Design and fabrication of Forced Convection Cabinet type of solar dryer for drying fruits and vegetables

The project's goal is for a sustainable livelihoods initiative for drying fruits and vegetables through solar technology intervention by the use of cabinet type solar dryer. People traditionally dry fruits or vegetables in open, often in unhygienic conditions. It results in poor price realization from the market. A Cabinet type of solar dryer has been designed and fabricated. The dryer will be used by rural people of Odisha, for earning their livelihood. The main component of the dryer is the solar collector, which is covered by glass and surrounded by glass wool which acts as an insulator. The heated air transferred from the solar collector and passes on to the food kept at the trays. As the temperature of air increases, the relative humidity reduces and moisture carrying capacity of air increases, and accordingly the performance of the dryer increases. The dry and warm air absorbs moisture from food, become saturated moisture air. The saturated air is withdrawn from the drying chamber by the exhaust fan which is powered by PV panel. The dryer being made of a good heat conducting material, transfers heat to the immediate dry air within the unit via convection. The dry air gets heated with via convective transfer of heat from the hot surface of the dryer. Application of solar drying technology has the potential for higher value addition of food products. Accordingly, a solar dryer has been designed and fabricated considering various system parameters such as inlet temperature of air, humidity, moisture carried by air per minute and outlet temperature of air. The dryer has been designed with a capacity of 20 kg/day and is manufactured with aluminum sheet and SS304 grade stainless steel perforated trays. The present initiative relates to an energy efficient solar dryer for drying foods, vegetables, seafood, edibles or organic foods. More specifically, the present set up eliminates moisture and provides sufficient drying in a reliable, hygienic and economic way with all three modes of heat transfer viz., conduction, convection and radiation. Further, the present system eliminates the use of auxiliary heaters by taking advantage of direct sunlight falling over the dryer that is made of a good heat conducting material to heat air within the drying room. The wire mesh type food holders are spaced at an equal distance from each other within the drying room to facilitate effective air circulation. The air blowing through fan is used to increase the rate of moisture removal and circulation of heated air in the drying room.

Keywords: Solar Energy; Moisture carrying capacity; Relative Humidity; PV panel; Hygienic.

1. Introduction

1.1 Solar Drying Technology

The first requirement is the transfer of heat to the surface of the moist material,(a) by conduction from heated surface in contact with the material ,convection i.e . absorption of heat by the material supplied the energy necessary for vaporisation of water from it.The drying of a product simply by circulating relatively dry air arround it,is known as the adiabatic drying.The heat required for vaporising the moisture is supplied by the air to the solid material ,thereby reducing the air temperature while increasing its relative humidity.Air leaving the dryer is almost saturated,nearly at the wet bulb temperature of the incoming

air.Hence drying involves both heat transfer and mass transfer.In convective drying the heat required for evaporating moisture from the drying product is supplied by air.
The total heat=Qconduction+Qconvection+Qradiation

Q**conduction**=-kAdt/dx ,where k=Thermal conductivity of the material in W/mK
A=Surface area of heat flow in m2
dt=temperature difference in 0C
dx=Thickness of the material in m
Q=heat transfer due to conduction in watt
Q**convection**=hA(Ts-Ta),Where h=coefficient of convective heat transfer in W/m2 0C
Q**radiation**=FA$\boldsymbol{\sigma}$(Ts4- Ta4) where F=1 for black body, $\boldsymbol{\sigma}$=stefen's boltzmann constant

1.1.1 Moisture content and its measurement

The moisture content of a substance is expressed in percentage by weight on wet basis and dry basis.For percentage wet basis is m=$W_m/W_m+W_d \times 100$
Moisture content for dry basis M= $W_m/W_d \times 100$

The drying process depend upon Psychometric condition.

(i) Energy required to raise the product temperature up to drying air temperature in the form of sensible heat. $E_1=MC_p dt$ where E_1=Energy in kCal,M=Quantity of product, C_p=Specific heat of product, dt=temperature rise

(ii)Latent heat of vaporization for removal of moisture E_2=M'L Where M'=Quantity of moisture to be removed, kg, L= latent heat of vaporization in kJ/kg

(iii).Losses which depends upon various factors like thermal insulation, material construction, area in contact of drying air. Therefore, total energy needed= $E1_+ E_2$+ Losses

2. Design and fabrication

In this work the solar dryer has been designed considering various system parameters such as inlet temperature of air, humidity, moisture carried by air per minute and outlet temperature of air. The materials are considered for various parts of the dryer and dryer is fabricated by various processes.

2.1 Design calculations

For design calculations dry bulb temperatures (DBT) and relative humidity (RH) at inlet and outlet are shown in Figure-I was considered. The parameters are based on brief study of atmosphere at the coastal area of south Odisha.

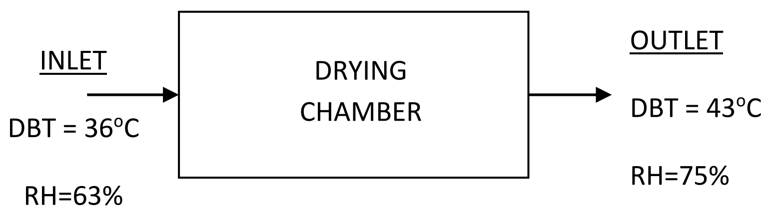


Figure-I. System parameters at inlet and outlet

Mass of the Product (M_p) = 20 kg

m_w = Mass of water to be removed from fruits
m_i = Weight of fruits in kg
M_i= Initial moisture content in fruits = 71%

M_f = Final moisture content in fruits = 20%

$\dot{m}_a$ = Mass flow rate of dry air in kg/sec

$m_w = \frac{m_i (M_i - M_f)}{(1 - M_f)} = \frac{20(0.71 - 0.2)}{1 - 0.2}$ = 12.75 kg of water is to be removed from 20 kg of wet fruit (1)

Using energy balance equation

$$\dot{m}_a C_p (T_2 - T_1) = m_w L$$

$\dot{m}_a = \frac{m_w L}{C_p (T_2 - T_1)} = \frac{12.75 \times 2260}{1.005(72 - 45)}$ =1061.912 kg of dry air

Assuming 24 hours to be dried

$\frac{1061.912}{24 \times 3600} = 0.01229$ Kg/sec of dry air

Volume flow rate = $\frac{\dot{m}_a}{\rho_a} = \frac{0.01229}{1.225}$ = 0.01003 m^3/sec

Bhubaneswar latitude = 20.2961°N, 85.8245°E on 1^{st} May

n = 31+28+31+30+31 = 151

$\delta = Declination = 23.45 \sin\left[\frac{360}{365}(284 + 151)\right]$ =21.8984°

w_s = $\cos^{-1}(-\tan\phi \tan\delta)$ = $\cos^{-1}[-\tan(20.2961)\tan(21.8984)]$

= 98.5458 = sunshine

Hour angle = 1.719 radian

Day length S_{max} = $\frac{2}{15}(98.5458)$ = 13.139 hours

Zenith angle = cos θ = $\sin\phi \sin\gamma + \cos\phi \cos\gamma \cos w$

$= \sin(20.2961)\sin(0) + \cos(20.2961)\cos(0)\cos(2.8725)$

θ = 20.495°

$$\frac{I_T}{I_g} = \left(1 - \frac{I_d}{I_g}\right) r_b + \frac{I_d}{I_g} r_d + r_r = \left(1 - \frac{102.65}{425.59}\right) 0.9378 + \frac{102.65}{425.59} 0.9689 + 6.20 \times 10^{-3}$$

From the above equation sun intensity I_T = 404.94 W/m^2

Assuming 50% instantaneous efficiency A_C was calculated to be $A_c = 1.647\,m^2$

Or $A_c = L \times B = 1.28 \times 1.28$ meter

2.2 Fabrication and Material

The solar collector made of aluminum is covered by glass and surrounded by an insulating material i.e. glass wool. The solar collector supplies heated air which passes on to the food kept at the stainless steel trays. The outlet temperature of air delivered by solar collector increases therefore the relative humidity reduces and moisture carrying capacity of air increases, and accordingly the performance of the dryer increases. The dry and warm air absorbs moisture from food, become saturated moisture in the air. The saturated air is withdrawn from the drying chamber by the exhaust fans. The dryer is made of Aluminum alloy 3003. It is a good heat conducting material, transfers heat to the immediate dry air within the unit via convection. The dry air gets further heated by transfer of heat from the hot surface of the Aluminum alloy dryer. Air blowing units; create convective air currents in the room, circulating warm air in the entire drying room. This warm air, passes across the food holders, through the perforations on the food holders, thereby drawing moisture from the food placed over the holders.

The dryer has been fabricated using aluminum sheets, steel angle and bars. The exhaust fan is fixed on the top of the drying chamber to withdraw the saturated air. Trays are stainless steel wire meshed for proper airflow and placed inside the dryer at equal space. To keep the trays, the angle bars are fixed on the side frame of the dryer. The collector is tilted at 20^oangle according to the latitude of the location and facing due south. The collector is fixed with glass plate (5 mm), absorbing plate (3mm aluminum sheet) and glass wool (75mm). The collector having 1.28X1.28m is fixed with the drying chamber.

COLLECTOR: The main component of flat plate collectoris1. Glass Transparent Cover 2. Aluminum alloy absorber plate 3. Glass Wool Insulation

As the Bhubaneswar latitude is 20.2961^oN, 85.8245^oE, so it is tilted with an angle 20^0 and facing due south so that more amount of sun radiation will incident on collector.

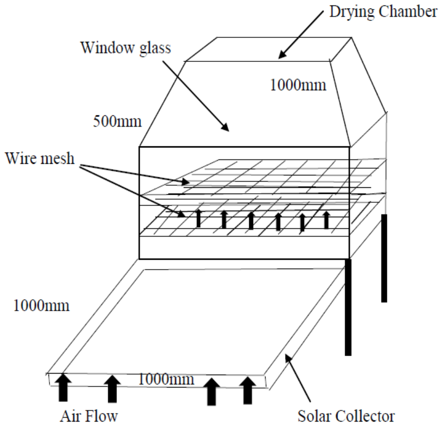
The dryer has 20kg/day drying capacity for mangoes. This dryer contains aluminum sheet and aluminum wire mesh as trays. The thermal design specification is as follows:

Calculated Physical size of Dryer

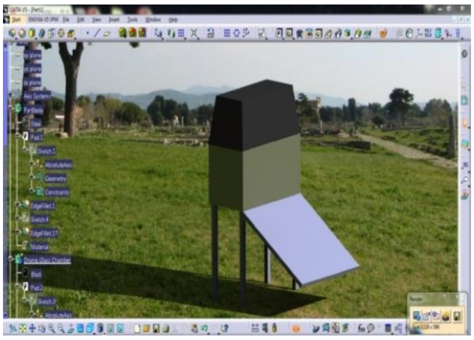
1. Drying Chamber-Length: 1000mm, Height: 500mm

2. Collector-Length: 1280mm and Breadth: 1280mm, Tray dimension: 980mm X 480mm

MATERIAL: Body of the dryer: Aluminum alloy 3003 thickness 3mm



Tray: Aluminum Mesh



SPECIFICATIONS

Sl.No	Parameter	Specifications
1.	Solar Collector Type	Flat plate air- heating solar collector
2.	Loading	Opening doors at back side
3.	Number of Trays	3
4.	Number of Doors	2
5.	Air Circulation	Forced
6.	Drying Capacity	20 kg-Fresh
7.	Construction Materials	Stainless steel wiremesh, aluminium sheets, window glass, glass wool.
8.	Flat Plate Air- Heating Solar Collector is of size	1280mm x 1280mm
9.	Solar Dryer Box size (Lx B x H)	1000mm x 500mm x 500mm
10	Diameter of draft for exhaust fan	300mm

Table-I Specification of Solar Dryer and Collector

3. Results and Discussions

In this experiments on the solar drying of 5 kg Mangos taken for trial and testing from 9AM to 4PM. The dryer was kept in open field so that the dryer can be exposed to the sun ray.at every one hour interval the inside temperatures,relative humidity,illuminance and speed of wind are measured by non-contact type infrared radiation pyrometer,hygrometer, light meter and animometer.

3.1. Inside Temperature and relative humidity of Collector

In the table 3.2 the temperature and relative humidity of collector has been shown. It has been observed that as the temperature of air inside the collector increases, relative humidity of air reduces and moisture carrying capacity of air increases. Due to the density difference between hot air inside the collector and drying chamber, the hot air is forced to the drying chamber. So the heated air at outlet while enter into the drying chamber it absorbs the moisture from the food product to be dried. The moisture air has been exhausted to the atmosphere by the help of exhaust fan provided at the top of the drying chamber.

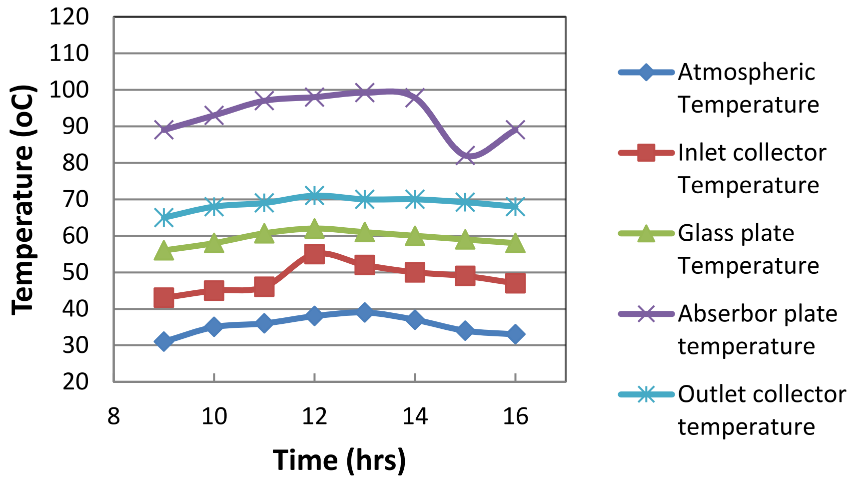
Temperature, Relative humidity in Collector (26.04.17)									
Day/Time (26.04.17)	**Time**	**Ambient T(0C)**	**RH(%)**	**Inlet T(0C)**	**RH(%)**	**Glass plate T(0C)**	**Absorber plate T(0C)**	**Outlet T(0C)**	**RH(%)**
AM	9	31	41	43	45	56	89	65	31
	10	35	38	45	42	58	93	68	25
	11	36	42	46	39	60.7	97	69	12
	12	38	43	55	35	62	98	71	11
PM	1	39	48	52	37	61	99.2	70	10
	2	37	49	50	38	60	97.8	70	13
	3	34	50	49	39	59	82	69.2	14
	4	33	49	47	42	58	89	68	31

Temperature, Relative humidity in Collector (27.04.17)									
Day/Time (27.04.17)	**Time**	**Ambient T(0C)**	**RH(%)**	**Inlet T(0C)**	**RH(%)**	**Glass plate T(0C)**	**Absorber plate T(0C)**	**Outlet T(0C)**	**RH(%)**
AM	9	32	45	40.1	46	42	78	58	35
	10	36	46	42	46.2	45	78.5	59	33.7
	11	39.5	49	45	47	48.2	79.9	59.7	32
	12	40	51.7	47.6	46.7	49.5	86	61	29
PM	1	40.5	44.8	52	45.9	50	87	62.4	30
	2	39	43	51.8	43	49.7	85	61.9	32
	3	37	42	49	43.9	46	83	60.8	33.5
	4	33	42	47	44	47	80.1	59	34.7

Temperature, Relative humidity in Collector (28.04.17)									
Day/Time (28.04.17)	**Time**	**Ambient T(0C)**	**RH(%)**	**Inlet T(0C)**	**RH(%)**	**Glass plate T(0C)**	**Absorber plate T(0C)**	**Outlet T(0C)**	**RH(%)**
AM	9	31.5	45	40.1	46.7	53	82	67	40.7
	10	33	44.5	42	46.2	54	83.7	68	39
	11	36.7	46.7	45	47	54.5	84.5	70	35
	12	38	50	47.6	46.5	54.2	86	70.1	34
PM	1	40.5	50.1	52	50	52.5	87	67.1	43
	2	39	49	51.8	48.3	51	84.5	64.5	45
	3	37	47	49	47.5	50.7	83	60.8	44
	4	33	46	47	46.2	50	81.8	60.3	46.7

Table-II Different Temperature and Relative Humidity of Collector

Figure 3.1.Temperature measurement in °C inside the dryer as on date 26.04.2017



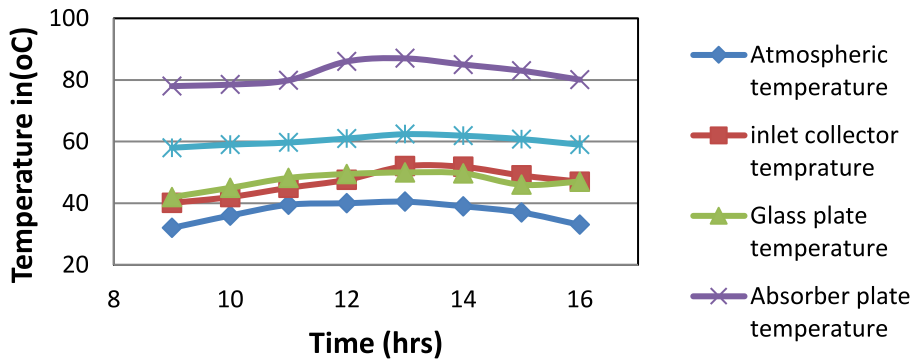


Figure 3.2.Temperature measurement in °C inside the dryer as on date 27.04.2017

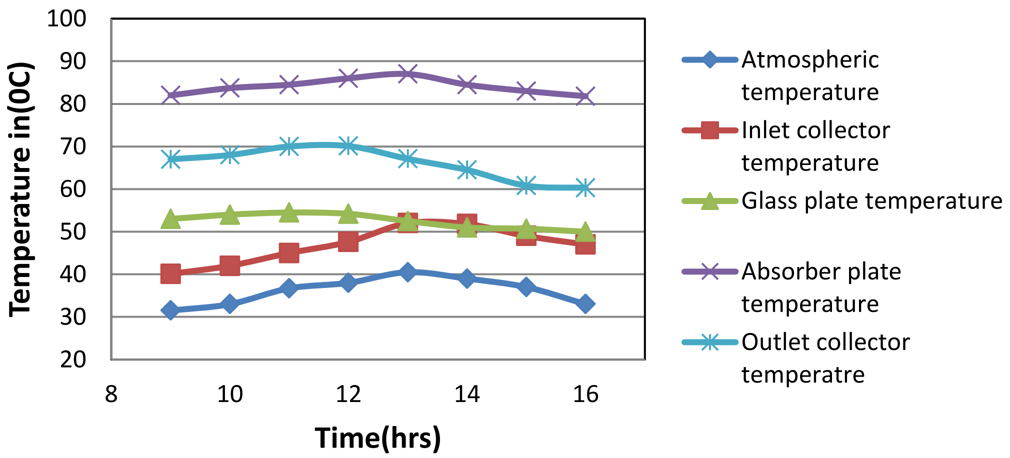


Figure 3.3.Temperature measurement in °C inside the dryer as on date 28.04.2017

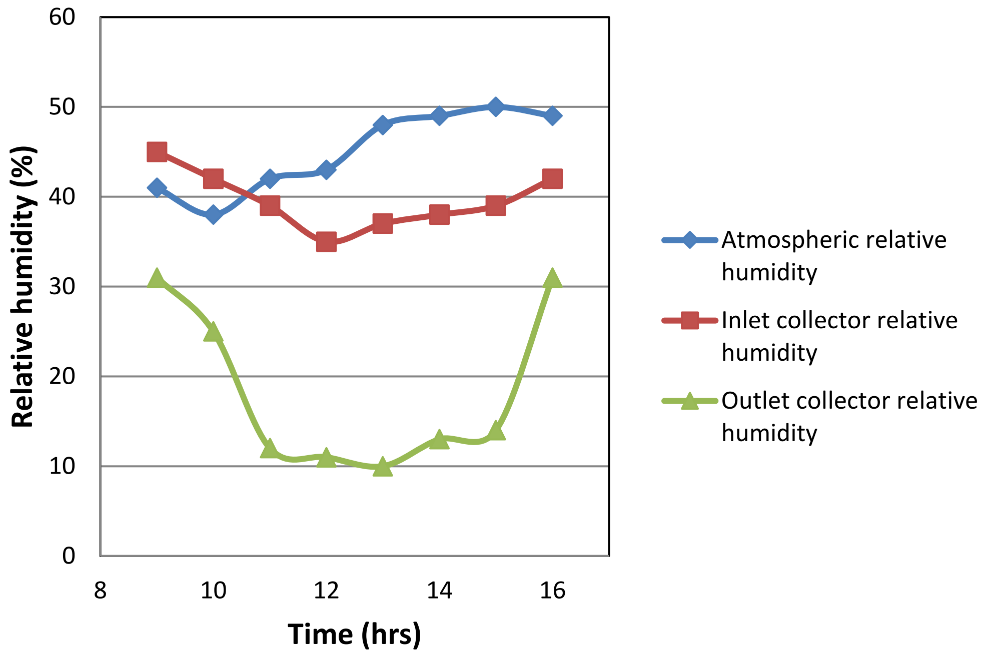


Figure 3.4.R.H. measurement in (%) inside the dryer as on date 26.04.2017

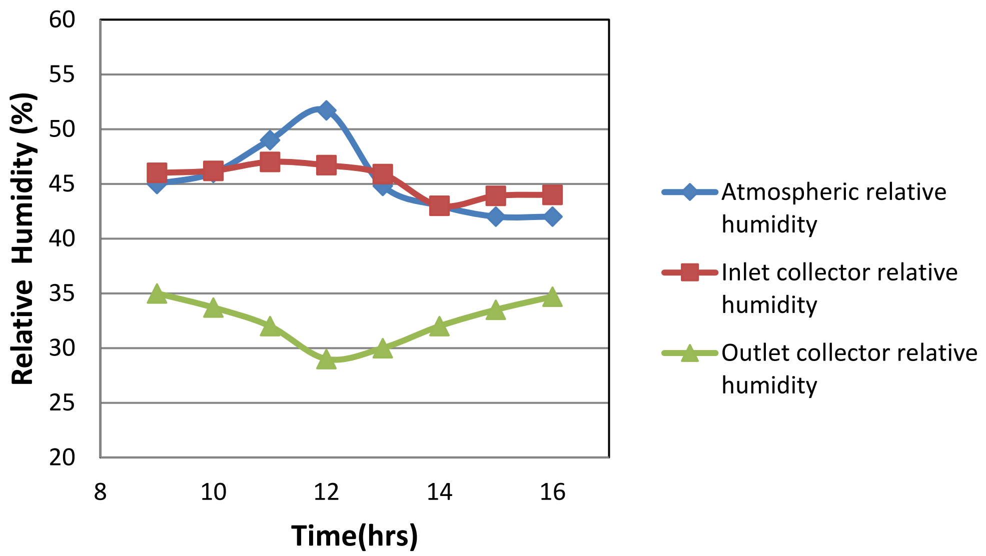


Figure 3.5.R.H. measurement in (%) inside the dryer as on date 27.04.2017

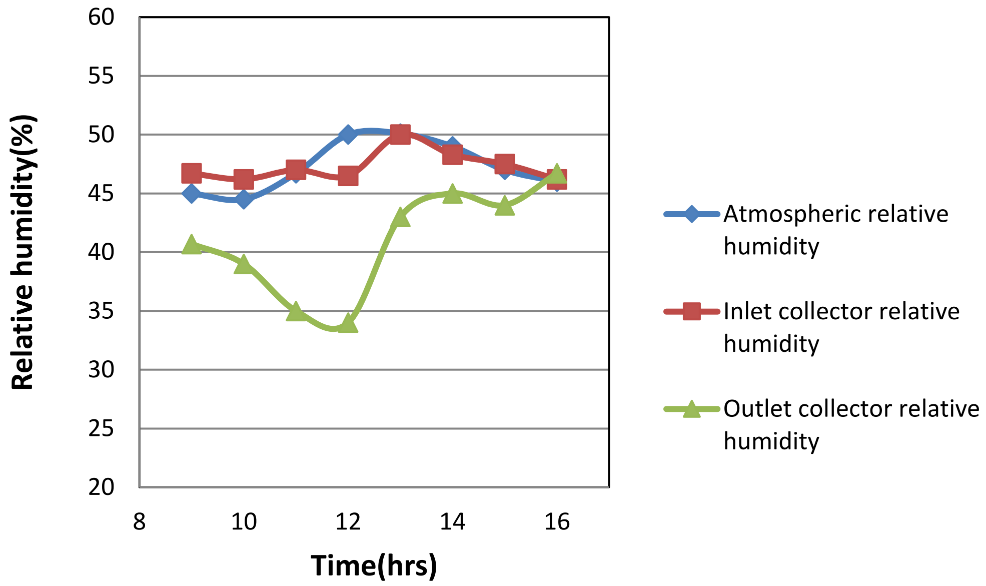


Figure 3.6.R.H. measurement in (%) inside the dryer as on date 28.04.2017

3.3. Temperature variation in three Trays

To measure the inside tray temperature, the dryer is kept in a open field so that the dryer can be exposed to sun ray. For the experiment the considered parameters are presented in the table 4.3. The experiment is started at 9 am and at every one hour interval the inside four trays temperatures are measured by non-contact type pyrometer. The temperatures obtained from the experiment are shown in the table 4.3. It has been found that there is a small variation in temperature from tray 1 to tray 3 as per the thermodynamics second law heat always flow from higher temperature to lower temperature.

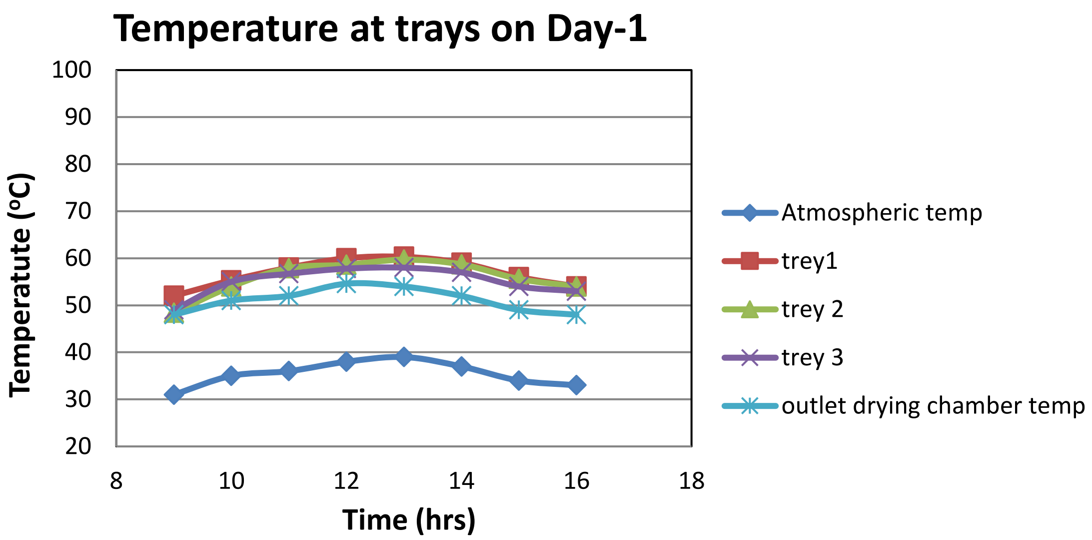
Table -III Different Temperature of Different Trays

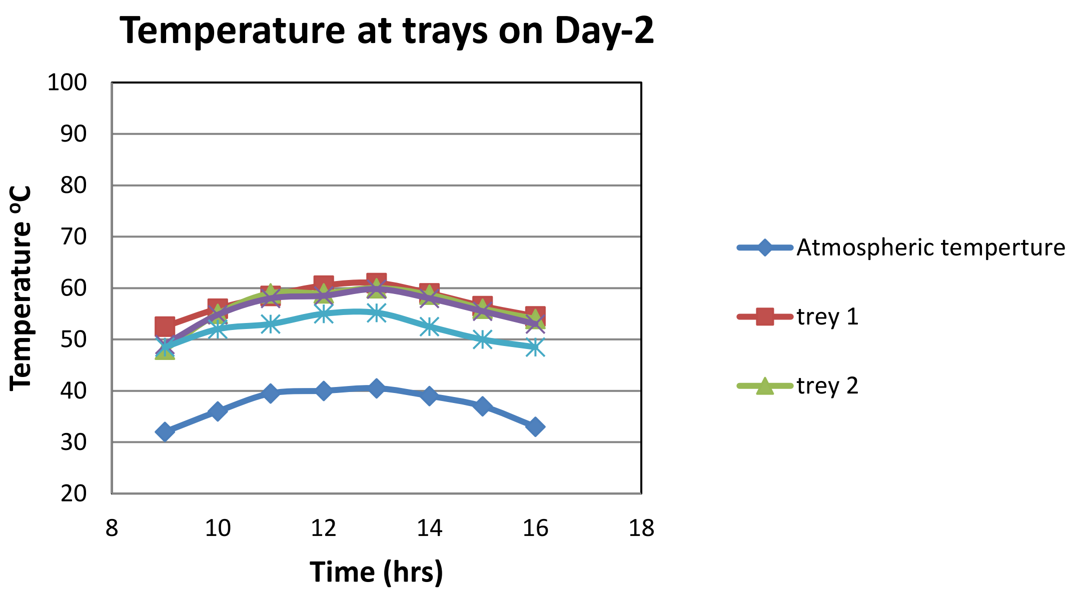
Temperature in Drying chamber (26.04.16)						
Day/Time(26.04.16)	**Time**	**Ambient T(0c)**	**1st tray T(0c)**	**2nd trey T(0c)**	**3rd trey T(0c)**	**Outlet T(0c)**
AM	9	31	52	48.4	49	48
	10	35	55.3	54	55	51
	11	36	58	57.9	56.7	52
	12	38	60	58.6	57.8	54.6
PM	1	39	60.3	59.7	58	54

	2	37	59	58.7	57	52
	3	34	56	55.6	54	49
	4	33	54	54	53	48

Temperature in Drying chamber (27.04.16)						
Day/Time(27.04.16)	**Time**	**Ambient T(0C)**	**1st tray T(0C)**	**2nd trey T(0C)**	**3rd trey T(0C)**	**Outlet T(0C)**
	9	32	52.5	48	49	48.5
60	10	36	56	55	54.8	52
	11	39.5	58.5	59	58	53
	12	40	60.5	59	58.5	55
PM	1	40.5	61	60	59.8	55.2
	2	39	59	58.7	58	52.5
	3	37	56.5	56	55.5	50
	4	33	54.5	54	53	48.5

Temperature in Drying chamber (28.04.16)						
Day/Time(28.04.16)	**Time**	**Ambient T(0C)**	**1st tray T(0C)**	**2nd trey T(0C)**	**3rd trey T(0C)**	**Outlet T(0C)**
	9	31.5	53	50	49	47.5
AM	10	33	55	53.5	54	52
	11	36.7	58	57.5	57	55
	12	38	62	61	59	56
PM	1	40.5	64	63	60	59
	2	39	63	62.5	62	58
	3	37	61	60	59	56
	4	33	58	57.5	57	54


Temperature at trays on Day-1
Temperatute (°C)
100
90
80
70
60
50
40
30
20
8
10
12
14
16
18
Time (hrs)
Atmospheric temp
trey1
trey 2
trey 3
outlet drying chamber temp


Temperature at trays on Day-2
Temperature °C
100
90
80
70
60
50
40
30
20
8
10
12
14
16
18
Time (hrs)
Atmospheric temperture
trey 1
trey 2

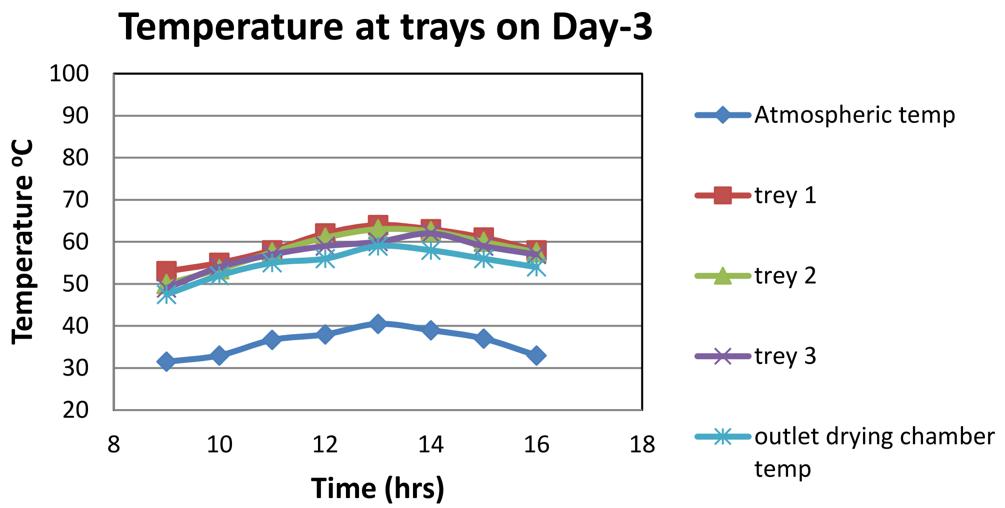


Table IV Relative humidity in drying chamber in different days

Relative humidity in Drying chamber						
Day/Time (26.04.16)	**Time**	**Ambient RH (%)**	**1st tray RH (%)**	**2nd trey RH (%)**	**3rd trey RH (%)**	**Outlet drying chamber RH (%)**
AM	9	57.5	45	45.5	45.8	44.9
	10	56	42	42.9	43	42
	11	54	40	40.5	41	40.5
	12	51.5	39.3	40	41	40
PM	1	51	38	39	40	39
	2	52	40	41	42	42.5
	3	53.5	42.5	43	42.8	42.7
	4	54.5	44	45.6	45.9	45.8
Day/Time (27.04.16)	**Time**	**Ambient RH (%)**	**1st tray RH (%)**	**2nd trey RH (%)**	**3rd trey RH (%)**	**Outlet drying chamber RH (%)**
AM	9	57	44.6	45.3	45.2	45
	10	55.9	41.9	42.5	42.3	42.5
	11	55	40.2	40	40	40.3
	12	51.5	39.5	39.7	39.5	39.8

PM	1	50	38.7	38.9	38.5	38.4
	2	51.9	39	40.8	40.4	40
	3	52.7	40.4	42.6	42.1	42
	4	53.9	42	45	44.8	44.5
Day/Time (28.04.16)	**Time**	**Ambient RH (%)**	**1st tray RH (%)**	**2nd trey RH (%)**	**3rd trey RH (%)**	**Outlet drying chamber RH (%)**
AM	9	56.8	40.3	40.1	39.8	39
	10	56.2	39	39.1	39	40
	11	54	38.7	38.4	38.3	38.8
	12	50.9	36	35.9	35.8	36
PM	1	50	35.7	35.6	35.5	36
	2	51	36.5	36.7	36.5	37
	3	52	37.2	37.4	37.2	38.1
	4	54	38.9	38.5	38.3	38.9

Table V Solar Illuminance and velocity in different days

		Solar Illuminance (Lux)	velocity of air (m/sec)	
Day/Time (26.04.16)	**Time**	**Glass plate of collector**	**Inlet of collector**	**Outlet of drying chamber**
AM	9	900	0.85	2.15
	10	950	0.86	2.25
	11	1000	0.88	2.32
	12	1032	0.90	2.37
PM	1	1025	0.91	2.30

	2	1005	0.88	2.22
	3	986	0.89	2.18
	4	960	0.85	2.15
Day/Time (27.04.16)	**Time**	**Glass plate of collector**	**Inlet of collector**	**Outlet of drying chamber**
AM	9	900	0.86	2.14
	10	950	0.87	2.22
	11	1008	0.89	2.29
	12	1019	0.90	2.35
PM	1	1020	0.92	2.29
	2	1008	0.89	2.20
	3	995	0.90	2.15
	4	987	0.86	2.10
Day/Time (28.04.16)	**Time**	**Glass plate of collector**	**Inlet of collector**	**Outlet of drying chamber**
AM	9	895	0.85	2.15
	10	955	0.87	2.21
	11	1106	0.87	2.30
	12	1020	0.89	2.33
PM	1	1010	0.91	2.29
	2	999	0.90	2.19
	3	970	0.89	2.14
	4	955	0.88	2.09

3. Testing of Dryer

To study the performance of the dryer mangos have been dried. The figure 3.7 shows the drying of mango in the solar dryer. The table 3.6 shows the comparison of weight reduction of mango dried in open sunlight and dried in solar dryer. It can be seen that the percentage of weight reduction is more in case of dryer with a less time.

Table VI Weight of Mangos before and after drying:

Fish	Initial Weight (gm.)	Final Weight (gm.)	Time Taken (Hrs.)	Weight Reduction %
Dried in Open Sunlight	5000	3500	56	22
Dried in Solar Dryer	5000	2500	24	50




Conclusion

- In this experiment the performance test of dryer had been made and it was observed that drying rate was more as compare to conventional method of drying.
- In the outlet of collector highest temperature generated is 70^0C which is sufficient enough to dry the food product.