

Design, Building and Performance Evaluation of a Mixed-Mode Solar Dryer for Agricultural Products

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Abstract: - This research work presents the detailed explanation of the design, construction and performance evaluation of mixed-mode solar agricultural products dryer. The experimental set up used for testing the performance of the mixed-mode solar agricultural products dryer and determining the influence of various drying methods on the drying behaviour of agricultural products. Evaluation of the dryer was centered on the moisture content reduction, temperatures and relative humidities variations. 1680 g of freshly potato slides were used for evaluation.

The test results gave that the temperatures inside the dryer cabinet and the solar collector were much higher than the ambient temperature during most hours of the daylight. The temperature inside the solar collector was up to 27 °C approximately higher than the ambient temperature. The temperature inside the drying cabinet was up to 22 °C approximately higher than the ambient temperature for about three hours immediately after 12.00 h (noon). The relative humidity in the solar collector and drying cabinet were lower than the ambient air relative humidity, with the ambient air recording the highest relative humidity at each reading followed by the drying cabinet and finally by the solar collector. Because of the decreased relative humidity inside the dryer, all the time, the temperature inside the dryer was high which is sufficient enough to dry the potato at an early time.

Based on the results obtained during the test, temperature above 65 °C was recorded inside the drying cabinet. This high temperature in the drying cabinet causes 419 g of moisture to be removed on the first day, 257 g on the second day, 191 g on the third day, 136 g on the fourth day and finally 108 g on the fifth day. At the end of the five days of drying process, the mass of 1680 g of potato was reduced to 569 g. Total amount of moisture removed was 1111 g and total moisture loss was 66.1 %, which is the required amount of moisture to be removed for safe drying of freshly potato slides. The moisture content of the freshly potato slides was 24.9 % at the end of drying for the first day at about 5:00 pm, 20.4 % at the end of drying for the second day, 19 % at the end of drying for the third day, 16.7 % at the end of drying for the fourth day and finally 15.9% at the end of drying for the fifth day. It was observed that the drying rate increased from the end of one day to another, which shows the earlier and faster removal of moisture from the dried item.

Key-Words: - Solar Energy, Mixed-Mode Solar Dryer, Solar Collector, Drying Cabinet, Solar Radiation, Ambient Temperature, Relative Humidity, Moisture Content, % Moisture Loss, Freshly Potatoes Slides

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1 Introduction

Agricultural products drying is the most energy consuming process in all processes on the farm. The purpose of drying is to remove moisture from the agricultural produce so that it can be processed safely and stored for increased periods of time. Drying is very important process applicable for agricultural and industrial products. Drying is the moisture removing process from the products. Drying reduces the bacterial growth in the products. It will be helpful for preserving the products for long time. Solar drying is the oldest method of products drying. Open air solar drying method is used frequently to dry the agricultural products. But this method has some disadvantages. Therefore to avoid disadvantages it is necessary to use the other solar

drying methods. Different solar drying methods are direct solar drying, indirect solar drying, and mixed mode solar drying. The device used for drying process with application of solar energy called the Solar dryer. Solar dryer are also classified with mode of air circulation to natural and forced convection [1, 2, 4].

Direct solar drying is the conventional way of drying the products. In this method the products are directly exposed to the solar radiation and reduce the moisture content to atmospheric air. The air movement is due to density difference.

Indirect solar drying or convective solar drying is the new technique of product drying. It is very efficient method than the direct type of solar drying. In this method the atmospheric air is heated in flat plate collector or concentrated type solar collector.

The heating process is either passive or active. This hot air then flow in the cabin where products are stored. Therefore moisture from the product may lost by convection. This method of drying is used to avoid direct exposing to the solar radiation. This method mainly reduces the disadvantages of direct solar drying.

Mixed mode solar drying is combination of direct and indirect solar drying method. Product may dry with both direct exposure to solar radiation and hot air supplier on it. Air may heated in solar energy collector first then pass to the cabinet where products are stored. In this process product may dry according to convective moisture loss. The same cabinet is partially or totally covered with the transparent material to exposure the products to solar radiation.

Drying is an essential process in the preservation of agricultural products. Drying preserves foods by removing enough moisture from food to prevent decay and spoilage. Drying of foods, the key is to remove moisture as quickly as possible at a temperature that does not seriously affect the flavour, texture and colour of the food. Various drying methods are employed to dry different agricultural products [5-10].

Drying is the reduction of moisture from the products and is a most important process for preserving agricultural products since it has a great effect on the quality of the dried products. The major objective in drying agricultural products is the reduction of the moisture content to a level which allows safe storage over an extended period. Solar dryer is the simple devices used to collect the solar radiations and transfer that radiation in the form of heat energy and this heat energy then transfer to product for drying [3, 11-15].

The objective of this study is to present the detailed explanation of the design, construction of the mixed-mode solar agricultural products dryer using locally available materials and to evaluate the performance of this dryer, in which the grains are dried simultaneously by both direct radiation through the transparent roof of the cabinet and by the heated air from the solar collector. The experimental set up used for testing the performance of the mixed-mode solar agricultural products dryer and determining the influence of various drying methods on the drying behaviour of agricultural products. Evaluation of the dryer was centered on the moisture content reduction and temperature variations. 1680g of freshly potato slides were used for evaluation. Temperatures and relative humidities of the drying cabinet, solar collector and ambient air were taken daily using digital sensors on an hourly

basis from 9:00 am to 5:00 pm. Moisture content was taken at the beginning and at the end of each drying days.

2 Materials and Methods

The solar dryer considered in this research paper is the mixed-mode forced convection solar dryer. The materials used for the construction of the mixed-mode solar dryer are cheap and easily obtainable in the local market. Figure 1 shows the main components of the mixed-mode solar dryer. The solar dryer consists of the solar collector (air heater), the drying cabinet and four drying trays. The flat-plate solar collector is always tilted and oriented in such a way that it receives maximum solar radiation during the desired season of used, therefore, solar collector in this research work is oriented facing south and tilted at 17.5° to the horizontal.

The mixed-mode solar dryer components:

- **Solar collector:** The two main components of the solar collector are firstly the absorber plate which made from a metal painted black to absorb the incident solar radiation and placed below the cover plate which used to cover the absorber plate, thereby preventing dust and rain from coming in contact with the absorber, it also retards heat from escaping, common materials used for cover plates is a glass. In this research paper, aluminum is chosen because of its quick response in the absorption of solar radiation and secondly the insulation which used to minimize heat loss from the system, it is under the absorber plate, the insulator must be able to withstand stagnation temperature, it should be fire resistant and not be damageable by moisture or insects.
- **Drying cabinet:** The drying cabinet is made from wood, the material has been chosen since wood is a poor conductor of heat and its smooth surface finish, heat loss by radiation is minimized.

The designed mixed-mode solar dryer with all components are shown in figure 2.1 – 2.4.

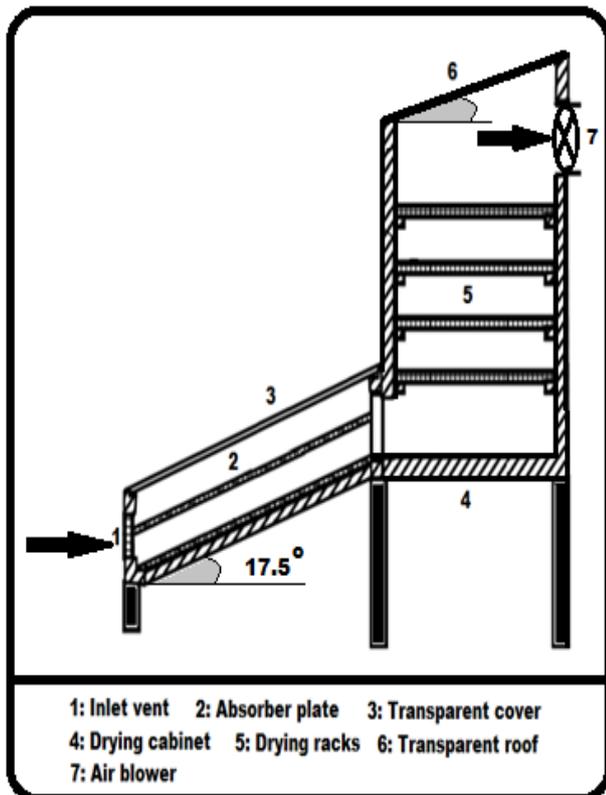


Fig. 1 Main components of the mixed-mode solar agricultural products dryer



Fig. 2.1 Photo of the designed mixed-mode solar dryer



Fig. 2.2 Photo of the designed drying cabinet with its drying racks



Fig. 2.3 Photo of the designed drying racks with freshly potato slides



Fig. 2.4 Photo of the designed mixed-mode dryer from the bottom with two air blowers

3 Testing

The testing of the mixed-mode solar dryer was done in the month of October for five days starting from 9:00 am to 5:00 pm. The solar Dryer was placed outside with the collector facing the direction of the sun. The collector has been rigidly fixed to the dryer at an angle approximately 17.5° to the horizontal to obtain approximately perpendicular beam of sun rays to avoid damage in transit. Slides of freshly potatoes were arranged on the drying bed in a single layer to avoid moisture being trapped in the lower layer. The dryer cabinet door was closed and seals placed in position. Evaluation of the dryer was centered on the temperature and relative humidity variations and moisture content reduction. 1680g of freshly potatoes slides were used for evaluation.

3.1 Evaluation of the Dryer:

Evaluation of the dryer was centered on the moisture content reduction and temperature variations. 1680g of freshly potatoes slides were used for evaluation.

3.2 Temperature:

Temperatures of the drying cabinet, solar collector and ambient air were taken daily using digital sensors on an hourly basis from 9:00 am to 5:00 pm.

3.3 Relative Humidity:

Relative humidity may be defined as the ratio of the water vapor density (mass per unit volume) to the saturation water vapor density, usually expressed in percent:

$$\text{Relative Humidity (RH)} = \frac{\text{Actual Vapour Density}}{\text{Saturation Vapour Density}} \times 100$$

Relative humidity of the drying cabinet, solar collector and ambient air were taken daily using digital sensors on an hourly basis from 9:00 am to 5:00 pm.

3.4 Moisture content:

Moisture content was taken at the beginning and at the end of each drying day using the oven drying method and calculated using the following equation:

$$\text{Moisture content} = \frac{M_i - M_f}{M_i} \times 100$$

Where:

M_i = Mass of potato slides before drying

M_f = Mass of potato slides after drying

4 Results and Discussions

4.1 Variation of temperatures with time

Variations in temperature were observed as shown in Tables 1 – 5 and Figures 3.1 – 3.5. Lower temperatures were recorded during the morning and evening hours with the morning hours recording the lowest temperatures. At 9:00 am, the ambient temperature was about 33 °C, while the solar collector recorded about 48 °C and the solar drying cabinet had about 43 °C. At 5:00 pm, the temperatures were about 38 °C, 58 °C and 53 °C for ambient, solar collector and drying cabinets respectively.

It is observed from Tables that, the temperatures in the solar collector and drying cabinet were higher than the ambient temperatures, with the solar collector recording the highest temperature at each reading followed by the drying cabinet. The highest temperatures were recorded during noon. At 2:00 pm, the ambient temperature was about 44 °C while the solar collector recorded 70 °C and the solar drying cabinet had 65 °C.

Results on 1st October 2015

Table 1: Variation of temperature with time on the first day

Day 1									
Time	9	10	11	12	13	14	15	16	17
A.T (°C)	34	37	38	40	42	43	41	39	38
C.T (°C)	48	51	56	64	67	68	64	60	58
D.C.T (°C)	43	46	51	59	62	63	59	55	53

A.T = Ambient Temp., C.T = Collector Temp., D.C.T = Drying Cabinet Temp.

Results on 2nd October 2015

Table 2: Variation of temperature with time on the second day

Day 2									
Time	9	10	11	12	13	14	15	16	17
A.T(°C)	34	38	39	41	43	44	42	40	39
C.T(°C)	49	52	57	65	68	69	66	62	59
D.C.T (°C)	44	47	52	60	63	64	61	57	54

Results on 3rd October 2015

Table 3: Variation of temperature with time on the third day

Day 3									
Time	9	10	11	12	13	14	15	16	17
A.T(°C)	33	37	38	40	42	43	41	40	40
C.T(°C)	50	53	58	66	69	70	67	63	60
D.C.T (°C)	45	48	53	61	64	65	62	58	55

Results on 4th October 2015

Table 4: Variation of temperature with time on the fourth day

Day 4									
Time	9	10	11	12	13	14	15	16	17
A.T (°C)	37	38	39	40	42	44	43	41	39
C.T (°C)	52	53	55	64	67	70	66	62	59
D.C.T (°C)	47	48	50	59	62	65	61	57	54

Results on 5th October 2015

Table 5: Variation of temperature with time on the fifth day

Day 5									
Time	9	10	11	12	13	14	15	16	17
A.T (°C)	37	38	39	41	43	44	42	41	40
C.T (°C)	51	53	55	65	68	69	65	63	61
D.C.T (°C)	46	48	50	60	63	64	60	58	56

Figures 3.1 to 3.5 show a typical day results of the hourly variation of the temperatures in the solar collector and the drying cabinet compared to the ambient temperature. The dryer is hottest about mid-day when the sun is usually overhead. The temperatures inside the dryer cabinet and the solar collector were much higher than the ambient temperature during most hours of the daylight. The temperature inside the solar collector was up to 27 °C approximately higher than the ambient temperature. The temperature inside the drying cabinet was up to 22 °C approximately higher than the ambient temperature for about three hours immediately after 12.00 h (noon).

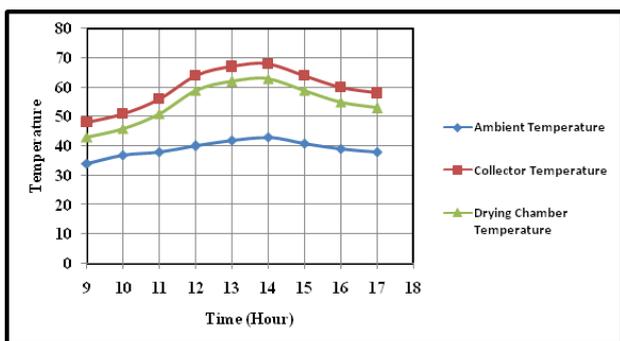


Fig. 3.1 Variation of temperature with time on the first day

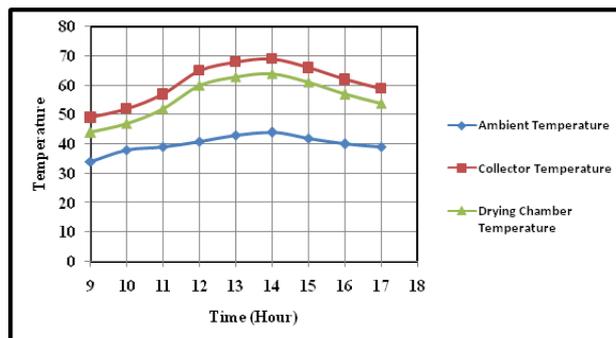


Fig. 3.2 Variation of temperature with time on the second day

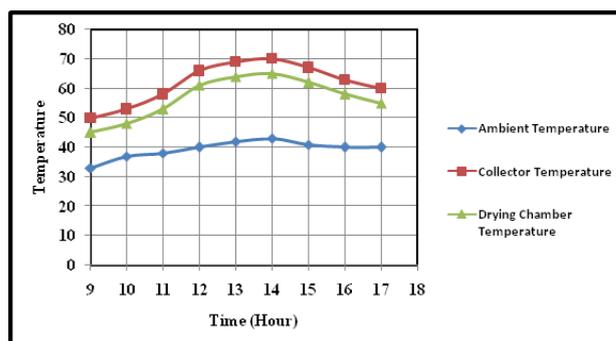


Fig. 3.3 Variation of temperature with time on the third day

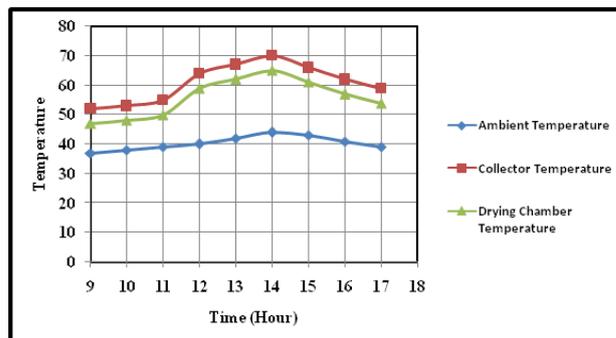


Fig. 3.4 Variation of temperature with time on the fourth day

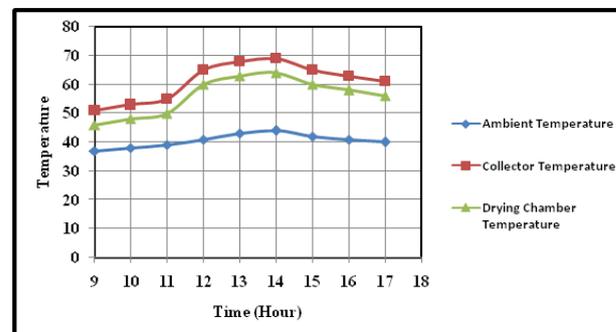


Fig. 3.5 Variation of temperature with time on the fifth day

4.2 Variation of relative humidity with time

Variations in relative humidity were observed as shown in tables 6 – 10 and figures 4. 1 – 4.5. It is observed from tables and figures that, the relative humidity in the solar collector and drying cabinet were lower than the ambient air relative humidity, with the ambient air recording the highest relative humidity at each reading followed by the drying cabinet and finally by the solar collector. Because of the decreased relative humidity inside the dryer, all the time, the temperature inside the dryer was high which is sufficient enough to dry the potato at an early time.

Results on 1st October 2015

Table 6: Variation of relative humidity with time on the first day

Day 1									
Time	9	10	11	12	13	14	15	16	17
A.R.H	66	62	62	61	59	58	59	58	58
C.R.H	31	27	27	26	24	23	24	23	23
D.C.R.H	39	35	35	34	32	31	32	31	31

A.R.H=Ambient Relative Humidity, C.R.H=Collector Relative Humidity, D.C.R.H=Drying Cabinet Relative Humidity

Results on 2nd October 2015

Table 7: Variation of relative humidity with time on the second day

Day 2									
Time	9	10	11	12	13	14	15	16	17
A.R.H	65	62	60	59	58	59	59	58	58
C.R.H	30	27	25	24	23	24	24	23	23
D.C.R.H	38	35	33	32	31	32	32	31	31

Results on 3rd October 2015

Table 8: Variation of relative humidity with time on the third day

Day 3									
Time	9	10	11	12	13	14	15	16	17
A.R.H	62	60	58	58	57	56	57	58	60
C.R.H	27	25	23	23	22	21	22	23	25
D.C.R.H	35	33	31	31	30	29	30	31	33

Results on 4th October 2015

Table 9: Variation of Relative Humidity with Time on the Fourth day

Day 4									
Time	9	10	11	12	13	14	15	16	17
A.R.H	63	62	59	58	61	63	63	64	67
C.R.H	28	27	24	23	26	28	28	29	32
D.C.R.H	36	35	32	31	34	36	36	37	40

Results on 5th October 2015

Table 10: Variation of relative humidity with time on the fifth day

Day 5									
Time	9	10	11	12	13	14	15	16	17
A.R.H	65	66	65	62	62	63	63	64	67
C.R.H	30	31	30	27	27	28	28	29	32
D.C.R.H	38	39	38	35	35	36	36	37	40

Figures 4.1 – 4.5 show a typical day results of the hourly variation of the relative humidities in the solar collector and the drying cabinet compared to the ambient temperature. The results show that the drying processes were enhanced by the heated air at very low humidity.

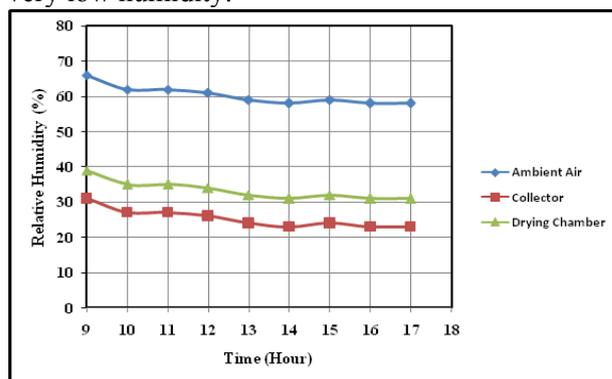


Fig. 4.1 Variation of air humidity with time on the first day

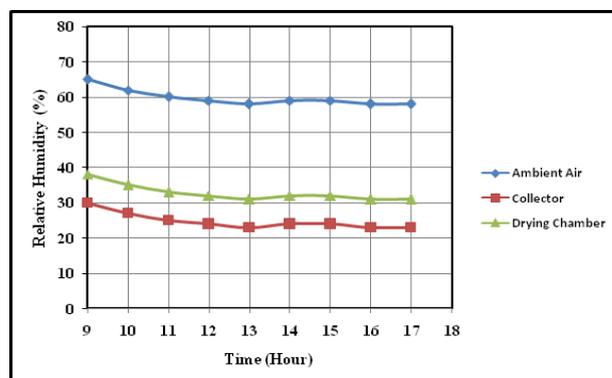


Fig. 4.2 Variation of air humidity with time on the second day

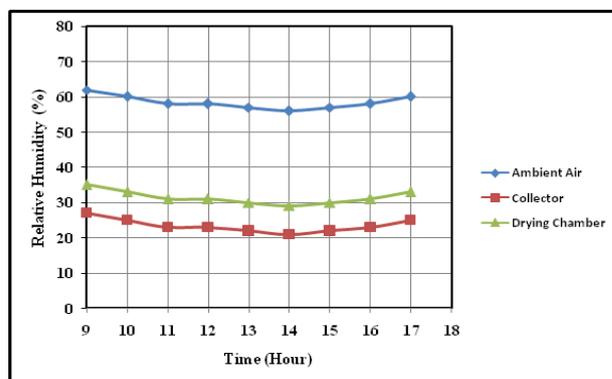


Fig. 4.3 Variation of air humidity with time on the third day

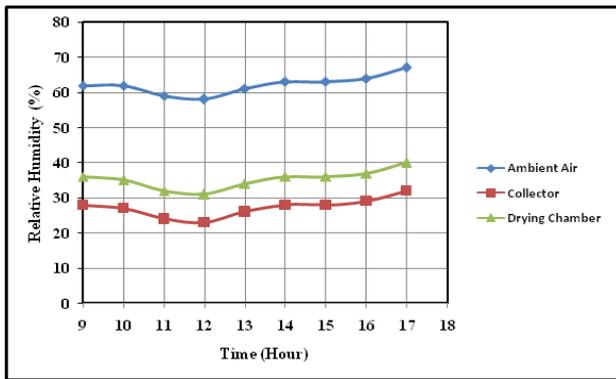


Fig. 4.4 Variation of air humidity with time on the fourth day

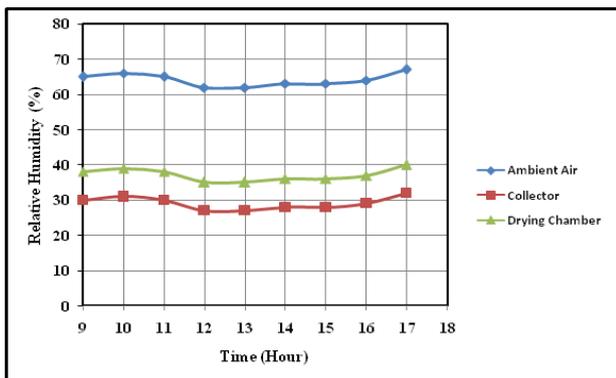


Fig. 4.5 Variation of air humidity with time on the fifth day

4.3 Variation of mass of the potato and moisture loss with time

Tables 11 – 15 and Figures 5.1 – 5.5 show the variation of mass of the potato and moisture loss in the mixed-mode solar food dryer. It was observed that the drying rate increased due to increase in temperature between 12.00h and 14.00h but decreased thereafter, which shows the earlier and faster removal of moisture from the dried item. Also It was observed from tables 11 - 15 that the moisture removed and total moisture loss in first day was greater than all days after, this happened as a result of an increase in moisture content on the first day from the following days, and then the moisture content begins to decrease gradually after that. It was observed that the moisture removed from first day was 419 g and the total moisture loss was 24.9 %. In the second day it was observed that the moisture removed was 257 g and the total moisture loss was 20.4 %. In the third day it was observed that the moisture removed was 191 g and the total moisture loss was 19 %. In the fourth day it was observed that the moisture removed was 136 g and the total moisture loss was 16.7 %. In the fifth day it was observed that the moisture removed was 108 g and the total moisture loss was 15.9 %.

Results on 1st October 2015

Table 11: Variation of mass of the potato and moisture loss with time on the first day

Day 1	Moisture removed = 1680 – 1261 = 419 g Total moisture loss = 24.9 %								
Time	9	10	11	12	13	14	15	16	17
Mass (g)	1680	1661	1624	1569	1503	1429	1362	1304	1261
M.L. (g)	-	19	37	55	66	74	67	58	43
% M.L.	-	1.1	2.2	3.3	3.9	4.4	4	3.5	2.5

Results on 2nd October 2015

Table 12: Variation of mass of the potato and moisture loss with time on the second day

Day 2	Moisture removed = 1261 – 1004 = 257 g Total moisture loss = 20.4 %								
Time	9	10	11	12	13	14	15	16	17
Mass (g)	1261	1252	1235	1210	1166	1112	1065	1027	1004
M.L. (g)	-	9	17	25	44	54	47	38	23
% M.L.	-	0.7	1.3	2	3.5	4.3	3.7	3.1	1.8

Results on 3rd October 2015

Table 13: Variation of mass of the potato and moisture loss with time on the third day

Day 3	Moisture removed = 1004 – 813 = 191 g Total moisture loss = 19 %								
Time	9	10	11	12	13	14	15	16	17
Mass (g)	1004	997	985	963	930	884	850	828	813
M.L. (g)	-	7	12	22	33	46	34	22	15
% M.L.	-	0.7	1.2	2.2	3.3	4.6	3.4	2.2	1.5

Results on 4th October 2015

Table 14: Variation of mass of the potato and moisture loss with time on the fourth day

Day 4	Moisture removed = 813 – 677 = 136 g Total moisture loss = 16.7 %								
Time	9	10	11	12	13	14	15	16	17
Mass (g)	813	808	800	784	762	730	706	690	677
M.L. (g)	-	5	8	16	22	32	24	16	13
% M.L.	-	0.6	1	2	2.7	3.9	2.9	2	1.6

Results on 5th October 2015

Table 15: Variation of mass of the potato and moisture loss with time on the fifth day

Day	Moisture removed = 677 – 569 = 108 g								
5	Total moisture loss = 15.9 %								
Time	9	10	11	12	13	14	15	16	17
Mass (g)	677	673	667	655	639	613	594	580	569
M.L. (g)	-	4	6	12	16	26	19	14	11
% M.L.	-	0.6	0.9	1.8	2.3	3.8	2.8	2.1	1.6

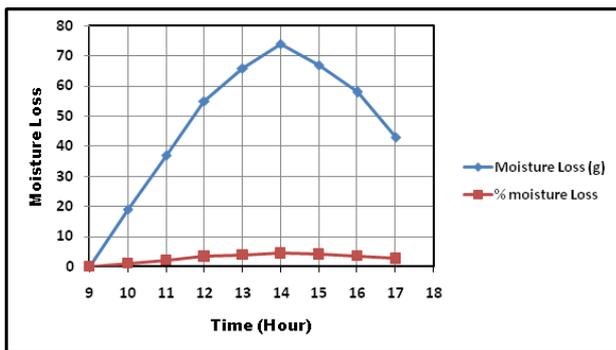


Fig. 5.1 Variation of moisture loss with time on the first day

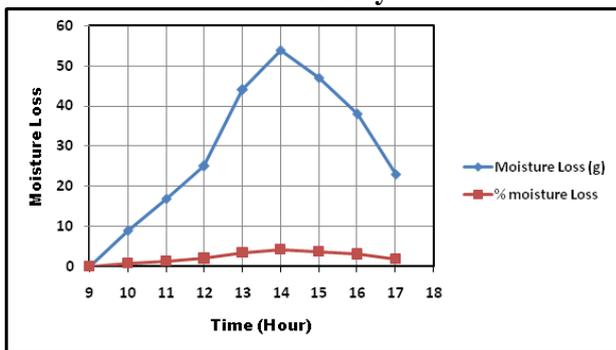


Fig. 5.2 Variation of moisture loss with time on the second day

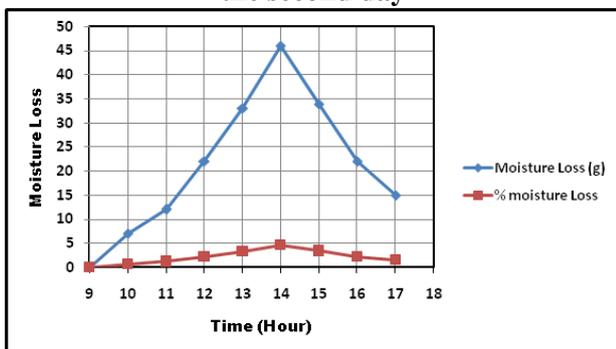


Fig. 5.3 Variation of moisture loss with time on the third day

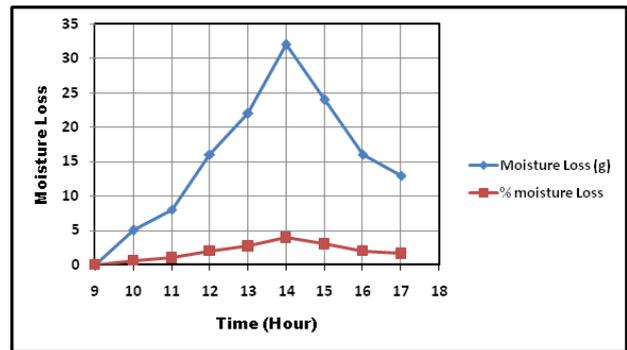


Fig. 5.4 Variation of moisture loss with time on the fourth day

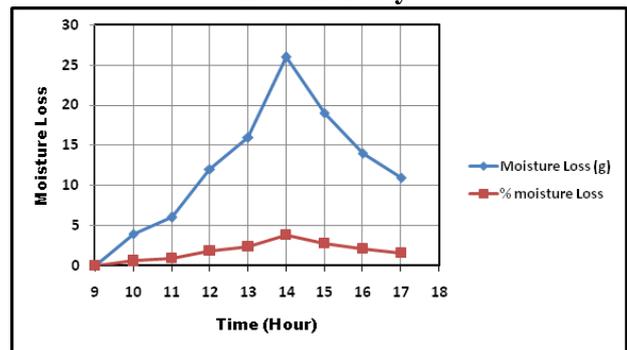


Fig. 5.5 Variation of moisture loss with time on the fifth day

Based on the results obtained during the test, temperature above 65 °C was recorded inside the drying cabinet. This high temperature in the drying cabinet causes 419 g of moisture to be removed on the first day, 257 g on the second day, 191 g on the third day, 136 g on the fourth day and finally 108 g on the fifth day. At the end of the five days of drying process, the mass of 1680 g of potato was reduced to 569 g. Total amount of moisture removed was 1111 g and total moisture loss was 66.1 %, which is the required amount of moisture to be removed for safe drying of freshly potato slides.

Variations in moisture removed and moisture content were observed as shown in Table 16 and Figures 6 & 7.

Table 16: Variation of moisture removed and moisture loss with time for the drying 5 days

Day	Moisture removed (g)	Total moisture loss (%)
1	419	24.9
2	257	20.4
3	191	19
4	136	16.7
5	108	15.9

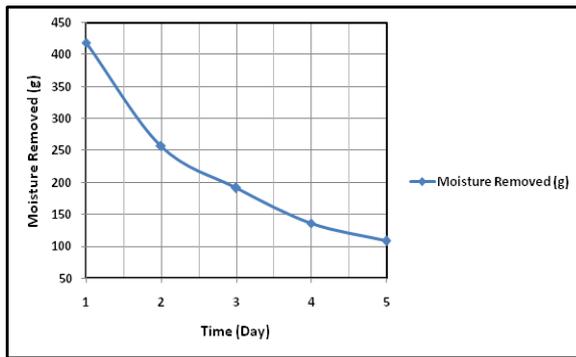


Fig. 6 Variation of moisture removed with time through 5 days

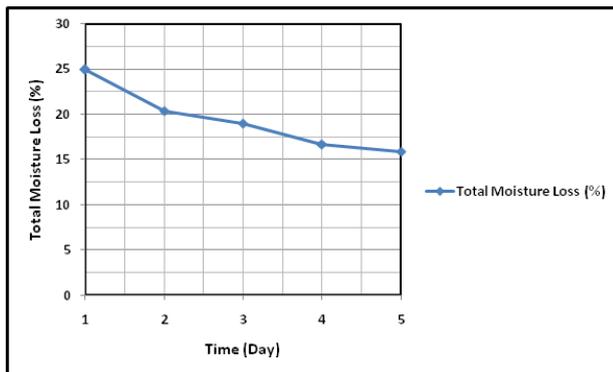


Fig. 7 Variation of total moisture loss with time through 5 days

The moisture content of the freshly potato slides was 24.9 % at the end of drying for the first day at about 5:00 pm, 20.4 % at the end of drying for the second day, 19 % at the end of drying for the third day, 16.7 % at the end of drying for the fourth day and finally 15.9% at the end of drying for the fifth day. It was observed that the drying rate increased from the end of one day to another, which shows the earlier and faster removal of moisture from the dried item.

5 Conclusions

- The temperatures inside the dryer cabinet and the solar collector are much higher than the ambient temperature during most hours of the daylight. The temperature inside the solar collector was up to 27 °C approximately higher than the ambient temperature. The temperature inside the drying cabinet was up to 22 °C approximately higher than the ambient temperature for about three hours immediately after 12.00 h (noon).
- The relative humidity in the solar collector and drying cabinet were lower than the ambient air relative humidity, with the ambient air recording the highest relative humidity at each reading followed by the drying cabinet and finally by the solar collector. Because of the decreased relative

humidity inside the dryer, all the time, the temperature inside the dryer was high which is sufficient enough to dry the potato at an early time.

- Based on the results obtained during the test, temperature above 65 °C was recorded inside the drying cabinet. This high temperature in the drying cabinet causes 419 g of moisture to be removed on the first day, 257 g on the second day, 191 g on the third day, 136 g on the fourth day and finally 108 g on the fifth day. At the end of the five days of drying process, the mass of 1680 g of potato was reduced to 569 g. Total amount of moisture removed was 1111 g and total moisture loss was 66.1 %, which is the required amount of moisture to be removed for safe drying of freshly potato slides.
- The moisture content of the freshly potato slides was 24.9 % at the end of drying for the first day at about 5:00 pm, 20.4 % at the end of drying for the second day, 19 % at the end of drying for the third day, 16.7 % at the end of drying for the fourth day and finally 15.9% at the end of drying for the fifth day. It was observed that the drying rate increased from the end of one day to another, which shows the earlier and faster removal of moisture from the dried item.

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