PERFORMANCE ANALYSIS, EVALUATION AND EFFICIENCY OF INTEGRATED SOLAR DRYER WITH THREE DRYING CHAMBERS

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Abstract

The discussion in this paper is a three chamber solar dryer which has been designed and used to monitor the drying rates of such agricultural produce as okra, yam slice and tomatoes. Performance analysis of the dryer was carried out. The dryer was also evaluated and the efficiency assessed and determined. The efficiencies of the three chambers were estimated using the thermal energy balance equation. Studies have shown that the potential amount of commercial energy that could be saved using solar energy has been estimated to between 657PJ and 1530PJ annually. The produce each weighing 100g in each of the three chambers were effectively dried between 0830 hours to 1830 hours for the three days as recorded.

Keywords: Solar dryer, forced convection, food preservation, drying rate, convectional methods.

Introduction

Recent studies have shown that potential of commercial energy that could be saved using solar energy is estimated to lie between 657 Pico Joules -1530 Pico Joules annually, Scalin (1997). Most developing Countries usually resort to the convectional methods of crop drying by spreading the agricultural produce on the ground, along the highway and in their farm lands thus allowing them to dry in the open sun. Using solar methods thus has become the immediate alternatives, Bala (1999). The method utilizes widely the physics principles with known advantages and time saving.

The solar drying in effect avoid such effects as hostile weather condition, crop contamination, crop infestation by insects and rodents and of course the chance of crop re-absorption of moisture which could affect the quality.

Energy as we know is the basic natural resources to the consumer. It is the heat for industrial furnace or the motive force that powers machinery. However, solar energy is one of the renewable energy resources.
Drying is an excellent way to preserve food and solar food dryer is an appropriate food preservation technology. Drying requires heat energy supply to have the water content of the food evaporated with air supply enough to carry away the water vapour produced as has been stated by Scalin (1997).

In effect it has been the view of some researchers that solar dryers have quick adaptability to rural dwellers on the farm as well as for household usage in view of their simplicity in terms of operations. There has also been improved technology in utilizing solar energy for drying grain. This is the use of solar dryers where air is heated in a solar collector and then passed through beds of grain, Mendoza, *et al* (1982)

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Performance and Efficiency of Three Chamber Solar Dryer.

The process requires enough heat to evaporate moisture from the crop and air flow needed to carry away the evaporated moisture. The rate of drying is determined by the moisture content, the temperature of the crop, the relative humidity and the velocity of the air in contact with the crop.

The drying equation obtained from the Newton's analogy according to Bor (1980) is

$$dm/dt = -K\,(M - Me) \qquad (1)$$

Integration yields

$$\frac{M - Me}{Mo - Me} = K_r \exp(-k_i) \qquad (2)$$

Where dm/dt = drying rate, K = the drying constant, M = mass of product, Me = equilibrium moisture content, Mo = original moisture content, K_r = drying rate constant and k_i = constant of integration.

In the follow up Huhill, (1947) developed and simplified the general drying equation for moisture ratio MR according to Bor and it is

$$MR = \frac{2^D}{2^D + 2^Y - 1} \qquad (3)$$

with D = equivalent depth factor and Y = time unit

Empirical data have been used to determine mathematical approximations of the relationship between drying rate and air conditions Brook and Foster (1981) thus have summarized the relations for many grains.

Focust *et al* (1982) and Ezeike (1986) have successfully made good graphical modeling which can be used to describe drying operations which are shown in Figures 1and 2.

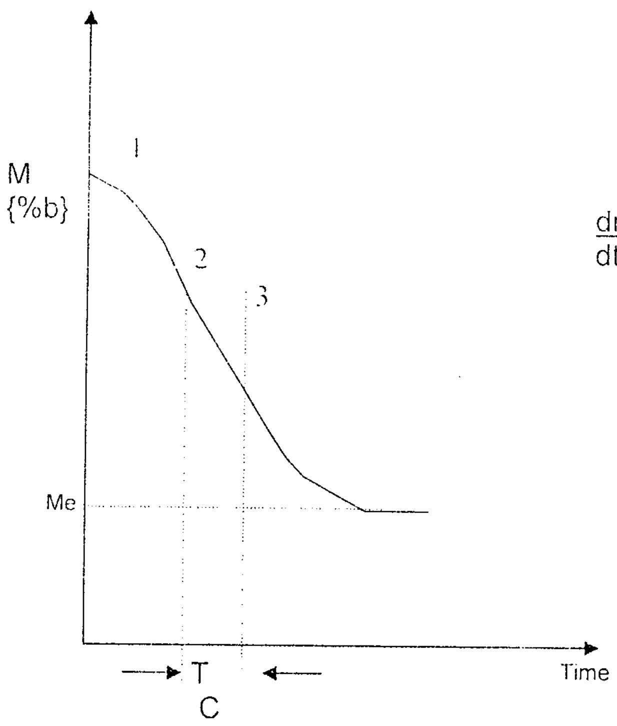

Fig.1: Moisture content and drying time relationship

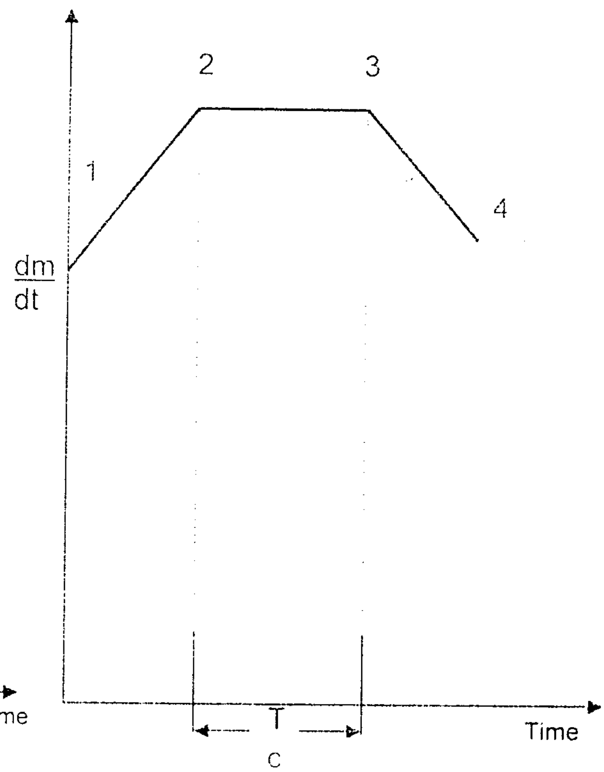

Fig. 2: Drying rate and drying time

In each case, stages 1-2 represent warming up period during which the solid surface condition approach equilibrium within the drying medium. Stages 2-3 are the constant drying rate period hence the surface remains unsaturated with the liquid water. Finally, stages 3-4 are the falling rate period; the movement of liquid to the drying surface becomes insufficient to replace the liquid being evaporated. There is rise in drying temperature and the moisture content at its end is in equilibrium.

The constant rate drying time tc equation according to Focust *et al* (1982) is

$$tc = \frac{Ms\ (Mo\text{-}Mx)}{Ap\ Rc} \quad (4)$$

Where Ms = mass of solids, Mo = original moisture content, Mx = critical moisture content, Ap = area of the absorber plate and Rc = Constant drying rate.
Also the falling rate drying time t_f is

$$t_f = Ms\ \frac{(Mx) - Mc)}{Ap\ Rc} \quad (5)$$

with Mc as the moisture content of the material at any level and time.

There is also an alternative but more accurate methods for estimation of drying performance. The method is based on dimensionless drying curves developed initially by Huhill. It involves the use of bulk drying curves and calculation of three diameters, moisture ratio, time unit and depth factor. The moisture ratio, MR is determined from equation (2).

$$MR = \frac{Mc - Me}{Mo - Me} \quad (6)$$

The time unit Y is determined using

$$Y = \frac{t_d}{T_{0.5}} \quad (7)$$

where t_d is the drying time and $T_{0.5}$ is the half-response time. Thus it is the time required for the fully exposed material to reach a moisture ratio of 0.5 under the drying air conditions employed if D is the equivalent depth factor as earlier stated, then Dm is the mass that can be dried from the initial moisture ratio MR = 1 to a final moisture ratio MR = 0.

DM can then be determined from the equation

$$Dm = \frac{V \times C_p \times t_{0.5} \times (T_{dh} - T_{wa})}{L_h \times (Mo\text{-}Me)} \quad (8)$$

where V = wind speed, C_p = specific heat of the collector fluid, T_{dh} = dry bulb temperature, T_{wa} = weight bulb temperature, L_h = length of the angle of incidence, Mo and Me as before.

The efficiency of the drying operation is an important factor in the assessment and selection of the optimum dryer for a given system. Three drying factors affect drying efficiency and they include:

- Those related to the environment such as ambient air condition.
- Those specific to the crop.
- Those specific to the design and operation of the dryer.

For total heat loss ql from black plates then,

$$ql = h_a\ (T_p - T_a) + h_{pc}\ (T_p + T_c) + \epsilon_p c\sigma\ (T_p^4 - T_c^4) \quad (9)$$

T_p is plate temperature, T_a is ambient temperature; T_c is cover temperature, h_a is heat transfer coefficient, h_{pc} is convective heat transfer from plate and $\epsilon c\sigma T^4$ is the long wave radiation from the glass cover. The moisture content according to Brooker *et al* (1986) for wet and dry basis (Mwb) is

$$Mwb = \frac{Mw}{Mp} \quad (10)$$

The equation of moisture dry basis (Mdb) is

$$Mdb = \frac{Mw}{Mb} \quad (11)$$

where Mw = mass of water, Mp = mass of the product and Mb = mass of the dry product. The equation of moisture dry basis (Mdb) is preferred as it expresses the amount of moisture over the quantity of solid matter.

The amount of air needed for drying is determined by ambient conditions such as temperature and humidity of the air and is related by

$$Ma = \frac{M_L}{W} \qquad (12)$$

and

$$M_L = \left(1 - \frac{M_f}{Mo}\right)Mw \qquad (13)$$

With Mw relating to the expression by

$$Mw = w\left(\frac{M_i - M_f}{100 - M_f}\right) \qquad (14)$$

In the three last equations, Ma = mass of moist air, M_L = mass of liquid removed, W = average air humidity, M_f = mass of final moisture content, M_i = mass of initial moisture content and Mo as before.

According to Eroklin *et al* (1986), the heat content of moist air h can be expressed as

$$h = ha + \overline{W}(2500+1.93T) \qquad (15)$$

where ha is the enthalpy, $\overline{W}$ is the average weight of the drying substance and T is the average temperature. It is also known that the energy gained from the collector at a given time is the difference between the amount of solar energy absorbed by the absorber plate and the energy lost to the surrounding. For the flat plate, the useful heat equation Q_u is giving by

$$Q_u = F_R \times A_T[(I_T T_\alpha - U_L - (T_o - T_a)] \qquad (16)$$

The collector efficiency is from

$$\eta_c = Q_u / A_T I_T \qquad (17)$$

The overall dryer efficiency is

$$\eta_D = \frac{MwL}{A_T I_T} \qquad (18)$$

where F_R is the heat removal factor, A_T is the area of plate, I_T is the solar incident radiation, Tα is the transmittance – absoptance factor, T_o is the initial temperature of the system, and L is the latent heat of evaporation of water and Mw is the mass of water.

Experiment

Samples of tomatoes, okra and yam slice were washed, cut and prepared for drying. The three product samples were differently weighed in drying pans and placed in each of the three chambers of the integrated solar dryer C_1, C_2 and C_3 and ready for drying.

The experiments were carried out for three days December 16, 2003, December 17, 2003 and January 28, 2004 for drying performance of tomatoes, okra, and yam slice. Lever chemical balance calibrated in grams was used to measure the wet and the dry weight of the drying samples. The humidity and pressure were measured using hygrometer and barometer. The various temperatures of the system were measured with mercury-in-glass thermometer and the solar radiation was measured with a pyranometer. The experiment lasted for 10 hours for each of the three days from 0830-1830 hours.

Results and Discussion

The results of the experiments 1,2, and 3 are shown in tables 1, 2 & 3. The masses were found steadily decreasing as the moisture content is reduced with rise in temperature for each of the three days the experiment lasted. When the moisture content attained zero value, further drying do not have further effect on the mass which in turn have attained constant drying rate. Giancoli, (1995) has stated that higher temperatures result in faster drying due to faster water movement and low relative humidity. This was confirmed by the results shown in Tables 1,2 and 3.

Table 1: Performance analysis of tomatoes, okra, and yam slice for December 16, 2003.

Time (1Hr)	Chambers	Tin (^0C)	Ta (^0C)	Humidity (^0C)	Tomatoes (g)		Okra (g)		Yam slice (g)	
					Sample weight	Moisture content	Sample weight	Moisture content	Sample weight	Moisture content
0830-0930	1	27	25	22	100	20.0	65.0	10.0	100	19.0
	2	27	25	22	100	20.0	65.0	10.0	100	19.0
	3	27	25	22	100	20.0	65.0	10.0	100	19.0
0930-1030	1	35	28	26	98	18.4	64.5	09.3	97	13.4
	2	36	28	26	97	17.5	63.5	07.9	96	12.5
	3	40	28	26	95	15.8	62.5	06.4	91	07.7
1030-1130	1	38	34	29	97	17.5	64.0	08.6	95	09.7
	2	40	34	29	94	14.9	62.5	06.4	91	07.7
	3	45	34	29	92	13.0	60.5	03.3	89	05.6
1130-1230	1	40	36	35	94	14.9	62.5	06.4	93	09.7
	2	45	36	35	91	12.1	61.5	04.9	89	05.6
	3	50	36	35	88	09.1	60.5	03.3	87	03.4
1230-1330	1	45	37	40	91	12.1	61.0	04.1	90	06.7
	2	50	37	40	89	10.1	60.5	03.0	88	04.5
	3	57	37	40	84	04.8	58.5	00.0	85	01.2
1330-1430	1	50	35	38	86	07.0	60.0	02.5	88	04.5
	2	55	35	38	85	05.9	59.5	00.0	85	01.2
	3	61	35	38	81	01.2	58.5	00.0	84	00.0
1430-1530	1	48	34	34	80	00.0	58.5	00.0	84	00.0
	2	53	34	34	80	00.0	58.5	00.0	84	00.0
	3	58	34	34	80	00.0	58.5	00.0	84	00.0
1530-1630	1	45	33	32	78	00.0	57.5	00.0	83	00.0
	2	51	33	32	77	00.0	57.0	00.0	81	00.0
	3	56	33	32	75	00.0	56.0	00.0	79	00.0

Table 2 :Performance analysis of tomatoes, okra, and yam slice for December 17, 2003.

Time (1Hr)	Chambers	Tin (°C)	Ta (°C)	Humidity (°C)	Tomatoes (g)		Okra (g)		Yam slice (g)	
					Sample weight	Moisture content	Sample weight	Moisture content	Sample weight	Moisture content
0830-0930	1	33	27	24	100	20.0	65.0	10.0	100	19.0
	2	33	27	24	100	20.0	65.0	10.0	100	19.0
	3	33	27	24	100	20.0	65.0	10.0	100	19.0
0930-1030	1	34	28	26	97	17.5	64.0	08.6	97	13.4
	2	35	28	26	96	16.7	63.5	07.9	94	10.6
	3	40	28	26	94	14.9	62.0	05.6	91	07.7
1030-1130	1	37	32	29	94	14.9	63.0	07.1	93	09.7
	2	40	32	29	91	12.1	62.0	05.6	91	07.7
	3	45	32	29	90	11.1	60.0	02.5	88	04.5
1130-1230	1	45	36	34	91	11.1	61.0	04.1	90	06.7
	2	50	36	34	87	08.8	60.0	02.5	88	04.5
	3	56	36	34	85	05.9	59.0	00.8	85	01.2
1230-1330	1	50	38	38	85	05.9	60.0	0.25	87	03.4
	2	57	38	38	83	03.6	59.0	00.8	86	02.3
	3	62	38	38	80	00.0	58.5	00.0	84	00.0
1330-1430	1	45	32	32	82	02.5	58.5	00.0	86	02.3
	2	50	32	32	80	00.0	58.5	00.0	85	01.2
	3	56	32	32	80	00.0	58.5	00.0	84	00.0
1430-1530	1	40	30	28	80	00.0	58.5	00.0	84	00.0
	2	46	30	28	100	20.0	58.5	00.0	84	00.0
	3	54	30	28	100	20.0	58.5	00.0	84	00.0
1530-1630	1	38	30	26	80	00.0	57.0	00.0	82	00.0
	2	47	30	26	100	20.0	56.5	00.0	82	00.0
	3	56	30	26	100	20.0	56.0	00.0	82	00.0

Table 3 : Performance analysis of tomatoes, okra, and yam slice for January 28, 2004.

Time (1Hr)	Chambers	Tin (°C)	Ta (°C)	Humidity (°C)	Tomatoes (g) Sample weight	Tomatoes (g) Moisture content	Okra (g) Sample weight	Okra (g) Moisture content	Yam slice (g) Sample weight	Yam slice (g) Moisture content
0830-0930	1	28	27	26	100	20.0	65.0	10.0	100	19.0
	2	28	27	26	100	20.0	65.0	10.0	100	19.0
	3	28	27	26	100	20.0	65.0	10.0	100	19.0
0930-1030	1	34	31	28	98	18.4	64.0	08.6	96	12.5
	2	35	31	28	96	16.7	63.0	07.1	95	09.7
	3	42	31	28	95	15.8	62.0	05.6	90	06.7
1030-1130	1	36	35	29	96	16.7	63.5	07.9	94	10.6
	2	40	35	29	94	14.9	62.0	05.6	90	06.7
	3	46	35	29	92	13.0	60.0	02.5	88	04.5
1130-1230	1	39	36	31	93	14.0	62.0	05.6	92	08.7
	2	45	36	31	90	11.1	61.0	04.1	87	03.4
	3	50	36	31	87	08.0	59.0	00.8	86	02.5
1230-1330	1	48	37	37	90	11.1	61.0	04.1	89	05.6
	2	50	37	37	88	09.1	59.0	00.8	87	03.4
	3	54	37	37	83	03.6	58.5	00.0	84	00.0
1330-1430	1	50	39	35	85	05.9	58.5	00.0	87	03.4
	2	54	39	35	84	04.8	58.5	00.0	84	00.0
	3	58	39	35	80	00.0	58.5	00.0	84	00 0
1430-1530	1	45	38	34	80	00.0	58.5	00.0	84	00.0
	2	50	38	34	80	00.0	58.5	00.0	84	00.0
	3	56	38	34	80	00.0	58.5	00.0	84	00.0
1530-1630	1	43	36	33	79	00.0	57.5	00.0	82	00.0
	2	49	36	33	76	00.0	57.0	00.0	82	00.0
	3	54	36	33	74	00.0	56.0	00.0	82	00.0

The various graphs plotted for chambers 1,2 & 3, (C_1, C_2, and C_3) are displayed as Figures 3,4, and 5, for moisture content against time for January 28, 2004 for each product. The graphs show typical drying patterns of the agricultural produce, tomatoes, okra and yam slice. The moisture content for each of the products was reduced to zero at which complete drying was achieved. In each case, the products in chamber C_3 remained fastest in drying on the average compared with the ones in chambers C_1 and C_2.

Thus for tomatoes, completely drying was achieved for C_1, C_2 and C_3 at 1530 hours for experiment 1, C_1 and C_3 at 1330 hours and C_1 at 1530 hours for experiment 2; C_3 at 1330 hours, C_1 and C_2 at 1530 hours for experiment 3.

For okra, C_3 at 1330 hours, C_2 at 1430 hours and C_1 at 1530 hours for experiment 1, C_3 at 1330 hours, C_1 and C_2 at 1430 hours for experiment 2, C_3 at 1330 hours, C_1 and C_2 at 1430 hours for experiment 3.

For yam slice, C_3 at 1430 hours, C_1 and C_2 at 1530 hours for experiment 1, C_3 at 1430 hours, C_1 and C_2 at 1530 hours for experiment 2, while C_2 and C_3 at 1430 hours and C_1 at 1530 hours for experiment 3. The drying patterns show that the system was very effective.

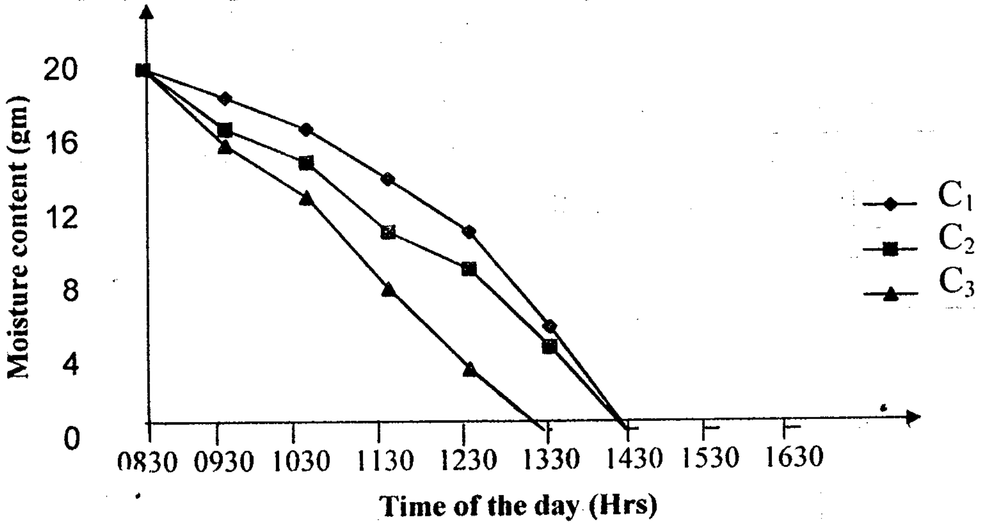

Fig.3: The Graph of moisture content for C_1, C_2, and C_3 against time of the day in hours for January 28, 2004 for tomatoes.
NOTE: For each case C_1 = Chamber 1; C_2 = Chamber 2 and C_3 = Chamber 3.

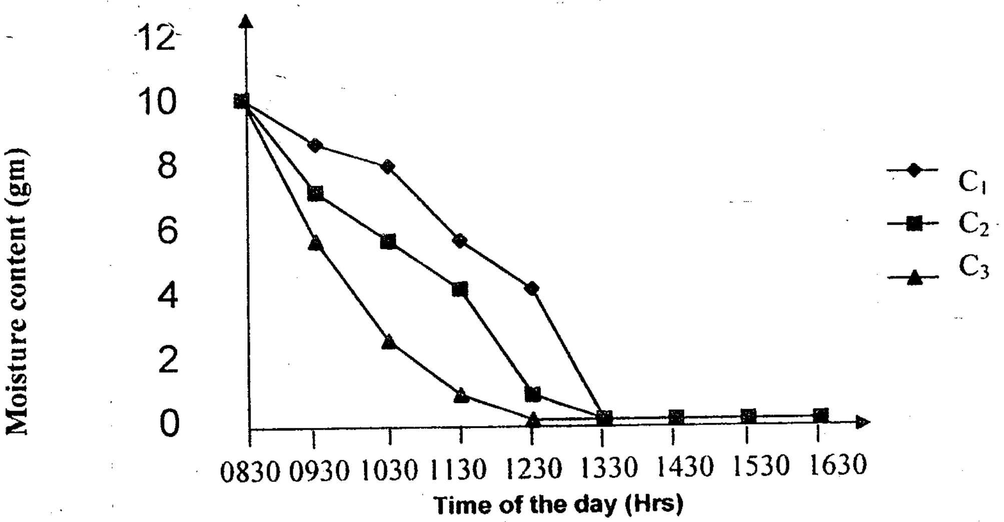

Fig. 4: The graph of moisture content for C_1, C_2, and C_3 against time of the day in hours for January 28, 2004 for okra.

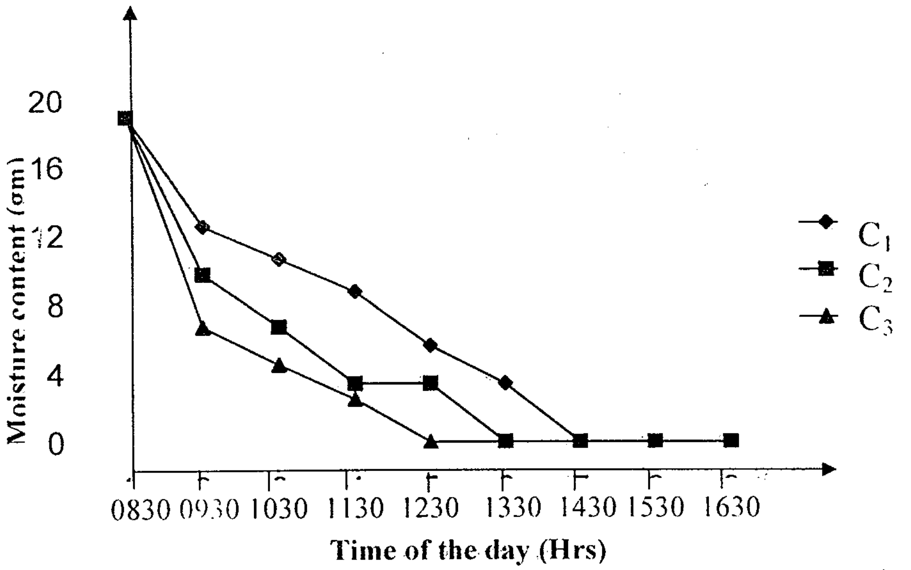

Fig. 5: The graph of moisture content for C_1, C_2, and C_3 against time of the day in hours for January 28, 2004 for yam slice.

Also graph of various inlet temperatures against time of the day for the three chambers for December, 16, 2003, December 17, 2003 and January 28, 2004 are shown in Figures, 6, 7, and 8. The products were found dried without moisture contents at various hours indicated earlier and is confirmed by the graphs too. Further drying made no significant change hence drying was stopped at 1630 hours for the three chambers C_1, C_2, and C_3.

The moisture drying rate, Figures 3- 5 were in line with that of falling –rate period Rai (2004). This was as for other cereal grains which depend upon the movement of moisture within the materials. As usual, drying was found to seize as soon as the product comes in equilibrium with the air, hence the experiment also confirmed this at the hours indicated.

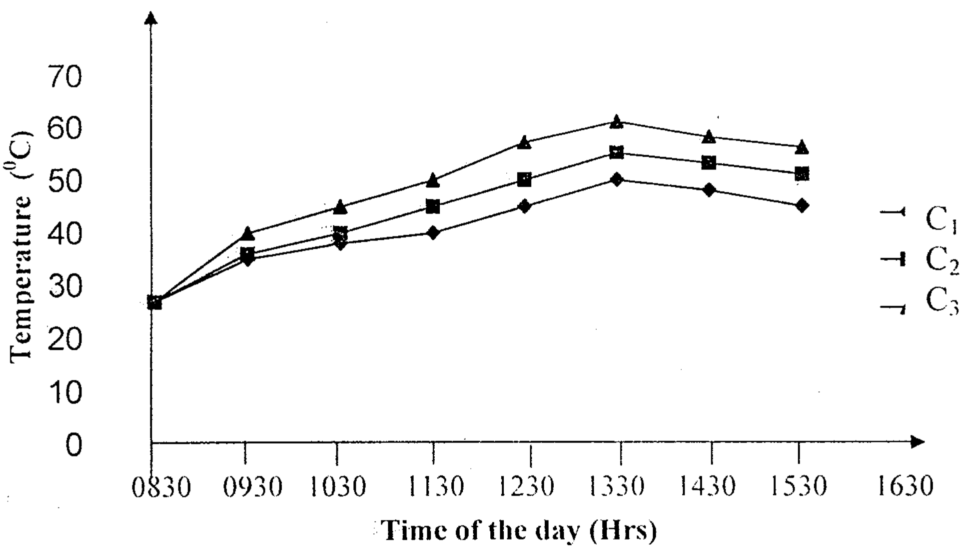

Fig.6: The graph of inlet temperature T_{in} for C_1, C_2, and C_3 against time of the day in hours for December 16, 2003.

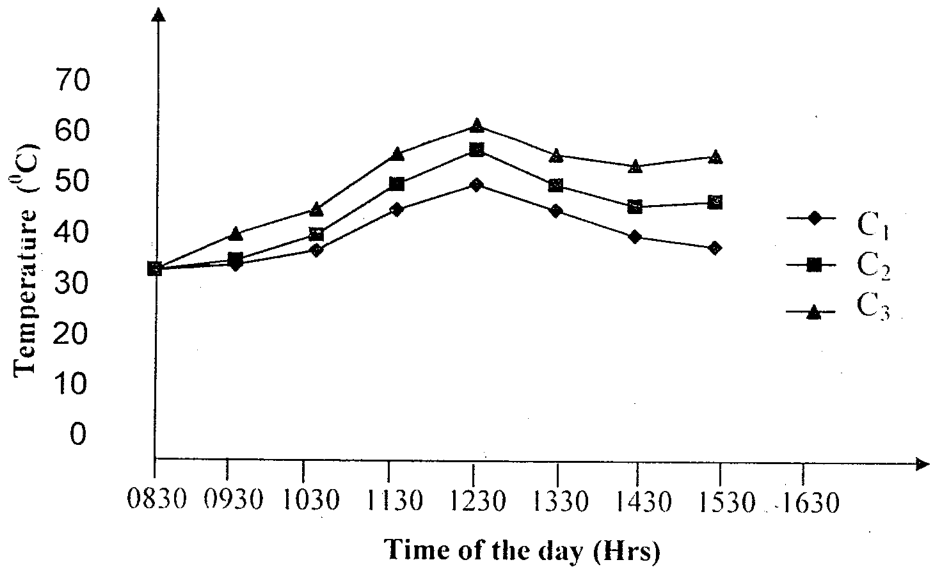

Fig. 7: The graph of inlet temperature T_{in} against time of the day in hours for December, 17, 2003.

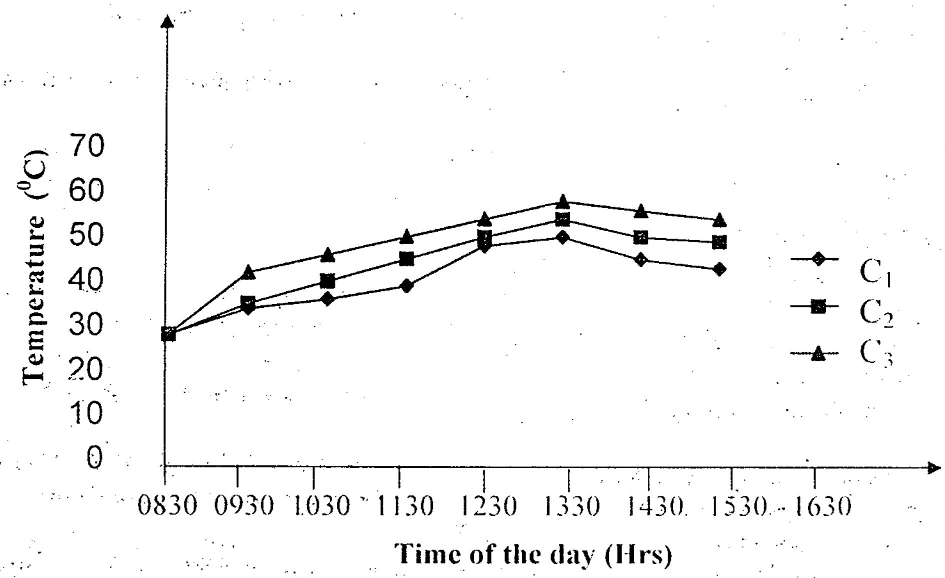

Fig. 8: The graph of inlet temperature T_{in} against time of the day in hours for January 28, 2004.

In effect, forced convection (solar) was at advantage compared with other methods such as natural convection drying, Habou *et al* (2003) as it usually provides greater rates as illustrated in Figures 6, 7 and 8.

CONCLUSION

Drying is one method that enhances quality of processed food. The result showed that drying rate increase with increasing temperature as shown in the various graphs of Figures 3-8.

The results were good and the pattern shown were in agreement with other known drying rate results. The experiment confirmed that solar energy drying remains an effective tool towards preserving agricultural produce.
The physics principles involved in the integrated solar dryer with three chambers showed encouraging results. The system

should be recommended for Farmers to dry their agricultural produce and as a replacement to open sun drying and the drying through spreading of agricultural produce on the high ways. The two old methods should be seriously discouraged due to inherent unforeseen adverse resulting effects, which could create health problems. A minimum temperature range of 27°C was achieved for the three chambers whereas maximum range of temperature of 61°C and 62°C were achieved for chamber 3.

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