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Energy Conservation Through Solar Energy Assisted Dryer For Plastic Processing Industry

D.H. Kokate[a], D. M. Kale[b], V. S. Korpale[a], Y. H. Shinde[c], S. V. Panse[b], S. P. Deshmukh[a], A. B. Pandit[c*]

[a] *General Engineering Department, Institute of Chemical Technology, Mumbai, 40019, India*
[b] *Physics Department, Institute of Chemical Technology, Mumbai, 400019, India*
[c*] *Chemical Engineering Department, Institute of Chemical Technology, Mumbai, 400019, India*

Abstract

Consumption of plastics is directly linked with economic growth of plastic industry of respective country. India's plastics consumption is only about 2% of the world. Despite of proposed growth, higher cost of Energy requirement for processing are obstructing growth of plasticulture. Energy efficiency/conservation measures in plastic processing requires attention to harness alternate energy sources through technological modifications during material processing. This paper depicts practical solution for partial usage of non- conventional energy source; solar energy in conventional plastic process method. About3-5 % of total energy required for processing is utilized for drying and precondition of material. Thus attempt is made to use solar energy for drying of Nylon-6 and polypropylene (PP) by designing natural convection based Solar Dryer. Drying of Nylon-6 is found to be in the falling rate period. Nylon-6 took nearly 6 hrs. (1days) to reach 0.15% moisture content value. Effective diffusivity is varied from 4 - 6.5 X 10^{-9} cm^2/sec. Temperature rise for PP material is achieved up to 70°C in the dryer, hence preheating is achieved with same dryer design. Solar dryer can certainly reduce conventional energy consumption during plastic processing at industrial scale. Cost benefit analysis shows that adaptation of solar energy dryer for plastic process industry lead to economic production of plastic goods.

Selection and peer-review under responsibility of Organizing Committee of ICAER 2013

Keywords: Plasticulture; Preconditioning; Solar Dryer;Energy conservation

*Corresponding Author. Tel: (022) 3361 1111, Fax: (022) 3361 2222,
E-mail: dr.pandit@gmail.com

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1. Introduction

Consumption of plastics is directly proportional to the economic growth of plastic industry of respective country. India has low consumption of plastics at 2% of total consumption of the world, whereas USA has 40 % and China has about 20%. Domestic demand has reached from 1.8 MMT in 1995-96 to 4.47 MMT in 2005-06. Riding on the current growth rate the same is expected to reach at 9.5 MMT up to 2012 [1]. At 15% Compound Annual Growth Rate (CAGR) consumption of plastics in India is expected to reach at 18.9 MMT up to 2015. [2].The sectorial analysis showed the Agriculture and Infrastructure sectors have less demand however plasticulture and packaging has large scope to plastic consumption. Plasticulture will be main driver to boost agriculture GDP, micro irrigation could be one of the major to promote plastic consumption for this sector. Indian Government is giving more emphasis to Agriculture sector to ensure food security and availability for end user. Hence sectorial dependence supports the growth of plastic industry for several years in future.

Nomenclature

A_p	Area of Absorber plate (m^2)
A_c	Area of cover (m^2)
C_a	Initial concentration (g/cm^3)
C_e	Concentration (g/cm^3) at time 't'
$D_{eff.}$	Effective diffusivity of penetrate in polymer matrix. (cm^2/s)
h_{fp}	Convection heat transfer coefficient between absorber plate and air (W/m^{2}K).
h_{fc}	Convection heat transfer coefficient between transparent cover and air (W/m^{2}K)
h_r	Convection heat transfer coefficient of re-radiation from absorber plate to air through transparent cover (W/m^{2}K)
L	Length of absorber plate (m)
S	Solar radiant energy falling on absorber (W/m^2)
S_f	Shape factor
T_{pm}	Mean temperature of absorber (K)
T_c	Mean temperature of cover (K)
T_a	Temperature of Ambient air (K)
t	time (s)
U_b	Bottom loss coefficient (W/m^{2}K)
U_t	Top loss coefficient (W/m^{2}K)
V_w	Total volume of wet solid in cm^3 and calculated by dividing mass of wet solid at a time with average density of polymer and water vapour diffusion.(cm^3)
W	Mean width of trapezoidal collector (m)
x_t	Moisture (g) at time 't'
ω	Ratio of surface area (cm^2) to volume (cm^3) of a plastic pellet

The plastic processing industry consists of sequence of operations from raw plastic resin up to finished product. At every stage there is energy saving potential. Plastic processing industry is mainly having types of Extrusion, Injection moulding, Blow moulding, etc. The details of estimation of demand of energy for typical plastic processing were developed in 1993 by Power Smart Inc. of Vancouver for natural resources, Canada [3]. If 1 kW of energy is supplied during extrusion, injection and blow/blown film process, then energy consumed in material drying is 30 W, 10 W and 27 W respectively making it about 1 to 3 % of the total.

A typical case study of Tangram technology for energy efficiency in plastic processing is depicted in figure 1. It contains simple Sankey diagram for air heated conventional oven dryers. The capacity of heater for the dryer is 5kW. Process air passing through the oven moves through the bed of plastic pellets carrying energy of 4kW and 1 kW energy is lost in transportation.

Energy actually used for drying of plastic pellets i.e. useful energy is only 1.7 kW. Remaining 1.9 kW of energy is lost through the exhaust. The efficiency of this drying process is only 34% which certainly affects the economic production plastic goods.

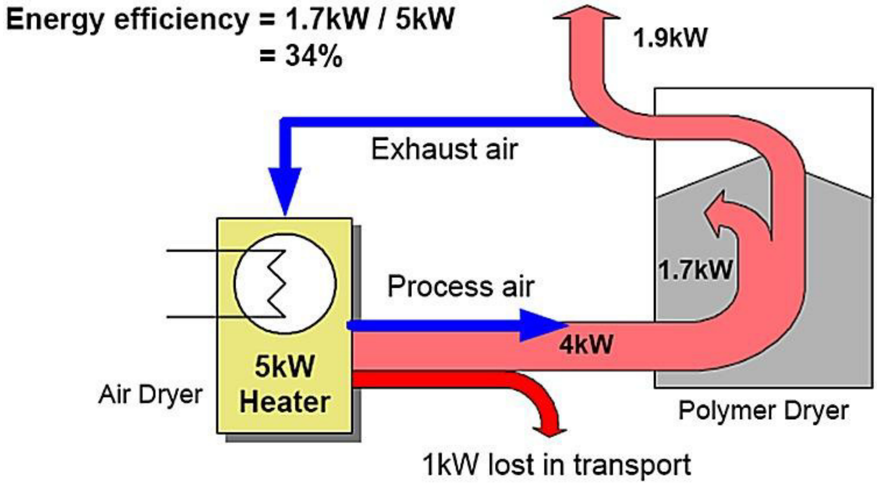

Figure 1 : Energy Expenditure in drying process [4]

Thus there is urgent need to address the inefficient drying process so as to achieve energy efficiency through better technology development. Thus, it is necessary to modify the technologies or alternative low cost energy supply for drying. Non-conventional energy; solar thermal energy would be the best option. Pre conditioning; dehumidification and pre heating can be achieved by using solar energy drying technology.

Thus, attempt is made to use solar energy for preconditioning of Nylon-6 and polypropylene (PP) by designing natural convection based solar dryer. At the end Economic feasibility study has also been carried out.

2. Materials and methods

2.1. Experimental Set-Up

Figure 2 shows a schematic diagram of south facing solar dryer system, which consists of an absorber plate, a transparent plastic cover which create a triangular cavity and drying chamber in which the material to be dried is kept on perforated tray. The length, width, and gap of the solar dryer were 4.9 m, 4.8 m, and 0.1m, respectively. Forces responsible for the flow of air through solar collector are buoyancy forces created due to pressure drop. Pressure drop across the collector is obtained as a result of air temperature increment while flowing along the absorber. Flat plate collectors having constant cross section areas yield low pressure driving force. Thus velocity of air flowing through collector is less. Lower value of air velocity affects the net heat transfer from the absorber plate to air limiting is maximum temperature. To achieve higher air velocity the cross sectional area of collector is designed in trapezoidal shape (similar to a Venturi).

The aluminium absorber plate is coated with blackboard black paint to absorb maximum incident solar radiation. The absorber plate is placed directly behind the transparent cover (plastic/polymer) with a layer of air separating it from the cover. The air to be heated passes between the transparent cover and the absorber plate. To increase the temperature of air by greenhouse effect, a transparent plastic cover was placed. The gap between the plastic cover and the absorber surface was maintained at 0.1m for air flow. The absorber was kept on 0.004m plywood to minimise heat losses to surrounding from the backside. Depending upon the latitude of the location, the inclined face of the stand is so chosen that it receives maximum solar insolation over the year of operation. For example, surfaces facing south with an angle of inclination of about 30^0 is efficient for locations for latitude 19^0[5, 6].

Transparent cover of the solar dryer consists of plastic material polycarbonate sheet and it allows the transmition of solar radiation with minimum amount of absorption and reflection in the solar spectrum. Also, it acts as resistance to thermal radiation heat transfer from the absorber to the atmosphere. The insulating material is used to reduce the heat losses from the bottom sides of the dryer, it also gives additional support. In this work, the insulating material is plywood and its thermal conductivity is reported to be 0.13 W/m^2 °C.

The drying chamber is positioned at the outlet of solar collector. Drying chamber is made up of galvanized iron metal sheet and has a rectangular cross section. The length, width, and height of the drying chamber were 0.5m, 0.4m, and 0.15m, respectively. The material to be dried is kept on perorated aluminium tray in a drying chamber, such that air flows through the tray in cross flow manner. At a time one tray can be placed in the drying chamber with material to be dried. Tray is placed at a distance of 0.25 m from the top of drying chamber.
In this dryer model energy from the sun is trapped between transparent cover and absorber plate, and heats the air by the "Green House Effect" and thus, thermal energy of air (enthalpy) is used for drying of the target material.

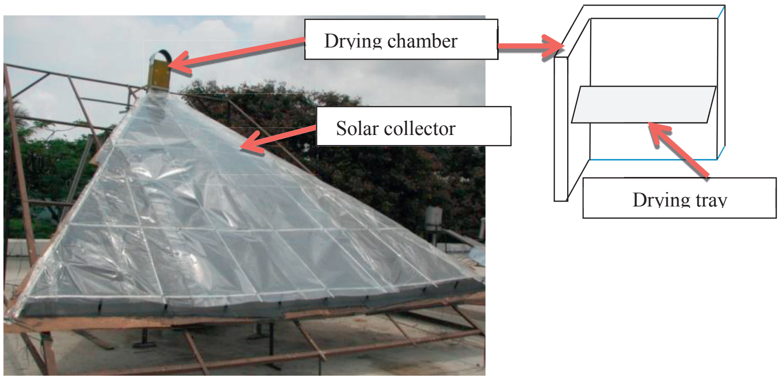

Figure 2: Pictorial view of solar dryer

2.2 Experimental procedure
Following procedure is followed for all the experiments:
1) 100 gm of drying sample (Nylon-6 and PP pellets) was taken in aluminium tray. Polymer pellets were uniformly spread across the tray to form thin layer.
2) Tray was kept in the drying chamber.
3) A set of air temperature at different locations are logged after every 2 minute in data logger.
4) Pyranometer was switched 'ON' after fixing it on its stand. The global solar intensity reading was noted after every half an hour. By shading its bulb the diffused solar intensity reading was noted.
5) Dry and wet bulb thermometer was fixed on stand and corresponding temperatures were noted.
6) Average inlet velocity of air is recorded after every half an hour with the help of anemometer; air velocity and the temperature at the outlet of the absorber is also noted. Ambient wind velocity is also recorded after every half an hour.
7) Drying sample was weighed after every hour to find moisture lost from the drying material.

2.3 Development of mathematical model for predicting air temperature inside the solar dryer

The mathematical model developed for solar dryer on the basis of energy balance of solar radiations falling on transparent cover, to give air temperature at the outlet of the collector. The collector is a most important part of the solar dryer. An absorber plate and top enclosure cover forms the entire collector. The performance of collector is the key factor in deciding total efficiency of solar dryer. Various convection heat transfer coefficients are associated with solar collector. Heat loss from the top is the function of re-radiation of absorbed heat from solar absorber. Side loss and bottom loss are also associated with collector of solar dryer. Thus careful design of collector is necessary to absorb more solar radiations and to increase heat absorption rate. Figure 3 describes modelling variables and losses incurred. Compared to top loss, side loss and bottom loss are negligible. Hence during model development they are assumed to be neglected. An aperture factor is defined on account for some area of cover is closed with black absorber enclosure. Ratio of Open area of cover to absorber area is the aperture factor.

Collector is as shown in the figure 3. The collector has absorber plate of length L and average width W. The air flow over the absorber plate is as shown in the figure 3. Consider a slice of trapezoidal collector having mean width W having thickness 'dx' at a distance 'x' from the bottom edge of the collector, we write down energy balance for the absorber plate, the transparent plastic cover, and air flowing in between[7,8]. We assume that,

- bulk mean temperature of air rises from T_f to $(T_f + dT_f)$flowing through the distance dx.
- The air mass flow rate m_d
- The mean temperature of absorber plate and cover are $T_{pm}$and T_c respectively. Their variation along the collector is neglected.
- Bottom and side losses are neglected.

The energy balance equations for absorber plate, transparent polyester cover and air flowing through collector are written as follows:
Aperture factor is defined as,

$$C_c = \left(1 - \frac{A_{enclosure}}{A_p}\right)$$

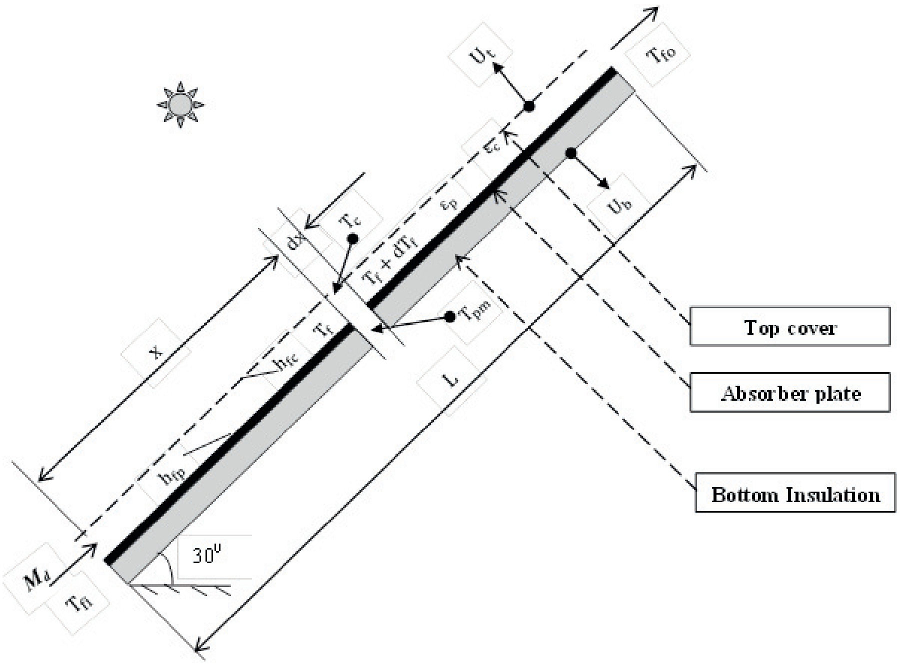

Figure 3: Solar Collector

Energy Balance for absorber plate:

$$C_c SWdx = h_{fp}Wdx(T_{pm} - T_f) + h_r Wdx(T_{pm} - T_c) + U_b Wdx(T_{pm} - T_a) \quad (1)$$

Where,

$$h_r = \frac{\sigma}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1\right)} \frac{(T_{pm}^4 - T_c^4)}{(T_{pm} - T_c)}$$

Energy balance for cover:

$$h_r W dx\left(T_{pm} - T_c\right) = C_c U_t W dx(T_c - T_a) + h_{fc} W dx\left(T_c - T_f\right) \tag{2}$$

Energy balance for air stream:

$$\frac{m_d C_p\, dT_f}{W\, dx} = h_{fp}\left(T_{pm} - T_f\right) + h_{fc}\left(T_c - T_f\right) \tag{3}$$

From Eq. (1) and (3) we get

$$\frac{m_d C_p\, dT_f}{W\, dx} = C_c S - C_c U_t (T_c - T_a) \tag{4}$$

Neglecting bottom loss and after rearranging the terms Eq. (1) becomes,

$$T_{pm} = \frac{C_c\, S + h_{fp} T_f + h_r T_c}{h_{fp} + h_r} \tag{5}$$

From Eq. (3) we get,

$$T_c = \frac{h_r T_{pm} + C_{c.} U_t + T_a T_c}{C_{c.} U_t + h_{fc} + h_r} \tag{6}$$

Substituting Eq. (5) in Eq. (6) we get,

$$T_c = \frac{C_c S h_r + \left(h_r h_{fp} + h_{fc} h_{fp} + h_{fc} h_r\right) T_f + \left(C_c U_t h_{fp} + C_c U_t h_r\right) T_a}{\left(h_{fp} + h_r\right)\left(C_{c.} U_t + h_{fc} + h_r\right) - h_r^2} \tag{7}$$

Subtracting T_a *from Eq. (7)*

$$T_c - T_a = \frac{C_c S h_r + \left(h_r h_{fp} + h_{fc} h_{fp} + h_{fc} h_r\right) T_f + \left(C_c U_t h_{fp} + C_c U_t h_r - \xi\right) T_a}{\xi} \tag{8}$$

Substituting Eq. (8) into Eq. (4)

$$\frac{m_d C_p}{W} \frac{dT_f}{dx} = \frac{S\left(C_c \xi - C_c^2 U_t h_r\right) - C_c U_t (\psi) T_f - C_c U_t (\gamma) T_a}{\xi} \tag{9}$$

Where,

$$\psi = \left(h_r\, h_{fp} + h_{fc}\, h_{fp} + h_{fc}\, h_r\right)$$

$$\gamma = \left(C_c U_t\, h_{fp} + C_c U_t\, h_r - \xi\right)$$

$$\frac{\dot{m} C_p\, dT_f}{U_t\, W dx} = C_c\left(\frac{\psi}{\xi}\right)\left\{\frac{S\,(\,\xi - C_c U_t h_r)}{U_t \psi} - T_f - \left(\frac{\gamma}{\psi}\right) T_a\right\} \tag{10}$$

The collector efficiency factor is incorporated as,

$$F' = C_c\left(\frac{\psi}{\xi}\right) = \frac{C_c\left(h_r\, h_{fp} + h_{fc}\, h_{fp} + h_{fc}\, h_r\right)}{\left(h_{fp} + h_r\right)\left(C_{c.} U_t + h_{fc} + h_r\right) - h_r^2}$$

In Eq. (10) coefficients and defined as,

$$\frac{m_d C_p\, dT_f}{F' U_t\, W dx} = S R_1 - T_a R_2 - T_f \tag{11}$$

Where,

$$R_1 = \frac{(\,\xi - C_c U_t h_r)}{U_t \psi} = \frac{\left\{\left(h_{fp} + h_r\right)\left(C_{c.} U_t + h_{fc} + h_r\right) - h_r^2 - C_c U_t h_r\right\}}{U_t\left(h_r\, h_{fp} + h_{fc}\, h_{fp} + h_{fc}\, h_r\right)}$$

$$R_2 = \left(\frac{\gamma}{\xi}\right) = \frac{\left\{C_c U_t\, h_{fp} + C_c U_t\, h_r - \left(h_{fp} + h_r\right)\left(C_{c.} U_t + h_{fc} + h_r\right) - h_r^2\right\}}{\left(h_{fp} + h_r\right)\left(C_{c.} U_t + h_{fc} + h_r\right) - h_r^2}$$

Now rearranging Eq. (11) in differential form we get,

$$\frac{dT_f}{dx} \frac{1}{(S\, R_1 - T_a R_2) - T_f} = \left(\frac{F' U_t\, W}{m_d C_p}\right) \tag{12}$$

Integrating both sides of Eq. (12) within limits,

$x = 0,\quad T_f = T_{fi}$

$x = L,\quad T_f = T_{fo}$

$$\int_{T_{fi}}^{T_{fo}} \left\{\frac{1}{(S\, R_1 - T_a R_2) - T_f}\right\} dT_f = \left(\frac{F' U_t\, W}{m_d C_p}\right) \int_0^L dx$$

$$\frac{(S\,R_1 - T_a R_2) - T_{fo}}{(S\,R_1 - T_a R_2) - T_{fi}} = e^{-\left(\frac{F' U_t W}{m_d C_p} L\right)} \quad (13)$$

3. Results and Discussion

3.1Air Temperature prediction inside the dryer using Model

Figure 4 shows experimental and calculated average air temperature using model developed, inside the dryer at a distance of 1, 2, 3, 4, and 4.8 m from inlet. Air temperature inside the dryer depends on many parameters such as solar intensity, wind velocity, collector length, width, ambient temperature, absorber plate temperature etc. Energy balance across various components of dryer is written while developing the mathematical model for predicting the air temperature inside the dryer. Detailed calculation procedure for calculating air temperature inside the dryer is given by Sukhatme [7] and Shinde [8].

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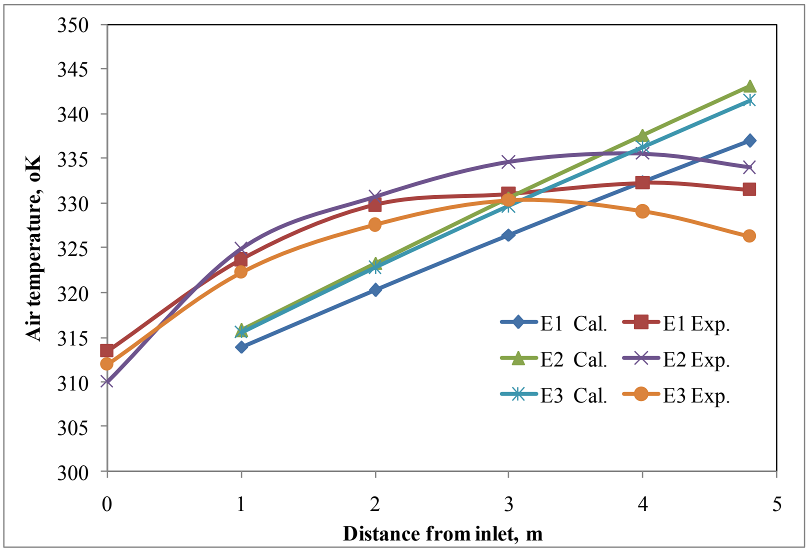

Figure 4: Average air temperature from inlet of collector

Figure 4 shows a good agreement between the predicted air temperature and actual experimental air temperature up to 3 m from the inlet. After 3 m of dryer length there is a considerable variation in the calculated air temperature. Up to 3 m of collector length temperature of absorber plate is increasing linearly and after that there is very little increment in the temperature. Air temperature inside the dryer is a result of pressure difference which is due to buoyancy forces and the height of the collector from ground. As we go towards the outlet of the collector temperature driving force for heat transfer from absorber plate to air reduces, at the same time heat losses which results into to the surrounding increases (due to higher air temperature) nearly constant air temperature after 3 m of collector length

From the figure4 it is clear that maximum air temperature attained inside the dryer is different on different days, as it is mostly dependant on ambient conditions such as solar intensity, wind velocity and ambient temperature. Air temperature shown by line E2 is greater than other two lines (E1 and E3), as average solar intensity was much higher on that day as compare to other two days. Figure 5 shows ambient conditions on a typical sunny day during experimentation

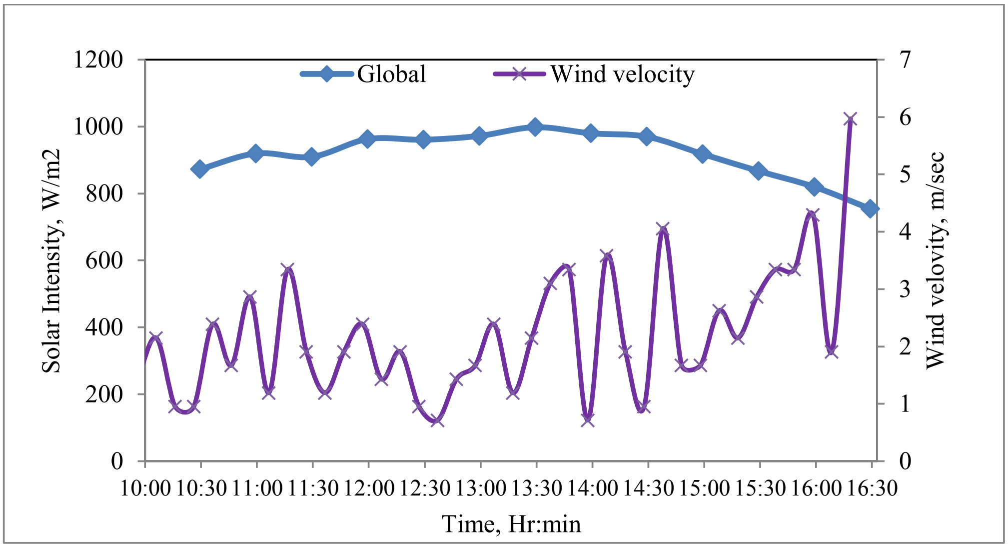

Figure 5 : Solar intensity and wind velocity for typical sunny day

3.2 Collector Efficiency

Table 1. Solar Collector Efficiency

Time	Solar Intensity (Watt/m^2	Wind Velocity m/sec	Ambient Temp. °C	Efficiency %
10:00:00 AM	891	1.29	34	9.0
10:30:00 AM	914	2.31	34	25.2
11:00:00 AM	931	2.11	34	26.4
11:30:00 AM	939	3.33	34	26.9
12:00:00 PM	945	3.02	34	32.2
12:30:00 PM	941	3.45	34	28.8
1:00:00 PM	950	2.51	33	29.8
1:30:00 PM	938	2.35	33	23.5
2:00:00 PM	950	2.4	33	27.2
2:30:00 PM	951	2.2	33	26.8
3:00:00 PM	950	2.6	34	21.7
3:30:00 PM	923	2.2	33	16.7
4:00:00 PM	865	2.3	32	10.9

Solar collector collects the heat by absorbing solar radiation. It is a vital component of solar dryer. Collector efficiency depends upon design parameters such as collector material, absorber coating, and collector inclination and environmental factors such as solar intensity, wind velocity etc. Collector efficiency is calculated for trial E1 throughout the day and given in Table 1. Efficiency was found to be minimum during the morning (at 10 a.m.) and late afternoon (at 4 p.m.), and it was maximum at afternoon (12 p.m.). It is interesting to note that collector efficiency is linearly related to the solar intensity and wind velocity. From 11 am to 2 pm efficiency remains nearly constant (around 25%), as solar intensity and wind velocity does not vary appreciably during that time.

3.3 Drying kinetics for Nylon-6 and Polypropylene

Nylon-6 and Polypropylene were selected for studying drying kinetics using solar chimney dryer, because of their extensive use in plastic industry. Cylindrical pellets of Nylon-6 and polypropylene were dried using solar chimney dryer. Three trials of Nylon-6 and two trials of polypropylene were carried out to check the reproducibility. All the experiments were started at 10 am in morning and stopped at 4 pm in afternoon. Moisture lost and product temperature were measured at every hour during the trial.

Figure 6 (a) shows the rate of moisture removal and temperature of Nylon-6 for all the three trials. During 6 hours of dying period temperature of Nylon-6 pellets varied between 50-60°C. Temperature of pellets increases initially then it attains maximum temperature at noon and again it starts falling during late afternoon. This behaviour of pellet temperature can be explained on the basis of solar intensity and air temperature. During 6 hrs of solar drying, moisture content of 100 g of Nylon-6 pellets were reduce from 0.82 to 0.15% on dry basis. Drying of Nylon-6 falls in the falling rate period, which is clearly shown by drying rate curve (figure 6(b)). All the three trials shows results are highly reproducible.

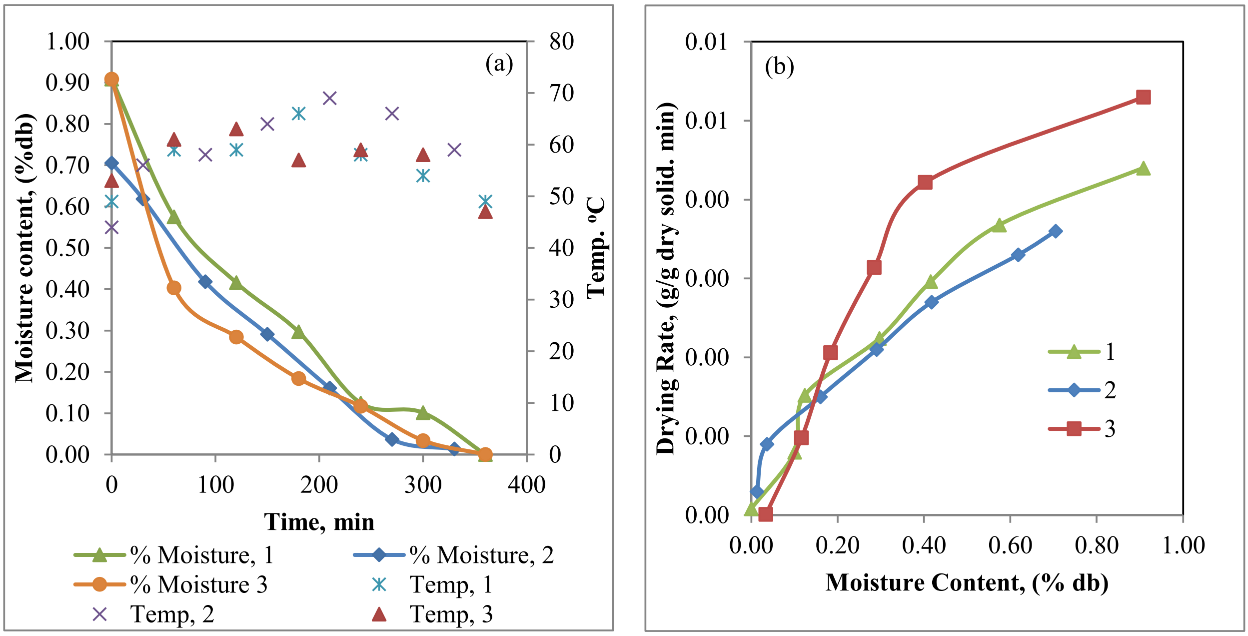

Figure 6: (a) Rate of moisture removal and temp rise for Nylon-6 (b) drying rate curve for nylon-**6**

Figure 7(a) shows the rate of moisture removal and temperature of Polypropylene for two trials. During 6 hours of dying period temperature of Polypropylene pellets varied between 50-60°C. Temperature of pellets increases initially then it attains maximum temperature at noon and again it starts falling during late afternoon. This behaviour of pellet temperature can be explained on the basis of solar intensity and air temperature. During 6 hours of solar drying, moisture content of 100 g of Polypropylene pellets were reduce from 0.082 to 0.0015% on dry basis. Reduction in moisture content for Polypropylene is very less as compared to that of Nylon-6. This can be increased if we use forced convection solar dryer. Drying of Polypropylene falls in the falling rate period, which is clearly shown by drying rate curve (figure 7 (b)). Trials shows results of drying polypropylene are highly reproducible.

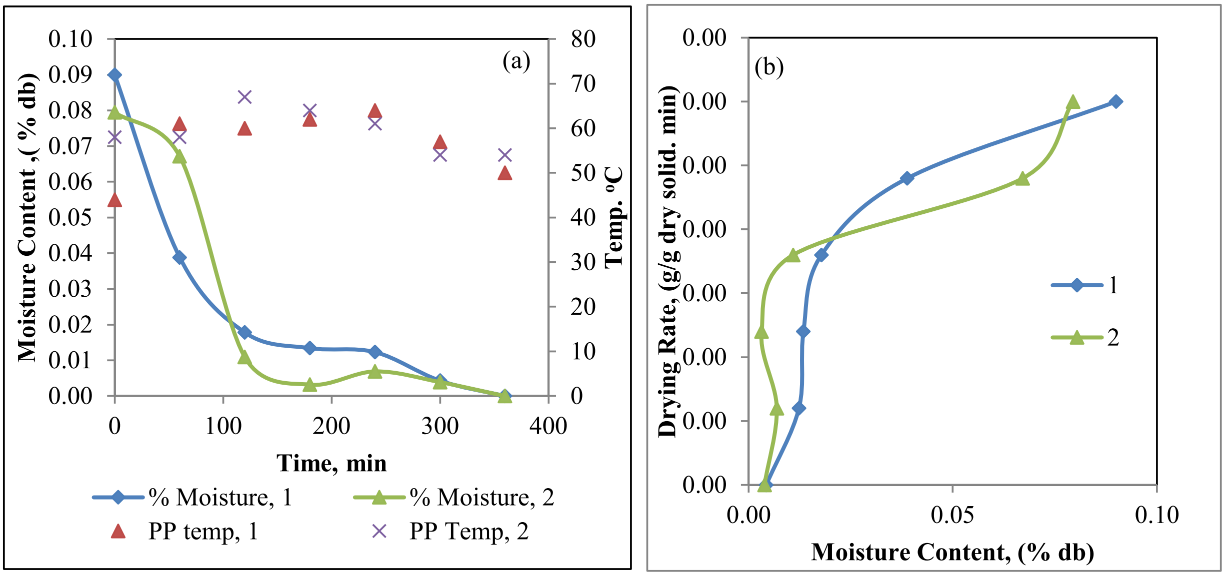

Figure 7: (a) Rate of moisture removal and temp rise for Polypropylene (b) drying rate curve for polypropylene

3. 4 Moisture diffusivity through Nylon-6 material

Effective moisture diffusivity through the Nylon-6 material is calculated using equation 14. It is dependent upon many factors which include concentration gradient for water vapour transport to the surface, shape of pellets, temperature of drying air etc. Effective moisture diffusivity was calculated for all trials, and found out to be in the range of 4 - 6.5 X 10^{-9} cm^2/sec. calculated value of effective moisture diffusivity is in good agreement with the value reported in the literature which is 5 X 10^{-9} cm^2/sec, for Nylon-6 [9].

$$\frac{x_t}{V_w(C_e-C_a)} = S_f\left(\omega\sqrt{D_{eff}.t}\right) \tag{14}$$

3.5 Economic evaluation of solar dryer

3.5.1Sizing of dryer

Following procedure has been adopted for calculating collector area required for a particular amount of Nylon-6 using solar dryer. Detailed calculation of collector area requirement to dry 1 kg/hr of Nylon-6 is given below. Procedure for sizing of solar dryer:

1) Find out the quantum of moisture to be removed from plastic pellets.
2) Plot the entire drying process on the Psychometric chart [10] by plotting temperature readings defining processes sensible heating, while air is passing through the solar collector. Allowed by its passage through the drying of plastic pellets in drying chamber. Note down relative humidity of air at the start of drying. Also, note down the absolute humidity at all the state points.
3) Find out the amount of moisture to be removed per kg of drying material.
4) Referring the moisture absorption-desorption isotherm find out the value of water activity for Nylon-6at the corresponding relative humidity of air. Assume water activity 1 for absorption and find the average of water activity at absorption and desorption as per the calculation.
5) Find out volumetric air flow rate and the total enthalpy required over the entire drying process.
6) Collector area required for drying of Nylon pellets can be calculated by using dying efficiency and thermal efficiency obtained from the reported experimental results in this work.

The drying process starts at average temperature of pellets and not the temperature of surrounding in the drying chamber. This means the drying of pellets start only when pellets are heated and moisture becomes free. And there may be some loss of outlet temperature when air flows from drying chamber inlet to drying tray.All the temperature and humidity values are averaged and taken for calculation from previously reported experimental trials. This generally it includes temperature of Nylon-6 placed in a drying tray and temperature of ambient air as well as relative humidity at various positions. Sample calculation for estimating collector area required for drying 1 kg of Nylon-6 are given below.

$$V_{flow} = \frac{m_w}{\rho_{air}(Y_C - Y_B)} \tag{15}$$

The absolute humidities at corresponding points are taken from Psychrometric chart. The density of air is taken at mean of temperature of pellets and air exit.

Let, the heat used to evaporate the moisture and total heat can be calculated from Eq.(16) to (18).

$$Q_{evaporation} = M_w h_{fg} \tag{16}$$

$$Q_{sensible} = M_s C_{pp}(T_p - T_a) \tag{17}$$

$$Q_{drying} = Q_{evaporation} + Q_{sensible} \tag{18}$$

Assuming drying efficiency to be 1.5 % the useful heat required to produce is calculated.

From Eq. 19 mass of water removed per kg of wet pellets is,

$$\dot{m_w} = \frac{(X_m - X_e)}{100 - (X_m - X_e)} \tag{19}$$

$$\dot{m_w} = \frac{(9 - 0.1)}{100 - (9 - 0.1)} = 0.09769 \text{ kg per kg of wet pellets}$$

Thus moisture removed from 1kg of wet pellets in 6 hours,

$$m_w = \frac{0.09769}{6} \times 1 = 0.01628 \text{ kg/hr}$$

Form Psychrometric chart,

$$Y_c = 0.025933 \text{ kg/m}^3$$

$$Y_B = 0.015258 \text{ kg/m}^3$$

$$\rho_{air} = 1.0788 \text{ kg/m}^3$$

Let from Eq.(15) volume flow rate required to remove moisture from 1 kg pellets,

$$V_f = \frac{0.01628}{1.0788 \times (0.025933 - 0.015258)} = 1.49\text{m}^3/\text{hr}$$

Let, at T_{ps}=327K, h_{fg}=2373.1 kJ/kg and From Eq.(16)

$$Q_e = 0.01628 \times 2373.1 = 38.638 \text{ kJ/hr}$$

From Eq.17,

$$Q_s = \frac{1}{6} \times 1.794 \times (327 - 303) = 7.176 \text{ kJ/hr}$$

Total heat used for drying is,

$$Q_d = 38.638 + 7.176 = 45.814 \text{ kJ/hr} = 12.726\ W$$

Assuming efficiency of drying as 1.5% the required useful heat can be calculated as,

$$Q_u = \frac{12.726}{0.015} = 848.4\ W$$

The collector constructed during experimental work is made from easily available country resources. Using better insulating materials normal Collector efficiency of solar dryer can be increased. Depending upon availability of solar radiations, the limiting average solar radiation intensity at Mumbai is taken as 800 W/m^2.

Assuming collector efficiency as 25 %, area of absorber plate required is,

$$A_p = \frac{848.4}{800 \times 0.25} = 4.242\ m^2$$

3.5.2 Cost analysis of solar dryer

Solar dryer consists of two main components, collector and the drying chamber.

Collector:

The roof of the collector should admit short wave radiations components of the solar radiation spectrum and block the long-wave radiations emitted by the heated absorber. The temperatures reached are up to 80^{0}C to 90^{0}C, and the materials should withstand them. Three choices are glass, acrylic and transparent polycarbonate sheets.

Glass is costlier and heavy, but has a long life. Acrylic is lighter and cheaper, but is affected by temperature, UV radiations and the weather. Polycarbonate sheets are quite light and inexpensive and are used for agricultural polyhouses, where their life span is taken as five years. The cost of constructing support structure for roof is taken as 20% of the material cost. With these assumptions, the cost of mounted collector i.e. a complete dryer assembly (without drying chamber) with a 2mm thick glass roof is INR360/m^2. That for 2mm thick acrylic is INR180/m^2, and of plastic used in polyhouse it is INR72/m^2.

Drying chamber

Drying chamber is constructed from lightweight plywood, which has same properties as that of plywood which is used for giving support to the absorber plate. Material cost for constructing the drying chamber is 50/m^2 of collector area.

Total cost of dryer

Total cost of dryer = collector cost + drying chamber cost + fabrication cost

= 72 + 50 + (72+50)

= INR 244 /m^2 of collector area

4. Further research scope

Existing experimental setup described in this paper is mean to assess and demonstrate the scope for polymer conditioning by using solar dryer. Based on experimental results it has been estimated about 20 % of energy saving potential can be achieved with solar dryer. Experiments are carried out lesser sample size of 100 gm. Observations and results of these experiments are useful to simulation purpose, with various computational techniques. Hence large scope exists for designing similar geometry solar dryers for large sample size for industrial scale. Computational fluid dynamics (CFD) software tools may be suitable to design industrial scale solar dryers. Integration of solar dryers with conventional plastic process at industrial scale is possible for economic production of plastic goods. Further scope exists in system engineering developments to design the complete plastic process with solar dryer for economic production with harnessing solar energy and energy conservation.

Further research scope also exists for solar dryers design with different configuration for other polymer material such as Acrylonitrile Butadiene Styrene (ABS), HDPE etc.

5. Conclusion:

Drying behaviour Nylon-6 was investigated using natural convection solar drying. Air temperature inside the dryer is found to be in the range of 55-60^{o}C, which is dependent on factors such as solar intensity, outside wind velocity, and type of absorber etc. Drying of Nylon-6 is found to be in the falling rate period. Nylon-6 took nearly 6 hrs (1days) to reach 0.15 % moisture content value. Value of effective diffusivity is varied from 4 - 6.5 $\times 10^{-9}$ cm^2/sec. The results presented in this work suggest that solar dryer can be used for pre conditioning that is de-humidification and pre heating of Nylon-6 satisfactorily. Poly propylene (PP) has very low moisture content equilibrium hence temperature curve for this material found to be linear and steep compared to Nylon-6. Preheating of PP material is achieved up to 60^0C by using same dryer design. Hence about 20 to 25 % energy saving potential can be achieved in actual industrial process. Cost benefit analysis shows that by using solar dryer in plastic processing industry economic production is achieved.

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