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RESEARCH ARTICLE

Thermal modeling of temperature for cabinet solar dryer

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ABSTRACT

In the present study, cabinet type solar dryer was evaluated mathematically to maintain the required temperature in the drying chamber. The mathematical analysis was based on the heat exchanges across the dryer void. The dryer system was equipped with heaters and exhaust fans to compensate for fluctuation in solar availability. The dryer was evaluated over a day for given environmental conditions. For given dryer configuration, the minimum auxiliary input 9.91 kW-hr is observed at 44 °C (optimum temperature). If the dryer is operated at this temperature, the utilization of solar energy is maximum. It was also noted that with increase in required drying temperature, initially the auxiliary energy consumption reduces to minimum and then increases. The increase was predominantly due to energy consumption by the heaters. The minimum air flow rate also affected the optimum temperature in the dryer. As the flow increased, the optimum temperature was found to decrease.

Keywords: Solar energy, solar dryer, thermal modelling

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INTRODUCTION

Food security is of prime importance for any country in the world considering the rising population and food demand. However, a large section of food produce is usually lost in harvesting and transportation. The food loss issue is particularly serious in developing countries. WRI India has identified post-harvest handling and food storage as one of the important key factor in addressing the food loss issue. A report by Ministry of Food Processing Industry, India (2015) has estimated the average harvest loss of around 10% in fruits category while average harvest and post-harvest loss of 9% for vegetables. Drying process of the food products, reduces the food wastage by decomposition. Drying of food products not only increases the shelf life but also improves product quality and reduces the post-harvest losses. This may make the more food availability to growing population (Barnwal et al., 2008; Yadav et al., 2021). Moreover, drying using solar energy, may conserve the decaying fossil fuel sources.

For direct mode dryers, the sunlight comes in direct contact with the product while in indirect mode, the heating of the air take place in isolated collector and then carried to the product chambers. Better nutritional quality and texture is observed in indirect

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solar dryers compared to direct dryers (El-sebaii et al., 2013; Goud et al., 2019). Different parameters that influences the drying process are temperature of drying medium and its velocity, type of drying method utilized, structure of the dryer, and moisture diffusivity (Alqadhi et al., 2017; Ansaz et al., 2021; Komble et al., 2022)). Also surface area of crop exposed to the drying medium affects the drying rate (Tiwari, 2016; Bolaji et al., 2008). However, the most significant parameters which influence the process of drying are drying air temperature and air velocity (Balbine et al., 2015; Chaudhari et al. 2022). Natural convection solar dryers uses density difference for circulation of air, in and out of the dryer void. But their use put forward the issues like inadequate air flow, small drying rates and sometimes rotting of the crops (Afriye et al., 2011; Ekka et al., 2021). In forced convection dryers, normally fan is used to have superior air circulation through the dryer void. Such dryers often provide improved drying rates and also better process control is possible (Sallam et al., 2013; Sharma et al., 2018).

Though solar drying is preferred option compared to mechanical drying owing to high cost and dwindling source of fossil fuels, the periodic and irregular behavior of solar availability pose a challenge in the design of any solar system. An alternative is to combine solar system with auxiliary heating system such that there will be maximum utilization of solar energy and auxiliary is to be supplied only when required. The solar dryer proposed in the present literature provides amalgamation of solar energy with auxiliary heater and exhaust fan. The system is analyzed mathematically so that auxiliary energy consumption is minimum keeping the required drying temperature in the dryer void.

SOLAR DRYER MODEL

The solar dryer configuration under study is as shown in Figure 1. It consists of drying chamber or dryer void which contains the trays to accommodate the substance to be dried. Normally the product to be dried is chopped in thin layers and spread over the trays. This enhances the heat transfer and helps in uniform drying of the product. The dryer has glass glazing located in such a position that maximum amount of solar energy falling on the glazing is trapped. The double glass glazing is considered so that heat lost by radiation and convection to the surrounding can be reduced and maximum solar heat is transpired inside the dryer void. For Pune location the glass glazing is kept at inclination of 21°. The cabinet of the dryer is having metallic structure with proper insulation cladding to reduce heat loss from the dryer void to the surrounding. The cabinet has composite wall structure. On the inner side, it has thin stainless steel sheet of 1mm thickness. Stainless steel sheet is followed by glass wool insulation of 5 mm thickness and insulation is cladded with aluminum sheet of 3 mm on the outer side. The inner steel sheet helps in more heat dispersion by reflection and glass wool reduces the loss of heat transmission to outer low temperature environment. The dryer is provided openings near the bottom which acts as entrances for the air. The air leaves the dryer void from the outlets located at the top.

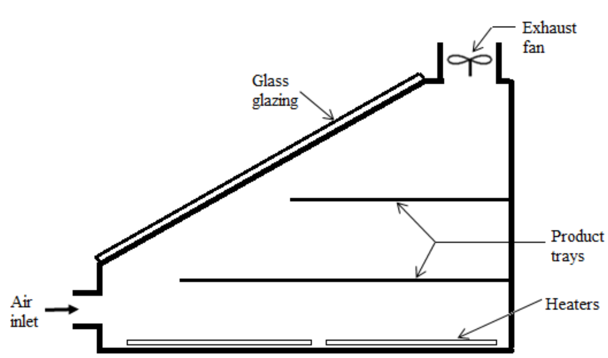

Figure 1: Layout of cabinet solar dryer

The dryer void houses the inner walls, tray frames, trays for product storage, products, and electric heaters, exhaust fans and air the dryer void. The electric heaters are installed near the bottom, to achieve even temperature distribution when solar heat is not sufficient to provide the required heat. The dyer is located at fixed place and oriented to receive highest quantity of solar energy. The dryer bottom is mounted on legs to keep openings above the floor. This helps to avoid the dirt and dust on the ground from entering, with fresh ambient air. With solar energy absorption, air temperature in the dryer void rises and this heat is transmitted to the product. With increasing temperature of the product, moisture is evaporated from the product and is carried away by leaving air to the atmosphere. The fresh air coming from inlet openings mixes with air in the dryer void and became warm and humid. If solar heat availability exceeds the required amount, the air temperature the dryer void rises surpasses the stipulated temperature. In such a case, the mixing of fresh air and air in void is accelerated by the fans provided at the outlet openings, till the temperature does not become equal to stipulated temperature. The auxiliary energy consumption reduces with increase in availability of solar energy. The dyer can be set at any stipulated temperature depending on the product.

THERMAL MODELLING OF THE DRYER

The dryer collects the solar irradiance falling on the glass glazing. Very little portion of the falling radiation energy is absorbed by the glazing, the balance portion is transmitted through it. The blackened absorber plate placed below the glazing, receives the transmitted energy portion. Some portion of this energy is lost to the surrounding by reflection and convection heat exchange. The energy received by the absorber plate is transferred to the air in the dryer void. Part of this energy is used for evaporation of moisture in the product, chunk of energy is swept by the leaving air and some is lost through the walls of the dryer void. Considering all these heat exchanges along the energy interactions taking place by the heaters and exhaust fans, the heat balance for the dryer void can be epitomized as in equation 1. In the heat balance equation, the left-hand side stands for the change in the internal energy of the dryer void while right hand side describes energy interactions across the control volume.

$$\Delta E_d = E_s - E_{L,top} - E_{L,side} - E_{L,air} \quad (1)$$

where, E_d is internal energy change of dryer void ingredients, E_s is energy gain by dryer void from solar as well as heater, E_L and E_S represents energy loss form top and side surfaces respectively and $E_{L,air}$ is the energy swept by the air. The rate of change of internal energy for dryer void is calculated considering internal energies of dryer intergradient and summing them up using equation 2.

$$\Delta E_d = \left(\sum_{i=1}^{i=n} m_i \times C_{pi} \times \frac{dT}{d\tau}\right) \quad (2)$$

The solar energy received by the glass glazing is calculated as

$$Q_s = \left(I_b R_b + I_d R_d + I_g R_g\right)\tau^2 A_g = \mathrm{q_{so}A_g} \quad (3)$$

where, I represent radiation intensity and R represents tilt factor. Ag is glass glazing area. Subscripts d, b and g are for diffused, beam and reflected radiation.

Heat energy lost from the dryer walls is computed using equation,

$$E = U\,A\,(\Delta T) \tag{4}$$

where U is heat transfer coefficient and A is surface area and ΔT is the temperature difference.

The heat energy carried away by the air is determined as:

$$Q_{L,air} = m_{out} Cp_{air} (T - T_{amb}) \tag{5}$$

When equation 2 to 4 are placed in equation 1, the following equation is obtained.

$$\left(\sum_{i=1}^{i=n} m_i \times C_{pi} \times \frac{dT}{d\tau} \right) = q_{so} A_a - U_t (T - T_{amb}) A_g - U_S A d_s (T - T_{amb}) - m_a C_{p,a} (T - T_{amb}) \tag{6}$$

The above equation is solved analytically and solution yield the result as given in equation

$$\frac{Q_S - U_t A_g \left(T_f - T_{ambient}\right) - U_S A_S \left(T_f - T_{amb}\right) - m_{air}\, C_{p,air} (T_f - T_{amb})}{Q_S - U_t A_g (T_i - T_{amb}) - U_S A_S (T_i - T_{amb}) - m_{air}\, C_{p,air} (T_i - T_{amb})} = e^{-\left(\frac{U_t A_a + U_S A_S + m_{air} C_{p,air}}{\sum m_i c_{pi}}\right) * \Delta t} \tag{7}$$

If the stipulated temperature is to be achieved, the solution to the energy balance can be used to determine the auxiliary energy required to maintain the temperature. It can also be used to arrive at the final temperature of air at the end time instant Δt knowing the other things.

RESULTS

The analysis of the dryer was carried out to understand the change of temperature with ambient temperature and solar radiation. For this purpose, the solar radiation data of single day was considered and model was executed. The variation of ambient temperature and solar radiation over the day considered, is as shown in Figure 2. The dryer considered for analysis had solar absorption area of 1 m x 2 m aperture. It was provided with double glass glazing to harness maximum amount of solar energy. Below the glazing, a blackened metal plate is placed. This plate got heated as solar radiation falls on it and also it avoided the solar rays to come in direct contact with the material to be dried. The dryer was cladded with glass wool insulation material to prevent the heat inside the dryer space to be transpired to outside environment. The dryer considered had inlet ports near the bottom and outlet ports at the top allowing for the natural flow direction of hot air.

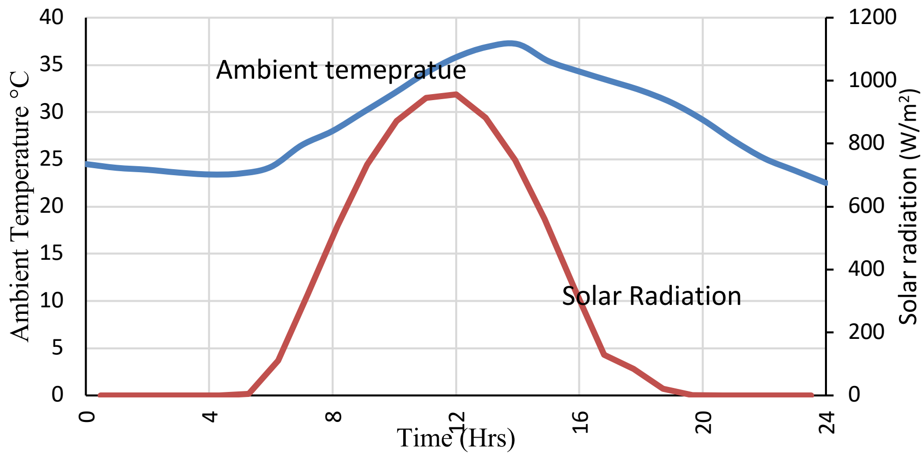

Figure 2: Change of ambient temperature and solar radiation over the day

For analyzing the temperature variation of drying air, the model was implemented for one complete day (12 am to 12 pm). The temperature of air inside the dryer void was obtained at each time interval and plotted with reference to time of the day. In first scenario, only solar energy was considered as energy input to the dryer system while in the next case, auxiliary heaters are also implied with solar heat input. The energy input to auxiliary heaters was computed in such a way that the dryer void temperature remains the same.

Temperature change with solar energy

The air temperature inside the dryer, was achieved considering solar radiation as the solitary energy input. The temperatures acquired at various instances are plotted with reference to day time as shown in Figure 3. With increase radiation intensity, more heat was gained by the air in the dryer and hence its temperature increases almost in similar manner to that of solar radiation. The temperature of ambient air also plays an important role and hence when observed carefully, it is noticed the fall of temperature in dryer space is not as sharp as expected during lower radiation periods after mid-noon. This temperature variation also indicated that uniform temperature was not available when using solar heat as the solitary heat input.

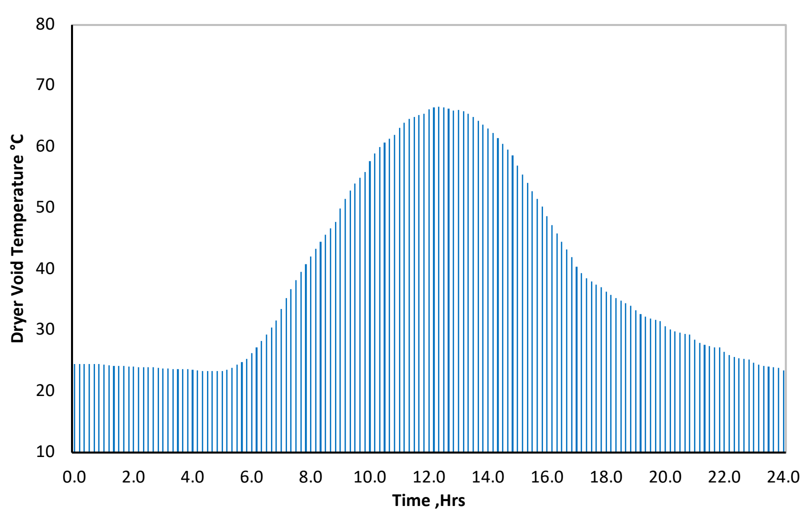

Figure 3: Dryer void temperature variation over the day with solar energy input

The linear characteristic in Figure 4, indicates the temperature to be upheld (42 °C) in the dryer void. Considering the temperature to be upheld in the dryer void, the time span was divided as: (a) time span when temperature is greater than stipulated temperature and (b) time span in which void temperature below stipulated temperature. In the first scenario, the additional energy needs to be supplied between 01.00 am to 08.00 am and 05.00 pm to 12.00 pm. While between 8.00 am to 04.00 pm, as dryer void temperature was greater than stipulated temperature and hence exhaust fans need to be turned on. For the given day, to retain a temperature of 42 °C in the dryer void, the energy requirement by the heater is 4.83 kWh and b the blower is 3.29 kWh. Total energy supply of 8.11 kWh in addition to solar energy available, thus helped to keep constant temperature of 42 °C in the dryer void.

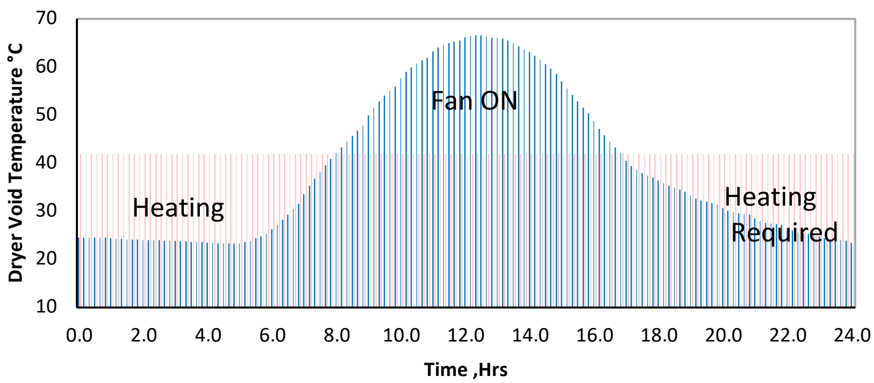

Figure 4: Dryer temperature change with required temperature of 42 °C

Energy consumption for uniform temperature maintenance

The change in temperature with day time revealed that it was very difficult to maintain temperature in the dryer while using solar heat only. To keep temperature nearby the requisite temperature, it is necessary to have some supplementary energy source. The mathematical analysis calculates the auxiliary energy necessary to maintain a particular temperature of air in the dryer void. The auxiliary energy constituted energy required by the heater as well as energy required by the blower. During the day time when temperature in the dryer void was less than the stipulated temperature, the heater provided the additional energy to raise the temperature to the requisite level. Contrariwise the blower provides the necessary air supply to carry away the heat when dryer void temperature was higher than the stipulated temperature.

The energy requirement by the dryer changes with change in stipulated temperature. The prime goal of the study was to employ the solar heat to maximum and use auxiliary whenever necessary. Figure 5 shows characteristics of temperature in the dryer void, with stipulated dryer temperature on the abscissa and energy consumption in kWh per day on ordinate. It was noticed that the auxiliary heat demand rises linearly while requirement of the blower declines non-linearly with the stipulated temperature.

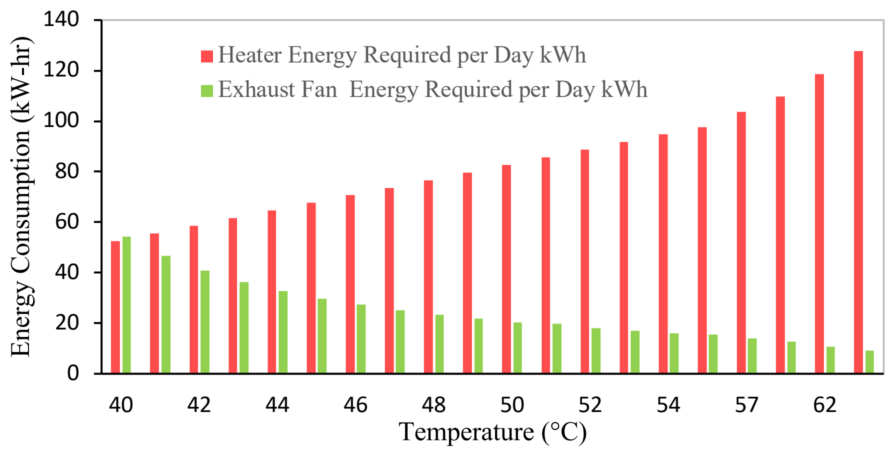

Figure 5: Change in heater energy and fan energy with stipulated air temperature

The total energy requirement initially declines up to a temperature of 44 ºC and then starts rising with stipulated temperature as represented in Figure 6. The total energy requirement at 44 ºC is 7.91 kW-hr of which energy requirement by heater was 5.39 kW-hr and by exhaust fan is 2.52 kW-hr. Initial decline of energy requirement is credited to reduce energy requirement at lower temperatures. Also, the energy usage of a fan was not as severe as that of an electric heater. As the stipulated temperature in the dryer void increased beyond 44 ºC, the heater consumption dominates the fan energy consumption. This results in increasing rate of total requirement of energy. This suggested that if the given dryer is operated at 44 ºC, it will utilize maximum amount of solar heat under given operating conditions. With increase in solar irradiance, the optimum temperature (minimum power consumption) will increase.

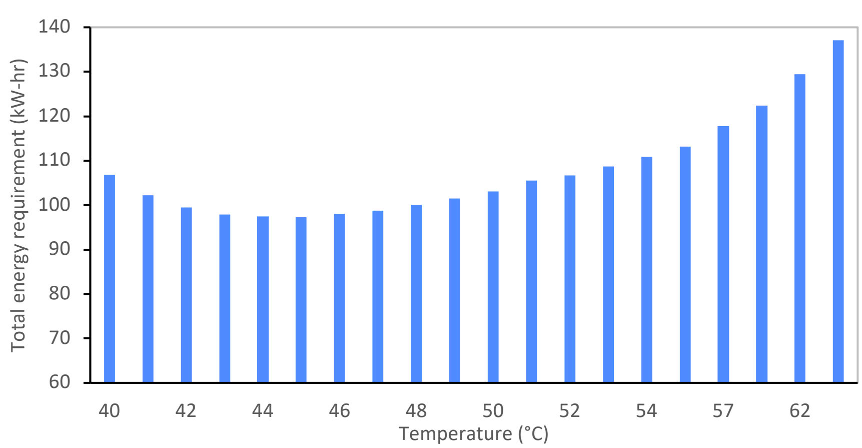

Figure 6: Change in total energy requirement with stipulated air temperature

Effect of minimum air circulation

To avoid accumulation of humid air in the dryer space, a minimum flow rate of air is required to be maintained in the dryer void. This underlying flow rate also affected the optimum drying air temperature. The effect is illustrated in Figure 7. It was observed that with change in minimum flow rate maintained, the value of optimum temperature changes. Though the change was small, the optimum temperature was found to increase with reduction in minimum flow rate. Also rise in total energy requirement was observed with increase in minimum flow rate.

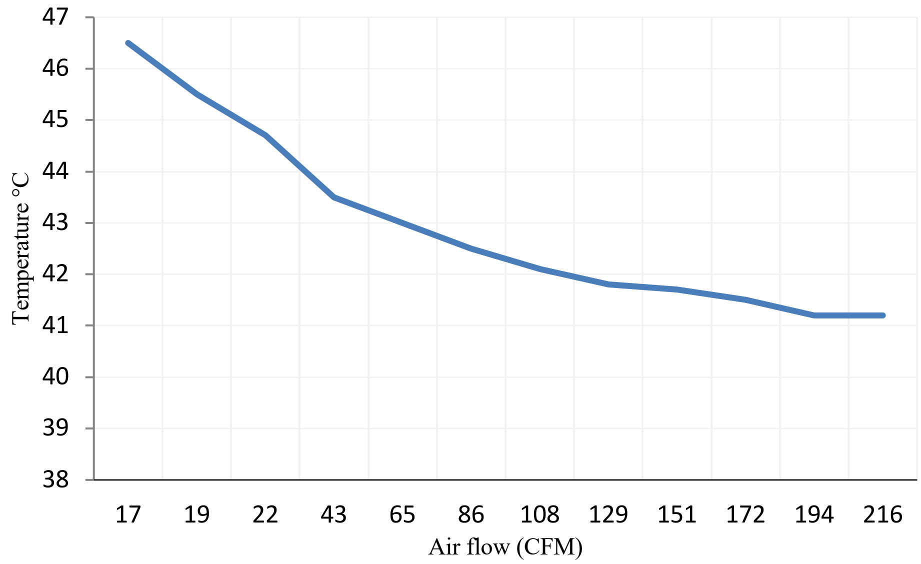

Figure 7: Variation of optimum temperature with minimum air flow

CONCLUSION

Integration of auxiliary heater and exhaust fan to solar dryer helps to achieve uniform drying conditions in the drying space. A cabinet type solar dryer having electric heater and fan is analyzed in the present paper. The average temperature of the air in the dryer void is computed from the energy balance. At first, the temperature is computed considering solar heat as the solitary energy input. The air temperature found to rise with solar radiation and ambient temperature. The further analysis is performed to have required temperature in dryer void with the combination of solar heat and auxiliary energy. It is observed that the total energy ingestion initially decrease, reaches to minimum and then rises. Thus there exists an optimum temperature where the auxiliary consumption is minimum and solar heat utilization is maximum. For the given conditions and dryer structure, the optimum temperature is found to be 44 °C. At this temperature, the power consumption by the blower is 2.52 kW-hr and by the heater is 5.39 kW-hr. The total auxiliary energy requirement at optimum temperature is 7.91 kW-hr. The approach proposed, takes into consideration the layout of the dryer as well as environmental conditions as input parameter. This makes it to use in any geographical location as well as for different dryer configurations.

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