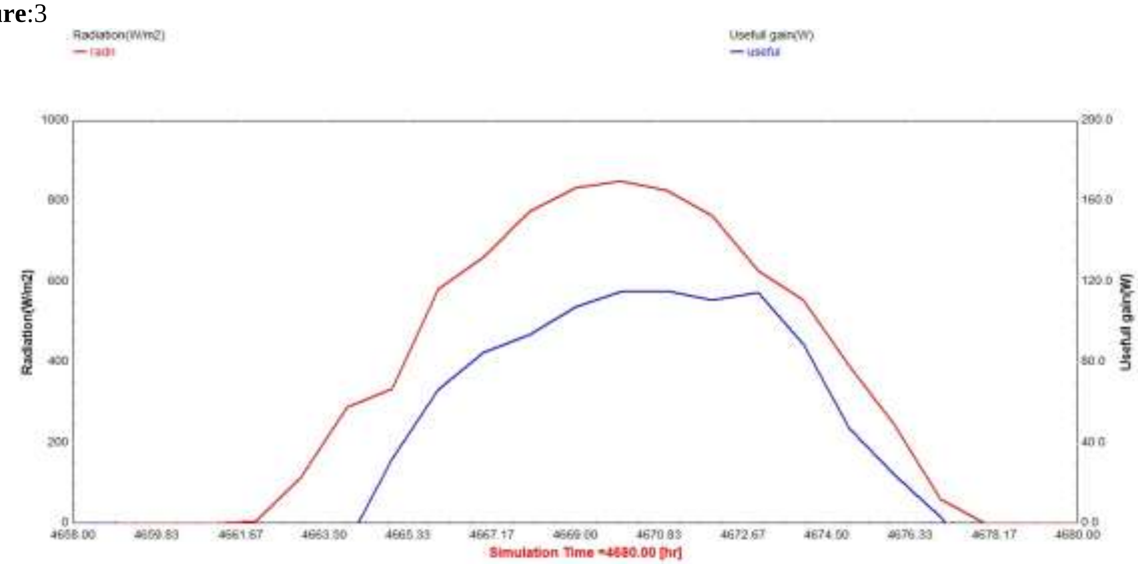
Solar Dryer Components

Here mixed mode solar dryer consists of two different drying techniques. One is drying by air which is heated using a solar air heater or a solar flat plate collector. Another drying technique included is a solar greenhouse. Simulations were done for both of the components for analysing their heat gain and temperature.

Solar air heater component models the thermal performance of a theoretical flat plate collector. The entire collector array might consist of collectors connected in series and in parallel. The thermal performance of the entire collector array is decided by the number of modules in series and also the characteristics of every module. This model provides for the theoretical analyses of a flat plate. The Hottel-Whillier steady-state model is employed for evaluating the thermal performance. The collector that has an area of 1 m^2 is simulated with air as the working fluid.[10]

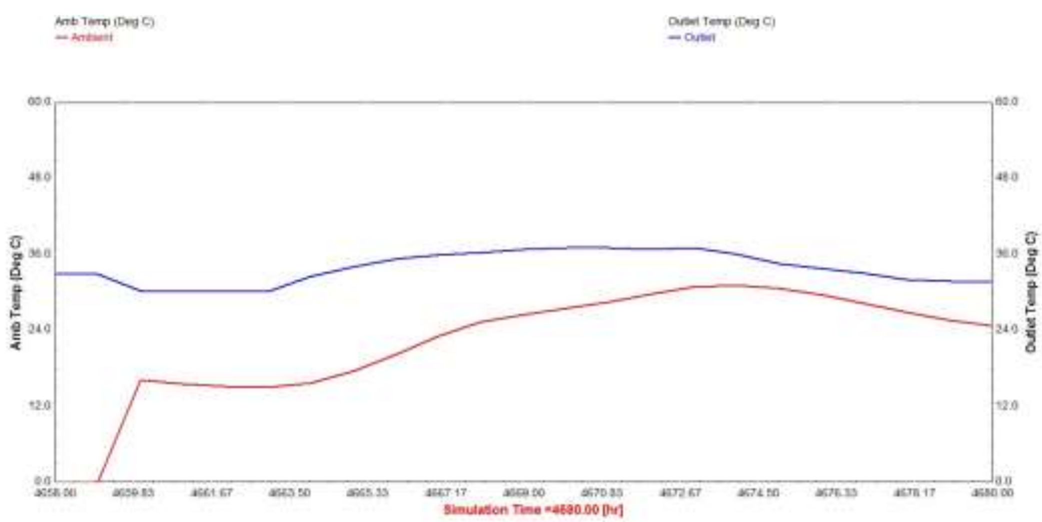
Useful gain of solar air heater and variation in ambient and outlet temperature for the month of July is analysed using TRNSYS simulation which is shown in Fig 3 and Fig. 4.

Figure:3



Solar radiation and Useful heat gain of solar air heater

Figure:4



Ambient temperature and outlet temperature of solar air heater

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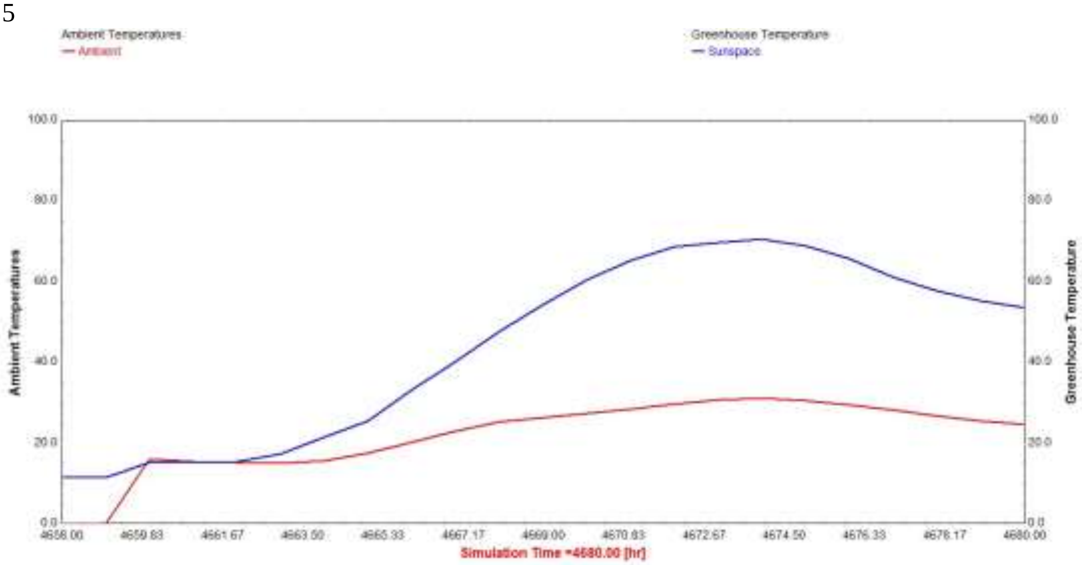
Solar greenhouse is almost equal to a solar sun-space which is a default component available in TRNSYS. An attached sun-space can be thought of as a large solar collector where the space between the glazing and absorbing surface is large. After passing through the glazing(s), solar radiation is trapped in the sun-space. The sun-space loses energy to the ground by conduction through the floor and to ambient by conduction, convection, radiation, and infiltration through the glazed surfaces. Considering the project set-up the floor of solar greenhouse is thermal storage. Hence the lose through floor is negligible here.

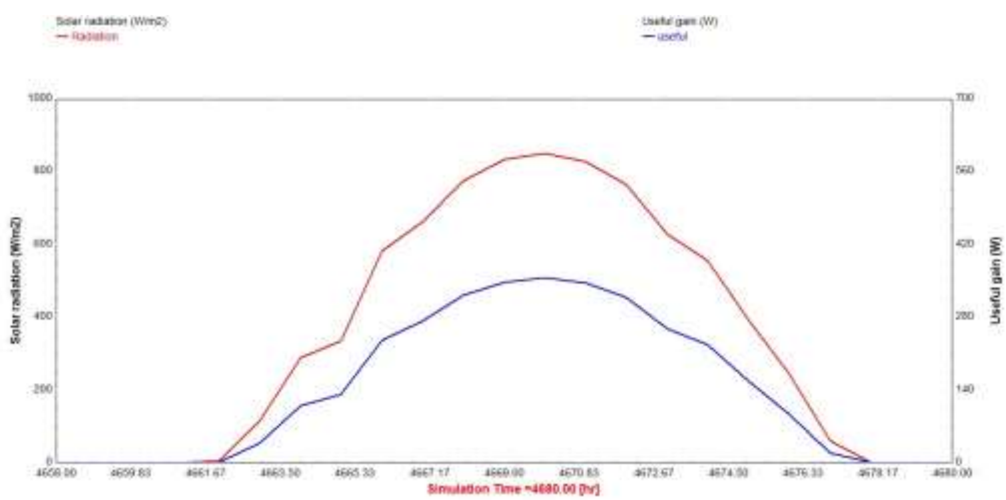
Figure:5



Ambient temperature and outlet temperature solar greenhouse

Ambient temperature and greenhouse temperature were analysed from the simulation (Fig. 5). From this it is assumed that the greenhouse can provide 30° C more than the ambient temperature. The useful heat gain of solar greenhouse with the solar radiation is plotted in Fig. 6. Solar radiation is around 800 W/m^2 and the useful heat gain from solar greenhouse is around 350 W.

Figure:6



Solar radiation and Useful energy gain of solar greenhouse

Simulation of Solar Drying

The efficiency of drying systems can be improved by the analysis of the drying process. Analysis of drying systems can be greatly expedited by using computer simulation. Heat transfer and mass transfer take place during drying of crops. Heat is transferred from the drying air to the liquid water vapour in the grain. Mass is transferred in the form of internal moisture and evaporated liquid. Drying is a continuous process where the moisture content, air and cereal temperature and the humidity of the air all changes simultaneously.
The general equation of the moisture-time relation proposed by Newman can be represented by the first term: [11]

$$M_r = \frac{M - M_e}{M_i - M_e} = Ae^{-akt} + Be^{-bkt} + Ce^{-ckt} \quad (1)$$

where:
M_r = moisture ratio, [decimal]
M_e = Equilibrium moisture content
M_i = Initial moisture content
k = drying constant, [sec^{-1}]
t = time [sec]
A,B,C,a,b,c etc = characteristic constants of the drying product

Newman observed that the series converges rapidly and after a period of time represented by the first term.

$$M_r = \frac{M - M_e}{M_i - M_e} = e^{-kt} \quad (2)$$

$$k = ae^{\left(\frac{b}{T+273}\right)} \quad (3)$$

The parameters a and b both varied with moisture ratio. Equation 2 is further modified to

$$M_r = exp(-kt^n) \quad (4)$$

This is the form most drying equations employ now. General exponential form was used for the time relationship. According to the drying parameters and constants of different crops the equation will also varies. Consider an example of rice as drying crop.

i. Constants

$$M_r = 0.134 \times exp(-5 \times 10^5 \times k \times t) + 0.586 \times exp(-5 \times 10^4 \times k \times t) + 0.28 \times exp(-8 \times 10^3 \times k \times t) \quad (5)$$

$$k = exp[-3590/(T + 273)] \quad (6)$$

ii. Ranges

$$17.3C \le T \le 60C \quad (7)$$

Using the above equations the drying curve can be plotted in MATLAB. The output obtained is shown in Fig 7. In this simulation the drying temperature is considered as ambient temperature considering that the drying is natural. ie around 30°C. It is observed that the crop takes around 20 hours to dry upto 10% moisture content.

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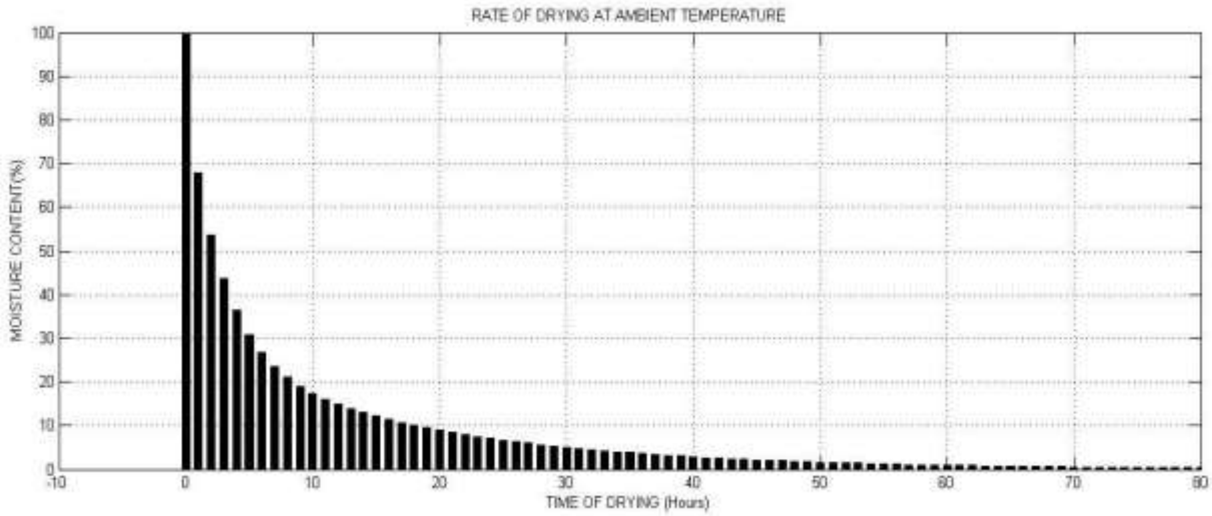
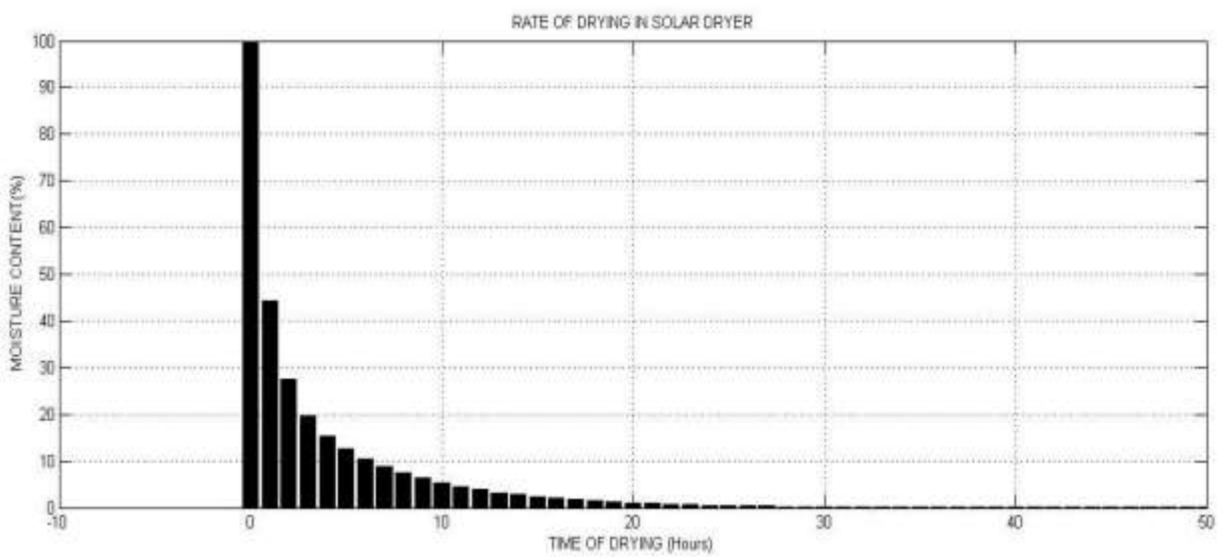
Figure:7



Rate of drying of rice at ambient temperature

From the TRNSYS simulation it is analysed that the mixed mode solar dryer can produce a temperature above 60°C. So it can be used for the rice drying problem and the observations are given in Fig. 8

Figure:8



Rate of drying of rice in solar dryer

It is found that that the drying rate is increased and the time requirement for drying to 10 % moisture is around 8 hours. Time requirement for drying is reduced considerably using solar dryer

RESULTS AND DISCUSSION

The proposed system which is put forward in this paper is a mixed mode solar dryer with solar greenhouse and flat plate solar air heater. PCM based thermal energy storage is also incorporated in the system to improve and maintain the continuity of drying. Two main components were simulated using TRNSYS software and the heat gain variations with solar radiation is analysed. Temperature variations inside solar dryer with ambient were also compared in this simulation. The drying process is also simulated with MATLAB using drying equation of rice as an example and drying rates of natural and solar drying were compared. It is observed that the time required for removing 90% of the moisture content in solar drying is around 8 hours which is around 20 hours in natural open drying.

CONCLUSION

Solar drying could be a promising technology for drying of food product for a developing country like India, wherever solar power is plentiful. This will dramatically scale back the post-harvest food spoilage that could be a major concern for the second largest populated country. Although the drying conditions for each product are totally different, a dryer can be modelled in such a way that it will dry any product with smart control parameters like temperature and also the mass flow.

The mixed mode solar crop dryer is an alternate to beat the disadvantages of ancient open sun drying and use of maximum accessible solar radiations. A dryer with packed bed PCM was capable of storing thermal energy in the form of latent heat and sensible heat throughout the daytime and release the same after the sunshine hours. This stored energy will maintain the drying temperature ranged between 40°C and 45°C, therefore, extended the period of drying. The simulation study shows that a solar dryer can effectively used for fast drying purposes. Increased drying temperature helps the crop to reduce the drying time which is one of the important plus point. Furthermore, the drying material is protected from direct sun's radiation, infestation by insects and contamination by dust particles. As a result, the product quality is high.

FUTURE WORKS

For further improvement of the dryer, the double slope passive solar dryer can attain higher efficiencies. By arranging copper tubes to the side walls of the dryer can recover heat from the side walls. Owing to the fact that the air will acquire more moisture only if its relative humidity is low, thus by introducing a device that reduces the relative humidity of the air before moving into the air heater will remove the additional moisture content. By using a metallic drying chamber the efficiency of the solar dryer can be further improved.

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