Design and Analysis of a Solar Dryer for the Rural Areas of Bangladesh

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ABSTRACT
Natural solar drying is a practical method for removing moisture from agricultural products. However, various issues arise in such processes, such as bird, insect, or other animal attacks, fungal attacks, unexpected changes in weather, low or prolonged exposure to the sun, dust mixing, and so on. These problems can be resolved by utilizing a solar dryer. This research is based on the development of a thermally efficient indirect-mode forced convection solar dryer for Bangladesh's rural communities. Our preliminary focus in this article is to design a solar dryer for the rural areas of Bangladesh and evaluate its performance at selected locations through simulations. Through the simulation process, the airflow, temperature change, and loss across the drying chamber were observed. Usable mesh fineness value for simulation, usable process for simulation and validation was found. Observations regarding the change of airflow in the three-axis and outlet temperature change are included in the results. The process and requirements of designing a solar dryer were presented throughout this study.

Keywords: *Solar Energy, Air Heaters, Solar Dryer, Efficiency of solar air heaters, Forced convection heat flow, Air Collector.*

1. INTRODUCTION

The purpose of using an indirect forced convection solar dryer is to remove moisture contents from crops by forced circulation of heated air with absorber plate, using solar energy so that the moisture can be removed safely and the products can be stored for increased periods. Adelaja et al. (2013) developed a natural convection solar dryer and also analysed and tested the solar dryer for the tropics [1]. In its design, it is positioned in such a way the food cabinet doesn't cast a shadow on the collector that it minimizes the heat loss. Four thermometers were placed in strategic locations on the assembly to measure its ambient, collector case and cabinet temperature. After analysing and testing, collector and system efficiency of 46.4% and 78.73%, percentage of moisture content removal of 77.5%.was obtained.

Baniasadi et al. (2017) developed a mixed-mode solar dryer, which consists of thermal storage [2]. The effect of phase change material was analysed. The mixed-mode solar dryer consists of a solar collector, drying chamber and fan which is driven by a PV panel. The drying rate increased by 50% for thermal storage. Overall thermal efficiency and pick up efficiency increases by about 11% and 10% for using PCM energy storage. The blower is used in our project to increase the volumetric flow rate which increases efficiency. Babalola et al. (2019) used an electric blower for mixing and air supply to a tilting furnace [3]. The blower is powered by using photovoltaic cells. For continuing the drying process even after the sunset PCM (Phase Change Material) can be used. Srivastava et al. (2014) designed a flat plate collector in which the author used PCM material as Lauric acid for drying purposes of potatoes and carrots [4].

We aim to optimize the thermal efficiency of an indirect forced convection solar dryer for drying raw paddy for a specific location in Bangladesh and to design a blower system with a solar photovoltaic panel and battery storage for better efficiency. The design will consist of a solar air collector, absorber plate, blower, solar photovoltaic panel, drying chamber, chimneys, trays etc. 20 kg of raw paddy will be used for drying with a moisture content of 20%-25%, under 35-45˚C temperature with 45% efficiency. The ultimate goal of this research is to design a solar dryer for drying raw paddy for the rural areas of Bangladesh, that will be easy to fabricate.

2. MATERIALS AND METHODS

2.1. Theoretical Study

The efficiency of solar dryers can be increased by evaluating inlet air characteristics, air heater performance, and analysing the accuracy of final results. Here the simulation model is highly important. Three types of thin-layer drying model, namely theoretical, semi-theoretical and experimental, can be characterized [4]. Solar dryer shows a lack of performance due to local weather conditions, interrupted insulation, radiation intensity. Many types of thermal storage are suggested to regain this efficiency, including sensible heat storage, chemical energy storage, latent heat storage etc. As it was planned as a forced convection solar dryer, a blower can be used. PCM can be kept along with the chamber, which releases heat during phase transformation from liquid to solid.

2.2. Design Consideration

As for the simulation, a study was done on possible fabrication processes and materials of this solar dryer, considering both economic and agricultural perspectives. The aim is to choose the proper material for building the dryer, low heat loss and availability was considered. Properties of these materials are used to simulate the whole dryer. The material and coating of the solar absorber plate will be selected considering their high absorptivity, cost-effectiveness and environment-friendly behaviour [5]. Carbon Nanotubes (CNT), Copper, Black Chrome, Nickel Oxide etc are some of the materials that can be used to meet the requirements for the absorber plate [6].

The proposed solar dryer consists of a solar air collector, a solar drying cabinet and an outlet which is a chimney. For building the drying cabinet and solar air collector mahogany wood and its thermal properties were considered [7]. One side of the solar air collector is a blower and another side is joined with the drying chamber. A 12V 0.3 A blower is in the opening of the solar air collector, which has an airflow rate of 18.2 cfm and a propeller area of 8.5 cm.

As, for the maximum solar irradiation, optimum tilt angle is equal to the location’s latitude. In our case we considered Ahsanullah University of Science and Technology as our experiment location which has a latitude of about 23˚. So, we have taken 23˚ as our optimal tilt angle. Figure 1 visualizes the design and important components of a forced convection solar dryer.

The solar absorber plate is situated in the solar air collector and on top of that solar air collector, transparent glass is set which will use greenhouse effect to heat the air and also trap the heat generated from the solar absorber plate.

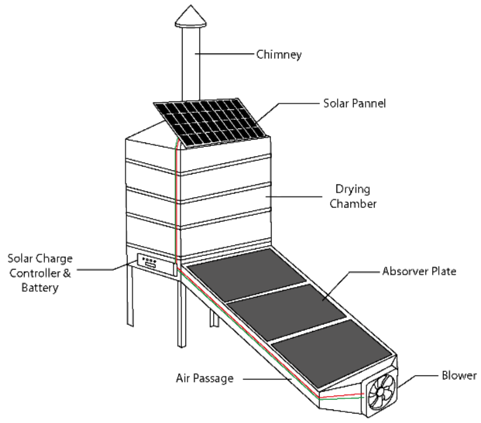

Figure 1 Indirect-mode forced convection solar dryer.

Inside the drying cabinet metal trays and nets are used. Lastly, the chimney which is connected on top of the drying chamber is made of PVC pipe. Five 6V 1W Mini Solar panels will power the blower. A 11.1V 1100mAh 3S 30C li-po battery for storage and 12V solar charge controller were used. For data acquisition, Arduino Uno R3 will be used. Temperature and humidity inside the solar cabinet will be measured by using the DHT22 Sensor.

2.3. Validation of Computational Results

For validation INSEL Simulation Works is used. It is mainly designed for complex energy project and its block diagram simulation system helps to do the simulation of the energy sector. A journal paper was used to validate accuracy of experimental values [8]. The temperature and efficiency of a solar air collector are defined. Inlet temperature, Ambient temperature, Solar irradiation, Volumetric flowrate, air flow rate are the basic input parameters of a solar air collector for doing simulation in INSEL and was converted in a graphic representational shape. This validation is documented evidence of the consistency of the solar dryer system process parameters.

2.4. Design Analysis

Design included these parameters listed in table 1. These parameters plays the vital role of designing a forced convection solar dryer [9].

2.4.1. Drying Temperature

The recommended temperature for drying raw paddy is 40˚C to 60˚C. Closer to 60˚C affects rice quality, but if kept for one hour, it decreases germination rate by 93% to 30% [10]. But less than 45˚C doesn't affect the eating or cooking quality of rice. So, the considered temperature was taken 45˚C.

2.4.2. Amount of Moisture Content to be Removed

The recommended moisture contents required for safe storage for different storage periods is 13% or less for 8 to 12 months storage [10].

Table 1. Design parameter of the Solar Dryer

Condition	Value
Solar irradiance	2.695 kWh/m^2 per day
Inlet temperature	45 ˚C
Ambient temperature	25.7 ˚C
Volumetric air flow rate	0.0382 m^3/s
Air velocity near the collector	1.60 m/s
Number of collectors	1
Collector tit angle	23˚
Collector length	0.56 m
Collector width	0.6 m
Channel width	0.026 m
Plate thickness	0.0006 m
Optical efficiency	81.2%
Thickness of insulation materials	0.06 m
Heat conductivity of insulation	0.084

$$m_f = m_i \times \frac{100-MC_i}{100-MC_f} \quad (1)$$
$$= 20 \times \frac{100-1}{100-0.13}$$
$$= 19.83\ kg$$

Where,

$m_i = Initial\ Weight = 20\ kg$

$m_f = Final\ Weight = 19.83\ kg$

$MC_i = Initial\ Moisture\ Content = 1$

$MC_f = Final\ Moisture\ Content = 0.13$

2.4.3. Required Heat

To remove the required moisture, the first stage is to raise the raw paddy's temperature to the desired level. The equation to do that is given by,

$$Q_1 = W_w \times C_p \times \Delta T \quad (2)$$
$$= 20 \times 1.98 \times (45 - 25)$$
$$= 594\ kJ$$

Where,

$C_p =$ The specific heat capacity (kJ/kg˚C)

$\Delta T =$ Temperature change (˚C)

The specific heat capacity of raw paddy is 1.98 (kJ/kg˚C). The drying temperature T_d is 45◦C and the ambient temperature T_a is considered 25◦C. h_g is the enthalpy of water as vapor, which is 2583 kJ/kg and h_f is the enthalpy of water as a liquid, which is188kJ/kg. So, using Equation (2), we get,

$$Q_1 = 0.17 \times (2583 - 188) = 407.15\ kJ$$

Hence, total required heat,

$$Q_1 + Q_2 = 594 \times 407.15 = 1001.15\ kJ$$

2.4.4. Collector Sizing

Our location's daily average insolation (Tejgaon, Dhaka, Bangladesh) is 4.48 MJ/m^2/day. The efficiency is considered to be 40%. So, for three days, expected energy produced by the collector,

$$= 4.48\ MJ/m^2/day \times 0.4 \times 3 \quad (3)$$
$$= 5.37\ MJ/m^2$$

Since, the requirement of heat energy for drying is 7.587 MJ, hence, the collector area will be,

$$Collector\ Area = \frac{1.792MJ}{5.37\ MJ/m^2} \quad (4)$$
$$= 0.334\ m^2$$

2.4.5. Optimum Tilt Angle

The location we considered for testing is Tejgaon, Dhaka, Bangladesh. The information related to our area was taken from The Global Solar Atlas website [11]. The latitude and the longitude of our site are 23.77˚ N and 90.38˚ E. The optimum tilt angle for this location is 23˚.

2.4.6. Required Air Flow

Recommended the range for the velocity of air to between 0.51 m/s to 5.08 m/s. The air channel's depth is also recommended to be 1/15 to 1/20 of the collector's length. Recommended the average factor of the air channel depth to be 0.05. So,

Depth of Air Channel = 0.05×1.5 m = 0.075m (5)

Recommended the optimum air gap between the transparent cover and the absorber to be 0.4m to 0.8m. The calculated depth of the air channel falls between this range. Now,

$$Vent\ Area = Collector\ Width \times Air\ Gap \quad (6)$$
$$= 1 \times 0.075$$
$$= 0.075\ m^2$$

Considering the velocity of air to be 0.51 m/s, volumetric flow rate,

$$V_f = Vent\ Area \times Air\ Velocity \quad (7)$$
$$= 0.075 \times 0.51$$
$$= 0.0382\ m^3/s$$

By multiplying the volumetric flow rate with the air density, which is 1.2 kg/m^3, we get mass flow rate.

$$Mass\ Flow\ Rate = 0.0382 \times 1.2 = 0.0458\ kg/s$$

Our mass flow rate value, which is 0.0458 kg/s lies between the recommend range of 0.02 to 0.9 kg/s [10].

2.4.7. Energy Analysis

Energy balance analysis was done following the conservation of mass and energy. To dry the paddy, heat and electricity, both from solar energy is used. General equation of mass conversion of drying process [12], for air,

$$\sum m_{air.in} = \sum m_{air.out} \tag{8}$$

for moisture,

$$\sum m_{air.in} \times W_{in} + m_{moisture} = \sum m_{air.out} \times W_{out} \tag{9}$$

General equation can be formed from equation (8) and (9) assuming steady air flow,

$$\sum m_{air.out}\left(h_{out} + \frac{V^2{}_{out}}{2}\right) - \sum m_{air.in}\left(h_{in} + \frac{V^2{}_{in}}{2}\right) = m_{air.out}\,(h_{out} - h_{in}) \tag{10}$$

Where, h= enthalpy (from psychrometric chart). The useful heat gained by the collector,

$$Q_u = m_{air} \times C_{p.air} \times (T_{out.air} - T_{in.in}) \tag{11}$$

The specific energy consumption (SEC) of the system from equation (11),

$$SEC = \left(\frac{Q_u + E_{blower}}{m_w}\right) \tag{12}$$

The drying efficiency of the system,

$$\eta = \left(\frac{m_w + h_{evap}}{I \times Vent\ Area \times E}\right) \tag{13}$$

Where, I=Solar radiation intensity. And the theoretical thermal efficiency,

$$\eta_{th} = \left(\frac{T_{dryer} - T_{dryer.out}}{T_{dryer} - T_{ambient}}\right) \tag{14}$$

3. RESULTS AND DISCUSSION

3.1. Drying Chamber Design

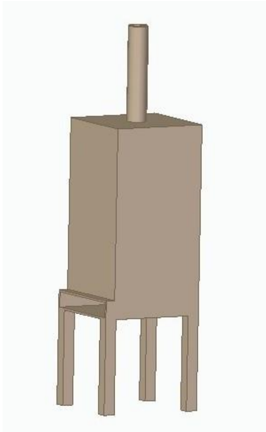

Figure 2 Simulation model of drying chamber.

The drying chamber will be used to keep trays filled with products inside it. The heated airflow will enter through the inlet vent and flow through the trays to eliminate moisture from the wet paddy. And will exit through the chimney. The chamber is made with Mehgony wood which is a highly available wood in Bangladesh, mostly in rural areas [7].

Thermal conductivity is also low comparing with others. The drying chamber is designed and simulated using Solid Edge 2021, with the safety factor as 3. The total mass of the design was 21.6 kg. The thickness of the chamber wall was 6 cm. The chamber will have a 2 cm entrance path which will have a height of 3 cm. Maximum deformation was found 0.00927 mm.

To determine the change of temperature and airflow, a simulation was used. Figure 2 includes a 3D model of the designed drying chamber for simulation. Figure 3 includes the fluid flow region of the designed solar dryer (Figure 2). It provides intersected overall result, simulated in SimScale, of the change of temperature and airflow through the main chamber area. The chamber will be 0.5 m long, 0.5 m wide and will have a height of 1 m.

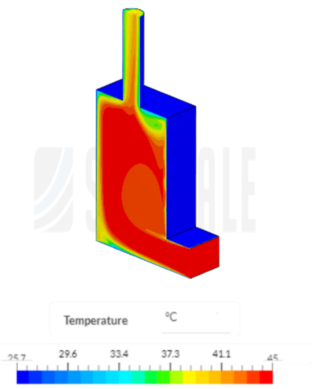

Figure 3 Temperature variation inside drying chamber.

3.2. Mesh Sensitivity Analysis

According to the mesh log and mesh quality statistics, the generated mesh of the fluid region has a very low impact on the results. But a few criteria were optimized to improve the mesh quality from the quality metrics. As referred by SimScale, the maximum value of Edge Ratio, volume Ratio and Aspect Ratio was kept under 50. Non-orthogonality is a measure of the angle between two faces of the same cell. The maximum value of non-orthogonality was kept below 75 for ideal mesh quality.

As a simple design, the options to modify the design was limited. For different mesh finesses in SimScale, graphical change of temperature for outlet was studied for 1000 seconds of airflow. In which Mesh Fineness value 7 was found having less time to reach highest temperature and have a low rate of fluctuation after a certain time. So, we have taken mesh fineness as 7 within the fine meshing range. This will contain 716.3 thousand cells and 328 thousand nodes. For structural simulation, the mesh quality improvement study cannot be practically implied as it found that making fillet and chamfer inside the chamber will improve stability, but as the chamber is made of wood, thus it is not practically applicable for fabrication of a solar dryer.

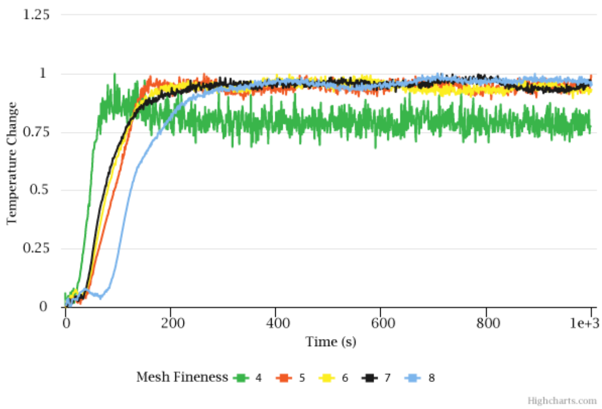

Figure 4 Variation of temperature with the change of Mesh.

3.3. Drying Chamber Heat Convection

With the heated flow received from the air passage, the products keep drying. The heated air was kept at 45˚C. The heat releases inside the main compartment and removes moisture from the paddy. Using SimScale, a virtual model of the whole system was built. Where the system was observed as a whole body of air. Inlet velocity with the heated air temperature was given while outlet velocity was zero and was having ambient temperature.

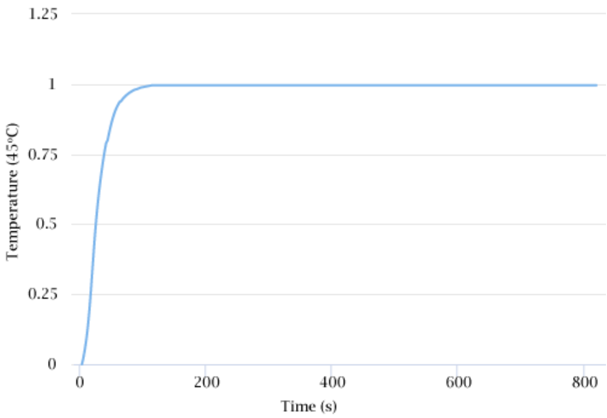

Figure 5 Variation of outlet temperature of the Drying Chamber.

The change of temperature from 45˚C along three axis was presented on Figure 5. In the simulation study, heat dissipated faster within the initial ten seconds.

3.4. Velocity Change

Change of velocity with the change of time is the key factor to dry the products faster. The paddy will need a good amount of air flow to remove the required amount of moisture content within a certain time. Excessive air flow will damage the quality of dried paddy. According to the final design, the estimation of air flow calculated 0.039 m/s. In the simulation study, a velocity of 0.04 m/s was used which showed sufficient combination to imply in the practical fabrication. The change of velocity from 0.04 m/s along three axis was presented on Figure 6.

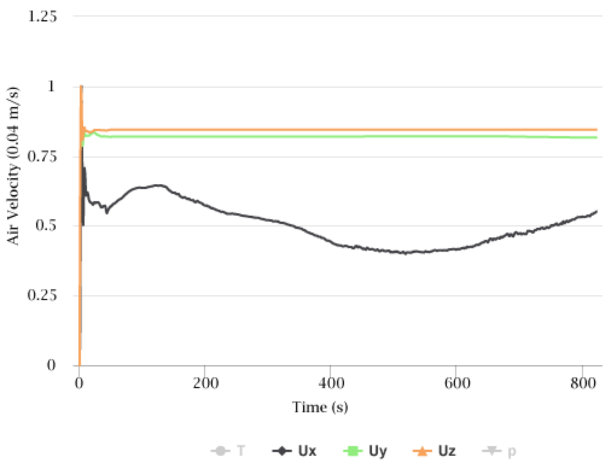

Figure 6 Variation of airflow in different axis inside Drying Chamber.

3.5. Result Validation

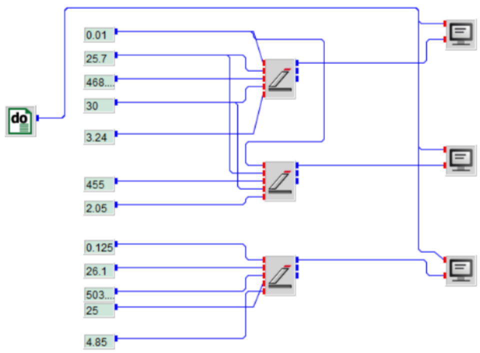

Figure 7 Insel block design of Drying Chamber.

In Figure 7, an INSEL block diagram represents the simulation block diagram of Solar air collector for different locations. From fig, this screen output displayed the outlet temperature in ˚C that will be entered in the drying chamber. Apart from the collector block diagram this 'Do block' diagram helps to measure the outlet temperature on a monthly basis. Also, this do value can be modified according to the basis of need.

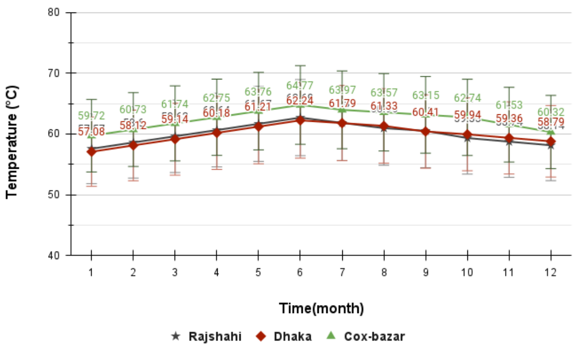

Figure 8 Resultant temperature variation for different area in Bangladesh.

Figure 8 is a graphical representation of the comparison between the data obtained from different locations. This comparison was done to validate the results of the outlet air temperature from the solar air collector as a function for different values of the air mass flow rate, solar irradiance, wind speed, air temperature for different locations like Rajshahi, Dhaka and Coxs-Bazar. Insel 8.2 simulator was used to do the simulation of the Solar Air Collector. The output temperature of the solar air collector varies. Some necessary data were collected from Global Solar Atlas & Global Wind Atlas data sheets. Using the output air temperatures of different locations from the solar air collector a graphical representation was displayed.

4. CONCLUSION

This work aimed to simulate and validate the design and optimize the efficiency of an indirect solar dryer. Initially, the validation of the simulation was done by cross-checking different papers. The simulation of the final design was done following various conditions. The significance of this research is, even though the area was selected to be Tejgaon, Dhaka, Bangladesh; any site on the earth can be used as the experiment location to find the optimum conditions for drying a specific number of products. It is possible because of the vast weather database included in the INSEL database. The ratio of sizing the collector was studied and the distribution of heat and the projection of air velocity inside the drying chamber was analysed using the SimScale. It showed the distribution inside the chamber box including the inlet and outlet. However, heat loss was neglected.

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