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Construction and Evaluation of a Drying Chamber Powered by Parabolic Trough Solar Concentrator for Drying of Agricultural and Other Materials

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Abstract

This work reports a design and construction of a drying chamber powered by parabolic trough solar concentrator. The constructed drying chamber is made of thin aluminum sheet material with two compartments; one is for installation of standby electrical heaters and the other is for material pallet. The chamber is powered by a parabolic trough solar concentrator with aperture area of 5 m^2. An electrical heater backup was employed to maintain the temperature inside the chamber at a given constant temperature when solar energy is not sufficient. The maximum variation of the temperature inside the chamber along the length of the material pallet was found to be 8 °C when the chamber is powered by solar concentrator. This variation was 16 °C when the chamber is powered by electric heaters. Temperature variation across the vertical direction is almost constant when the chamber is empty and a 10 % drop in temperature was observed over the material pallet relative to the other areas. The drying characteristics of samples of cabbage, boiled rice, scraped coconut, dry leaves and grass for different temperatures obtained using the drying chamber are found to be fitted well with the page model and the corresponding drying constants at 80 °C are found to be 0.0197, 0.0139, 0.0319, 0.0296, 0.0564 respectively.

1. Introduction

Drying is a process which deals with the removal of water or moisture through evaporation from a solid or a semi solid material. During the drying of a wet material, two processes are taken place. First the heat energy is transferred from the surrounding to the material to evaporate the moisture from the outer surface creating a moisture gradient close to the surface. Once the surface moisture is removed from the material, the second process begins and internal moisture is transferred to the surface via diffusion and is removed due to the first process. The rate of the drying process is governed by the rates of these two processes. The removal of moisture from the surface of the material depends on the external factors such as temperature, relative humidity, surface area of the material, pressure and the internal transfer of moisture depend on the internal factors of the material such as physical nature of the material, temperature and the moisture content and its gradient.

Drying is an essential process in day-to-day life as well as in most of the industries such as food processing, food preservation, waste management, wood drying etc. It is widely being employed to improve the shelf life of organic materials such as food items by reducing the moisture content up to which the microorganisms cannot survive. Drying of grains such as paddy will improve the shelf life and hence longer storage periods can be achieved. Drying of fruits and vegetables is a popular preservation method when there is an excess of harvest. Apart from the food processing, drying techniques are used in the processing of materials such as timber. The moisture content of natural wood needs to be reduced before it can be used as a construction material or as a fuel material. It has been reported that the bio-degradable organic garbage can also be converted into a fuel material by drying[1]. There are numerous other industrial and non-industrial applications in which the drying is the key process.

There are different techniques that can be used for drying of organic materials. Sun drying, convective drying, infrared drying, vacuum drying, freeze drying and low-humid drying are some of them [2]. Although, conventional sun drying is the most economical method, many problems such as unreliability of the sun shine and inability to achieve higher temperatures to remove moisture make it less attractive especially for countries like Sri Lanka where the humidity level is very high. Vacuum drying and freeze drying techniques are more efficient and popular in food industry, but they are very expensive. However literature shows that the drying at higher temperatures is more efficient compared to drying at low relative humidity levels [2]. Therefore convective drying at high temperature has become a popular method to dry organic materials. Convective drying method reduces the drying time compared to traditional sun drying method and has the ability to keep the quality of the dried material at a higher level [3].

The aim of this study is to design and construct a drying chamber, powered by parabolic trough solar concentrator, for drying of organic materials.

2. Materials and methods

2.1 Fick’s second law of diffusion

It is well known that the drying of biological materials is governed by the diffusion of water through the material in liquid or vapor form. The Fick’s second law of diffusion has been implemented with the assumption that the sample is made of homogeneous isotropic material which imparts a uniform resistance to the moisture flow [4]. Fick’s second law can be derived as a second order differential equation for a spherical volume with a constant diffusion coefficient, D as shown below.

$$\frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial r^2} \quad \text{..........} 1$$

Where M is the local moisture content (kg water/kg dry solids), at a radius r from the centre of the spherical volume, and t is the time (s), and D is the diffusion coefficient in dimensions of [length^2 time^{-1}] (m^2/s) [5]. Analytical solutions for the equation 1 have been obtained by giving different boundary conditions for various regular shapes such as cubes, cylinders and spheres.

By assuming that the initial moisture content throughout the sample is constant and thickness of the sample as L, initial condition for the equation 1 can be written as,

At $t = 0$, $MC = MCi$, for $0 < r < L$

By assuming that the moisture at the top surface of the slice reaches equilibrium with the surroundings instantaneously, a boundary condition for the equation 1 can also be written as,

At $t > 0$, $MC = MCe$, for $r = L$ (for top evaporating surface)

By assuming that there is no moisture diffusion from the bottom surface of the slice, another boundary condition for the equation 1 can be written as,

At $t > 0$, $\frac{\partial M}{\partial t} = 0$, for $r = 0$ (for bottom, non – evaporating surface)

The equation 1 together with the above boundary conditions and the definitions,

$MR = \frac{MC_t - MC_e}{MC_i - MC_e}$ will yield.

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left[\frac{-(2n+1)^2\pi^2 Dt}{4L^2}\right] \quad \text{..2}$$

Where MR is the fractional moisture ratio, MC_i is the initial moisture content, MC_t is the mean moisture content at time t, MC_e is the moisture content at equilibrium and L is the thickness of the slice when drying occurs only through one surface. In the situation where drying occurs from both sides of a slice, by considering the symmetry, equation 2 can be rewritten by replacing L with $L/2$.

Moisture content is the ratio of amount of removable moisture in a sample to the sample weight (wet basis) or to the dried weight (dry basis). There are different methods to calculate dry weight of a sample, and oven drying method is one of the widely used methods [6]. Different oven drying temperatures and durations have been found for different types of materials.

$$\text{Moisture Content (Dry Basis)} = \left[\frac{\text{Current Weight} - \text{Oven dry weight}}{\text{Oven dry weight}}\right] \quad \text{..........................3}$$

2.2 Semi-theoretical and empirical solutions for the Fick's 2nd law of diffusion

Many semi-theoretical and empirical thin layer drying models shown in Table 1 have been derived originally to explain the drying behaviors of fruits and vegetables [7, 8]. These models were derived by simplifying the general solution of Fick's second law.

Table 1 –Semi-theoretical and empirical models

Model Name	**Model**
Newton	$MR = \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Henderson and Pabis	$MR = a\exp(-kt)$
Logarithmic	$MR = a.\exp(-kt) + c$
Two term exponential	$MR = a\exp(-k_o t) + b\exp(-k_1 t)$

Wang and Singh	$MR = 1 + at + bt^2$
Midilli – Kucuk	$MR = a\exp(-kt^n) + bt$

3. Design and Construction of the Drying Chamber

The drying chamber is made of thin aluminum sheet material with two compartments; one is for installation of electrical heaters and the other is for material pallet as illustrated in Figure 1. The electrical heating system is employed to maintain the drying chamber at a given constant temperature when the sun light is insufficient. Five electrical heating elements, each of 800 W, have been used for this purpose. The complete drying system consists of five subsystems, namely, air generator, parabolic trough solar thermal energy collector, electrical heating backup, materials pallet and the moistened air exhaust system and a readout system for moisture, humidity and temperature.

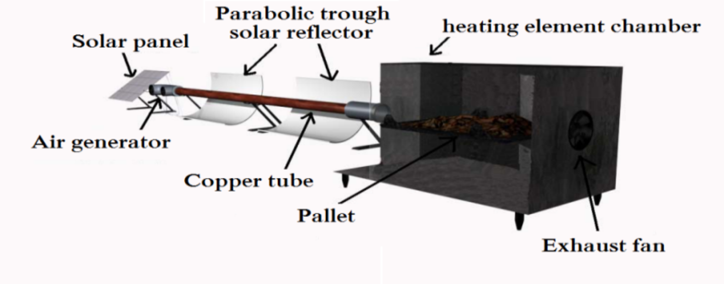

Figure 1: The schematic diagram of complete drying system

The air generator consists of four computer DC fans powered by a 60 W solar panel. Air flow velocity is controlled by a regulator connected to the power supply of the fans. The air output is connected to the receiver tube of the parabolic trough collector. The concentrated solar radiation reflected onto the receiver pipe by the parabolic trough collector heats up the air flowing through it to higher temperatures and this hot air is fed into the drying chamber. The parabolic trough collector tracks the sun throughout the day in order to maintain the maximum temperature in the air flow. Hot air coming from the parabolic trough solar concentrator is pumped into the compartment consisting of electrical heaters as shown in Figure 2. The positions of air inlet and the outlet were designed in such a way that incoming air is swept by all the heating elements for a maximum heat transfer and distributes it evenly throughout the drying chamber. Hot air is then fed into the drying chamber through two long slits with the dimensions of 36 x 4 cm. In order to maintain a constant temperature along the material pallet, the openings of slits are designed with angled flaps as illustrated in Figure 2. The drying chamber and the electrical heating chamber are separated by the Aluminum sheet with slits.

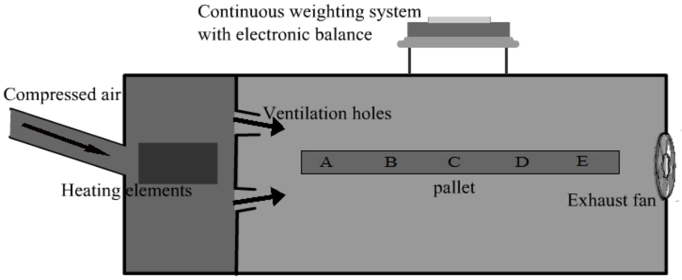

Figure 2 : Schematic diagram of the drying chamber

The drying chamber is a flatbed type chamber with length width and height of 2 m, 1 m and 40 cm respectively. The material pallet can be inserted through the door at the opposite side of the chamber. In order to remove moistened air from the chamber, an exhaust fan is fitted to the door as shown in figure 2. The entire chamber is thermally insulated with glass wool to minimize the heat loss. The material pallet of the drying chamber is constructed with wire mesh of 2 x 2 mm openings.

The temperature of the drying chamber is monitored by the main controlling system at five different positions along the chamber with Sensiron SHT75 relative humidity/ temperature sensors. When the temperature inside the chamber cannot be maintained at a given constant temperature by solar thermal power, the electrical heaters are automatically switched on by the system to supply the shortage.

For the evaluation purpose of the drying system, the material pallet has been modified to measure the weight of the drying material continuously as shown in Figure 2. The sample pallet is hung by an electronic balance throughout the drying period and hence the reduction of the weight of the material can be read continuously without disturbing the drying process. The material layer on the sample pallet and the material pallet should be same in order to generalize the weight measurement throughout the entire pallet.

3.1 Parabolic Trough Concentrator

Parabolic tough solar concentrator is used as the main heating device of the drying system. The direct solar radiation is concentrated by parabolic trough shaped reflectors onto the receiver pipe fitted at the focal line of trough. The air flow through the receiver pipe is heated to a higher temperature by the concentrated solar radiation fallen on receiver unit and this hot air stream is then fed in to the drying chamber as mentioned above. The table 2 shows the specifications of the parabolic trough system used for this drying system.

Table 2 : Specifications of the parabolic trough concentrator

Feature	**Description**
Collector aperture area	1 m x 4 m
Collector length	3.6 m
Rim angle	45°
Receiver type	Cavity
Mode of tracking	N – S horizontal

4. Results and discussion

Figure 3 shows the temperature distribution inside the drying chamber along the material pallet when the chamber is operated at 80 °C. The temperature is measured at five different points at the top surface level of the material pallet as discussed above. Two curves of the Figure 3 represent the variation of the temperature inside the chamber when the chamber is powered by solar energy and when the chamber is powered by electric heaters. The set temperature of the chamber is maintained by taking the average temperature value of all the five sensors.

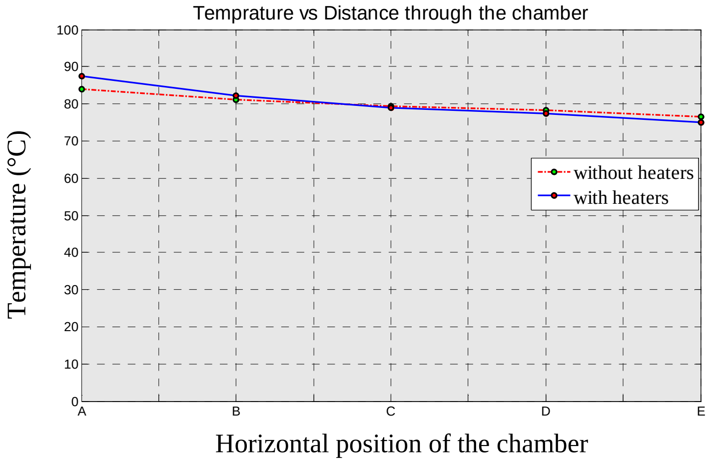

Figure 3 : Temperature variation with the length of the material pallet

According to the Figure 3, there is a slight variation of the temperature along the length of the drying chamber. The temperature inside the drying chamber close to the electric heaters is slightly higher than the set temperature. When the operating temperature is 80 °C and is powered only by solar energy, the maximum variation of temperature is 8 °C and when the chamber is powered only by heaters, the corresponding value is 16 °C. This could be due to the influence of the high surface temperature of filaments. The temperature across vertical direction of the drying chamber is also measured at five places and the variation is illustrated in Figure 4. In this direction, the temperature is almost constant when the chamber is empty. When the pallet is filled with organic material, the temperature at the level of material pallet becomes lower compared to the top and bottom ends of the chamber. This type of variation could be expected as the heat-exchange which takes place between the organic material and the heated air creates a temperature gradient just above the surface of the organic material. Since the temperature measurement for the controlling purposes is taken at the top surface level of the material pallet, the drying temperature around the material pallet when the it is filled with material is maintained at the required temperature by the controlling of air flow at the inlet to the system.

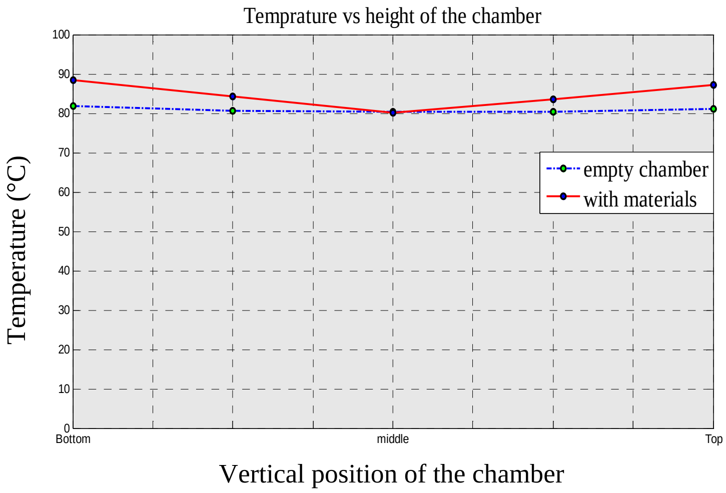

Figure 4 :Temperature variation across the vertical direction

Drying characteristics of the component of a sample of cabbage, boiled rice, scraped coconut, dry leaves and grass at the temperatures of 60 °C, 80 °C and 95 °C were obtained using the drying chamber. The data set was fitted with the semi-theoretical and empirical models according to the Fick’s second law of diffusion. The ‘page model’ was found to fit best for the data and the curves obtained by fitting the drying data for all the above five materials at 80 °C are given in Figure 5. The drying constants (k) obtained for the above five materials are tabulated in Table 2.

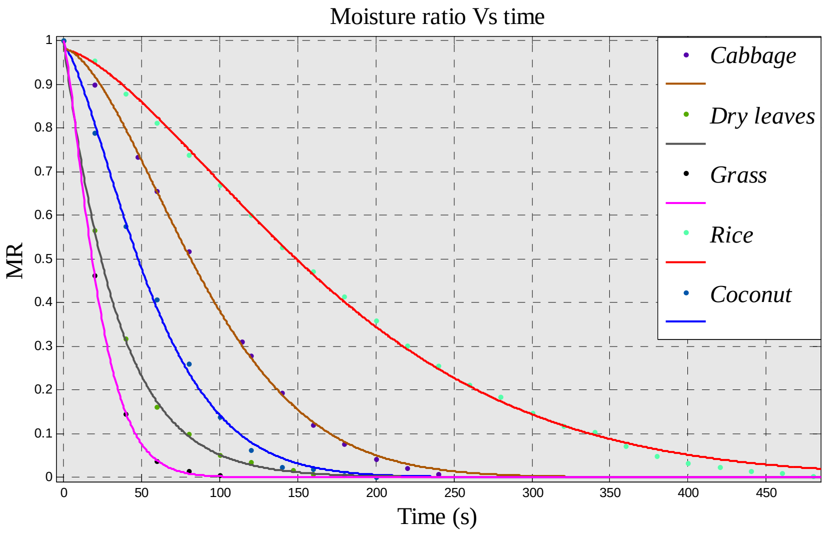

Figure 5: Drying behaviour of five organic materials inside the chamber

Table 3: Drying constants for dried organic materials

Organic Material	Drying constants
Cabbage	0.0197

Dry leaves	0.0296
Grass	0.0564
Boiled Rice	0.0139
Coconut	0.0319

Out of the materials studied, it can be observed that rice has the smallest drying constants. This emphasize that the drying of rice is slow compared to the other materials. This is because the boiled rice being a lump of sticky starch with negligible porosity takes considerable time to remove its moisture. On the other hand, grass being thin and having very high porosity gives rise to the highest drying coefficient.

5. Conclusions

Design and construction of a drying chamber powered by parabolic trough solar concentrator was the main objective of this study. The chamber is powered by a parabolic trough solar concentrator with the aperture area of 5 m^2. An electrical heater backup was employed to maintain the temperature inside the chamber at a given constant temperature when solar energy is not sufficient. This dual heat generating system provided a constant temperature throughout the drying process.

The temperature inside the drying chamber is slightly varied with the length of the material pallet. This variation is 8 °C (10 %) when the chamber is powered only by solar radiation and the variation is 16 °C (20 %) when the chamber is powered solely by electric heaters. The temperature across the vertical direction of the chamber is almost constant when the material pallet is empty. When the pallet is filled with organic material the temperature at the level of the material pallet becomes lower due to the heat exchange between the organic material and the heated air. Drying characteristics of samples of cabbage; boiled rice, scraped coconut, dry leaves and grass for different temperatures obtained using the drying chamber are found to be fitted with the page model and the corresponding drying constants at 80 °C are found to be 0.0197, 0.0139, 0.0319, 0.0296, 0.0564 respectively.

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7. References

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