CHAPTER – III

MATERIALS AND METHODS

This chapter deals with the materials employed and the methods followed in the evaluation and comparative study of forced convection type solar tunnel dryer with the conventional drying pattern at the selected industry and as per decided objectives. The solar tunnel dryer was designed, fabricated and installed at M/s Miraj Pvt. Ltd., Nathdwara for drying processed tobacco and M/s Phosphate India Pvt. Ltd, Udaipur for drying Di-basic Calcium Phosphate. This chapter is presented under the following headings:

1. Design of Forced Convection type Solar Tunnel Dryer
2. Method of Construction of the Solar Tunnel Dryer
3. Installation of the Industrial level Solar Tunnel Dryer
4. Instrumentation for Drying Experiments and Evaluating Performance
5. Study of Micro-Climatic Variations inside the Solar Tunnel Dryer
6. Performance Evaluation of Solar Collector
7. Economic Analysis of Solar Tunnel Dryer in actual Use

3.1 Design of Forced Convection type Solar Tunnel Dryer

Forced convection type Solar Tunnel Dryer was designed and developed for material such as industrial non-chemical and chemical products. The system was designed keeping in view manufacturing aspects, choice of material of construction, to accommodate large quantity, ease of operation and least cost of installation. Required number and suitable size of flat plate collector for maximizing inner air temperature and size of north wall for prevention of heat losses especially for winter season and maintaining adequate temperature for drying has been designed as per standard method of thermodynamics and heat transfer. The forced convection solar tunnel dryer was designed with the assumption that 50% of energy may be supplied from tunnel and remaining energy from solar collectors placed outside the tunnel for drying products. The solar tunnel dryer was installed in a selected industry and its performance evaluated in actual use in the industry.
3.1.1 Assumptions

The assumptions of certain parameters were made for design of forced convection type solar tunnel dryer (Amir et al. 1991), which includes:

1. Specific heat of air \((C_a)\), kJ/kg \(^{o}\)C = 1.005
2. Density of exit air \((\rho_e)\), kg/ m\(^3\) = 1.0539
3. Density of air at 0 \(^{o}\)C \((\rho_o)\), kg/ m\(^3\) = 1.252
4. Gravitational constant, m/s\(^2\) = 9.8
5. Temperature of air at 0 \(^{o}\)C (\(T_o\)), K = 273
6. Global solar radiation for Udaipur region \((I_g)\), Kcal/m\(^2\)/hr = 820
7. Overall thermal efficiency of solar tunnel dryer (\(\eta\)), % = 25-35
   (Rathore et al. 2011)
8. Collector overall heat loss coefficient \((U_L)\), W/m\(^2\) \(^{o}\)C = 7.38
9. Transmissivity \((\tau\alpha)\), \((\tau = 0.85\) to \(0.90\), \(\alpha = 0.92\) to \(0.98\)) = 0.89
10. Heat removal factor of collector \((F_R)\), = 0.9
    (Klein, 1975; Folaranmi, 2008; ANON, 1978a, 1978b)

3.1.2 Quantity of water to be removed

Mass of initial water content \((M)\), kg = \(\frac{(m_1 \times x)}{100}\)

Mass of bone dry product \((M_d)\), kg = \(x - M\)

Initial moisture content (d.b.), % = \(\frac{m_1}{100 - m_1} \times 100\)

Final moisture content (d.b.), % = \(\frac{m_2}{100 - m_2} \times 100\)

Weight of water to be removed \((M_w)\), kg = \(\frac{(m_1 - m_2)}{100 - m_2} \times x\)

Where,

\(m_1 = \) Initial moisture content of selected product (w.b.), %
\(m_2 = \) Final moisture content of selected product in (w.b.), %
\(x = \) Mass of selected product taken for drying, kg
3.1.3 Total energy required $Q$, kcal

$$Q = M_d \times C_d \times (T_2 - T_1) + M \times C_p \times (T_2 - T_1) + M_w \times \lambda$$

$$C_p = (0.80m + 0.20)4.1868 \times 10^{-3} \text{ MJ/kg}^\circ\text{C}$$

(Siebel’s formula, ASHRAE, 1974)

Where,

$T_1$ = Ambient air temperature, °C
$T_2$ = Temperature inside the solar tunnel dryer, °C
(Assumed 60 °C, as required optimally for drying of agricultural products)

$C_p$ = Specific heat of water, kJ/kg °C
$C_d$ = Specific heat of product, kJ/kg °C
$\lambda$ = Latent heat of vaporization of water, kJ/kg

3.1.4 Energy required per hour $Q_t$, kcal/h

$$Q_t = \frac{Q}{t}$$

Where,

$t$ = Total drying time, h

3.1.5 Collector area of solar tunnel dryer required $A_t$, m²

As per earlier study it has been found that about 68% area of solar tunnel dryer is receiving sunlight whereas remaining 32% area is under shadow and energy loser, when solar tunnel dryer is oriented East–West direction (Garg and Kumar, 1998; Sevda, 2003). Therefore, for reducing heat loss, a north wall has been constructed.

Drying area ($A_t$) = \[
\frac{\text{Total heat requirement per hour}}{\text{Global radiation} (I_g) \times \text{Thermal efficiency} (\eta)}
\]

$$A_t = \frac{Q_{t1}}{k} \times \frac{1}{\eta} \times \frac{100}{68}$$

$$Q_{t1} = Q_{t2} = \frac{Q_t}{2}$$

Where,

$Q_{t1}$ = Energy required from solar tunnel per hour, kcal/h
$Q_{t2}$ = Energy required from flat plate collectors per hour, kcal/h
3.1.6 Flat plate collector area required $A_c, \text{ m}^2$

$$A_c = \frac{Q_i^2}{F_R[I_\alpha + U_i(T_a - T_i)]}$$  

(Hottel-Whillier-Bliss equation)

Where,

$I = \text{Intensity of solar radiation, W/m}^2$

$T_a = \text{Ambient air temperature, } ^\circ\text{C}$

$T_i = \text{Inlet mean fluid temperature, } ^\circ\text{C}$

$T_a = \text{Collector's absorber plate temperature, } ^\circ\text{C}$

$F_R = \text{Heat removal factor}$

$$F_R = \frac{m_c C_a (T_a - T_i)}{A_c[I_\alpha + U_i(T_a - T_i)]}$$

$m_c = V_r \times \rho_e$  

(Itodo et al., 2002; Folaranmi, 2008)

$V_r = \text{Air flow rate through the collector, (m}^3/\text{s)}$

$\rho_e = \text{Density of exit air (}\rho_e, \text{ kg/m}^3$

In most places, however, less sun is available in winter season; thus it is usual to give the tilt a winter bias, that is, to set the tilt as the latitude $+10^\circ$ to reduce the difference between winter and summer performance, $\theta = 35^\circ$ (Szokaloy, 1975)

3.1.7 Dimensions of solar tunnel dryer

Area of solar collector of tunnel = Area of semi-cylindrical shape of solar tunnel dryer

Area of semi-cylindrical shape of solar tunnel dryer ($a$), $m^2 = \pi \times r \times (r + l)$

Diameter ($d$) of solar tunnel dryer 3.75 m is kept as constant for easy entry and other convenience,

Radius of solar tunnel dryer ($r$), $m = \frac{d}{2}$

Length of solar tunnel dryer ($l$), $m = \frac{a - \pi r^2}{\pi r}$

Floor area (Drying area) of solar tunnel dryer ($a$), $m^2 = l \times d$
3.1.8 Design of north-wall

Total area of transparent cover \((a_i)\), \(m^2 = \pi \times r \times (r + l)\)

Since 32 percent of collector area toward north has to protect.
So, Area to be protected \((a_p)\), \(m^2 = 0.32 \times a_i\)

Arc width of cover through which energy losses \((w)\), \(m = \frac{a_p}{l}\)

Perimeter of solar tunnel dryer \((p)\), \(m = \pi \times r\)
Since, perimeter \((p)\) covers diametrical length, \(m = d\)

Therefore, arc width \((e)\) will cover diametrical length \((d_i)\), \(m = \frac{(d \times w)}{p}\)

Hence, required height of protector \((h_p)\), \(m = \sqrt{w^2 - d_i^2}\)

3.1.9 Flat plate collector

Wooden frame covered by GI sheet used for collector.
No. of cover glass (toughened glass, 4 mm) = 2
Aluminum foil used for absorber, thickness = 2 mm
Gap between glass covers = 15 mm
Gap between cover and absorber = 3.5 cm
Insulation of glass wool \((k = 0.042 \text{ W/mk}, \rho = 40 \text{ kg/m}^3)\) thickness = 25 mm
Black Board paint on absorber plate for maximize solar heat absorption
[design & details of components used in collectors were taken by IS 12933(part 2), 1992 & IS 2933(part 2), 2003]

3.2 Method of Construction of Solar Tunnel Dryer

3.2.1 Foundation

Foundation was provided to anchorage to the super structure and supports it against different forces. Pit foundation also called pier foundation is common in solar tunnel dryer because the structural members are widely spaced. Hence the pit foundation was constructed a regular interval of 1.0 meter.
3.2.2 Foundation pipes

Foundation pipes are meant to provide a firm support to the hoops. A 90 cm long piece of 25 cm GI pipe (class-A) were used as foundation pieces. A 10 cm piece of MS flat (25 mm x 3 mm) was centrally welded to the one end of pipe and a hole of 8 mm diameter drilled at 10 cm distance from the other 75 cm grouting with concrete. A 15 cm of pipe remains above ground level to hold super structure. The foundation pipes were spaces in apart in parallel rows. The foundation pipes are spaced 1.0 m apart in parallel rows. It is important that the tops of these foundation pipes all be at same elevation.

3.2.3 Hoops

These were the integral part of the structure of solar tunnel dryer. These were semi-circular in shape and are formed using bending galvanized iron pipe (15 mm diameter and desired length). The long pipes were fed into the bending machine and uniform bending was achieved in semi-circular shape. About 30 cm length on each end was kept unbent which enables the end to easily fit into the foundation pipe.

3.2.4 End frame

End frames were MS members fitted on both ends of the solar tunnel dryer. The MS ‘L’ angle member has the provision for door and supporting fixtures for the exhaust fan and instruments. A single door is provided at front side of the dryer with frame (75 cm x 160 cm). The open area was covered by polyethylene film, which was attached to the doorframe with rivets. The door was finally hinged to the end frames.

3.2.5 Lateral support

Lateral support were provided to exchange the structures rigidly of end frames and were fabricated from 8 gauge GI wire (15 mm diameter) with interval of 1 m on along the length of the hoops. MS flats of 3 mm were used on top of the dryer.

3.2.6 Cover material

Ultra-Violet stabilized low density polythene sheets of 200- micron thickness was used as a cover material. Its higher strength and low cost have made it most popular replacement for glass cover material. It is available in wide width and has average service life of 2 years.
3.2.7 Drying floor

Floor of solar tunnel dryer was made of Cement Concrete of 1:2:4 ratio and was painted black board for better absorption of solar radiation.

3.2.8 North wall

The provision of north wall was made to prevent heat radiation loss from north side of the tunnel dryer, so that optimum temperature for drying may be achieved especially during winter months. The selection of material of north wall was made on the basis of fact that the wall may absorb solar radiation during day hours, which otherwise are going out unutilized and also may emit heat radiation during night because of temperature difference of black body concept. Glass wool sandwich in metallic cover was used as north wall and commissioned inside the solar tunnel dryer.

3.2.9 Exhaust fan

Initially, it was calculated that 266.67 kg of water is to be removed for drying 500 kg of processed tobacco. This is further employed in psychometric chart for humidity ratio. Assuming an input air temperature of 32 °C (dry bulb) and relative humidity of 40 to 45 per cent the psychometric chart gives corresponding humidity ratio as 0.0146 kg water/kg dry air. When the solar collector heats it to say, 65 °C (dry bulb), the humidity ratio remains constant. Then the air absorbs moisture until its relative humidity is 90 per cent, the psychometric chart shows that its humidity ratio is 0.020 kg water/kg dry air. The change in humidity ratio is therefore 0.020-0.0146 = 0.0054 kg water/kg dry air.

From the gas laws

\[ PV = MaRT \]

Where,

\[ P = \text{Atmospheric pressure, 101.3 kPa} \]
\[ V = \text{Volume of air, kg} \]
\[ Ma = \text{Mass of air, kg} \]
\[ T = \text{Absolute temperature, K} \]
\[ R = \text{Gas constant, 0.291 kPa m}^3/\text{kgK} \]

For increase of 0.0054 kg water/kg dry air in humidity ratio, the one kg of water will require \( \frac{1}{0.0054} = 185.18 \) kg of dry air for evaporation. Thus the quantity of air on volume
basis required for removing 1 kg of water is calculated as, keeping absolute temperature (338 k)

\[
\frac{185.18 \times 0.291 \times 338}{101.3} = 179.8 \text{ m}^3;
\]

Thus 266.67 kg of water will require \(266.67 \times 179.8 = 47947.27 \text{ m}^3\) of air for evaporation. For a drying time of 8 h per day, the air flow rate would be \(47947.27/28800 = 1.665 \text{ m}^3/s\). Assuming pressure drop inside the tunnel dryer as 747 Pa (Kandekar, 2007) and negligible pressure drop inside collector, due to smaller frictional loss in the duct & collector, the power requirement for operating fan \((P_f)\) is calculated as below:

\[
P_F = \frac{V_a \times P_d}{\eta_F}
\]

Where,

- \(P_F\) = Power required by fan, Watt
- \(V_a\) = Air flow rate, m\(^3\)/s
- \(P_d\) = Pressure drop, Pa
- \(\eta_F\) = Fan efficiency, taken as 0.8 for calculation.

Therefore the fan power requirement is \(P_F = \frac{1.665 \times 747}{0.8} = 1554.7 \text{ Watt} \approx 1.5 \text{ kW}\)

Hence, two exhaust fans of power rating 0.5 and 1 kW were provided at front and back end of the dryer respectively to remove moist air. Higher capacity fan at back end were preferred to accommodate gradient in tunnel and more volume of moist air at back. For running this exhaust fan 220 V A.C. 50 Hz supply was required.

### 3.3 Installation of Industrial Level Forced Convection Type Solar Tunnel Dryer

Based on design criterion as mentioned above two solar dryers were designed and commissioned at two different places for drying industrial products:

1. Solar tunnel dryer for drying processed tobacco
2. Solar tunnel dryer for drying of Di-basic Calcium Phosphate
3.3.1 Solar tunnel dryer for drying Processed tobacco

A solar tunnel dryer for drying 500 kg processed tobacco from 138 to 9 per cent moisture content (d.b.) has been installed at M/s Miraj Pvt. Ltd., Nathdawara. Solar tunnel dryer consists of a drying chamber of 3.75 × 16 m for drying 500 kg processed tobacco per batch. It was essentially a metallic frame structure of tunnel shaped covered by UV stabilized semi-transparent polythene sheet of 200 micron thickness. Door was provided on upper end of tunnel of size 1.60 m x 0.75 m to facilitate movement in the dryer. The processed tobacco spread in thin layers in the sliding trays of 15.9 m x 3.6 m, 15.9 m x 2.5 m, and 15.9 m x 1.6 m size. Incoming air through twelve Flat plate collectors of size 2 m x 1 m and outgoing air forced by two exhaust fans of duct size 450 mm and 250 mm. The schematic view of solar tunnel dryer installed at factory site is shown in Fig. 3.1.

![Figure 3.1 Designed Solar Tunnel Dryer installed at M/s Miraj Pvt. Ltd., Nathdawara.](image)

3.3.2 Solar tunnel dryer for drying of Di-basic Calcium Phosphate

A solar tunnel dryer has been installed at M/s Phosphate India Pvt. Ltd, Udaipur for drying one ton Di-basic Calcium Phosphate (DCP) from 66 to 11 per cent moisture content (d.b.) of in a batch. It was semi-cylindrical shaped walk-in type and had a base area of 3.75 × 21.00 m for drying one ton per batch. The chemical spread in thin layers in the trays of 800 × 400 × 40 mm size arranged as 24 trays per trolley, total no. of trolleys were ten. Incoming air through eight Flat plate collectors of size 2.5 m x 1 m and outgoing air forced by two
exhaust fans of duct size 450 mm. A view of solar tunnel dryer installed at the factory site is shown in Figure. 3.2.

![Figure. 3.2 Designed Solar Tunnel Dryer installed at M/s Phosphate India Pvt. Ltd, Udaipur](image)

3.4 Instrumentation for Experiments and Performance Evaluation

The drying experiments were conducted on no load and full load condition of solar tunnel dryer at different season having different conditions of the environment. All the observations were made every one hour interval of time. Instruments, which were used during performance evaluation of solar dryer, are described as follows:

3.4.1 Measurement of temperature

3.4.1.1 Electronic data-logger

Electronic data-logger (Figure. 3.3) with six temperature sensors (probes) manufactured by M/s Century instruments limited, Chandigarh, was used to record temperature at different locations inside solar tunnel dryer. The data-logger was able to display as well as record any temperature from 0 °C to 600 °C with 1 °C resolution. The instrument was having facility for recording the temperatures automatically at set intervals.
3.4.1.2 Calibration of data-logger

Probes of data-logger were calibrated against an ordinary glass thermometer for two different conditions viz. normal tap water and boiling water. For first condition, normal tap water was taken in a beaker and all sensors with ordinary glass thermometer were dipped into the water and placed in such a way that all sensors and thermometer were at the same elevation without touching to each other and then temperature was noted. Further, the water in the beaker was boiled on the heater and again all probes and ordinary thermometer were dipped into the water and placed in such a way that all the sensors and thermometer were at the same elevation and than temperature were noted. Percentage errors were then calculated as shown in Appendix A-I.

3.4.1.3 Thermometers

Electronic thermometer and ordinary glass thermometer (Figure. 3.4) having temperature range from 0-100 °C was used for measurement of maximum and minimum temperature and also used to record temperature of ambient air, air leaving the dryer, temperature at different locations inside the solar tunnel dryer and also for calibrating data-logger’s probes/sensors.

3.4.2 Measurement of relative humidity

A digital relative humidity/temperature meter (Figure. 3.5) manufactured by M/s Lutron Instruments (Lutron HT 3004) was used for measuring relative humidity. It has range of 10 to 95 % of relative humidity and corresponding provision of measuring temperature in the range of 0-60 °C.

3.4.3 Measurement of solar intensity

Solar insolometer manufactured by M/s Lutron Instruments, Taiwan was used for measurement of solar intensity (Figure. 3.6). It has a sensor which senses the solar radiation falling over its surface and displays the insolation in lux. The sensor was kept in a horizontal position. It has range of 200 to 200000 lux. A 9-volt, DC battery was used to operate it.

3.4.4 Measurement of air velocity

Anemometer was used during the experiments for the measurement of air velocity. It was a hand held vane type anemometer (Figure. 3.7) manufactured by M/s Escrop Instruments. It was capable of measuring air velocities up to 54 km/hr. The rotor blades were simply put in the direction of air flow and corresponding velocity was indicated by the
indicator directly in m/s or km/hr or ft/hr or lb/sec. The least count of the indicator is 0.1 m/s. Two batteries of 9 Volt dry DC each were used with this instrument. Air flow was calculated by multiplying air velocity with the area of flow.

Fig. 3.3 Electronic Data logger

Fig. 3.4 Thermometer

Fig. 3.5 Digital Relative Humidity and Temperature Meter

Fig. 3.6 Solar Insolometer

Fig. 3.7 Vane Type Anemometer
3.5 Study of Micro-Climatic Variations inside Solar Tunnel Dryer

The microclimatic variations have been studied inside the solar tunnel dryer under hot and cold climatic conditions throughout the year. Which include the measurement of the natural rise of temperature due to reduced air movement and green house effect, which helps to maintain the desirable thermal conditions for drying and relative humidity inside the solar tunnel dryer.

For studying the microclimatic variation inside a solar tunnel dryer, the following parameters were selected for monitoring:

1. Temperature
2. Moisture content variations
3. Relative humidity
4. Radiant flux density
5. Reflectance and transmittance of radiation
6. Air flow rate

3.5.1 Temperature

3.5.1.1 No load testing in natural convection mode without using solar collectors

The experiments were conducted without product inside dryer for finding out the temperature profile at different locations in solar tunnel dryer. Under this condition the useful heat was extracted by the tunnel dryer. To measures the variation in temperature of air at various location of the dryer, five sensors inside and one outside the tunnel were placed for recording. Sensor number (T1), (T2), (T3), (T4) and (T5) were placed in tunnel at bottom, center, top, towards south from center and towards north from center respectively, as shown in Figure. 3.8 and sensor (T0) was kept outside the dryer.

All temperature readings were registered at interval of one hour, starting from 8:00 hours to 18:00 hours. No load testing in natural convection mode was conducted with a view to find out temperature profile and maximum stagnation temperature attended in inside the solar tunnel dryer during winter and summer to judge effectiveness of the dryer for drying. For this solar insolation, ambient temperature, air temperature variation at different locations of the solar tunnel dryer, ambient relative humidity, relative humidity inside the dryer and air flow rate were measured. The testing during no load without connecting Solar Flat Plate Collectors to the tunnel dryer was made in the month of December and April respectively.
3.5.1.2 No load testing with forced convection mode using solar collectors

No load testing in forced convection mode was also conducted with a view to find temperature profile, relative humidity and solar insolation at different places in solar tunnel dryer in the month of December and April. The experiments were conducted without product inside dryer for finding out the temperature profile at different locations in solar tunnel dryer. To measures the variation in temperature of air at various location of the dryer, five sensors inside and one outside the tunnel were placed same as in no load testing natural convection mode for recording. All temperature readings were registered at interval of one hour, starting from 8:00 hours to 18:00 hours.

3.5.1.3 Full load testing

The full load testing of forced convection type solar tunnel dryer was made for evaluating the performance in actual use for drying. This test was conducted by loading the dryer at its designed capacity and for performance evaluation in actual loaded condition with drying product. To measures the variation in temperature of air at various location of the dryer, five sensors inside and one outside the tunnel were placed for recording. Sensor number (T1), (T2), (T3), (T4) and (T5) were placed in tunnel at bottom, center, top, towards south from center and towards north from center respectively, and sensor (T0) was kept outside the dryer. All temperature data were registered at an interval of one hour by a data logger.
Three trays were loaded containing 500 kg of processed tobacco having moisture content 138 percent (d.b.). The loading was made at 8:00 hrs in morning and corresponding readings were recorded up to 18:00 hrs. at one hour interval. Solar tunnel dryer consists of a drying chamber of 3.75 × 16 m for drying 500 kg processed tobacco per batch. The Processed tobacco spread in thin layers in the sliding trays of 15.9 m × 3.6 m, 15.9 m × 2.5 m, and 15.9 m × 1.6 m size. Incoming air through twelve Flat plate collectors of size 2 m × 1 m and outgoing air forced by two exhaust fans of duct size 450 mm and 250 mm.

Di-basic Calcium Phosphate having moisture content 66 percent (d.b.) was spread in 3 cm thick layer in trays drying full load condition. Total ten trolleys having equally distributed 24 trays of size 80 cm × 40 cm in each trolley were provided to accommodate 1 ton of material at a time in each batch. Each tray carried approximate 4.16 kg of wet material. Drying tests were started at 8:00 hours and stopped at 18:00 hours in the month of December and April.

3.5.2 Moisture content variations

3.5.2.1 Determination of moisture content

The moisture content of the product was determined by oven drying method. Sample of the product were weighed and placed in the oven at temperature of 105 °C for 24 h for drying. Then the samples were again weighed and their moisture content was determined as per standard formula. Moisture content was determined by two methods (i) Wet basis (w.b.) and (ii) Dry basis (d.b.).

The moisture content on wet basis was computed using the following formula.

\[ M_{wb} = \frac{W_o - W_d}{W_o} \times 100 \]

The moisture content on dry basis was computed using the following formula.

\[ M_{db} = \frac{W_o - W_d}{W_d} \times 100 \]

Where,

\[ M_{wb} = \text{Moisture content in wet basis, } (\%) \]

\[ M_{db} = \text{Moisture content in dry basis, } (\%) \]

\[ W_o = \text{Initial weight of sample, kg} \]

\[ W_d = \text{Bone dry weight of sample, kg} \]
3.5.2.2 Determination of moisture ratio

The moisture ratio was calculated by using the following equation

\[ MR = \frac{M - M_e}{M_0 - M_e} = e^{-kt} \]

Where,
- \( MR \) = Moisture ratio
- \( M \) = Moisture content at any time \( \theta \), % (db)
- \( M_e \) = Equilibrium moisture content, % (db)
- \( M_0 \) = Initial moisture content, % (db)
- \( k \) = Drying constant,
- \( \theta \) = time, h

3.5.2.3 Determination of drying rate

Drying rate was calculated from the following equation

\[ k = \frac{W_L}{T} \]

Where,
- \( K \) = Drying rate, g/min
- \( W_L \) = Amount of moisture evaporated, g
- \( T \) = Time taken, min

3.5.3 Relative humidity

The ratio of actual vapour pressure in air water mixture and the saturated water vapour at same temperature is known as the relative humidity of air and expressed in percentage. It is largely dependent on atmospheric temperature. During experiment the relative humidity was measured by digital hygrometer and recorded.

3.5.4 Radiant flux density

Radiant flux density is an important parameter in energy balance of atmosphere and earth surface. All bodies emit energy in the form of electromagnetic waves, when they are at a temperature above absolute zero. The source of this thermal radiation or temperature radiation is in the molecular motion. During collision or more generally as a result of interaction between molecules; part of their energy is transformed into radiation. The emission and the absorption of thermal radiation are governed by the temperature and nature of emitting and absorbing substance. It is expressed in \( \text{W/m}^2 \).
3.5.5 Determination of air flow rate

Vane type anemometer was used to measure air velocity inside the dryer. The air flow rate was calculated using the formula
Air flow rate, m³/h = Air velocity, m/h × Area of inlet opening, m²

3.6 Performance Evaluation of Solar Collector

The performance of solar collector was evaluated in terms of collector efficiency. The hourly collector efficiency was calculated by following formula for each day.

3.6.1 Determination of mass flow rate

The mass flow rate of air was calculated using the formula
Mass flow rate, kg/h = Air flow rate, m³/h × Density of air, kg/m³

3.6.2 Determination of heat gained by drying air

Heat gained by air in the solar tunnel dryer was calculated by using the formula

\[ Q_s = m \cdot C_a \cdot (T_2 - T_1) \]

Where,
- \( Q_s \) = Heat gained by the drying air, kcal/h
- \( m \) = Mass flow rate, kg/h
- \( C_a \) = Specific heat of air, kcal/kg °C
- \( T_1 \) = Ambient temperature, °C
- \( T_2 \) = Dryer air temperature, °C

3.6.3 Collection efficiency (\( \eta_c \))

Collection efficiency is defined as the ratio of heat received by the drying air to the insolation upon the absorber surface of flat plate collector and is calculated from the following equation.

\[ \eta_c = \frac{V \times \rho \times \Delta T \times C_p}{A_c \times I_c} \]

Where,
- \( V \) = Volumetric flow rate of air (m³/s⁻¹)
- \( \rho \) = Air density (kg/m³)
- \( \Delta T \) = Air temperature elevation (K)
- \( C_p \) = Air specific heat (J/kg °C⁻¹)
- \( A_c \) = Collector area (m²)
- \( I_c \) = Insolation on collector surface (W/m²)
Since $\eta_c$ is a means of assessing the performance of the flat plate collector, it was calculated using the readings of no load tests.

3.6.4 System drying efficiency ($\eta_d$)

This parameter is defined as the ratio of the energy required to evaporate the moisture to the energy supplied to the dryer. For solar calculations the heat supplied to the dryer is the insolation upon the collector. The system drying efficiency is calculated from the following equation.

$$\eta_d = \frac{w \times \Delta HL}{I_d \times A_c}$$

Where,

- $w$ = moisture evaporated (kg),
- $\Delta HL$ = latent heat of vaporization of water, 2320 (kJ/kg$^{-1}$),
- $I_d$ = total hourly insolation upon collector, (kJ/m$^2$)
- $A_c$ = area of collector (m$^2$)

3.6.5 Pick-up efficiency ($\eta_p$)

This parameter is more useful for evaluating the actual evaporation of moisture from the commodity inside the solar dryer. The pick-up efficiency is defined as the ratio of moisture ‘picked up’ by the air in the drying chamber to the theoretical capacity of the air to absorb moisture. The pick-up efficiency can also be calculated from the following equation.

$$\eta_p = \frac{w}{V \times \rho \times t \times (h_{as} - h_i)}$$

Where,

- $w$ = moisture evaporated (kg),
- $V$ = air flow rate (m$^3$ s$^{-1}$),
- $\rho$ = air density (kg m$^{-3}$),
- $t$ = drying time (s),
- $h_i$ = absolute humidity of air entering the drying chamber,
- $h_{as}$ = adiabatic saturation humidity of the air

3.7 Economic Analysis of Solar Tunnel Dryer in Actual Use

For the success and commercialization of any new technology, it is essential to know whether the technology is economically viable or not. Therefore, an attempt was made to determine economics of the solar tunnel dryer. Different economic indicators were used for economic analysis of solar system under this study.
1. Net present worth (NPW)
2. Benefit cost ratio (B/C ratio)
3. Pay back period

3.7.1 Net present worth (NPW)

This is simply the present worth of the cash flow stream. The difference between the present value of all future returns and the present money required to make an investment is the net present worth or net present principal for the investment. The present values of the future returns calculated through the use of discounting. Discounting is essentially a technique by which future benefits and cost streams can be reduced to their present worth. The process of finding the present worth of a future value is called discounting. The discounting rate is the interest rate assumed for discounting.

The most straightforward discounted cash flow measure of project worth is the Net Present Worth (NPW). The net present worth may be computed by subtracting the total discounted present worth of the cost stream from that of the benefit stream. To obtain the incremental net benefit, gross cost was subtracted from gross benefit or the investment cost from the net benefit. The mathematical statement for net present worth can be written as:

\[
NPW = \sum_{t=1}^{n} \frac{B_t - C_t}{(1 + i)^t}
\]

Where,
- \(C_t\) = Cost in each year
- \(B_t\) = Benefit in each year
- \(t = 1, 2, 3, \ldots \ldots n\)
- \(i = \) discount rate

3.7.2 Benefit cost ratio

This is the ratio obtained when the present worth of the benefit stream is divided by the present worth of the cost stream. The formal selection criterion for the benefit-cost ratio for measure of project worth was to accept projects for a benefit-cost ratio of 1 or greater.

In practice, it is probably more common not to compute the benefit-cost ratio using gross cost and gross benefit, but rather to compare the present worth of the net benefit with the present worth of the investment cost plus the operation and maintenance cost. The ratio is computed by taking the present worth of the gross benefit less associated cost and then comparing it with the present worth of the project cost. The associated cost is the value of goods and services over and above those included in project costs needed to make the
immediate products or services of the project available for use or sale. Project economic cost is the sum of installation costs, operation and maintenance cost and replacement costs.

The mathematical benefit-cost ratio can be expressed as:

\[
\text{Benefit-cost ratio} = \frac{\sum_{t=1}^{n} B_t}{\sum_{t=1}^{n} C_t (1 + i)^t} 
\]

Where,
- \( C_t \) = Cost in each year
- \( B_t \) = Benefit in each year
- \( t = 1, 2, 3, \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots n \) (year)
- \( i \) = discount rate

3.7.3 Payback period

The payback period is the length of time from the beginning of the project until the net value of the incremental production stream reaches the total amount of the capital investment. It shows the length of time between cumulative net cash outflow recovered in the form of yearly net cash inflows.

The payback period of the project is estimated by using the straightforward formula:

\[
P = \frac{I}{E}
\]

Where,
- \( P \) = Payback period of the project in years
- \( I \) = Investment of the project in rupees and
- \( E \) = Annual net cash revenue in rupees