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Thermal Modelling and Experimental Validation of a Walk-in Type Solar Tunnel Dryer for Drying *Fenugreek* Leaves (Methi) in Indian Climate

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Abstract This paper presents the thermal modelling and experimental validation of a walk-in type solar tunnel dryer for drying of *fenugreek* leaves in Indian climatic conditions. The tunnel dryer is a metallic framed structure covered with a 200-μm ultraviolet stabilized plastic sheet. This dryer has a 5×3.75-m floor area and is 1.75 m in height. Its loading capacity of leafy vegetables is about 100 kg. The dryer works on natural convection mode, and maximum temperature attained during experiment was 58.11 °C. Fenugreek leaves were dried from moisture content of 89 % (wb) to 9 % (wb) in 17 solar hours under typical Indian climatic conditions. Experimental energy and exergy efficiency of drying chamber ranged from 2.72 to 28.01 % and 69.43 to 90.76 % respectively. The mathematical modelling was programmed in MATLAB version 2010a. The theoretical results agreed well with experiential data for drying of fenugreek leaves. Some additional parametric studies and payback period analysis are presented.

Keyword Thermal model · Exergy analysis · Energy analysis · Solar drying · Tunnel dryer

1 Introduction

The demand for food products is rising with the increasing global population. Such demands can be minimized by increasing agricultural produce and facilitating safe storage. Drying of agricultural produce is the universal method for preserving food material; it also helps to achieve better product quality, increase shelf life, reduce post-harvest loss and extend the economic life of these agricultural products without losing nutritional properties before consumption [1–6].

Solar dryers have presented high potential, and their demand is increasing continuously in developing countries like India as an alternative to open-air drying [7]. Drying is the process of moisture removal through simultaneous heat and mass transfer [8]. The drying process mainly depends on air temperature, wind velocity, relative humidity of the air, airflow rate, physical nature and initial moisture content of the drying product, and the surface characteristics of product [9]. Thin-layer and deep-bed drying are common drying methods. Most agricultural producers have adopted the thin-layer drying. There is a vast and exhaustive literature available for thin-layer drying kinematics of agricultural produce, and carried out by several scientists and academicians [10–21]. A number of research studies have also been reported on the modelling of a greenhouse-type dryer integrated with a hot air collector [22–30].

Although, research studies on the performance evaluation of the solar tunnel dryer have been reported in literature [31–35]. Still limited studies on thermal modelling of a walk in type solar tunnel dryers are available. The exhaustive study on thermal modelling and experimental validation of large-scale polyethylene-covered greenhouse solar dryer for drying banana, chilli and coffee under Thailand climatic condition was reported by Janjai et al. [36] and Intawee and Janjai [37]. But, there is no such similar and validation study reported so far in Indian climatic conditions. During the drying of agricultural commodities, it is important to remove moisture from the produce as quickly as possible at a temperature that does not seriously affect the flavour, texture and colour of the product. The air temperature is responsible for the phenomenon. It is essential to develop a model to assess to environmental parameters of drying air. The model considers mainly the heat transfer mechanisms at the different components of dryer and shows how inside environmental conditions vary

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corresponding to solar radiation. The experiment was carried out for drying of fenugreek leaves in the walk-in type solar tunnel dryer to verify the accuracy of the developed model.

The dryer chosen for study is a low-cost option for farm drying at a large scale. Fenugreek leaves are basically a kind of green leafy vegetable and have a slightly bitter taste. The leaves are available only in winter season of Indian climatic conditions. Most of the people dry it in an open sun, to use it in off-season. Fenugreek leaves stimulate the digestive process as well as the metabolism. A range of 18 to 26% of protein in 17 varieties of fenugreek is found. A wide variation in hemi-celluloses and cellulose contents was also found. This is the reason why it is used by people [38, 39].

2 Materials and Methods

2.1 Dryer Description

Rathore and Panwar [34] conducted an experimental study on grape drying under a walk-in type solar tunnel dryer. In the present study, we have carried out thermal modelling and experimental validation of this dryer. The dryer has been commissioned at College of Technology and Engineering, Udaipur (27′ 42° N, 75′ 33° E) for drying agricultural produces. The walk-in type solar tunnel dryer consists of a metallic-type frame structure covered with a UV-stabilized semi-transparent polyethylene sheet of 200-μm thickness as illustrated in Fig. 1, and its technical specification is presented in Table 1. The dryer works on natural draft mode, and to maintain such a draft; chimneys are provided on the top of the dryer. It is the well-known fact that natural draft works on buoyancy force, and it is directly proportional to the difference between the mean air density within the chimney and the density of outside air [40]. The perforated bench is provided to spread the produce over it. This dryer is capable of drying

Table 1 Technical specification of solar tunnel dryer

Location	Udaipur (27′ 42° N, 75′ 33° E)
Floor area	18.75 m^2
Diameter of dryer	3.75 m
Length of dryer	5.0 m
Number of chimney	2
Height of chimney	0.44 m.
Diameter of chimney	0.20 m
Thickness of plastic cover	200 μ (UV-stabilized)

all types of agriculture produces at 50–60 °C, and it is maintained at 10–20 °C above the ambient temperature as suggested by earlier studies [2].

Fresh fenugreek (methi) leaves were purchased from a local market and washed thoroughly in fresh water, and roots were removed. After washing and weighing, the methi with stem, just as farmer dries it in open field conditions, was loaded in the tray as shown in Fig. 2.

2.2 Instrumentation

The global solar radiation incident on a horizontal surface was measured by using a Kipp & Zonen, SP Lite2 type Solar Pyranometer. Ambient wind speed and exit air velocity at the chimney outlet were measured using an anemometer (Lutron Model No. AM-4822) and hot wire anemometer (Model No. LM-4204) respectively. Calibrated NiCr–Ni thermocouples connected to a multi-channel temperature scanner (ADI, Vadodara, Gujarat, India) were used to measure the temperatures inside the dryer at the different positions. The ambient temperature and moisture content (wb) of product during drying were also measured. Total experimental uncertainties of different parameters measured during the experiment were calculated and are presented in Table 2.

Fig. 1 Experimental solar tunnel dryer

Fig. 2 Inside view of solar dryer with drying product

Table 2 Uncertainties of the experimental parameter

Parameters	Unit	Uncertainty
Uncertainty in the solar energy measurement	W m^{-2}	±0.17
Uncertainty in the temperature measurement	°C	±0.17
Uncertainty in the relative humidity measurement	Rh	±0.14
Uncertainty in the exit air velocity measurement	m s^{-1}	±0.14
Uncertainty in the air velocity measurement	m s^{-1}	±0.17

3 Mathematical Modelling

The present thermal modelling work was inspired by work of Janjai et al. [36]. A thermal model to assess the thermal performance of a tunnel dryer was developed. The following assumptions were made while developing the thermal model:

(a) There is no stratification of the air inside the tunnel dryer.
(b) Drying computation is based on a thin-layer drying model.
(c) Specific heat of air, cover and product are constant.
(d) Absorptivity of air is negligible.
(e) Radiative heat transfers from the floor to the cover and from the floor to the product are negligible.

Schematic diagram of heat transfers of the solar tunnel dryer and the energy flows through different components of the dryer is shown in Fig. 3.

3.1 Energy Balance of the Cover

The tunnel is covered with a UV-stabilized low-density plastic sheet. Solar radiations falling on cover are allowed to be transmitted inside the tunnel. Energy balances on the tunnel cover are considered as follows:

The thermal energy accumulation in the tunnel cover = convective heat transfer between air inside the tunnel and cover + radiative heat transfer between the sky and the cover due to radiation + convective heat transfer between cover and ambient air + radiative heat transfer between the product and the cover + solar radiation absorbed by the cover.

Energy balance of the cover is as follows:

$$Q_{th-c} = Q_{c,c-a} + Q_{r,c-s} + Q_{c,c-w} + Q_{r,p-c} + Q_{ab}$$

$$m_c C_{pc}\left(\frac{dT_c}{dt}\right) = A_c h_{c,c-a}(T_a - T_c) + A_c h_{r,c-s}(T_s - T_c) + A_c h_w(T_{am} - T_c) + A_p h_{r,p-c}(T_p - T_c) + A_c \alpha_c I_s \quad (1)$$

where

rate of thermal energy accumulated in the cover

$$Q_{th\_cover} = m_c C_{pc}\left(\frac{dT_c}{dt}\right)$$

convective heat transfer between air inside the tunnel and cover

$$Q_{c,c-a} = A_c h_{c,c-a}(T_a - T_c)$$

radiative heat transfer between the sky and the cover due to radiation

$$Q_{r,c-s} = A_c h_{r,c-s}(T_s - T_c)$$

convective heat transfer between cover and ambient air

$$Q_{c,c-w} = A_c h_w(T_{am} - T_c)$$

radiative heat transfer between the product and the cover

$$Q_{r,p-c} = A_p h_{r,p-c}(T_p - T_c)$$

solar radiation absorbed by the cover

$$Q_{s,c} = A_c \alpha_c I_s$$

3.2 Energy Balance of Air Inside the Tunnel

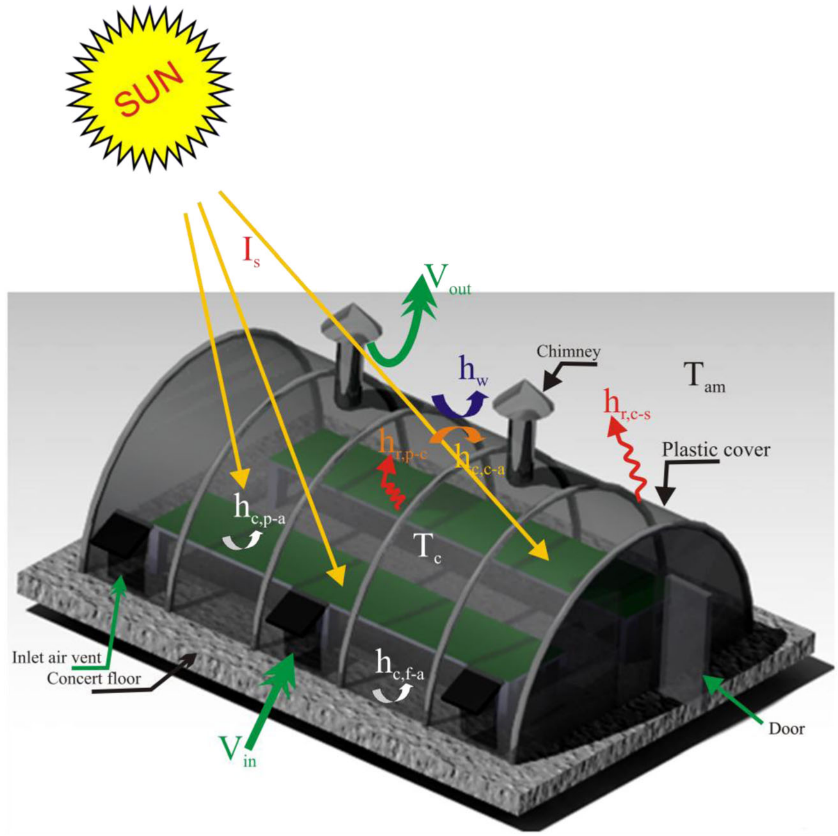
Air inside the tunnel dryer gets heated because of convective heat transfer among the floor, product and air. The energy balances for the same can be written as follows:

Thermal energy accumulation in the air inside the tunnel dryer = convective heat transfer between product and air + convective heat transfer between floor and air + thermal energy gain of air from product due to sensible heat transfer + thermal energy gained by air inside the dyer due to inflow and outflow of the air in the chamber + overall heat loss from the air inside the dryer to ambient + solar energy absorbed by the air inside the dryer.

Energy balance of air inside the tunnel dryer is as follows:

$$Q_{th\_air} = Q_{c,p-a} + Q_{c,f-a} + Q_{s,a-p} + Q_{t,gain} + Q_{l,am} + Q_{s,ab}$$

Fig. 3 Schematic of heat transfer flows in solar tunnel dryer



$$m_aC_{pa}\left(\frac{dT_a}{dt}\right) = A_ph_{c,p-a}\left(T_p-T_a\right) + A_fh_{c,f-a}\left(T_f-T_a\right) + D_pA_pC_{pw}\rho_p\left(T_p-T_a\right)\frac{dM_p}{dt} + \rho_aV_{out}C_{pa}T_{out}-\rho_aV_{in}C_{pa}T_{am} + U_cA_c(T_{am}-T_a) + \left[\left(1-F_p\right)\left(1-a_f\right) + \left(1-a_f\right)F_p\right]I_sA_c\tau_c \quad (2)$$

where

thermal energy accumulated in the air inside the dryer

$$Q_{th\_air} = m_aC_{pa}\left(\frac{dT_a}{dt}\right)$$

convective heat transfer between product and air

$$Q_{c,p-a} = A_ph_{c,p-a}\left(T_p-T_a\right)$$

convective heat transfer between floor and air

$$Q_{c,f-a} = A_fh_{c,f-a}\left(T_f-T_a\right)$$

thermal energy gain of air from product due to sensible heat transfer

$$Q_{s,a-p} = D_pA_pC_{pv}\rho_p\left(T_p-T_a\right)\frac{dM_p}{dt}$$

thermal energy gain by air inside the dyer due to inflow and outflow of the air in the chamber

$$Q_{t,gain} = \rho_aV_{out}C_{pa}T_{out}-\rho_aV_{in}C_{pa}T_{am}$$

overall heat loss from the air inside the dryer to ambient

$$Q_{l,am} = U_cA_c(T_{am}-T_a)$$

solar energy absorbed by the air inside the dryer

$$Q_{s,air} = \left[\left(1-F_p\right)\left(1-\alpha_f\right) + \left(1-\alpha_f\right)F_p\right]I_sA_c\tau_c$$

3.3 Energy Balance of the Product

Convective and radiative are major heat transfer modes while balancing energy of the product inside the tunnel. The energy balances energy for the same can be written as follows:

The thermal energy accumulation in the product = convective heat transfer between product and air + radiative heat transfer between product and cover + thermal energy lost from the product due to sensible and latent heat transfer + thermal energy gain by the product.

The energy balance on the product gives

$$Q_{th\_pro} = Q_{c,p-a} + Q_{r,p-c} + Q_{lost} + Q_{s,pro}$$

$$\begin{aligned} m_p\left(C_{pp} + C_{pl}M_p\right)\frac{dT_p}{dt} &= A_p h_{c,p-a}\left(T_a - T_p\right) \\ &+ A_p h_{r,p-c}\left(T_c - T_p\right) \\ &+ D_p A_p \rho_p L_p \frac{dM_p}{dt} \\ &+ F_p \alpha_p I_s A_c \tau_c \end{aligned} \tag{3}$$

where

thermal energy accumulation in the product

$$Q_{th\_pro} = m_p\left(C_{pg} + C_{pl}M_p\right)\frac{dT_p}{dt}$$

convective heat transfer between product and air

$$Q_{c,p-a} = A_p h_{c,p-a}\left(T_a - T_p\right)$$

radiative heat transfer between product and cover

$$Q_{r,p-c} = A_p h_{r,p-c}\left(T_c - T_p\right)$$

thermal energy lost from the product due to sensible and latent heat transfer

$$Q_{lost} = D_p A_p \rho_p L_p \frac{dM_p}{dt}$$

solar thermal energy gain by the product

$$Q_{s,pro} = F_p \alpha_p I_s A_c \tau_c$$

3.3.1 Energy Balances on the Concrete Floor

Thermocol sheet was sandwiched between dyer floor and the ground to reduce the conductive heat losses. The energy balances on the concrete floor of the tunnel dryer can be considered as follows:

Thermal energy accumulation in the floor = heat transfer between air inside the tunnel and the floor due to convection + solar radiation absorption on the floor.

The energy balance on the concrete floor of the tunnel dryer can be written as

$$Q_{th\_floor} = Q_{c,f-a} + Q_{s,floor}$$

$$m_f C_{pf}\frac{dT_f}{dt} = A_f h_{c,f-a}\left(T_a - T_f\right) + \left(1 - F_p\right)\alpha_f I_s A_f \tau_c \tag{4}$$

where

Thermal energy accumulation in the floor

$$Q_{th\_floor} = m_f C_{pf}\frac{dT_f}{dt}$$

convective heat transfer between inside dryer air and the floor

$$Q_{c,f-a} = A_f h_{c,f-a}\left(T_a - T_f\right)$$

solar radiation absorption on the floor

$$Q_{s,floor} = \left(1 - F_p\right) a_f I_s A_f \tau_c$$

3.4 Mass Balance Equation

Air temperature inside the tunnel dryer is higher than corresponding ambient temperature. It increases the ability to pick up moisture from the product, and the product gets dried.

The rate of moisture accumulation in the air inside tunnel dryer = moisture inflow into the dryer due to entry of ambient air + moisture outflow with exit air from the tunnel dryer + moisture removed from the product inside the dryer.

The mass balance inside the tunnel dryer can be written as

$$M_{in\_air} = M_{inflow} + M_{outflow} + M_{rem}$$

$$\rho_a V \frac{dH}{dt} = A_{in}\rho_a H_{in} v_{in} - A_{out}\rho_a H_{out} v_{out} + D_p A_p \rho_p \frac{dM_p}{dt} \quad (5)$$

where

The rate of moisture accumulation in the air inside tunnel dryer

$$M_{in\_air} = \rho_a V \frac{dH}{dt}$$

moisture inflow into the dryer due to entry of ambient air

$$M_{\mathrm{inflow}} = A_{in}\rho_a H_{in} \nu_{in}$$

moisture outflow with exit air from the tunnel dryer

$$M_{outflow} = A_{out}\rho_a H_{out} \nu_{out}$$

moisture removed from the product inside the dryer

$$M_{rem} = D_p A_p \rho_p \frac{dM_p}{dt}$$

3.4.1 Heat Transfer and Heat Loss Coefficient

Radiative heat transfer coefficient from the cover to the sky ($h_{r,c\text{–}s}$) was computed according to Duffie and Beckman [46]:

$$h_{r,c-s} = \varepsilon_c \sigma \left(T_c^2 + T_s^2\right)(T_c + T_s) \quad (6)$$

Radiative heat transfer coefficient between the product and cover ($h_{r,p-c}$) is computed as suggested by Duffie and Beckman [46]:

$$h_{r,p-c} = \varepsilon_p \sigma \left(T_p^2 + T_c^2\right)(T_p + T_c) \quad (7)$$

The correlation with sky temperature (T_s) and ambient temperature (T_{am}) is adapted from Diffie and Becman [41]:

$$T_s = 0.552 (T_{am})^{1.5} \quad (8)$$

Convective heat transfer coefficient from the cover to ambient due to wind (h_w) is computed as [42]

$$h_w = 2.8 + 3.0 V_w \quad (9)$$

Convective heat transfer coefficient inside the solar greenhouse dryer for either the cover or product and floor (h_c) is computed from the following relationship:

$$h_{c,f-a} = h_{c,c-a} = h_{c,p-a} = h_c = \frac{Nuku}{D_h} \quad (10)$$

where D_h is given by

$$D_h = \frac{4WD}{2(W+D)} \quad (11)$$

Nusselt number (Nu) is computed from the following relationship [43]:

$$Nu = 0.0158 \mathrm{Re}^{0.8} \quad (12)$$

Reynolds number is given by

$$\mathrm{Re} = \frac{D_h V_a \rho_a}{v} \quad (13)$$

As the wind speed outside the dryer and the speed of drying air inside the dryer are very low, it is assumed that the overall heat loss coefficient (U_c) of heat transfer from air inside the dryer to ambient air is approximately equal to the conductive heat transfer coefficient of the cover. This coefficient can be written as

$$U_c = \frac{k_c}{\delta_c} \quad (15)$$

Humidity ratio (H) is given as

$$H = 0.62198 \frac{Pws}{\left[(100 \times P_{vp}) - P_{ws}\right]} \quad (16)$$

Saturation vapour pressure (P_{ws}) is calculated by Weiss [44] expression:

$$P_{ws} = 0.61078exp(17.2694T_a)/(T_a + 237.3) \tag{17}$$

Vapour pressure (P_{vs}) is calculated by Antoine expression as shown in Singh and Kaushik [45]:

$$P_{vp} = \exp\left(25.317 - \frac{5144}{T_a}\right) \tag{18}$$

Relative humidity (R_h) is given as

$$R_h = \frac{P_{vp}}{P_{ws}} \tag{19}$$

4 Thin-Layer Drying Equation

The thin-layer drying equation developed by Janjai [46] for drying tomato under greenhouse-type dryer similar to tunnel dryer was used to estimate the moisture ratio as follows:

$$M_p = MR = \frac{M - M_e}{M_o - M_e} = \exp\left(-At^B\right) \tag{20}$$

4.1 Software Description

MATLAB 2010a was used for computing the unknown of Eqs. (1) to (5). The inbuilt first-order differential equation ODE45 was used. The input values of data were read from Excel using MATLAB; the values were then written back to the same Excel file. The flow chart of solution is illustrated in Fig. 4. The input parameters are given in Table 3.

5 Energy and Exergy Assessment

5.1 Energy Assessment

The heat utilized during drying process can be estimated by using the following formula:

$$Q_{utl} = m_a(h_a - h_{out}) \tag{21}$$

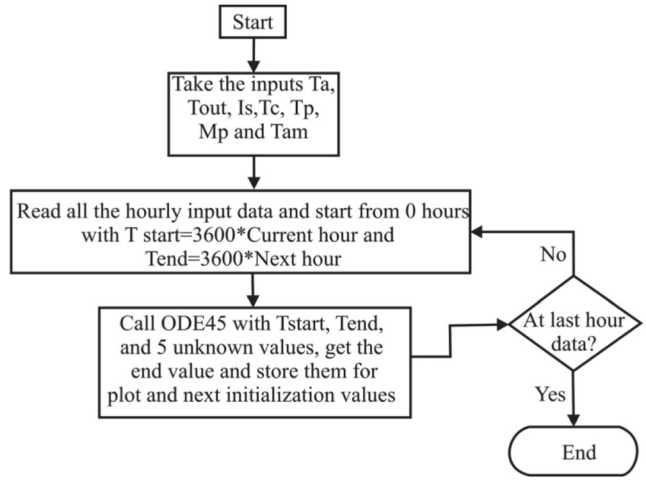


Fig. 4 Flow chart of simulation procedure

The instantaneous useful energy gained from the solar tunnel dryer was calculated using the following equation:

$$Q_{gain} = 1_s \times A_c \tag{22}$$

The energy utilization ratio (EUR) in solar tunnel dryer is as follows:

$$EUR = \frac{Q_{utl}}{Qgain} = \frac{m_a(h_{in} - h_{out})}{1_s \times A_c} \tag{23}$$

Table 3 The parameter used for MATLAB computation of tunnel dryer

Parameters	Values	Parameters	Values
A_c	29.45 m^2	α_c	0.80
A_f	18.75 m^2	α_f	0.80
A_{in}	0.039 m^2	α_p	0.90
A_{out}	0.0628 m^2	δc	0.2×10^{-3}
A_p	1.67 m^2	σ	5.67×10^{-8}
C_{pa}	1,005 J kg^{-1} K^{-1}	ρ_c	930 kg m^{-3}
C_{pc}	2,500 J kg^{-1} K^{-1}	ρ_p	1,100 kg m^{-3}
C_{pf}	750 J kg^{-1} K^{-1}	τc	0.92
C_{pl}	4,186 J kg^{-1} K^{-1}	εc	0.9
C_{pp}	4,220 J kg^{-1} K^{-1}	εp	0.88
C_{pv}	1,864 J kg^{-1} K^{-1}	v	15.11×10^{-6} m^2 s^{-1}
D_p	0.03 m		
F_p	0.80		
k_a	0.025 W m^{-1} K^{-1}		
k_f	1.28 W m^{-1} K^{-1}		
L_p	2,257 × 10^{-3} J kg^{-1}		
M_o	809.09 (% db)		
W	3.75 m		

5.2 Exergy Analysis

Exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment [46–52]. Exergy is a true measurement of the quality or grade of energy, and it can be destroyed in the thermal system. The second law states that part of the exergy entering a thermal system may be destroyed within the system due to irreversibilities.

The exergy analysis is carried out considering the steady flow systems; the exergy equation can be derived by simplification of the general exergy equation as [53]

$$Exergy = \overline{c}_p\left[(T - T_\infty) - T_\infty \ln\frac{T}{T_\infty}\right]$$

The equation of exergy inflow into tunnel dryer can also be written as follows:

$$Ex_{inflow} = C_{pa}\left[(T_a - T_\infty) - T_\infty \ln\frac{T_a}{T_\infty}\right] \quad (24)$$

Exergy outflow for solar tunnel dryer is as follows:

$$Ex_{outflow} = C_{pa}\left[(T_{out} - T_\infty) - T_\infty \ln\frac{T_{out}}{T_\infty}\right] \quad (25)$$

$$Exergy\ loss = Exergy\ inflow$$
$$\sum Ex_L = \sum Ex_I - \sum Ex_o$$
$$Exergetic\ Efficiency = \frac{Exergy\ inflow - Exergy\ loss}{Exergy\ inflow}$$

$$\eta_{Ex} = 1 - \frac{Ex_{Loss}}{Ex_{inflow}} \quad (26)$$

6 Statistical Analysis of Proposed Model

In order to assess the consistencies between predicted and measured air temperature, a statistical analysis was carried out. The standard error (SE), root-mean-square error (RSME) and coefficient of correlation (r) parameters used in the study are defined after Holman [54], 2010:

Standard error (SE) is given as

$$SE = \frac{\sigma}{\sqrt{n}} \quad (27)$$

where

$$\sigma = \left[\frac{\sum_{i=1}^{n}\left(x_{\exp} - x_{pre}\right)^2}{n-1}\right]^{1/2}$$

root-mean-square error ($RMSE$)

$$RMSE = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left[x_{i,\exp} - x_{i,pre}\right]^2} \quad (28)$$

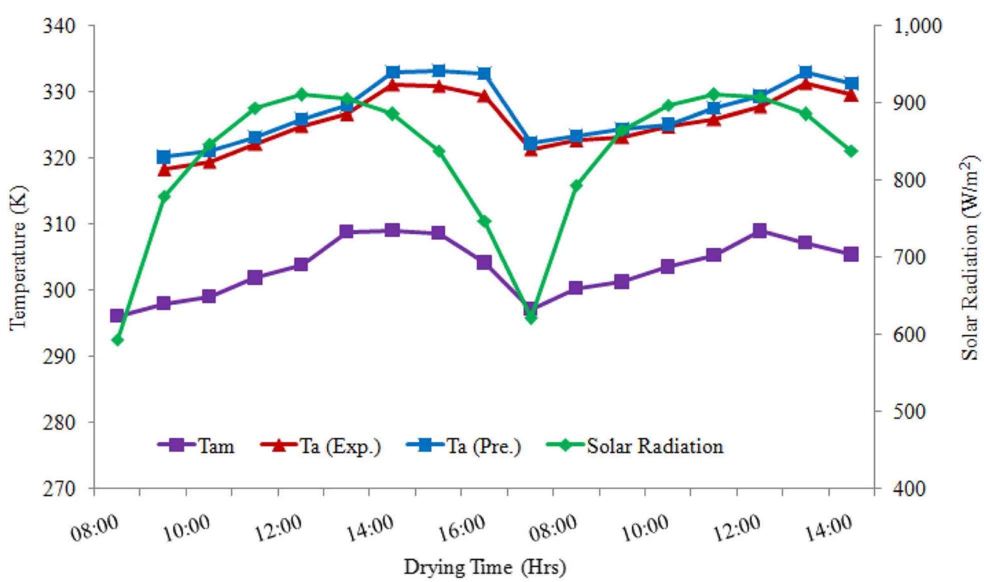


Fig. 5 Variation in experimental and predicted temperature with time for consecutive days

Table 4 Results of error estimation of air temperature inside the dryer

Parameters	Inside air temperature
Standard error (SE)	0.426
Root mean square error (RSME)	0.413
Correlation coefficient (*r*)	0.990

A relationship for the correlation coefficient (r) may be preferable as follows:

$$r=\frac{n\sum x_{\exp}x_{pre}-\left(\sum x_{\exp}\right)\left(\sum_{xpre}\right)}{\left[n\sum x_{\exp}^{2}-\left(\sum x_{\exp}\right)^{2}\right]^{1/2}\left[n\sum x_{pre}^{2}-\left(\sum x_{pre}\right)^{2}\right]^{1/2}} \quad (29)$$

7 Results and Discussion

7.1 Drying Air Temperature

The inside air temperature plays a major role in removing moisture from a wet product. Drying chamber air temperature should be higher than the ambient air temperature. Maximum air temperature attained during the experiment was around 58.11 °C. The difference between predicted and experimental air temperature was in the range of 0.41–3.34 °C as illustrated in Fig. 5. Equations (27), (28) and (29) are used for statistical assessment and the differences between the experimental and predicted values in terms of standard error (SE), root mean square error (RSME), and coefficient of correlation (r). The values of these statistical parameters for air temperature inside the tunnel dryer are presented in Table 4. The values of the correlation coefficients (r) were greater than 0.97 for air the temperature inside the tunnel dryer; thus, it is demonstrated that the proposed analytical model can provide a good fit with the experimental values.

7.2 Energy Analysis

Energy output is the function of enthalpy (Eq. (21)), and it is higher for higher enthalpy; it also affects the energy utilization ratio. The enthalpy difference between air inside the dryer and outlet air is low as compared to the predicted value of air inside the tunnel, and that is why the experimental EUR is lower than that for the corresponding predicted EUR. Figure 6 illustrates the variation in experimental and predicted energy utilization ratio with time for consecutive days. Experimental EUR varies in the range of 2.72–28.01 %, whereas predicted EUR varies in terms in a range of 15.01–44.03 %.

7.3 Exergy Analysis

The predicted exergy efficiency of drying chamber is lower than that of corresponding experimental exergy efficiency.

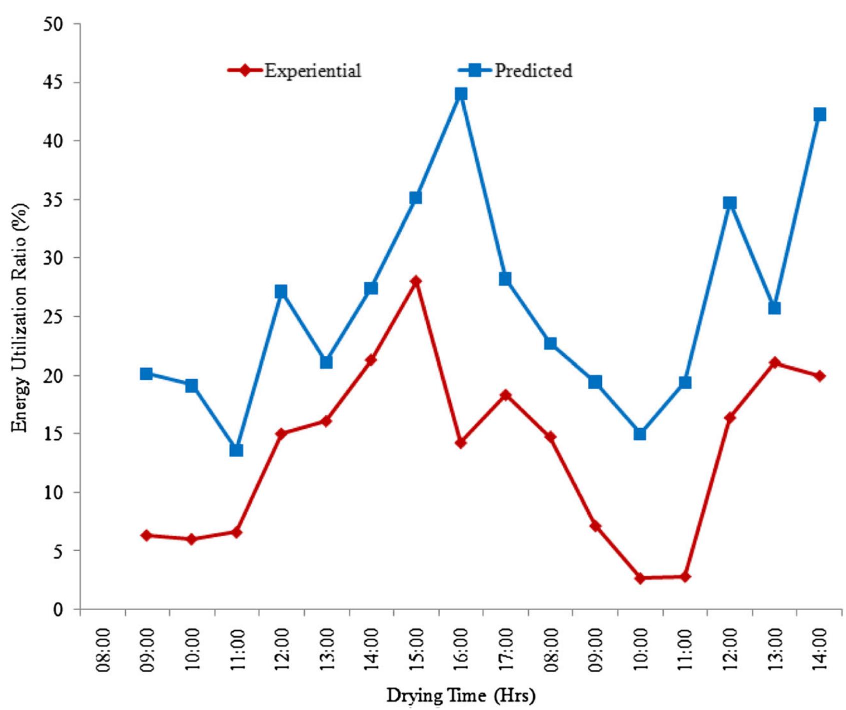


Fig. 6 Variation in energy utilization ratio with time for consecutive days

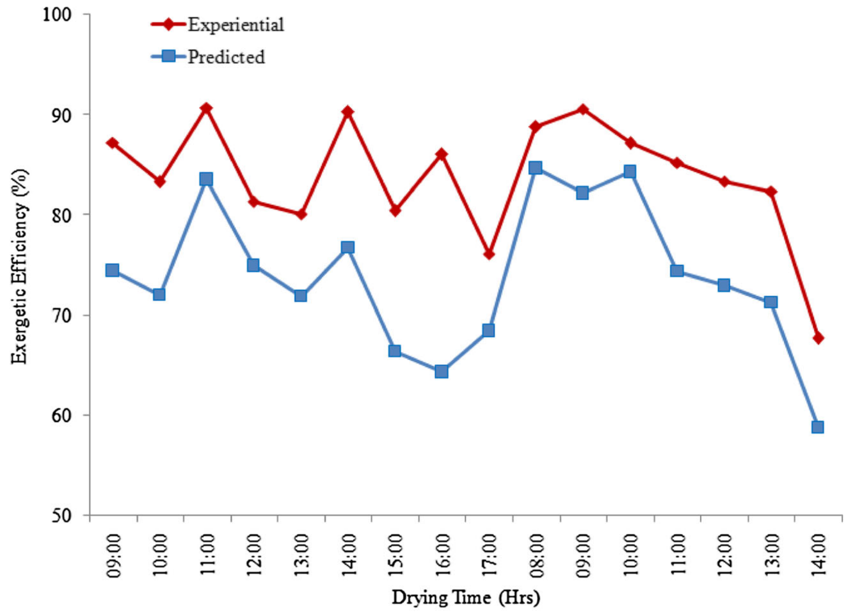


Fig. 7 Variation in experimental and predicted exergetic efficiency with time for consecutive days

The exergy inflow is the function of temperature difference, such that higher difference in temperature indicates lower exergy efficiency. The predicted air temperature is higher than experimental values, which increase the temperature difference; that is why exergy efficiency with predicted drying air temperature is lower compared to the experimental values. Experimental exergy efficiency during the first day of experiment ranged from 69.43 to 90.76 %, and during the second day, it ranged from 66.40 to 87.17 %. The predicted exergy efficiency for the first day ranged from 51.93 to 83.57 %, whereas for the second day, it ranged from 59.29 to 84.32 % as illustrated in Fig. 7.

7.4 Economic Assessment

The values of the correlation coefficients (r) for predicted drying air were greater than 0.97; thus, it provided a good fit with the experimental values. It is a well-known fact that a model developed for any application is viable only when it has a good fit with experimental values. With this justification, economic evaluation was carried out for its viability. The developed dryer can accommodate 100 kg of fresh fenugreek leaves. Component-wise cost of a solar tunnel dryer is presented in Table 5. Fenugreek leaves are normally available during months of February and March in Indian market. The price of freshly harvested fenugreek leaves is 0.2 USD per kilogram. Table 6 shows the cost analysis and simple payback period analysis of a tunnel dryer. The capital cost can be recovered in 11 drying batches, which take 22 working days. In the off-season, other seasonal leafy products can be dried for more benefit.

8 Conclusion

Hence, it can be concluded that a walk-in type solar tunnel dryer is found suitable for drying leafy vegetable products and adding value to the product. The initial investment can be recovered

Table 5 Component wise cost of a tunnel dryer

S. No.	Item	Quantity	Cost (USD)
1.	Galvanized iron pipe 15 mm class A	40 m	110
2.	Galvanized iron pipe 25 mm class A	10 m	30
3.	Metallic door	one	10
4.	200 l UV-stabilized polythene sheet	20 kg	110
5.	Pucca floor with black paint (5.5×4 m^2)	22 m^2	100
6.	Insulation inside the floor	5 cm	40
7.	Drying beds of 2.75 m wide having 7.5-cm depth		100
8.	Skilled labour for fabrications		100
9.	Miscellaneous (cement, nut bolt, cable, wire, etc.)		80
Total installation cost			680

Table 6 Economic assessment of solar dryer for drying fenugreek leaves

Particular	Value
Input cost of raw material per batch (USD), procurement cost (USD), and labour cost (USD)	20, 3, 3
Total input cost (USD)	26
Market value of 9 kg at 10 USD	90
Net profit per batch (B-A)	64
Number of batches required to recover capital cost	11
Payback period	22 days

within 22 working days, and thereafter; net profitability increases, which can improve the financial conditions of farmers. When integrated with other drying technologies, solar tunnel dryer gives clean and environmental friendly technology. On-farm installation of the dryer is recommended. The statistical analysis of the developed model yielded correlation coefficients (r) greater than 0.97 for the air temperature inside the tunnel dryer which demonstrates that the proposed model can provide good fitness with experimental values. The modelling and assessment of this renewable energy based drying system will increase energy savings and avoid environmental pollution.

Nomenclature

A_c	Area of the cover material (m^2)
A_f	Area of the concrete floor (m^2)
A_p	Area of the product (m^2)
A_{in}	Cross-section area of the air inlet (m^2)
A_{out}	Cross-section area of the air outlet (m^2)
C_{pa}	Specific heat of air (J/kg K)
C_{pc}	Specific heat of cover material (J/kg K)
C_{pl}	Specific heat of liquid (J/kg K)
C_{pf}	Specific heat of floor(J/kg K)
C_{pp}	Specific heat of product (J/kg K)
C_{pv}	Specific heat of water vapour (J/kg K)
D	Average distance between the floor and the cover (m)
D_p	Thickness of the product (m)
EUR	Energy utilization ration (%)
F_p	Fraction of solar radiation falling on the product (decimal)
H	Humidity ratio of air inside the dryer (kg/kg)
$h_{c,c\text{-}a}$	Convective heat transfer between the cover and the air (W/m^2 K)
$h_{c,f\text{-}a}$	Convective heat transfer between the floor cover and the air (W/m^2 K)
$h_{c,p\text{-}a}$	Convective heat transfer between the product and the air (W/m^2 K)
H_{in}	Humidity ratio of air entering the dryer (kg/kg)
$h_{k,f\text{-}g}$	Conductive heat transfer between the floor and the underground (W/m^2 K)
H_{out}	Humidity ratio of the air leaving the dryer (kg/kg)
$h_{r,c\text{-}s}$	Radiative heat transfer between the cover and the sky (W/m^2 K)
$h_{r,p\text{-}c}$	Radiative heat transfer between the product and the cover (W/m^2 K)
A_c	Area of the cover material (m^2)
h_w	Convective heat transfer between the cover and the ambient (W/m^2 K)
I_s	Incident solar radiation (W/m^2)
k_a	Thermal conductivity of air (W/m K)
k_c	Thermal conductivity of insulation material (W/m K)
k_f	Thermal conductivity of floor material (W/m K)
L_p	Latent heat of vaporization of moisture from product (J/kg)
M	Moisture content of product (% db)
m_a	Mass of air inside the tunnel dryer (kg)
m_c	Mass of cover (kg)
M_e	Equilibrium moisture content of product (% db)
m_f	Mass of concrete floor (kg)
M_o	Initial moisture content of product (% db)
M_p	Moisture content of dry product (% db)
m_p	Mass of product (kg)
Nu	Nusselt number
Re	Reynolds number
Rh	Relative humidity (decimal)
t	Time (h)
T_∞	Reference temperature (K)
T_a	Air temperature in the dryer (K)
T_{am}	Ambient temperature (K)
T_c	Cover temperature (K)
T_{out}	Chimney outlet temperature (K)
T_f	Floor temperature (K)
T_p	Temperature of product (K)
T_s	Sky temperature (K)
U_c	Overall heat loss coefficient from the cover to ambient air (W/m^2 K)
V	Volume of the drying chamber (m^3)
V_{in}	Inlet airflow rate (m^3/s)
v_{in}	Inlet air speed (m/s)
V_{out}	Outlet airflow rate (m^3/s)
v_{out}	Outlet air speed (m/s)
V_w	Wind speed (m/s)
W	Width of the dryer floor (m)
Greek letters	
α_c	Absorptance of the cover material
α_f	Absorptance of floor (decimal)
α_p	Absorptance of product
δ_c	Thickness of the cover (m)
σ	Stefane Boltzmann's constant (W/m^2 K^4)
ρ_a	Density of air (kg/m^3)
ρ_c	Density of the cover material (kg/m^3)
ρ_d	Density of the dry product (kg/m^3)
ρ_p	Density of the product (kg/m^3)
τc	Transmittance of the cover material
εc	Emissivity of the cover material
εp	Emissivity of the product
v	Viscosity of air (m^2/s)

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References

1. Muhlbauer, W. (1981). Solar drying of agricultural products', in *Proc. Reg. Workshop Rural Development Technology*, 25–29 May, Korea Advanced Institute of Science and Technology, Seoul 415–433.
2. Garg, H. P., & Kumar, R. (1998). Studies on semi-cylindrical solar tunnel dryers: year round collector performance. *Int. J. Energ. Res., 22*, 1381–1395.
3. Sarasavadia, P. N., et al. (1999). Drying behaviour of brined onion slices. *Journal of Food Engineering, 40*, 219–226.
4. Kothari, S., et al. (2009). Performance evaluation of exhaust air recirculation system of mixed mode solar dryer for drying of onion flakes. *International Journal of Renewal Energy Technology, 1*, 29–41.
5. Cakmak, G., & Yıldız, C. (2011). The prediction of seedy grape drying rate using a neural network method. *Computer Electronic Agriculture, 75*, 132–138.
6. Zomorodian, A., et al. (2007). Optimization and evaluation of a semi-continuous solar dryer for cereals (rice, etc.). *Desalination, 209*, 129–135.
7. Hernando, E. C., et al. (2011). Development of model based sensors for the supervision of a solar dryer. *Computer Electronic Agriculture, 78*, 167–175.
8. Maskan, M. F., & Gogus, F. (1998). Sorption isotherms and drying characteristics of mulberry (*Morus alba*). *Journal of Food Engineering, 37*, 437–449.
9. Akpinar, E. K., et al. (2003). Modeling and experimental study on drying of apple slices in a convective cyclone dryer. *Journal of Food Process Engineering, 26*, 515–541.
10. Henderson S. M. (1974). Progress in developing the thin layer drying equation, Trans. ASAE*,* 1167–1172.
11. Verma, L. R., et al. (1985). Effects of drying air parameters on rice drying models. *T. ASAE, 28*, 296–301.
12. Eldeen, Y. I. S., et al. (1980). A model for ear corn drying, Trans. *ASAE, 23*, 1261–1271.
13. Diamante, L. M., & Munro, P. A. (1993). Mathematical modelling of thin layer solar drying of sweet potato slices. *Solid Energy, 51*, 271–276.
14. Ozdemir, M., & Devres, Y. O. (1999). The thin layer drying characteristics of hazelnuts during roasting. *Journal of Food Engineering, 42*, 225–233.
15. Midilli, A., et al. (2002). A new model for single layer drying of some vegetables. *Drying Technology, 20*, 1503–1513.
16. Togrul, I. T., & Pehlivan, D. (2003). Modeling of drying kinetics of single apricot. *Journal of Food Engineering, 58*, 23–32.
17. Akpinar, E. K. (2006). Mathematical modelling of thin layer drying process under open sun of some aromatic plants. *Journal of Food Engineering, 77*, 864–870.
18. Akpinar, E. K., et al. (2006). Modelling of thin layer drying of parsley leaves in a convective dryer and under open sun. *Journal of Food Engineering, 75*, 308–315.
19. Yaldiz, O., & Ertekin, C. (2011). Thin layer solar drying of some vegetables. *Drying Technology, 19*, 583–596.
20. Garavand, A. T., Rafiee, S., Keyhani, A., et al. (2011). Mathematical modeling of thin layer drying kinetics of tomato influence of air dryer conditions. *International Transactions Journal Engg. Mangt. & Application Science & Technology, 2*, 147–160.
21. Daoud, K., & Abchiche, H. (2008). Hydrodynamic study of the granular flow in the solar dryer. *Desalination, 220*, 661–668.
22. Garg, R., et al. (1998). Simulation model of the thermal performance of a natural convection-type solar tunnel dryer. *International Journal of Energ Research, 22*(1998), 1165–1177.
23. Garg, H. P., & Kumar, R. (2000). Studies on semi-cylindrical solar tunnel dryers: thermal performance of collector. *Applied Thermal Engineering, 20*, 115–131.
24. Bala, B. K., et al. (2003). Solar drying of pineapple using solar tunnel drier. *Renew Energy, 28*, 183–190.
25. Condorı, M., & Saravia, L. (2003). Analytical model for the performance of the tunnel-type greenhouse drier. *Renew Energy, 28*, 467–485.
26. Hossain, M. A., et al. (2005). Optimisation of solar tunnel drier for drying of chilli without color loss. *Renew Energy, 30*, 729–742.
27. Sacilik, K., et al. (2006). Mathematical modelling of solar tunnel drying of thin layer organic tomato. *Journal of Food Engineering, 73*, 231–238.
28. Janjai, S., et al. (2009). Solar drying of peeled longan using a side loading type solar tunnel dryer: experimental and simulated performance. *Drying Technology, 27*, 595–605.
29. Srisittipokakun, N., et al. (2012). Solar drying of Andrographis paniculata using a parabolicshaped solar tunnel dryer. *Procedia Engineering, 32*, 839–846.
30. Eltiet, S. A., et al. (2007). Drying chamber performance of V-groove forced convective solar dryer. *Desalination, 209*, 151–155.
31. Schirmer, P., et al. (1996). Experimental investigation of the performance of the solar tunnel dryer for drying bananas. *Renew Energy, 7*, 119–129.
32. Hossain, M. A., & Bala, B. K. (2007). Drying of hot chilli using solar tunnel drier. *Solid Energy, 81*, 85–92.
33. Sevda, M. S., & Rathore, N. S. (2009). Experimental investigation of the performance of the solar tunnel dryer for drying aonla pulp. *International Journal of Global Energy, 31*, 183–192.
34. Rathore, N. S., & Panwar, N. L. (2010). Experimental studies on hemi cylindrical walk-in type solar tunnel dryer for grape drying. *Applied Energy, 87*, 2764–2767.
35. Rathore, N. S., & Panwar, N. L. (2011). Design and development of energy efficient solar tunnel dryer for industrial drying. *Clean Technologies and Environmental Policy, 13*, 125–132.
36. Janjai, S., et al. (2011). A large-scale solar greenhouse dryer using polycarbonate cover: modeling and testing in a tropical environment of Lao People's democratic republic. *Renew Energy, 36*, 1053–1062.
37. Intawee, P., & Janjai, S. (2011). Performance evaluation of a large-scale polyethylene covered greenhouse solar dryer. *International Energy Journal, 12*, 39–52.
38. Sharma, R. D. (1986). Effect of fenugreek seeds and leaves on blood glucose and serum insulin responses in human subjects. *Nutrition Research, 6*, 1353–1364.
39. Devi, B. A., et al. (2003). Supplementation of fenugreek leaves to diabetic rats, effect on carbohydrate metabolic enzymes in diabetic liver and kidney. *Phytotherapy Research, 17*, 1231–1233.
40. Ekechukwu, O. V., & Norton, B. (1997). Design and measured performance of a solar chimney for natural circulation solar energy dryers. *Renew Energy, 10*, 81–90.
41. Diffie, J. A., & Beckman, W. A. (1991). *Solar engineering of thermal processes*. New York: Wiley.
42. Watmuff, J. H., et al. (1977). Solar and wind induced external coefficients for solar collectors. *Comples, 2*, 56.
43. Kays, W. M., & Crawford, M. F. (1980). *Convective heat and mass transfer*. New York: McGraw Hill.
44. Weiss, A. (1977). Algorithms for the calculation of moist air properties on a hand calculator. *Transactions of ASAE, 20*, 1133–1136.
45. Singh, O. K., Kaushik, S. C. (2012). Variables influencing the exergy based performance of a Steam Power Plant, Int J Green Energ (Article in press) DOI: 10.1080/15435075.2011.653847

46. Janjai, S. (2012). A greenhouse type solar dryer for small-scale dried food industries: development and dissemination. *International Journalof Energy Environment, 3*, 383–398.
47. Dincer, I. (2000). Thermodynamic, exergy and environmental impact. *Energy Source, 22*, 723–732.
48. Dincer, I., & Cengel, A. Y. (2001). Energy, entropy and exergy concepts and their roles in thermal engineering. *Entropy-International Journal, 3*, 116–149.
49. Midilli, A., & Kucuk, H. (2003). Energy and exergy analyses of solar drying process of pistachio. *Energy, 28*, 539–556.
50. Bayrak, M., et al. (2003). Energy and Exergy analyses of sugar production stages. *International Journal of Energy Research, 27*, 989–1001.
51. Gupta, M. K., & Kaushik, S. C. (2009). Performance evaluation of solar air heater for various artificial roughness geometry based on energy, effective and exergy efficiencies. *Renew Energy, 34*, 465–476.
52. Panwar, N. L., et al. (2012). A review on energy and exergy analysis of solar dying systems. *Renewable and Sustainable Energy Reviews, 16*, 2812–2819.
53. Akpinar, E. K. (2011). Drying of parsley leaves in a solar dryer and under open sun: modeling, energy and exergy aspects. *Journal of Food Process Engineering, 34*, 27–48.
54. Holman, J. P. (2010). Experimental methods for engineers, Tata McGraw Hill Education Private Limited, India