Determination of Loading Capacity of a Direct Solar Boiler Dryer

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Abstract

Thermodynamic analysis of solar boiler natural convection dryer used for drying agricultural products was employed to dry restaurant wastes. Practical steps were taken to determine the loading capacity of the dryer. Replicas of the dryer (dimensions and materials) were selected and employed but with varying loads. This dryer is made up of glass flat-plate collector which serves as the drying chamber cover. Thermodynamic properties of the working fluid were measured at input and exit points. Energy analysis was carried out to determine their performances. Energy balance equations at the various segments of the dryer are formulated based on the balances in the solar grains dryer. The results show that energy (specific energy consumption) is optimally utilized when the dryer is optimally (not under-loaded or over-loaded with product). The dried product was tested at the end of the drying hours determine its moisture content and suitable for animal consumption and for long storage period. These results are useful for proper loading of solar grain dryer used restaurant waste.

Keywords: flat-plate collector; energy analysis; solar grain dryers; restaurant wastes.

Introduction

Drying crops by solar energy is of great economic importance the world over, especially in Nigeria where most of the crops and grain harvests are lost to fungal and microbial attacks. These wastages could be easily prevented by proper drying, which enhances storage of crops and grains over long periods of time. Nigeria is blessed with abundance of solar energy. This solar energy can easily be harnessed by a proper design of solar dryers for crop drying. This method of drying requires the transfer of both heat and water vapor (Forson et al., 2007). Most of our crops and grain are harvested during the peak period of rainy season and so preservation proves difficult and most of these grains and crops get spoilt. This results in the crops not lasting the year, resulting in subsequent hunger and malnutrition. Solar drying may be classified into direct, indirect and mixed-modes. In direct solar dryers, the air heater contains the grains and solar energy passes through a transparent cover and is absorbed by the grains. Essentially, the heat required for drying is provided by radiation to the upper layers and subsequent conduction into the grain bed. In indirect dryers, solar energy is collected in a separate solar collector (air heater) and the heated air then passes through the grain bed, while in the mixed mode type of dryer, the heated air from a separate solar collector is passed through a grain bed and at the same time, the drying cabinet absorbs solar energy directly through the transparent walls or roof (Gatea, 2010). These crops can be preserved and stored, so that they can be of economic importance both to the farmers and the entire populace. Rural farmers do this by open-air drying. This practice in the rural areas has some obvious disadvantages (Henry et al., 1999). This method is unhygienic since the crops are easily contaminated by animal droppings and consequent infestation by fungi and bacteria. Human health is thus endangered as a result of food poisoning. Drying is widely used in a variety of applications ranging from food drying to wood drying. Dryer supplies the product with more heat than is available under ambient conditions thus sufficiently increasing the vapor pressure of the moisture held within the product to enhance moisture migration from within the product and significantly decreasing the relative humidity of the drying air to increase its moisture carrying capability and to ensure sufficiently low equilibrium moisture content.

Energy from the thermodynamic point of view is made up of available and unavailable forms. Work done by a system is obtained from the available energy, while the unavailable form of energy remains unexploited (Ozegerner and Ozegerner, 2006; Kotas, 1995). The available form of energy of a system is convertible to maximum useful work, otherwise known as exergy as it comes to equilibrium with its environment from its original state (Coskun *et al*., 2009; Hou *et al*., 2007). This exergy is dependent on the thermodynamic properties of the working fluid – temperature and pressure (Coskun *et al*., 2009).

The thermodynamic analysis – energy and exergy of a thermal system is very important to engineers in order to optimize the efficiency of the system, minimize losses, reduce the operational and capital investment costs, and improvement of productivity of the thermal system (Riviere *et al*., 2009).

This paper presents a systematic energy analysis of flat-plate direct solar boiler dryer (DSBD) employed in drying restaurant wastes, to ascertain its performance characteristics and quality of the dried product. The local farmer may simply be excited of the fact that the dryer is made available but may still encounter problem of food spoilage if the dryer is not properly loaded. This work was carried out in Makurdi Nigeria, 2011 to help the local farmers select and load dryers to get optimal result. The necessity of this research stemmed from the fact that Makurdi, a town in the middle belt of Nigeria has abundant sun light and very rich in various agricultural products and animal husbandry. A lot of restaurant wastes which are normally thrown away never to be directly used again can be dried and given to the animals. As a lot of researches on solar food dryers concentrate on drying single products like pepper, okra, ground nut etc., it was necessary to apply it to drying restaurant wastes to feed animals and for longer period.

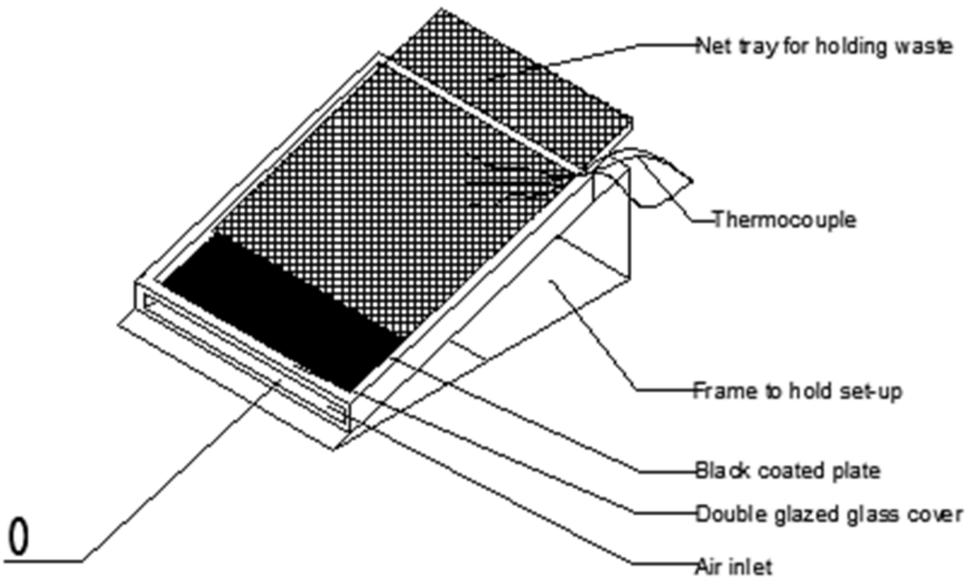

Figure 1(a) Schematic of Direct Boiler Solar Dryer (DSBD)

2.0 Theoretical Analysis

This section presents energy analysis of drying processes. The system is illustrated with input and output terms in Figure 1(b), where there are four major interactions:

1. Input of drying air to the drying chamber to dry the products.
2. Input of moist products to be dried in the chamber.
3. Output of moist air after containing the evaporated moisture removed from the products.
4. Output of the dried products, with moisture content reduced to the desired level.

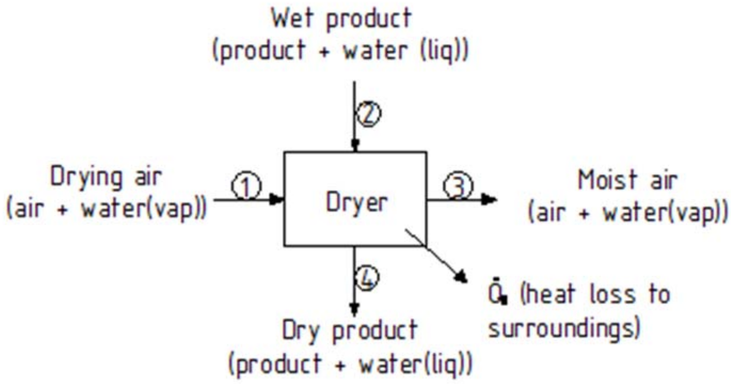

Figure 1(b) Schematic of a Drying Process Showing Input and Output Terms

The efficiency of solar drying system can be evaluated basically on the thermal performance or on drying rates of the products (Joshi and Gewali 2004). Drying rates evaluations are complex and are associated with tedious calculations.

(Pathak et al 1991) showed in a study that factors which affect drying rate, in thin-layer drying, are air temperature, initial moisture content, air velocity, and relative humidity. The drying characteristics of many food products were successfully obtained by Page Equation (Yunfei Li et al. 1987). The Eq. is given as:

$$MR = e^{-kt^N} \quad (1)$$

Where MR is the moisture ratio, t is the drying time in hours; K and N are drying constants. The moisture ratio is defined by:

$$MR = \left[\frac{M_d - M_e}{M_0 - M_e}\right] \quad (2)$$

Where M_d is the instantaneous moisture content (% db), M_e is the equilibrium moisture content (% db), and $M_0$is the initial moisture content (% db).
The dry basis moisture content M_d (% db), (ASHRAE 2001) is defined by:

$$M_d = \left[\frac{m - m_d}{m_d}\right] \quad (3)$$

And the wet basis moisture content (% db) is defined by:

$$M_w = \left[\frac{m - m_d}{m_d}\right] \quad (4)$$

Where m is the instantaneous mass and M_d is the fully dried mass.
The Page Eq. is a modification of the exponential or the Newtonian model (Sun D., Woods J.L 1994) described as:

$$\frac{dM}{dt} = -K\,(M - M_e) \quad (5)$$

K is the drying rate constant, per hour. Differentiating the exponential drying model yields:

$$MR = e^{-kt} \quad (6)$$

This Eq. assumes that resistance to moisture movement and gradients within the material are negligible. At constant temperature, pressure, and humidity, this Eq. is valid if drying is characterized by "falling rate" regime (Nellist M.E, 1976), which is characteristic of low moisture content products such as grains.
Another important factor in describing the characteristics of the drying process is the drying rate (-K (M -M_e), is defined, with dry basis moisture content, by (Fatouh and Metwally, 2006):

$$DR = -\frac{dM_d}{dt} = -\frac{M_{d.i+1} - M_{d.i}}{t_{i+1} - t_i} \quad (7)$$

Where $M_{d.i}$ and $M_{d.i+1}$ are the moisture contents at the times t_i and t_{i+1} respectively.
Two thermal performance parameters (Singh P, et al., 2006) are defined, thermal efficiency and specific energy consumption. Thermal efficiency is defined as the thermal energy utilized for drying divided by the thermal energy available for drying.

$$\eta = \frac{M_v L}{I_{av} A_{in} t} \times 100 \quad (8)$$

where M_v is the mass of moisture evaporated in total drying time, I_{av} is the daily average solar intensity on the dryer surface area, and A_{in} is the effective energy collection area (area of the absorber exposed to the solar radiation), and t is the time in seconds. Specific energy consumption can be defined as the solar energy required for 1 kg of moisture removal:

$$S = \frac{I_{av} A_{in} t}{M_v} \times \frac{1}{1000} \quad (9)$$

Where t is the time in seconds
There are various sources of heat loss from collectors as observed by (Kreith and Black, 1980).
Hence; heat loss coefficient of the collector due to wind,

$$h_{wind} = 5.7 + 3.8v \quad (10)$$

where, v is the average wind velocity.

The radiative heat loss coefficient, $h_r = 4\sigma_g T_g^3$ (11)

(Duffie and Beckman, 1974), where g is the emissivity of glass, σ is Stefan-Boltzmann constant and T_g is the temperature of glass above ambient.

The overall heat loss coefficient, $U_L = h_r + h_{wind}$ (12)

The overall heat loss coefficient U_L can be calculated using the Eq. reported in literature (Singh and Singh et al., 1995) as:

$$I_{av}(\tau\alpha)_{av} = U_L(T_s - T_a) \quad (13)$$

Where T_s and T_a are the solid temperature in the drying chamber and the ambient air temperature respectively.

3 .0 Experimental Apparatus

The boiler solar dryer shown in Fig. 1(a) is designed to accommodate the tray measuring 2.0 m x 1.0 m holding the products and an inlet and outlet for the air passing through the product to be dried. It measures 2.0 m in length by 1.0 m in width and a depth of 0.3 m is made out of galvanized steel sheet metal of 0.7 mm thick or 0.6 [m^3] in capacity. The drying chamber is insulated with 50 mm polystyrene at the bottom and 30 mm at the sides. The top is made of 4 mm thick transparent glass sheet for solar interception. One end of the dryer is used for loading and unloading the trays. Air flows from one end and exit from the opposite end due to the angle of orientation. The inner sides of the insulated surfaces were painted by matt black paint to enhance the absorption of solar irradiance. The dryer is on immoveable base frame tilted at angle that enables the highest energy absorption.

The whole setup was directed due south at an inclination of 23^0, which was found to give the maximum energy gain throughout the day, in Makurdi, Nigeria at the month of testing, March 2011.
The air heater was fitted with thermocouples and relative humidity meter at its inlet and exit to the chamber to measure the drying air properties. The thermocouple also measures the solid temperature. The amount of air leaving has to be measured to give an indication of the actual amount of water lost to the air, and the heat loss from the surface of the collector.

The solar radiation was measured directly using an SL200 solarimeter, which was controlled to give readings at one-hour interval. The solarimeter was placed at an angle of 23^0, which is the same angle as the dryer.
Having fixed the measuring instruments at the various points of the interaction, the dryer was left onto the open sky void of any obstructing shadows.

4.0 Experimental Procedure

4.1 Solid material

The waste food used in the present work was obtained from local domestic kitchens or restaurants and was manually separated from any non-organic materials within it, such as glass, paper, plastic, foil, etc. The waste was then well mixed and ground using local pestle and mortar, and this was done to ensure the highest possible homogeneity of the constituents. The waste at this stage was in the state of a paste, and to determine the moisture content of the waste, a weighed sample was heated gently in a crucible and re-weighed until a constant weight was obtained. By simple ratio the weight of water in the sample to be dried was calculated and recorded. The final stage in preparation of the food involved manually forming the paste into spheres of approximately 6.0 cm diameter and putting them on the net- tray, which was then inserted into the dryer. This was done in the morning before the scheduled time of drying.

4.2 Test at no load

This was carried out to determine the average overall heat loss coefficient U_L based on the effective energy collection area of the dryer. Both ends of the dryer were closed so as to determine the stagnation temperature of the dryer with no useful gain. The dryer was placed facing south, and the test started at 8:00 A.M. to 18:00 P.M. Since this experiment was carried out to determine the loading capacity of the dryer, under the solar conditions of that region, five of these dryers (all made of the same materials and dimensions) were set up at the same time. At the end of the experiment, U_L was calculated from Eq. 13.

4.3 Test with load

Masses of 1.0, 2.0, 3.0, 4.0 and 5.0 kg of the wastes to be dried were placed respectively into dryers 1 to 5 after the thermocouple and other measuring instruments were fixed in place. The materials were evenly spread on the trays to minimize the resistance of passage of air. The experiment was repeated for several days and each day with entirely fresh materials. The average values obtained are shown in tables 3. The results indicate that the initial moisture content of the wastes was 70% (wb).
Samples were weighed at the beginning of the experiment and placed in the chambers of each dryer which were withdrawn at every 60 minutes interval and their new weights recorded for 10 hours. The air temperature and relative humidity were recorded in the collector unit; the temperature of the solid in the drying chamber was also recorded hourly throughout the duration of drying. The moisture content of the solid was determined by Standard Test Method (ASTMD2216).
The weighing was done fast in order to avoid error due to moisture loss during the process.

The purpose of this experiment was to determine the optimum loading capacity of the dryer, the possibility of the products to reach the desired 0.23 kg moisture content within a single day drying period; the suitability of the dried products as animal feed and for better and longer storage.

5.0 Results and Discussion

5.1 Test at no load

The results of the no load test condition is shown in Fig. 2, where the changes in dryer temperature, ambient temperature and the change between the dryer and ambient temperatures are shown.

The stagnation temperature was found to be about 85^0C less than 100^0C, which was reported by (Singh P. P and Singh S., 2006). It can be noticed that the temperature profiles in the dryer are nearly uniform and continues to have high values throughout the drying period. The condition of constant temperature in the dryer is required to satisfy the exponential model. The temperature difference can be calculated by the Eq.:

$$\Delta T = T_d - T_a \quad (14)$$

whereT_d is the dryer temperature and T_a is the ambient temperature. This measures the drying potential of the air since it affects its ability to pick up moisture (Mwithiga G., Kigo S.N.; 2004) from the wet solid and to flow out of the exit. This means then that the drying potential remains nearly constant as the curves indicate.

The average overall heat transfer coefficient based on the effective energy collection area was calculated by Eq. (13), substituting appropriate values of transmissivity of glass (τ = 0.9) and absorptivity of dryer (α = 0.9). Its value was found to be 10.44W/m^2 K. this value is less than (11.9W/m^2K), the value reported by (Singh P. P and Singh S., 2006). It is compensated by having longer drying hours.

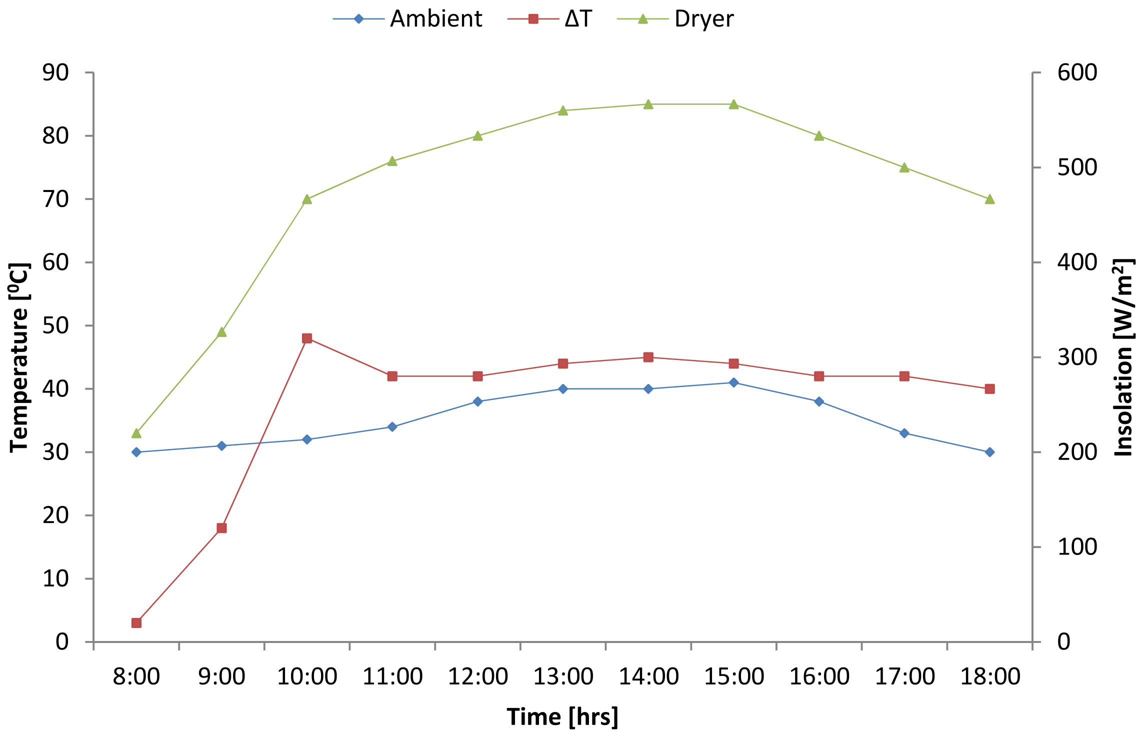

Figure 2 Temperature variation of no-load test

5.2 Test on load

The result of the test of the loaded dryers is shown in Fig 3. The temperature profiles in each dryer are shown to vary with the weight of solid and the intensity of the solar insolation on the effective dryer collection area. Since the inlet and exit ends of the dryers were opened, the heated air was able to absorb moisture from the wastes and exiting at the prevailing air velocity which was recorded by anemometer. The highest temperature values were recorded between hours of 12:00 and 15:00 which correspond with the highest values of insolation. The temperature profiles in the first and second dryers approximate to the values of the no load test. This means that the dryers were under-loaded; hence the wastage of the available energy since there was not enough moisture to pick. This means that there will be both economic and energy wastages if the dryer is under- loaded.

Another thing that is observable also in Fig.4 is that the weight loss from each dryer is proportional to the weight of the waste in it. More weight means more moisture to be absorbed by the working fluid. The pattern of weight loss (moisture reduction) from the five different dryers were approximately similar and the curves in Fig. 5. show almost similar drying rate.

Table 1 Thermal Efficiency, Specific Heat Consumption and Drying Rate

	Dryer				
	[1]	**[2]**	**[3]**	**[4]**	**[5]**
Thermal Efficiency [%]	5.57	5.40	4.70	3.97	3.73
Specific Energy Consumption [MJ/kg]	40.5	41.7	48.2	57.0	60.8
Drying Rate [kg/hr]	0.069	0.067	0.058	0.049	0.046

Table 2 shows the thermal efficiencies of dryers 1 to 5 which were calculated from Eq. (8) and found to be 5.57, 5.40, 4.70, 3.97 and 3.73 % respectively. This trend was expected since the test was limited to a single drying day and not all the dryers attained the required 0.23 moisture content during this time. Dryers 1 and 2 attained this value between 12:00 and 13:00 hrs, while dryer 3 achieved this value at 15:00 hrs. The thermal efficiencies are expected to be very low according to Eq. (8) while the specific energy consumption high as defined by Eq. (9). This is expected when the dryer is tested, to a large extent, under-loaded. This means that most of the captured energy beyond this required moisture content was wasted without any drying effect. The effect of the increased load on the thermal efficiency can be easily noticed. Under these present conditions, dryers 4 and 5 performed optimally. Dryer 5 could not attain the required moisture content in the first drying day experiment but could attain it in a few hours if continued the next day. Four (4 kg) of food waste should be the most appropriate load for the dryer.

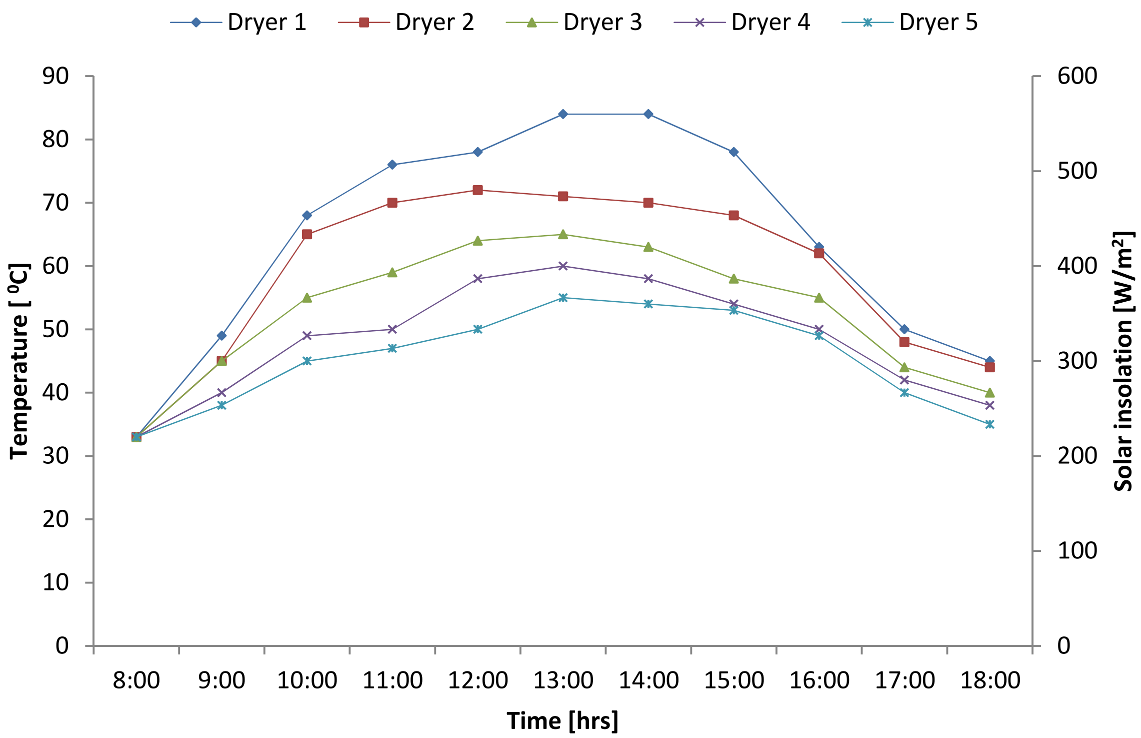

Figure 3 Temperature variation of test on load

Table 2 Input Constant

S/№	Symbol	Units	Value
1	g	m/s^2	9.81
2	A_{in}	m^2	2.0
3	б	W/m^2K^4	5.6×10^{-8}
5	R_v	kJ/kg^0C	0.4615

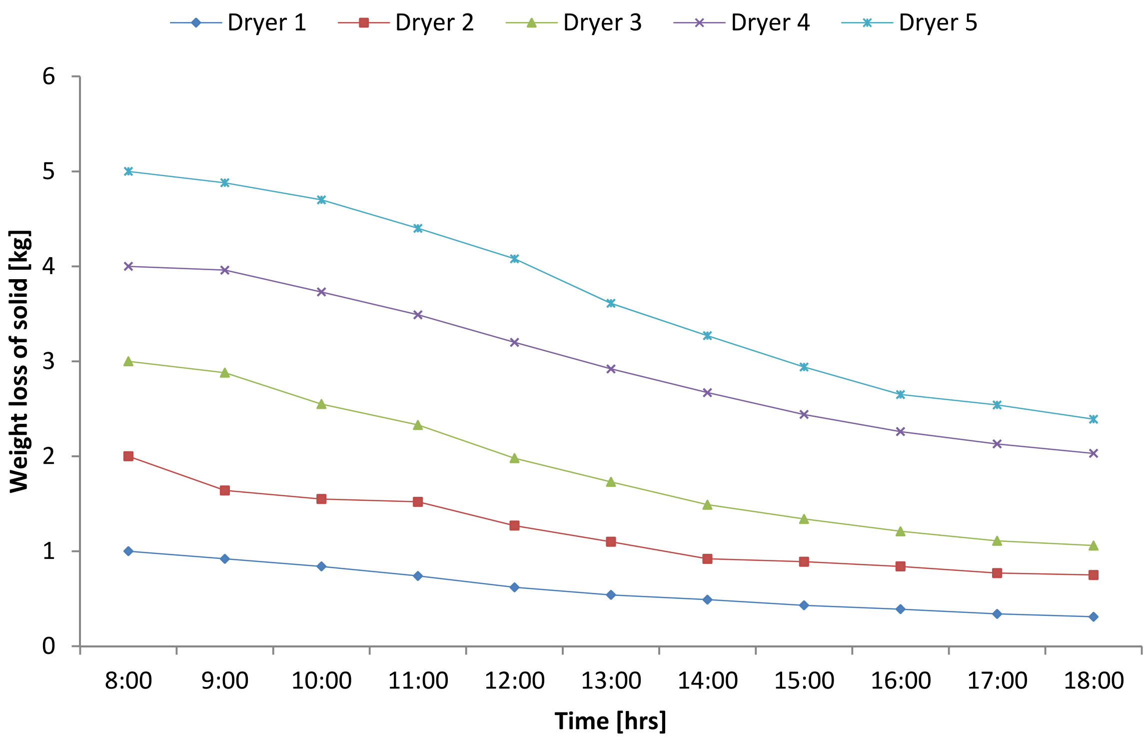

Figure 4 Curves of weights of solids in the dryers

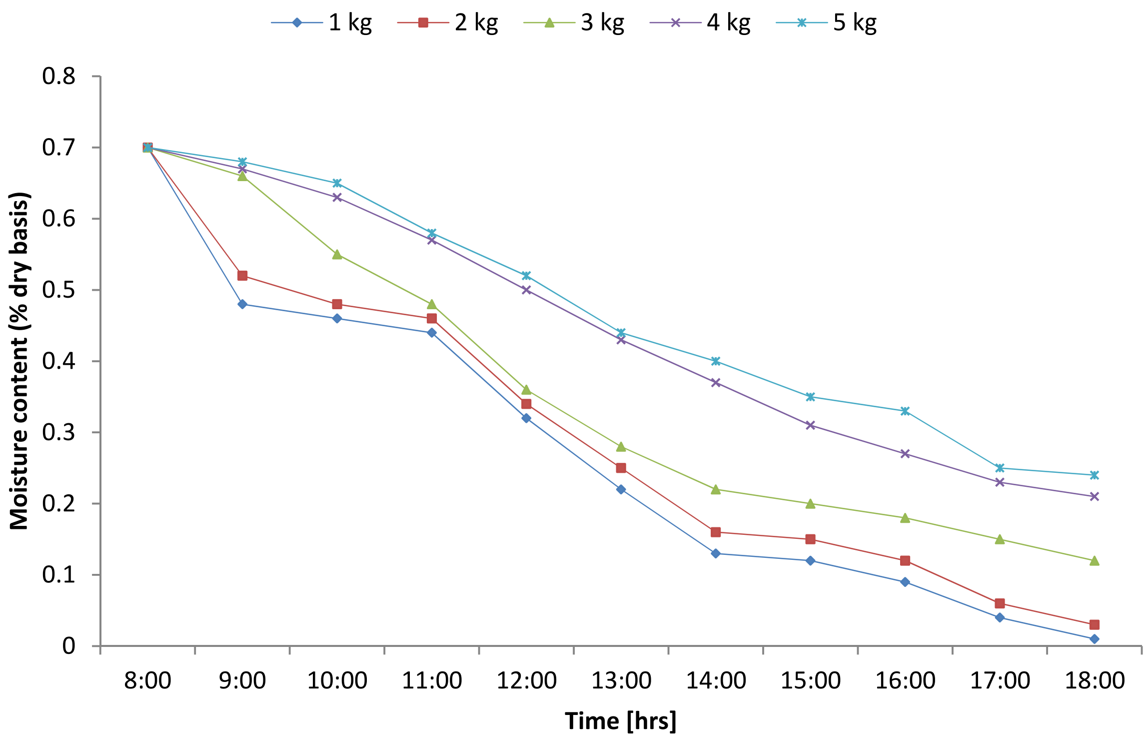

Figure 5 Curve of overall solid moisture content in the dryers

Table 3 Mean Input Data

		Chamber Temperature						Air speed	Moisture Content				
Time	**Insolation**	**Ambient**	**Dryer 1**	**Dryer 2**	**Dryer 3**	**Dryer 4**	**Dryer 5**	**V**	**Dryer 1**	**Dryer 2**	**Dryer 3**	**Dryer 4**	**Dryer 5**
hr	**[W/m^2]**	**[^{0}C]**	**[^{0}C]**	**[^{0}C]**	**[^{0}C]**	**[^{0}C]**	**[^{0}C]**	**m/s**	**kg**	**kg**	**kg**	**kg**	**kg**
8:00	74	30	33	33	33	33	33	1.0	0.70	0.70	0.70	0.70	0.70
9:00	120	31	49	45	45	40	38	0.5	0.48	0.52	0.66	0.67	0.68
10:00	295	32	68	65	55	49	45	0.5	0.46	0.48	0.55	0.63	0.65
11:00	390	34	76	70	59	50	47	1.0	0.44	0.46	0.48	0.57	0.58
12:00	415	42	78	72	64	58	50	1.0	0.32	0.34	0.36	0.50	0.52
13:00	540	43	84	71	65	60	55	1.0	0.22	0.25	0.28	0.43	0.44
14:00	540	44	84	70	63	58	54	1.0	0.13	0.16	0.22	0.37	0.40
15:00	558	41	78	68	58	54	53	2.0	0.12	0.15	0.20	0.31	0.35
16:00	500	40	63	62	55	50	49	1.0	0.09	0.12	0.18	0.27	0.33
17:00	360	39	50	48	44	42	40	1.0	0.04	0.06	0.15	0.23	0.25
18:00	90	36	45	44	40	38	35	1.0	0.01	0.03	0.12	0.21	0.24

6.0 Conclusions

In this study, replicas (5) of the proposed boiler solar dryer were selected and investigated to determine practically its operational loading conditions within a single drying day. Based on this work, it is possible to make the following conclusions:

- Available energy wasted in under-loaded dryer is higher than in optimally loaded dryer.
- Under-loaded dryer attained the required moisture content in shorter time than the optimally loaded dryer.
- Under-loaded dryer has higher thermal efficiency but lower specific energy consumption than the optimally loaded.
- For this dryer, the optimal load was 4 kg of waste for the single day drying operation.
- A 5 kg mass of waste can be recommended if at least two drying days are required.
- Performance of the dryer is dependent of the intensity of the available solar insolation and length of drying time.

References

[1] ASHRAE. Fundamental handbook: 2001 [Atlanta GA. USA]

[2] Coskun, C., Bayraktar, M., Oktay, Z. and Dincer, I. (2009) 'Energy and exergy analyses of an Industrial wood chips drying process', Int. J. Low-carbon Tech., Vol. 4, pp. 224-229

[3] Duffie, J.A. and Beckman, W.A. (1974) Solar Energy Thermal Processes, John Wiley and Sons. Inc.

[4] Forson F.K., Nazha M.A.A., Akufo F.O. Natural convection solar crop dryers of commercial scale design in Ghana: Design, construction and performance. Ambient Energy 1996:17(3):123-30.

[5] Fatouh M., Metwally M.N., Helali A.B., Shedid M.H. Herbs drying using a heat pump dryer. Energy Conversion and Management 2006:47:2629-43.

[6] Gatea A.A. Design, Construction and Performance Evaluation of solar maize dryer. Journal of Agricultural Biotechnology and Sustainable Development, 2010: 2(3): 039-046.

[7] Henry, T. Sabarez and W.E. Price, 1999. A diffusion model for prune dehydration. Journal of Food Engineering 1999: 42: 167–72.

[8] Joshi C.B., Gewali M.B., Bhadari R.C. Performance of Solar Drying System: a case study of Nepal. Journal of the Institution of Engineers 2004:85:53-7.

[9] Kotas T.J. The thermal Exergy Method of Thermal Plant Analysis (1995). Krieger , Malabar, Florida

[10] Kreith, F. Principles of heat transfer. Third edition. Intext Educational Publishers, 1980 ,New York, N.Y.

[11] Mwithiga G., Kigo S.N. Performance of a solar dryer with limited sun tracking capability. Journal of Food Engineering 2006:74:247-52.

[12] Nellist M.E. Exposed layer drying of ryegrass seeds. Journal of Agricultural Engineering Research 1976:21:49-66.

[13] Hou, S., Zang, D., Ye, S. and Zhang, H. (2007) 'Energy analysis of the solar multi-effect Humidification – dehumidification desalination processes*, Desalination (The Int. J. Scs. & Tech. of Desalting and water purification), Vol. 203, №s 1-3, pp.403-409.*

[14] Ozegerner, L. and Ozegerner, O. (2006) 'Energy analysis of industrial pasta drying processes', *Int. J. of Energy Research, Vol. 30, № 15. Pp 1323-1335*

[15] Pathak P.K, Agrawal Y.C., Singh, B.P.N. Thin layer drying model for rapeseed. Transaction of the American Society of Agricultural Engineers 1991:34(6):1172-5.

[16] Riviere, A., Khalil, B.A. and Berthou, M. (2009) 'An energy efficiency assessment, tool base on Process energy and exergy analysis method', paper presented at the *proceedings of the European Council for Energy Efficient Economy (ECEEE) Summer Study, Panel 5, June 9-10. Stockholm, Sweden.*

[17] Singh, P.P, Singh, S., Dhaliwal, S.S. Multi-shelf domestic solar dryer. Energy Conversion and Management 2006; 47:779-815.

[18] Sun D., Woods J.L. Low-temperature moisture transfer characteristics of barley: Thin layer models and equilibrium isotherms.Journal of Agricultural Engineering Research 1994:59:273-83.

[19] Yufei Li R., Morey V., Afinrud M. Thin-layer drying rates of oil seed sunflower.Transaction of the American Society of Agricultural Engineers 1991:34(6):1172-5.

Nomenclature

A_{in}	Effective energy collection area (m^2)	t	Time (h/s)
DR	Drying rate ($kg_{dry\ matter}h$)	T_a	Ambient temperature (^0C)
I_{av}	Daily average intensity of solar insolation (W/m^2)	T_{av}	Daily average temperature (^0C)
L	Latent heat of water (J/kg)	T_s	Stagnation Temperature (^0C)
m	instantaneous mass (kg)	s	specific energy consumption (kJ/kg_{water})
m_d	Fully dried mass (kg)	U_L	Overall heat loss coefficient (W/m^2K)
m_v	Moisture evaporated in total drying time (kg)	η	Thermal efficiency (%)
m	Moisture content ($kg_{water}/kg_{dry\ matter}$)	α	Glass absorptance
M_d	Moisture content dry basis (% db)	τ	Glass transmittance
M_e	Equilibrium moisture content (% db)	$(\tau\alpha)_{av}$	Transmittance absorptance product
M_o	Initial moisture content (% db)	σ	Stefan-Boltzmann constant
M_w	Moisture content wet basis (% wb)	T_g	Temperature of glass above ambient
MR	Moisture ratio	v	Velocity of wind (m/s)
h_r	Radiative heat loss coefficient (W/m^2)	h_{wind}	Heat loss coefficient due to wind (W/m^2)