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*Research Article*

# Design and Development of Walk-In Type Hemicylindrical Solar Tunnel Dryer for Industrial Use

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This paper deals with the critical design specifications and field performance of walk in type hemicylindrical solar tunnel dryer for drying 1500vkg industrial product (dibasic calcium phosphate) in actual use. A tunnel like framed structural covered with UV-stabilized polythene sheet walk-in type solar tunnel dryer was designed, developed, and commissioned at Udaipur (27° 42′ N, 75° 33′ E), Rajasthan, India with a solar collector area of 134.74 $m^2$ for drying di-basic calcium phosphate, having an initial moisture content of 62.87% dry basis and to get a desired moisture content of 10.62% dry basis within two days. The performance of solar tunnel dryer for drying di-basic calcium phosphate was evaluated through no-load and full-load conditions tests in the summer and winter months. The results were shown in terms of the variation of air temperature, solar radiation, relative humidity, air flow rate, moisture content, drying rate, and so forth.

## 1. Introduction

The sun is the source of all energy sources whether it is conventional energy sources or nonconventional energy sources. The sun provides us heat and light energy free of cost, which ultimately provides us energy and sensation of sight. Solar energy is the most readily available source of energy [1]. It does not belong to anybody and is, therefore, free. It is also the most important nonconventional sources of energy because it is nonpolluting and, therefore, helps in lessening the greenhouse effect [2]. Solar energy is one of the most promising renewable energy sources in the world compared to nonrenewable sources for the purpose of drying of agriculture and industrial products [3]. The concept of a dryer powered by solar energy is becoming increasingly feasible because of the gradual reduction in price of solar collectors coupled with the increasing concern about atmospheric pollution caused by conventional fossil fuels used for drying crops.

The solar dryer is a device which uses solar energy for drying. There are several processes by which heat can be transferred to a substance like conduction, convention, and radiation. Open sun drying is one of the oldest techniques employed for processing agricultural and food products. Considerable savings can be made with this type of drying since the source of energy is free and sustainable. However, this method of drying is extremely weather dependent and has the problems of contamination, infestation, microbial attacks and so forth, thus affecting the product quality. Additionally, the drying time required for a given commodity can be quite long and results in postharvest losses [4].

Solar dryer is an improved form of sun drying in which drying is accomplished in a closed structure under relatively controlled conditions utilizing the thermal energy of sun. Various types of solar dryers have been developed as an alternative to open air sun drying and other conventional drying methods. There are different types of solar dryer used for drying application worldwide. Broadly solar dryer can be classified into two categories (a) passive solar dryer (natural circulation) and (b) active solar dryer (forced circulation). Solar drying of agricultural products in enclosed structures by natural convection is an attractive way of reducing postharvest losses and low quality of dried products associated with traditional sun drying methods [5, 6].

M/s Phosphate India Pvt. Limited, Udaipur, Rajasthan, India produces feed grade dibasic calcium phosphate

($CaHPO_4 \cdot 2H_2O$) in their plant using rock phosphate as the prime raw material. The initial moisture content of the dibasic calcium phosphate is about 60–65 per cent (db), and this is to be reduced to around 10 per cent (db) for further usages [7]. Presently mechanical methods are used for drying the material. It consists of tray drying system which is equipped with a 5.6 kW blower and 7.5 kW suction motor. The air is heated to a temperature of around 60°C in diesel fired hot air generator. Its drying is costly, time consuming, and labour intensive. Looking to the power requirement and high cost of existing mechanical dryer, a solar tunnel dryer has been designed and commissioned at the factory site.

## 2. Principles of Drying

The drying of any material involves the migration of water from the interior of the material to its surface and removal of the water from the surface. The rate of movement differs from one substance to another. The rate of drying is dependent on the volume, temperature, and moisture content of air passing over the material. The usual practice is to heat ambient air which lowers relative humidity and increases its capacity to absorb water. This warm dry air is then passed over the material to be dried [8]. The warm air absorbs the moisture and dries the produce, and then the moisture laden air is exhausted. The energy requirement for drying different products can be determined from the initial and final moisture content of each product [9]. Products have different drying rates and maximum allowable temperatures.

In the natural convection type solar tunnel dryer, air is heated inside the dryer due to greenhouse effect by natural means. Increased drying process takes place by hot air flow, and the passage of an air mass around a product represents a complex thermal process where unsteady heat and moisture transfers occur simultaneously. Heat and moisture transfer removal rate depends on air velocity and temperature of the circulating drying air [10]. In natural convection type dryer, air velocity depends on created draft because of temperature difference.

## 3. Design of Solar Tunnel Dryer

To carry out design calculation and size of the solar tunnel dryer, the following assumptions and conditions were made as summarized in Table 1.

Table 1: Design conditions and assumptions for design of the dryer.

| Items | Condition or assumptions |
|---|---|
| Location | Udaipur (27°42′ N, 75°33′ E) |
| Orientation | E-W direction |
| Product dried | Di-basic calcium phosphate |
| Loading capacity | 1500 kg per batch |
| Initial moisture content | 62.87% (db) |
| Final moisture content | 10.62% (db) |
| Sunshine hour | 10 h |
| Drying period required | 18 h |
| Global solar radiation (I) for Udaipur region | 5.5 kWh/m$^2$ |
| Dryer efficiency (g) | 30% |
| Collector material (cover) | UV polythene 200 micron sheet |
| Density of air at ambient (kg/m$^3$) | 1.252 |
| North wall | Glass wool sandwich in metallic cover |
| Height of chimney (H) | 3.75 |

*3.1. Quantity of Water to Be Removed.* Mass of initial water content was calculated using following equation:

$$M = \frac{(m_1 \times x)}{100}. \tag{1}$$

Mass of bone dry product was calculated as follows:

$$M_d = x - M. \tag{2}$$

Initial moisture content (db) was calculated as follows:

$$M_1 = \frac{m_1}{(100 - m_1)} \times 100. \tag{3}$$

Final moisture content (db) was calculated as follows:

$$M_2 = \frac{m_2}{(100 - m_2)} \times 100. \tag{4}$$

The mass of water to be removed during drying was calculated using following equation:

$$M_w = \frac{(m_1 - m_2)}{100} \times x. \tag{5}$$

*3.2. Total Energy Required for Drying.* Total energy required for drying was calculated using following equation:

$$\begin{aligned} Q = {} & M_d \times C_d \times (T_2 - T_1) \\ & + M \times C_p \times (T_2 - T_1) + M_w \times \lambda. \end{aligned} \tag{6}$$

Energy required per hour for drying was calculated using following equation:

$$Q = \frac{Q}{t}. \tag{7}$$

*3.3. Drying Rate.* Drying rate was calculated as follows:

$$k = \frac{Mw}{t}. \tag{8}$$

*3.4. Collector Area of Solar Tunnel Dryer Required for Drying.* It has been found that about 68 per cent area of hemispherical shaped solar tunnel dryer towards south is able to receive sunlight whereas remaining 32 per cent area toward north is from the sun [11]. It is assumed that the overall thermal efficiency of solar tunnel dryer is 40 per cent. Collector area of solar tunnel dryer required for drying was calculated using the following equation:

$$A_c = \frac{Q_t}{I \times \eta \times 0.68}. \tag{9}$$

*3.5. Dimensions of Solar Tunnel Dryer.* Area of solar collector equals area of hemicylindrical shape of solar tunnel dryer.

Area of hemicylindrical shape of solar tunnel dryer was calculated as follows:

$$a = \pi \times r \times (r + L). \tag{10}$$

Diameter ($d$) of solar tunnel dryer 3.75 m is kept as constant for easy entry and other convenience. Radius of solar tunnel dryer was calculated as follows:

$$r = \frac{d}{2}. \tag{11}$$

Length of solar tunnel dryer was calculated as follows:

$$L = \frac{(a - \pi r^2)}{\pi r}. \tag{12}$$

Floor area (drying area) of solar tunnel dryer was calculated as follows:

$$A = L \times d. \tag{13}$$

*3.6. Design of North Wall.* Total area of transparent cover was calculated as follows:

$$a_1 = \pi \times r \times (r + L). \tag{14}$$

Since 32 percent of collector area toward north has to protect.

So, total area of north wall to be protected was calculated as follows:

$$a_p = 0.32 \times a_1. \tag{15}$$

Arc width of cover through which energy losses was calculated as follows:

$$W = \frac{a_p}{L}. \tag{16}$$

Perimeter of solar tunnel dryer was calculated as follows:

$$p = \pi \times r. \tag{17}$$

Since perimeter ($p$) covers diametrical length, $m = d_l$.

Therefore, arc width will cover diametrical length was calculated as follows:

$$d_l = \frac{(d \times w)}{p}. \tag{18}$$

Hence, required height of protector was calculated as follows:

$$h_p = \sqrt{w^2 - d_l^2}. \tag{19}$$

*3.7. Design of Chimney.* Since airflow in the dryer takes places due to the draft caused by the density difference between outside cold air and inside hot air, a natural draft uses the basic law that warm air rises. Air as it is warmed expands and becomes lighter in mass [12]. Colder, heavier air pushes in under it and forces it up. This causes a draft. Mass of air needed for removing $M_w$, kg of water was calculated using the following equation:

$$q_a = \frac{(M_w \times \lambda)}{C_a \times (T_3 - T_1)}. \tag{20}$$

Mass of exit air was calculated as follows:

$$q = (M_w + q_a). \tag{21}$$

Density of inlet air was calculated as follows:

$$\rho_i = \rho_0 \times \frac{T_0}{T_1}. \tag{22}$$

Produced draft in chimney (Height of chimney assumed by 3.75 m) (five numbers of 0.75 m)

$$D_p = H \times g \times (\rho_i - \rho_e). \tag{23}$$

But actual draft was calculated as follows:

$$D_a = 0.75 \times D_p. \tag{24}$$

Velocity of exit air was calculated as follows:

$$V = \sqrt{\frac{2D_a}{\rho_e}}. \tag{25}$$

Volume of exit air was calculated as follows:

$$V_e = \frac{q}{\rho_e}. \tag{26}$$

Rate of exit air was calculated as follows:

$$Q_a = \frac{V_e}{t}. \tag{27}$$

Thus if assumed this exit air is being carried by $n$ number of chimney.

Rate of exit air for single chimney was calculated as follows:

$$Q_c = \frac{Q_a}{n}. \tag{28}$$

Area of chimney was calculated using following equation:

$$a_c = \frac{Q_c}{V}. \tag{29}$$

Diameter of chimney was calculated as follows:

$$d_c = \sqrt{\frac{4 \times a_c}{\pi}}. \tag{30}$$

## 4. Dimension of Solar Tunnel Dryer

The solar tunnel dryer was designed as per the procedure mentioned above, and its dimensions are given in Table 2.

Table 2: Dimensions of solar tunnel dryer.

| Components | Specifications |
|---|---|
| Length of solar tunnel dryer | 21.0 m |
| Diameter of solar tunnel dryer | 3.75 m |
| Floor area of solar tunnel dryer | 78.75 $m^2$ |
| Area of hemicylindrical shape of solar tunnel dryer | 134.74 $m^2$ |
| Height of north wall | 1.57 m |
| Length of north wall | 21 m |
| Number of chimney | 5 |
| Diameter of chimney | 0.20 m |
| Height of chimney | 0.75 m |
| Tray size | 800 × 400 × 40 mm |
| Number of trays | 24 trays per trolley |
| Number of trolleys | 10 |
| Door size | 1.6 × 0.75 m |

## 5. System Description of Natural Convection Solar Tunnel Dryer

Figure 1 shows a schematic view of a natural convection solar tunnel drying system, designed and developed for drying industrial products (dibasic calcium phosphate) on large scale at moderate temperature in this region. A solar tunnel dryer has been commissioned at M/s Phosphate India Pvt. Ltd, Udaipur (27° 42′ N, 75° 33′ E), Rajasthan, India or drying 1500 kg dibasic calcium phosphate from 62.87 to 10.62 per cent moisture content (db) of in a batch. Earlier electricity was used for air heating and blowing inside the drying chamber. It is consisted of a hemicylindrical walk-in type metallic frame structure covered with UV-stabilized semitransparent polyethylene sheet of 200 micron thickness and had a base area of 3.75 × 21.00 m for drying 1500 kg per batch. The orientation of solar tunnel dryer is in east-west direction. The structural components of solar tunnel drier include Hoops foundation, floor, ultraviolet stabilized polythene film, and drying trays. A slope of 2-3° along the length of the tunnel and an exhaust fan of 0.75 kW power rating and having volume flow rate 1,500 $m^3\,h^{-1}$ is provided at the upper end of the tunnel for occasional removal of moist air to maintain humidity at a preset level inside the tunnel. The exhaust fan operation was automatic to maintain average relative humidity of the inside air between 30 and 40 per cent.

Adequate provisions were made to reduce heat losses from the floor and the northern side of the tunnel [13]. The product to be dried is put into a continuous perforated tray in thin layers. Five chimneys were placed on equidistance apart on the top of tunnel to remove moisture during drying. On the bottom side of southern side, five holes having equal diameter as that of chimney were provided to allow fresh air entry into tunnel. This fresh air gets heated and owing to density difference moves upward through the products and picked up moisture and finally passed out through chimneys [6].

## 6. Salient Features of Solar Tunnel Dryer

Solar tunnel dryer is a simple, walk-in type, convenient, and efficient dryer at low cost for drying large quantity [14]. It is essentially a poly house type structure having loading capacity up to 1500 kg dibasic calcium phosphate per batch, in which drying takes place through natural flow of hot air. Few salient features of the solar tunnel dryer are listed below.

(1) It is a modular walk-in type hemicylindrical poly house type design.

(2) The metallic frame structure of the tunnel dryer was covered with ultraviolet stabilized semi-transparent polyethylene sheet of at least 200-micron thickness. It has long life and does not allow the trapped radiation to escape.

(3) Loading and unloading of material on large scale is quite easy.

(4) The axis of solar tunnel dryer is east-west direction so that maximum exposure of southern radiation can be obtained.

(5) The cement concrete floor was painted black for better absorption of solar radiation. Five-cm thick glass wool insulation was provided to reduce heat loss through the floor.

(6) A black body was installed to reduce heat losses from the northern side of the tunnel.

(7) Inlets for fresh air were provided all along the periphery of the tunnel near ground level.

(8) Upper end of the tunnel was provided with a steel door of at least 1.6 m × 0.75 m size for loading and unloading of the material.

(9) The number and size of chimney was decided on the basis of amount of moisture removed on a day and drying rate required.

(10) Local artisan can fabricate the system with locally available cheaper materials.

## 7. Construction of Prototype Dryer

A natural convection solar tunnel dryer was designed and constructed at M/s Phosphate India Pvt. Ltd, Udaipur (27° 42′ N, 75° 33′ E), Rajasthan, India for drying 1500 kg industrial product (dibasic calcium phosphate) from 62.87 to 10.62 per cent moisture content (db) of in a batch. It was hemicylindrical shaped walk-in type and had a base area of 3.75 × 21.00 m for drying 1500 kg per batch. The constructed dryer consisted of drying chamber and solar collector combined in one unit as shown in Figure 2.

## 8. Instrumentation and Experiments

For drying dibasic calcium phosphate at industrial level experiments were conducted during the typical day of summer and winter months. The system is oriented to face south to maximize the solar radiation incident on the dryer [15]. Electronic data logger with six temperature sensors (probes)

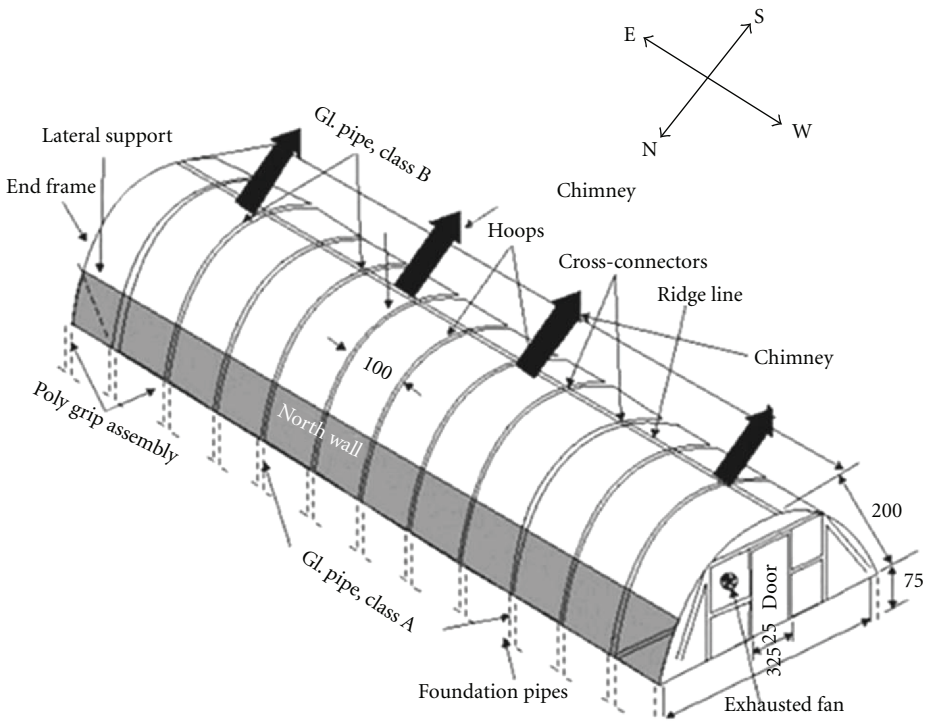


Figure 1: Schematic view of walk in type hemicylindrical solar tunnel dryer.

Figure 2: Closed view of solar tunnel dryer installed at factory premises.

was used to record temperature at different locations inside solar tunnel dryer and ambient temperature. The global solar radiation incident on a horizontal surface is measured using Pyranometer. Wind speed and exit air velocity at chimney outlet are measured by using Lutron Anemometer and hot wire anemometer, respectively. The temperatures of the different parts of the system are measured after every one hour. The ambient temperatures were also recorded; the moisture contents of product during drying are measured on the dry basis.

## 9. Performance of the Dryer

The performance of the solar tunnel dryer was evaluated by conducting tests at no load and full load that were made for summer and winter months. Temperature variation during no-load testing in walk in type hemicylindrical solar tunnel dryer on a typical day [16] of summer month and winter month at different locations inside the dryer, namely, at midbottom point, at 1 m above bottom point, and at north wall, respectively, and the outside is graphically illustrated in Figures 3 and 4, respectively. It is observed from Figure 3 that the maximum temperature inside the dryer on a typical day was 63.1°C at 15:00 hrs while the minimum temperature was 29.4°C at 8:00 hrs on summer day. The maximum ambient temperature recorded on the summer day was 41.6°C at 15:00 hrs, while minimum ambient temperature was 27.1°C at 8:00 hrs. It was also observed that the maximum and minimum solar insulation in this month was 1008 $Wm^{-2}$ at 13:00 hrs and 320 $Wm^{-2}$ at 18:00 hrs, respectively. It is observed from Figure 4 that the maximum temperature inside the dryer during no load was 47.4°C at 15:00 hrs, while the minimum temperature was 12.5°C at 8:00 hrs in the winter day. Maximum ambient temperature on a typical day of winter season was 26.6°C at 15:00 hrs while the minimum was 11.6°C at 8:00 hrs. It was also observed that the maximum and minimum solar insulation in this month was 896 $Wm^{-2}$ at 13:00 hrs and 64 $Wm^{-2}$ at 17:00 hrs, respectively.

In full-load testing dibasic calcium phosphate was placed in solar tunnel dryer, and some materials were placed in open air for comparison purpose. An interior view of the solar tunnel dryer under full load condition is given in Figure 5.

Drying was continued till the moisture content of the material reached to 10.62% (db) in both conditions. The

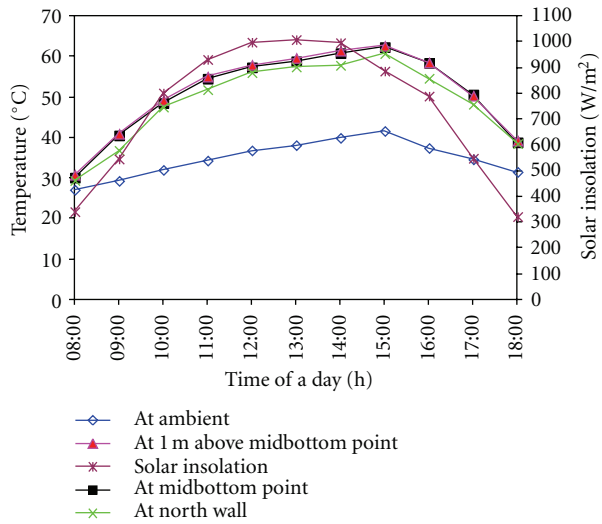


Figure 3: Temperature and solar radiation variation at no load in the summer month.

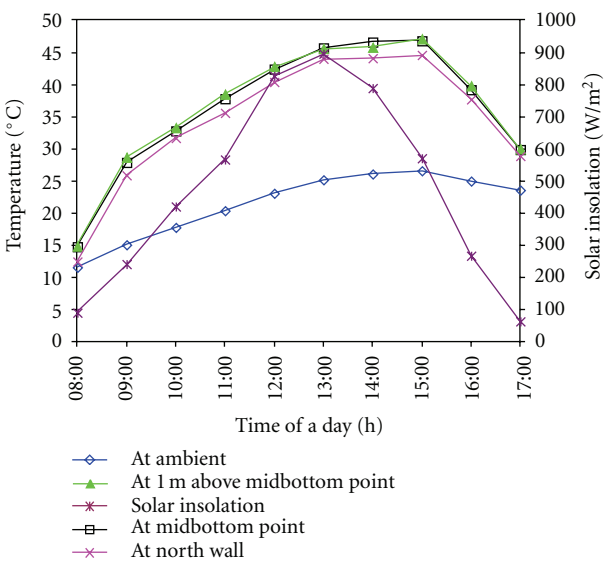


Figure 4: Temperature and solar radiation variation at no load in the winter month.

Figure 5: Inside view of solar tunnel dryer under full load condition for drying of dibasic calcium phosphate.

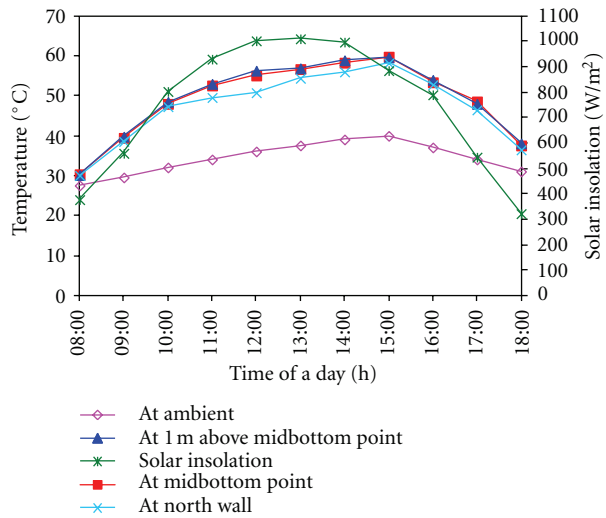


Figure 6: Temperature and solar radiation variation at full load in the summer month.

maximum temperature inside the solar tunnel dryer in full-load test was 60.0°C at 15:00 hrs while the minimum temperature was 30.1°C at 8:00 hrs during summer day as illustrated in Figure 6. The maximum ambient temperature recorded on this day was 40.0°C at 15:00 hrs, and minimum ambient temperature was 27.6°C at 8:00 hrs. It was also observed that the maximum and minimum solar insulation in this month was 1010 $Wm^{-2}$ at 13:00 hrs and 323 $Wm^{-2}$ at 18:00 hrs respectively. It was observed that the maximum temperature inside the dryer was 46.1°C at 15:00 hrs while the minimum temperature inside the dryer was 13°C at 8:00 hrs in typical day in the winter month against the maximum and minimum ambient temperature of 26.3°C and 12°C, respectively, as illustrated in Figure 7. It was also observed that the maximum and minimum solar insulation in this month was 891 $Wm^{-2}$ at 13:00 hrs and 68 $Wm^{-2}$ at 18:00 hrs, respectively. Figure 8 reveals the variation of moisture content and drying rate with drying time for solar tunnel dryer and open sun drying for a typical day of the summer month. The initial moisture content of dibasic calcium phosphate was 64.5% (db). It was observed that the moisture content of dibasic calcium phosphate decreases with drying time and reduced to 11.40% (db) in 18 sunshine hours, while in the open air it was 27.52% (db). It was observed that the drying rate for the first two hour was 0.02 $kg\,h^{-1}$ and at the end of the trial the drying rate was 0.02 $kg\,h^{-1}$. The drying rate was found to be comparatively higher in the dryer than open sun drying.

It is observed from Figure 9 that moisture content was reduced from 62.87 to 20.13% (db), while in the open air it was 45.62% (db) during first day drying in typical day of winter month. It was further reduced to 10.62% (db), while in the open air it was 31.94% (db) at the end of second day. The variation of drying rate with drying time is shown in Figure 9 for dryer and open sun drying for a typical day of the winter month.

Table 3: Detail of the costs of solar tunnel dryer.

| S. N. | Item | Quantity | Cost (US$) |
|---|---|---|---|
| (1) | Galvanized Iron pipe 15 mm class B | 200 m | 450.00 |
| (2) | Galvanized Iron pipe 25 mm class A | 50 m | 178.00 |
| (3) | Exhaust fan with automatic one humidity controller | One | 150.00 |
| (4) | Metallic door | One | 120.00 |
| (5) | 200 micron UV-stabilized polythene sheet | 200 $m^2$ | 245.00 |
| (6) | Pucca floor with black paint | 78.75 $m^2$ | 450.00 |
| (7) | Insulation inside the floor | 5 cm thick | 225.00 |
| (8) | MS sheet sandwich with insulating material for north wall | 32.97 $m^2$ | 350.00 |
| (9) | Metallic chimney with stand | | 115.00 |
| (10) | SS trays cum trolley for drying material | 100 $m^2$ | 556.00 |
| (11) | Skilled labour for fabrications | 30 man days | 126.00 |
| (12) | Miscellaneous (G.I. wires, cross bar, nut bolt, cable, wire, etc.) | — | 90.00 |
| Total cost of installation | | | 3055.00 |

Table 4: Economic Indicators.

| Economic indicators | Value |
|---|---|
| B/C ratio | 3.06 |
| Payback period (years) | 2 years 5 months |

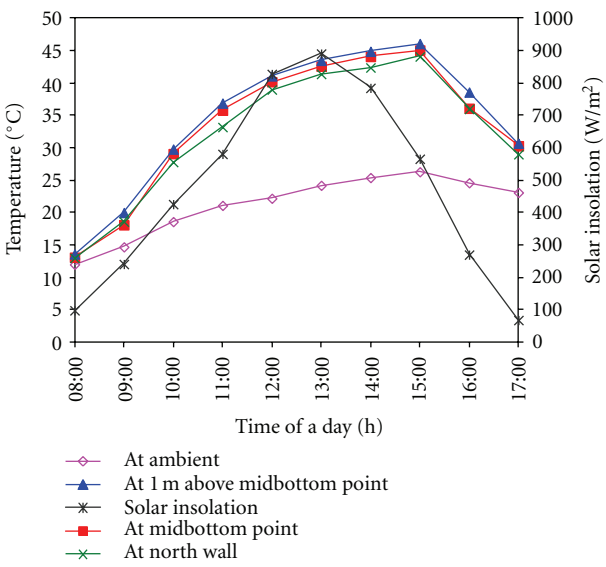


Figure 7: Temperature and solar radiation variation at full load in the winter month.

## 10. Cost of Operation

Cost for material and construction of the walk in type hemicylindrical solar tunnel dryer for drying 1500 kg of industrial product (dibasic calcium phosphate) was estimated as around US$ 3055.00. Average cost of drying for one batch of dibasic calcium phosphate in the dryer was worked out approximately as US$ 12.25 as compared to US$ 67.00 in the existing diesel fired dryer. The cost of construction of solar tunnel drying system and its economics is presented in Tables 3 and 4, respectively. The cost benefit ratio was 3.06

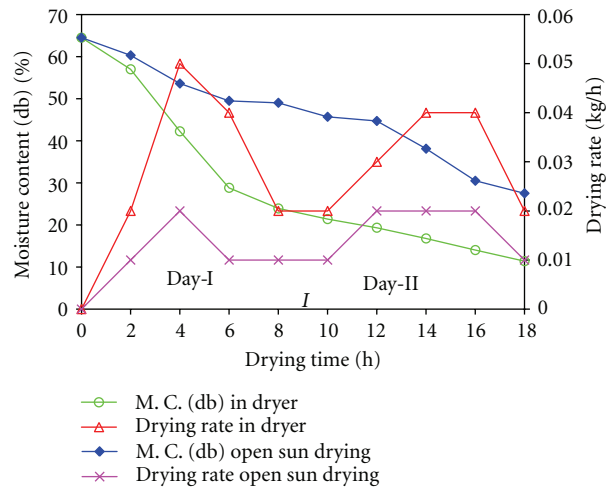


Figure 8: Relationship between moisture content and drying rate with drying time in the summer month.

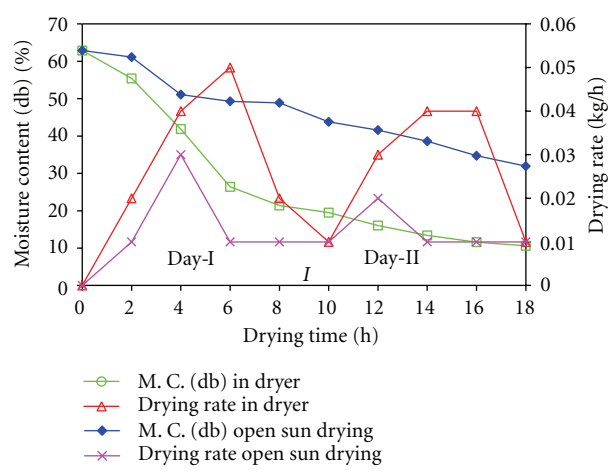


Figure 9: Relationship between moisture content and drying rate with drying time in the winter month.

with a payback period of 2 years 5 months. It can be inferred that the developed solar tunnel dryer is technically as well as economically feasible.

## 11. Conclusions

A natural convection solar tunnel dryer was designed and constructed based on preliminary investigation of industrial product (dibasic calcium phosphate) drying under controlled conditions. The designed dryer with a collector area of 78.75 $m^2$ is expected to dry 1500 kg wet dibasic calcium phosphate from 62.87% to 10.62% dry basis in two days under ambient conditions during summer and winter months. A prototype of the solar tunnel dryer was constructed and commissioned at the factory site. The performance of solar tunnel dryer for drying dibasic calcium phosphate was evaluated through no-load and full-load conditions tests in the summer and winter months. The air temperature inside the solar tunnel dryer was higher than outside by 18–21°C. No constant rate drying period was observed. The drying rate for wet dibasic calcium phosphate varied similarly as solar insolation, whereas the moisture reduced continuously with cumulative drying hours. The system is saving about US$ 54.75 per day.

## Nomenclature

wb: Wet basis
db: Dry basis
$x$: Mass of selected product taken for drying, kg
$m_1$: Initial moisture content of selected product in % (wb)
$m_2$: Final moisture content of selected product in % (wb)
$T_1$: Ambient air temperature (°C)
$T_2$: Temperature inside the solar tunnel dryer (°C)
$T_3$: Temperature inside the chimney of dryer (°C)
$C_p$: Specific heat of water (kJ $kg^{-1}$ °$C^{-1}$)
$t$: Total drying time (h)
$C_d$: Specific heat of product (kJ $kg^{-1}$ °$C^{-1}$)
$C_a$: Specific heat of air (kJ $kg^{-1}$ °$C^{-1}$)
$\lambda$: Latent heat of vaporization of water (kJ $kg^{-1}$)
$\rho_i$: Density of inlet air (kg $m^{-3}$)
$\rho_e$: Density of exit air (kg $m^{-3}$)
$\rho_o$: Density of air at 0°C (kg $m^{-3}$)
$G$: Gravity constant (m $s^{-2}$)
$T_0$: Temperature of air at 0°C (°K)
$M$: Mass of initial water content (kg)
$M_1$: Initial moisture content in % (db)
$M_2$: Final moisture content in % (db)
$M_d$: Mass of bone dry product (kg)
$M_w$: Mass of water to be removed (kg)
$Q$: Total energy required for drying of selected product (kJ)
$Q_t$: Energy required per hour for drying of selected product (kJ $h^{-1}$)
$A_c$: Collector area of solar tunnel dryer required ($m^2$)
$\eta$: Overall thermal efficiency of solar tunnel dryer, %
$I$: Global solar radiation for Udaipur region (kJ $h^{-1}$ $m^{-2}$)
$a$: Area of hemicylindrical shape of solar tunnel dryer ($m^2$)
$r$: Radius of dryer (m)
$L$: Length of dryer (m)
$A$: Drying area of solar tunnel dryer ($m^2$)
$D_a$: Actual draft (kg $m^{-1}$ $s^{-2}$)
$D_p$: Produced draft (kg $m^{-1}$ $s^{-2}$)
$a_c$: Area of chimney ($m^2$)
$d_c$: Diameter of chimney (m)
$Q_c$: Rate of air flow in chimney ($m^3$ $s^{-1}$)
$Q_a$: Rate of air required ($m^3$ $s^{-1}$)
$V$: Velocity of exit air (m $s^{-1}$)
$q$: Mass of exit air (kg)
$a_1$: Area of transparent cover ($m^2$)
$a_p$: Area of north wall to be protected ($m^2$)
$w$: Arc width of north wall (m)
$p$: Perimeter of solar tunnel dryer (m)
$d_l$: Diametrical length of north wall(m)
$h_p$: Height of protector (m)
Pvt: Private
Ltd: Limited
kW: Kilowatt
°C: Degree centigrade
$k$: Drying rate (kg $h^{-1}$)
M/s: Messrs
UV: Ultraviolet
US$: United States dollar.

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