

# DESIGN, FABRICATION AND PERFORMANCE EVALUATION OF AN INDIRECT SOLAR DRYER FOR DRYING AGRICULTURAL PRODUCTS

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**Abstract-** In a developing country like India, having the second largest population and agriculture as the source of income to nearly 60 % of the total population, post - harvest and storage loss of agricultural commodities is a major quandary, which needs to be addressed in due diligence. Many food preservation techniques like cold storage, drying, etc. have been evolved out over the years to tackle the above losses. The major constraint is that almost all the technologies are utilizing fossil fuel resources, which are depleting very fast and wise use of these precious resources are preferred for long-term energy sustainability. Therefore, sustainable methods for food preservation are the need of the hour. Solar drying is one of the best choices in this context. This paper presents the design, fabrication and performance evaluation of an indirect forced convection solar dryer consisting of a solar air collector, drying cabinet and a centrifugal blower. The dryer has been designed indigenously using locally available materials for construction and it is cost effective. In the dryer, the heated air from a separate solar collector is allowed to pass through the products placed inside the drying chamber. The solar energy which is get absorbed inside the collector is allowed to pass through some well created baffles. The baffles are placed inside the collector so that flow of hot air inside the collector become non linear, thus, taking more time to pass from the collector to the drying chamber and the air get heated. A centrifugal blower has also been employed in order to speed up the rate of drying process. The dryer can be used effectively for drying agricultural products and as a model green apple slices were used to evaluate the performance.

**Key words:** Indirect solar dryer, forced convection, drying, agricultural products, green apple

## 1. INTRODUCTION

Drying is one of the methods used to preserve food products for longer periods. The heat from the sun coupled with the wind has been used to dry food for preservation for several years. 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. Drying of agricultural products like fruits and vegetables using

renewable energy such as solar energy is environmental friendly and has less environmental impact.

Solar thermal technology is a technology that is rapidly gaining acceptance as an energy saving measure in agriculture application. It is preferred to other alternative sources of energy such as wind and shale, because it is abundant, inexhaustible, and non-polluting. Different types of solar dryers have been designed, developed and tested in the different regions of the tropics and subtropics [1, 2]. The two major categories of the dryers are natural convection solar dryers and forced convection solar dryers [3]. 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. Solar air dryers are simple devices to heat air by utilizing solar energy and it is employed in many applications requiring low to moderate temperature below 80°C, such as crop drying and space heating. Drying of agricultural products under direct sunlight also has several disadvantages like poor quality and contamination [3]. In comparison to natural sun drying, solar dryers generate higher temperatures, lower relative humidity, lower product moisture content and reduced spoilage during the drying process. In addition, it takes up less space, takes less time and relatively inexpensive compared to artificial mechanical drying method. Thus, solar drying is a better alternative solution to all the drawbacks of natural drying and artificial mechanical drying.

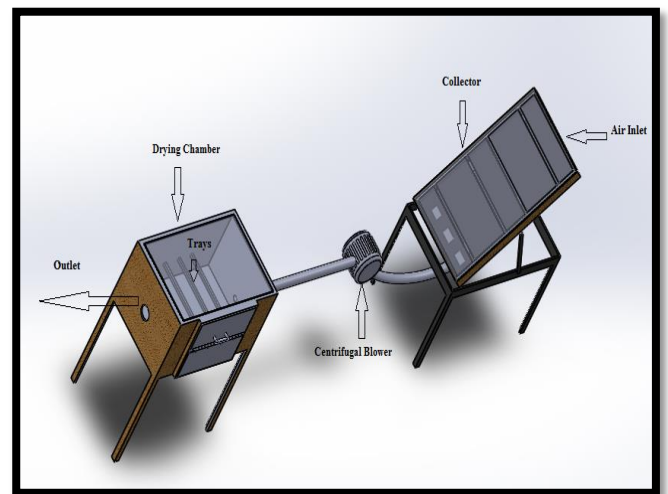
Solar dryers are a very useful device for agricultural crop drying, food processing industries for dehydration of fruits and vegetables, fish and meat drying, dairy industries for production of milk powder, seasoning of wood and timber, textile industries for drying of textile materials, etc. Thus, solar dryer is one of the many ways of making use of solar energy efficiently in meeting man's demand for energy and food supply, total system cost is a most important consideration in designing a solar dryer for agricultural uses. No matter how well a solar system operates, it will not gain widespread use unless it presents an economically feasible alternative to other available energy sources

The application of solar dryers in developing countries can reduce post-harvest losses and significantly contribute to the availability of food in these countries. Estimated post-harvest losses are generally cited to be of the order of 40% but they can, under very adverse conditions, be nearly as high as 80%. A significant percentage of these losses are related to improper and/or untimely drying of foodstuffs such as cereal grains, pulses, tubers, meat, fish, etc. [4, 5]. Use of indirect type natural convection solar dryer for drying grapes, figs, onions, apples, tomatoes and green peas has been reported [3].

Solar drying is a potential decentralized thermal application of solar energy particularly in developing countries [6]. However, so far, there has been very little field penetration of solar drying technology. In the initial phase of dissemination, identification of suitable areas for using solar dryers would be extremely helpful towards their market penetration. Thus, the solar dryer is one of the many ways of making use of solar energy efficiently in meeting man's demand for energy and food supply. No matter how well a solar system operates, it will not gain widespread use unless it presents an economically feasible alternative to other available energy sources.

## 2. DESIGN APPROACH AND METHODOLOGY

In this project we have designed, fabricated and evaluated the performance of an indirect type solar dryer also called forced convection (active) type for drying agricultural products. The working model of indirect type solar dryer is based upon the concept of solar radiation absorption. The solar energy (sun energy) is trapped inside by using solar collector. The collector was made of wood and the absorber plate was painted with black colour so that it absorbs the maximum amount of sun radiation falling on it. A special care was taken by aligning it in an acute angle (30-40 degrees) so that the collector receives maximum amount of radiation. The solar energy, which gets absorbed inside the collector was allowed to pass through four well created baffles. The baffles were placed inside the collector so that flow of hot air inside the collector is not linear and when it is not linear, it will take more time to travel and thereby it will raise the temperature of the air trapped inside. This high temperature air gets exhausted from the collector through the passage provided at the exit of the collector. The temperature at the entry and exit of solar collector was measured using digital thermometer. The hot air was then sucked by using a centrifugal air blower so that this hot air gets forced inside the drying chamber. The products (green apple slices) were placed on the drying trays in the horizontal manner. The hot air was forced from the solar collector onto the drying chamber with the help of a centrifugal blower and the heated air inside the drying chamber moves out through the exhaust vent. The orthogonal view of the indirect solar dryer is shown in Fig- 1.



**Fig- 1:** Orthogonal view of the Indirect Solar Dryer (dimensions in cm)

### 2.1 Appliances used

The appliances used in solar dryer consist of solar collector (air heater), cover plate, absorber plate, drying cabinet and air blower, which are mentioned below along with the specifications:

**Solar Collector:** The inner box of the solar air collector was constructed using 1 mm thick galvanized plate and the surface facing sunlight was painted with black paint. The solar collector was insulated with wood of about 3cm thickness and thermal conductivity of 0.04 Wm<sup>-1</sup> K<sup>-1</sup> on all sides. The solar collector assembly consists of air flow channel enclosed by transparent cover (fibre glass). The fibre glass is a single layer of 4 mm thick transparent glass sheet. It has a surface area of 0.82 by 1.20 m, thermal conductivity 0.024 Wm<sup>-1</sup> K<sup>-1</sup> and of transmittance above 0.85.

**Cover plate:** This is a transparent sheet used to cover the absorber, thereby preventing dust and rain from coming in contact with the absorber. The material used in the cover plate is fibre glass of having length of 170 cm, breadth 100 cm and thickness 4 mm.

**Absorber plate:** This is a metal sheet painted black and placed below the cover to absorb, the incident solar radiation transmitted by cover thereby heating the air between it and the cover. Here GI sheet is chosen because its quick response in absorption of solar radiation and also aluminium sheet is placed

below the GI sheet because of its good ability to keep the absorbed solar radiation.

**Insulation:** This is used to minimize heat loss from the system. Insulations were provided on the surface of the pipes connecting the collector with the dryer. The insulating material used is foam rubber. Construction of the solar collector is shown in Fig.2



**Fig-2:** Construction of solar collector

**Drying Cabinet:** The drying cabinet together with the structural frame of the dryer was built from well-seasoned woods, which could withstand termite and atmospheric attacks. An outlet vent was provided toward the upper end at the back of the cabinet to facilitate and control the convection flow of air through the dryer (Fig-3). Access door to the drying chamber was also provided at the side of the cabinet. Chamber dimensions are: Length=146 cm, Breadth=100 cm, Height=60 cm, Thickness=0.45 cm.



**Fig-3:** Construction of Drying Cabinet

**Air Blower:** The air blower that is used is the centrifugal air blower that has a Horse Power of 0.28; Power of 210 Watts; Speed is 2800 rpm(Fig-4).



**Fig-4:** Air Blower

**Electronic devices:** The electronic devices that were employed for calculating the readings include Hygrometer ( Range: -20°C to 50°C, dimension (l× b ×h): 30cm×9cm×2.5cm), Digital LCD Thermometer ( Range: -50°C to 250°C and accuracy: +1° C, Operating Voltage: 2 × 1.5V ), Digital Thermometer Temperature Test Pen (Temperature range: -50°C to 300°C ).

## 2.2 Experimental setup

The solar dryer was placed on the ground level of a building based on the design. A centrifugal pump was employed in order to speed up the rate of drying process and baffles were employed as a new introduction. The baffles were placed inside the collector so that flow of hot air inside the collector becomes non-linear, thus it will take more time to travel and thereby it will raise the temperature of the air trapped inside. The experimental setup of the solar dryer is shown in Fig-5.



**Fig-5:** The experimental Setup of the Solar Dryer

### 2.3 Thermal Analysis

In the design, a flat plate collector with an area of 1.7 x 1 m<sup>2</sup> is considered. The performance of the collector is described by an energy balance that indicates the conversion of solar radiation into useful energy gain and losses. The thermal analysis was done to calculate the heat gain and the losses for flow of air between glass cover and absorber plate. Several formulations were employed and calculations were done to find out the overall efficiency of the dryer and the collector. The concept of heat transfer has been used throughout the whole project.

The transmittance  $\tau(\theta)$  of a glass cover for solar radiation depends on the angle of incidence  $\theta$ . Typical values for clear glass are given in Table 1.

**Table-1:** Transmittance of a glass cover

Transmittance of a Glass Cover					
$\theta$ :	0°	60°	70°	80°	90°
$\tau(\theta)$ :	0.9	0.8	0.65	0.35	0

The absorptance  $\alpha(\theta)$  of the black plate for solar radiation also depends on the angle of incidence  $\theta$ . Table 2 shows typical values for  $\alpha(\theta)$  and the product  $\tau(\theta).\alpha(\theta)$ .

**Table- 2 :** Absorptance of black plate

Absorptance of a Black Plate.					
$\theta$ :	0°	60°	70°	80°	90°
$\alpha(\theta)$ :	0.92	0.85	0.75	0.60	0
$\tau(\theta).\alpha(\theta)$ :	0.83	0.68	0.49	0.21	0

The solar irradiance  $I_{in}$  incident on the cover glass is given by

$$I_{in} = I_b \cos \theta + I_d \dots\dots\dots(1)$$

Where  $I_b$  is the beam solar irradiance,  $\theta$  is the angle of incidence, and  $I_d$  is the diffuse irradiance.

If there is one glass cover the solar irradiance on the black plate is

$$\tau(\theta).I_b \cos \theta + \tau_m I_d \dots\dots\dots(2)$$

Where  $\tau_m$  is the mean value of  $\tau(\theta)$ . The solar radiation flux  $q_{abs}$  absorbed by the black plate is given by

$$q_{abs} = \tau(\theta).\alpha(\theta)I_b \cos \theta + (\tau.\alpha)_m I_d \dots\dots\dots(3)$$

Where  $(\tau.\alpha)_m$  is the mean value of  $\tau(\theta).\alpha(\theta)$ . The mean value of  $\tau(\theta).\alpha(\theta)$  can be found by means of integrals over the hemispherical sky as follows:

$$(\tau.\alpha)_m = \left[ \int_0^{\pi/2} \tau(\theta).\alpha(\theta).\sin \theta.\cos \theta.d(\theta) \right] / \left[ \int_0^{\pi/2} \sin \theta.\cos \theta.d(\theta) \right]$$

**For one glass cover the result is approximately  $(\tau.\alpha)_m = 0.70$ .**

#### Heat Losses

The glass cover behaves nearly as a black body for long-wave radiation. We can assume that the emittance  $\epsilon_c$  of the glass cover is 0.95.

The emittance  $\epsilon_b$  of the black plate for long-wave radiation depends on whether the surface is non-selective or selective. Typically we have

$$\begin{aligned} \epsilon_b &= 0.92 \text{ for a non-selective surface,} \\ \epsilon_b &= 0.10 \text{ for a selective surface.} \end{aligned}$$

We shall consider a collector with one glass cover. Let

$$\begin{aligned} T_a &= \text{ambient temperature,} \\ T_b &= \text{black plate temperature,} \\ T_c &= \text{glass cover temperature,} \end{aligned}$$

where absolute temperatures must be used for radiation calculations.

Heat is lost by conduction through the back insulation. It can be reduced to a low rate by inexpensive insulation materials. Typically the back loss might be given by the formula

$$h_{ba} (T_b - T_a) \dots\dots\dots(4)$$

where the heat transfer coefficient is  $h_{ba} = 0.3W/m^2K$ .

Heat is lost from the black plate to the glass cover by convection and radiation. Experience has shown that, for free convection the Nusselt number  $Nu$  in air spaces between parallel plates with Grashoff numbers ( $Gr$ ) in the range  $10^4$  to  $10^7$ , we have

$$N_u = 0.152 Gr^{0.281} \text{ for horizontal plates,}$$

$$N_u = 0.093 Gr^{0.310} \text{ for plates tilted at an angle } 45^\circ.$$

Here

$$G_r = g \cdot \beta (T_b - T_c) L^3 / \nu^2, \dots\dots\dots(5)$$

where we assume as a typical example for air:

$g =$  acceleration of gravity  $= 9.8m/s^2$ ,  
 $\beta =$  coefficient of thermal expansion  $= 1/T$ ,  $T = 69^\circ C = 342K$ ,

$$\beta = 0.002923$$

$$T_b - T_c = 89^\circ C - 40^\circ C = 49K,$$

$$L = \text{spacing} = 50mm = 0.075m,$$

$$\nu = \text{kinematic viscosity} = 0.194 \times 10^{-4} m^2/s.$$

$$G_r = \frac{9.8 \cdot 2.92210^{-3} \cdot 49 \cdot 0.075^3}{(0.194 \cdot 10^5)^2}$$

This gives  $G_r = 15.7 \times 10^5$ , which is within the range  $10^4$  to  $10^7$  mentioned above.

Assume a tilt angle  $45^\circ$ . Then we estimate, by interpolation,

$$N_u = 0.132$$

$$G_r^{0.291} = 8.386$$

Also since

$$N_u = hL/k,$$

$$h = 8.386 \cdot 0.02750 / 0.075$$

$$h = 3.07W/m^2K$$

where

$h =$  heat transfer coefficient,  
 $L = 0.075m$ ,  
 $k =$  thermal conductivity of air  $= 0.02750W/mK$ ,

we have  $h = 3.07W/m^2K$

$$\tau_g = 0.875$$

$$\alpha(\theta) = 0.95$$

$$I_T = (800 - 1100) W / m^2$$

mass of air  $= 0.0214kg/sec$

$$\epsilon_g = 0.94; \epsilon_r = 0.94$$

The Overall Heat transfer coefficient ( $U$ )

$$\frac{1}{U} = \frac{1}{h \cdot A} + \frac{K \cdot A}{L} + \frac{1}{h \cdot A} \dots\dots\dots(6)$$

$$A = 1.75 m^2$$

$$h = 3.07 W / m^2$$

$$K = 0.0275 W / mK$$

$$U = 2.5 W / m^2K$$

The energy balance on the absorber is obtained by equating the total heat gained to the total heat loosed by the heat absorber of the solar collector. Therefore,

$$I A_c = Q_u + Q_{cond} + Q_{conv} + Q_R + Q_p \dots\dots\dots(7)$$

If  $\tau$  is the transmittance of the top glazing and  $I_T$  is the total solar radiation incident on the top surface, where total solar radiation value is (800 - 1100) W/m<sup>2</sup>. Therefore,

$$IA_c = \tau I_T A_c \dots\dots\dots(8)$$

$$= 0.8 \times 800 \times 1.75$$

$$= 1120 \text{ W}$$

$$Q_L = U_L A_c (T_c - T_a) \dots\dots\dots(9)$$

$$= 2.5 \times 1.75 \times (57.9 - 32.8)$$

$$= 109.81 \text{ W}$$

where:  $= U_L$  overall heat transfer coefficient of the absorber (Wm<sup>-2</sup>K<sup>-1</sup>);

For an absorber  $(1 - \rho) = \alpha$  and hence,

$$Q_u = (\alpha \tau) I_T A_c - Q_L \dots\dots\dots(10)$$

$$= 0.8 \times 0.95 \times 800 \times (1.75 - 109.81)$$

$$= 954.19 \text{ W}$$

The collector heat removal factor,  $F_R$  is the quantity that relates the actual useful energy gained of a collector. Therefore,

$$F_R = \frac{\dot{m}_a C_{pa} (T_c - T_a)}{A_c [\alpha \tau I_T - U_L (T_c - T_a)]} \dots\dots\dots(11)$$

$$= (0.0214 \times 1005 (57.9 - 32.8)) /$$

$$(1.75 [0.8 \times 0.95 \times 800 - 2.5 (57.9 - 32.8)])$$

$$= 0.5464$$

If  $Q_g$  the heated air leaving the collector is at collector temperature, the heat gained by the air is:

$$Q_g = A_c F_R [(\alpha \tau) I_T - U_L A_c (T_c - T_a)] \dots\dots\dots(12)$$

$$= 1.75 \times 0.5464 \times [0.8 \times 0.95 \times 800 - 2.5 \times 1.75 (57.9 - 32.8)]$$

$$= 494.72 \text{ W}$$

The thermal efficiency of the collector is given by:

$$n_c = \frac{Q_g}{A_c I_T} \dots\dots\dots(13)$$

$$= 494.72 / (1.75 \times 800)$$

$$= 0.3533$$

$$\approx 35.33 \%$$

The thermal efficiency of the dryer is given by:

$$n_d = \frac{ML}{I_c A t} \dots\dots\dots(14)$$

$$= (0.1642 \times 25.5 \times 10^6) /$$

$$(800 \times 1.75 \times 6 \times 3600)$$

$$= 0.1384$$

$$\approx 13.8 \%$$

### 2.4 Experimental Procedure

The experiments were conducted in the months of March and April, from daily 9 am to 4:30 pm. The readings of the temperatures at the entry, middle and exit of the glass cover, absorber plate and bottom insulation were calculated using various electronic instruments as mentioned above. The temperature of the air in the drying chamber and the atmosphere were measured using hygrometer. Good quality green apples were washed and cut into small slices (5mm). The sample was measured using a digital weighing pan and 800 grams of the slices divided equally in two parts were used for drying. One part of the sample was placed inside the drying chamber and the other part was placed under direct sunlight. Temperature and humidity readings were taken at equal intervals from 9 am to 4 pm. Chemical analysis of the solar dried and sun dried samples was carried out in order to find out its quality. Chemical analysis was carried out using standard methods [7] to find out the organic matter (OM), crude protein (CP), ether extract (EE), ash content and dry matter (DM) of samples.

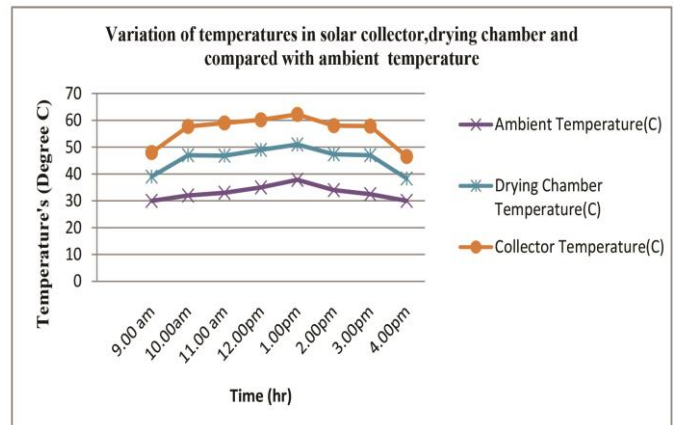
### 3. RESULTS AND DISCUSSIONS

The results of the hourly variations of the temperatures in the drying chamber and solar collector compared to the ambient temperature are shown in Table- 3 and Chart-1. The temperature inside the drying chamber and the solar collector was much higher than the ambient temperature during most hours of the daylight. The temperature inside the drying chamber was found to be the highest (51°C) at 1 pm. The relative humidity percentage of the drying chamber and the ambient

air humidity was observed and the results are given in the Table -4 and Chart- 2. The relative humidity percentage in drying chamber was almost equal to the ambient humidity percentage at 9 am, but the humidity percentage declines sharply up to 3pm in the drying chamber compared to the ambient humidity. The lowest humidity inside the drying chamber was also recorded at 1 pm. The higher temperature and lower humidity favours better drying without much change in colour (Figs-6,7,8). Other workers have also reported that agricultural products specially fruit and vegetables require higher temperature for safe drying and drying under controlled condition at specific humidity gives superior quality products [8]. Use of forced convection solar dryer for drying fruits and vegetables has been reported by several workers and it is considered as more efficient than natural convection dryers [9,10]. In the present study the thermal efficiency of the collector and the dryer was found to be 35.33 % and 13.8 % respectively.

**Table -3:** A typical day results of the diurnal variation of temperatures in the solar dryer

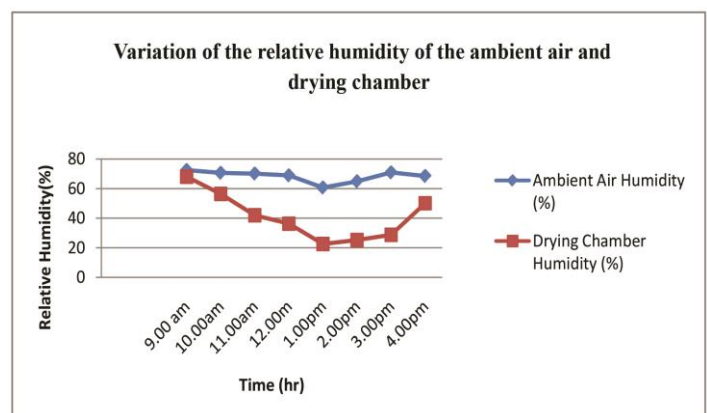
Time (hr)	Ambient Temp.(C)	Drying Chamber Temp.(C)	Collector Temperature(C)
9.00 am	30	39	48
10.00am	32	47	57.7
11.00 am	33	46.8	59
12.00pm	35	49	60.2
1.00pm	37.85	51	62.2
2.00pm	34	47.32	58
3.00pm	32.5	47	57.85
4.00pm	30	38.3	46.5



**Chart-1:** Variation of temperatures in solar collector, drying chamber and ambient temperature

**Table - 4:** A typical day results of the diurnal variation of relative humidity in the dryer

Time (hr)	Ambient Temp .(C) DBT	Ambient Temp .(C) WBT	Ambient Air Humidity (%)	Drying Chamber Temp. (C) DBT	Drying Chamber Temp .(C) WBT	Drying Chamber Humidity (%)
9 am	30	26	72.7	39	34	71
10am	32	28	73.6	47	38	56.4
11am	33	29	74.1	46.8	34	42
12am	35	31	74.9	49	34	36.3
1 pm	37.8	30	57.7	51	30.5	22.6
2 pm	34	28.3	64.9	47.32	29	25.3
3 pm	32.5	28	70.9	47	30	28.8
4 pm	30	25	66.5	38.3	31	59.1

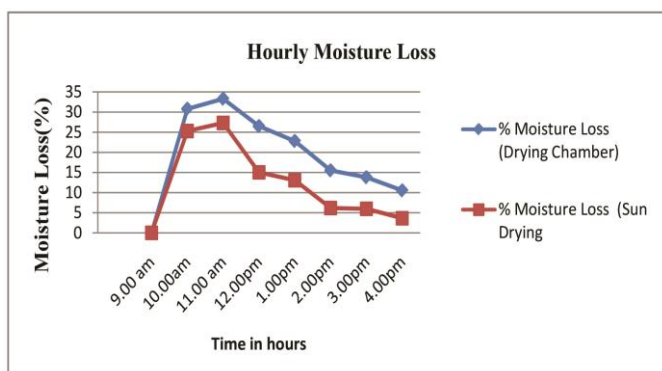


**Chart- 2 :** Variation of the relative humidity of the ambient air and drying chamber

The results of hourly moisture loss and mass of the green apple slices in the drying chamber and under sun drying are shown in the Table- 5 and Chart-3. The percentage of moisture loss of the sample in the drying chamber was found to be higher as compared to the sun drying in all the hours from 10 am to 4 pm. The mass of water removed in the drying chamber was also found to be higher (164.2 g) as compared to the sun drying (155.4 g).

**Table -5 :** Hourly moisture loss and mass of the green apple sample

Time (hr)	Mass of green apple (g) (Drying Chamber)	Moisture Loss (g) (Drying Chamber)	% Moisture Loss (Drying Chamber)	Mass of green apple (g) (Sun Drying)	Moisture Loss (g) (Sun Drying)	% Moisture Loss (Sun Drying)
9.00 am	200	0	0	200	0	0
10.00am	138.3	61.7	30.8	149.2	50.78	25.3
11.00am	92.2	46	33.3	108.6	40.64	27.3
12.00pm	67.7	24.5	26.5	92.25	16.33	15.03
1.00pm	52.2	15.5	22.8	80.2	12.05	13.06
2.00pm	44.1	8.1	15.5	75.25	4.95	6.17
3.00pm	38	6.1	13.8	70.2	5.05	5.97
4.00pm	34	4	10.53	44.6	3	3.64



**Chart- 3:** Hourly moisture loss of green apple sample at different time period

The results of the chemical analysis in respect to the organic matter(OM),crude protein(CP) ,ether extract(EE), ash and dry matter (DM) content of the green apple slices dried under the open sun and the solar dryer are shown in the Table -6 . Crude protein

content of the solar dried samples was found to be higher compared to the sun dried samples, which indicates the loss of crude protein during sun drying . Lower organic matter and higher dry matter in the solar dried samples compared to the sun dried samples also suggests that solar drying is advantageous for better preservation.

**Table -6:** Chemical analysis of the sun dried and solar dried green apple slices

Samples	OM %	CP %	EE %	Ash %	DM
Sun dried green apple slices	96.6 ± 0.17	2.78 ± 0.28	2.10 ± 0.02	3.36 ± 0.17	82.52 ± 0.33
Solar dried green apple slices	96.5 ± 0.13	3.32 ± 0.69	2.11 ± 0.03	3.50 ± 0.13	83.17 ± 0.20



**Fig-6:** Fresh Sample of Green Apple Slices



**Fig-7:** Green Apple slices dried inside the drying chamber



**Fig-8:** Green Apple slices dried under open sunlight



#### 4. CONCLUSIONS

An indirect forced convection solar dryer was designed, fabricated and its performance was evaluated using green apple slices. The dryer has been designed indigenously using locally available materials for construction and it is cost effective. In the dryer, the heated air from a separate solar collector is allowed to pass through the products placed inside the drying chamber. The solar energy which is get absorbed inside the collector is allowed to pass through some well created baffles. The temperature inside the drying chamber and the solar collector was much higher than the ambient temperature during most hours of the daylight, which was useful for better drying. The relative humidity inside the drying chamber was also less during different time. The percentage of moisture loss and mass of water removed in the drying chamber was higher compared to open sun drying. Higher crude protein and dry matter contents in the solar dried green apple slices also indicate that the solar drying is better than the sun drying. The constructed solar dryer will be useful for drying agricultural products in rural areas as it is cost effective.

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