A Mixed-Mode Natural Convection Solar Dryer with Biomass Burner and Heat Storage Back-up Heater

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Abstract

This paper describes a mixed mode natural convection of solar dryer integrated with a simple biomass burner and bricks for storing heats. The dryer was designed for small-scale commercial producers of agricultural products in non-electrified locations. From a series of evaluation trials of the system, the capacity of the dryer was found to be 60–65 kg of unshelled fresh harvested groundnuts. The drying efficiency of the solar component alone was found to be 23%. While, the efficiency of the burner with heat storage in producing useful heat for drying was found to be 40%.The key design features of the dryer contributed to produce an acceptable thermal efficiency, and uniformity of drying air temperature across the trays, were the jacket and gap enclosing the drying chamber and arranged bricks for storing heats. Further modifications to further improve the performance of the dryer are suggested

1. INTRODUCTION

Drying is one of the most important means for the preservation of many kinds of agricultural products. Open sun drying, where the product is exposed directly to the sun allowing the solar radiation to be absorbed by the material, is one of the oldest techniques employed in agriculture. The term solar dryer is applied to a structure made for the deliberate use of solar energy to heat air and/or the products so achieve dehydration, or drying, of the products, and the process is called solar drying. The advantages of solar drying over sun drying have been well-documented (Simate, 2003; Janjai et al.,1998). However, compared to some other solar technologies, solar dryers continue to struggle to gain acceptance by commercial producers of dried products. The reasons for this are complex and varied, and depend on many factors (Battock, 1990; Bena & Fuller, 2001).

A natural convection solar dryer is the most possible for use in areas where electricity is not available. Among the different types of natural convection solar dryers, the mixed-mode type has been demonstrated to be superior in the speed of drying (Simate, 2003). In this type of dryer, during day time the heat for drying are from both direct and indirect solar radiation. For direct mode, the product is allowed to directly absorb heat from solar radiation by applied a transparent cover on drying chamber. While, for indirect mode a solar collector system is commonly applied to collect heat to heat air, and the heated air flows through the drying products.

One significant limitation of solar dryer is that it can only be used during the daytime when there is adequate solar radiation. This will limit production, and moreover it can result in an inferior product. For commercial producers, the ability to process continuously with reliability is important to satisfy their markets. Therefore, it is neccesarry to provide solar dryer with any form of back-up heating. A review of the literature indicates that there have been few attempts to overcome this limitation in simple natural convection solar dryers. One exception is a cabinet solar dryer reported by Bena & Fuller (2001) which used a fuelwood burner to provide heat during poor weather and at night. The burner was constructed from a 0.2-m 3 steel drum by integrating it with the drying cabinet. An overall efficiency of the burner was reported to be 22%. Another dryer reported by Bassey *et al*. (1987) was used a sawdust burner, constructed as a separate component, to provide a back-up heat. The burner was designed to provide 400 W m-2 of energy to the drying cabinet, and used steam as the heat transfer medium.

In addition, by applying thermal storage material in the burner, a continuously drying is applicable with minimum biomass fuel, less frequent fuel supply period, and easily controlled temperature of the chamber.This paper describes a mixed mode natural convection of solar dryer integrated with a simple biomass burner and bricks for storing heats. The biomass burner was constructed from a 0.2-m^3 concrete wall, and it was surrounded by bricks as the thermal storage. Fuelwood, which is the most common source of energy in rural areas of developing countries, is mainly designated to be the fuel for the burner. The dryer has been evaluated under various conditions to dry fresh goundnuts. The results of these tests are reported and discussed. Some recommendations to further improve the dryer's performance are also proposed at the end of this paper.

2. DRYER DESIGN

The solar dryer was constructed and operated at department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Thailand. The main parts of the dryer are solar collector system, biomass burner, and drying chambers. Figure 1 shows cross section through each part of the dryer.

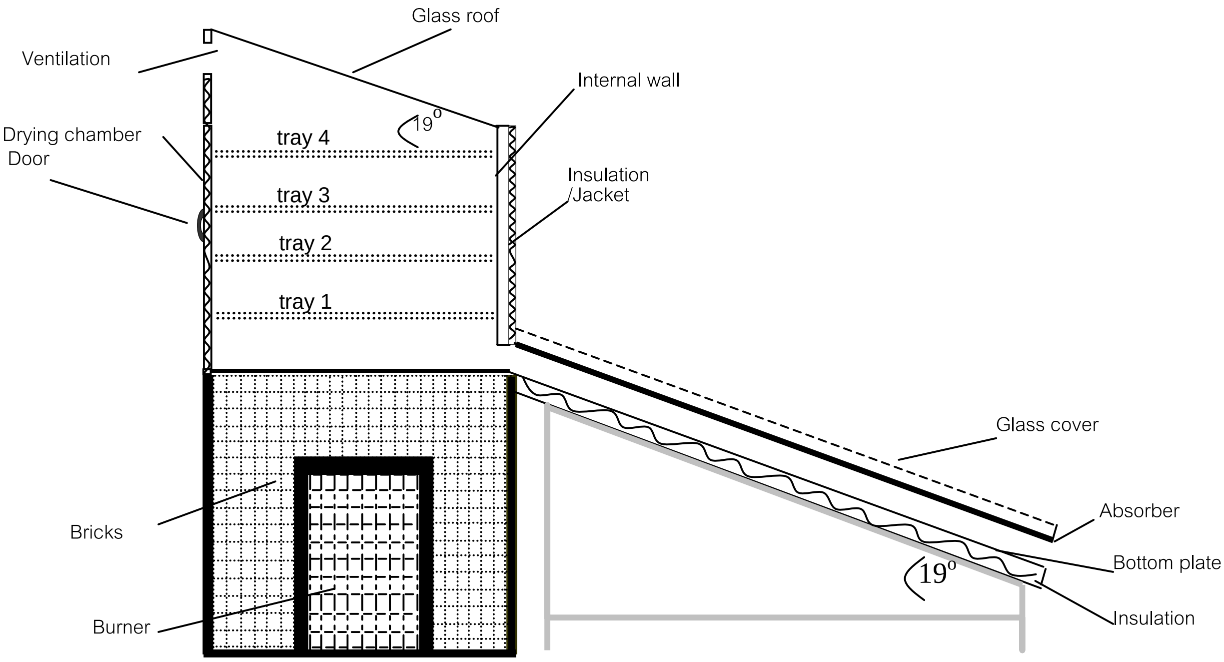
Solar collector system, with length of 2.75 m and width of 1.75 m, consists of absorber, single glass cover, back plate, and insulation. The system is framed with the aluminum logs. Absorber is made of black painted of metal (zinc) plate with thickness of 0.05 cm. The single layer of typical glass cover with thickness of 0.5 cm is applied on the top surface of the collector. Backside and edges of the collector are insulated with 3 cm of mineral wool. These are to minimize heat losses. In operation, air flows through the space between absorber and back plate that set just above the bottom/back insulation. The heated air than goes up to the drying chamber. The distance between absorber and glass cover is 5 cm, and between absorber and back plate is 8 cm. The solar collector system was facing south and tilted 19^o from the horizontal level.

For back up heating system for the solar collector, a biomass burner with total dimension of 1.75m $\times$ 0.9m $\times$ 1.5m, was constructed from concrete as the wall, and filled up with bricks as heat storage. In the biomass burner, a free space of 0.75m $\times$ 0.5m $\times$ 1m was occupied, including 0.25 cm extruded wall to out side of the burner, for space for burning fuels. A door of 0.75m $\times$ 0.5m was set up at front side of the extruding wall for the way of feeding fuel. A hole of 0.1m $\times$ 0.4 at bottom edge of the door was made for fresh air inlet to burner during burning fuels. The bricks, for the heat storage, were arranged so in the burner that the exhausts gas and smoke from burning fuel can pass through them. This is to maximize the heat stored from burning fuel.

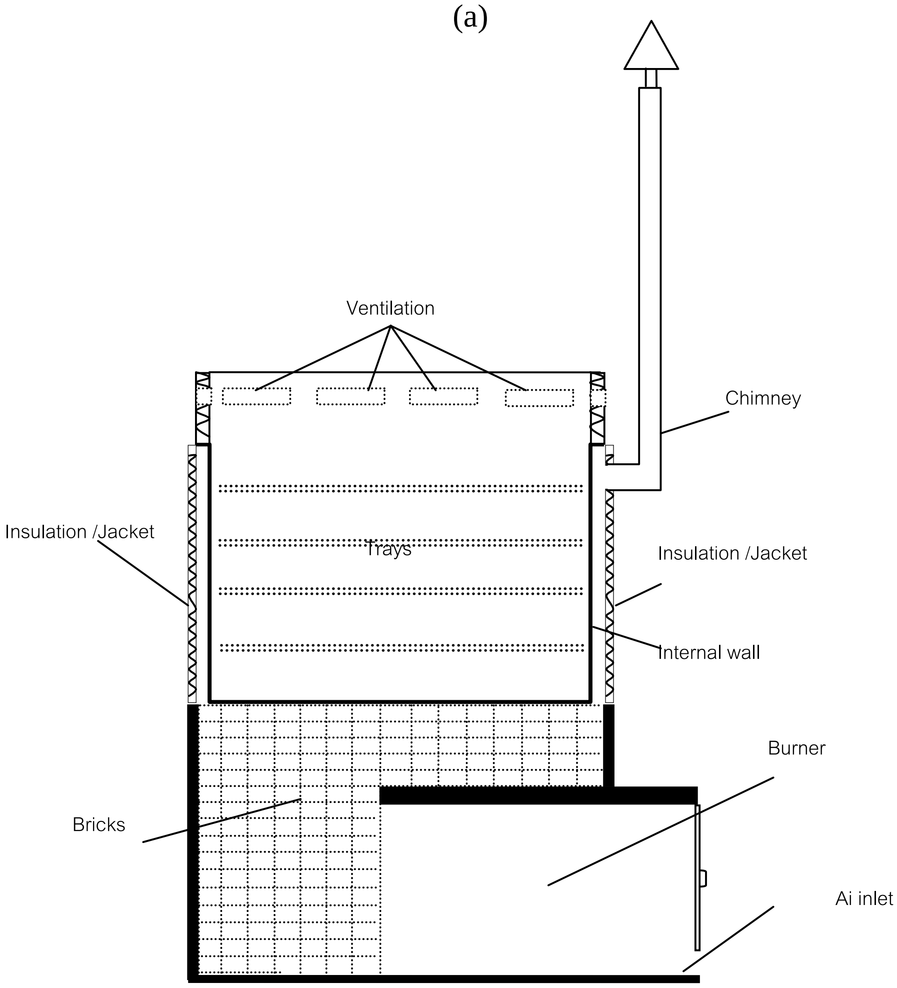
The drying chamber, where the product will be dried, is installed just above the biomass burner. The drying chamber comprises to 19^o tilted single layer glass cover, trays, bottom plate, doors, ventilation, internal walls, and external walls so called "*jacket*". The trays consist of 4 levels with 2 trays on each level. The effective dimension of one tray was 1.45 m $\times$ 0.82 m. The bottom plate of the drying chamber was in contact with the top surface of the biomass burner/heat storage, and exhaust gas and smoke would not pass through the product to be dried. The jacket is consists of 5 cm of insulation (mineral wool) and covered with zinc sheet. The jacket is applied to left, right, and front sides of the chamber. A 5-cm free space between internal wall and jackets is applied for the way of outlet gas and smoke from burning fuel, before releasing it to the ambient through a chimney. The chimney is attached to upper edge, on the right side of jacket. By this way, it is expected that more heat will be gained from the exhaust gas and smoke that further heats up the internal wall of drying chamber, and the internal wall further supply heat to the trays. Moreover, this will also be useful for the uniformity of drying among of the trays, especially during burning fuels.

3. MATERIALS AND INSTRUMENTATION FOR THE DRYER EVALUATION

The dryer was tested during the months of June and July 2005. Ten days with four separate trials of the dryer were conducted with both loaded and unloaded condition. In the drying experiments, fresh unshelled groundnuts were used as the test samples in the dryer. Biomass burner was only used at night, while solar energy, or combination with stored heats were used during the daytime. This is to simplify the evaluation



(a)



(b)

Figure 1. Cross section through the dryer: (a) side view, (b) back view.

During the trials the parameters measured were: temperatures, moisture content levels, solar radiation, mass of groundnuts dried and the woods burnt, relative humidities, wind speed, and airflow through the dryer. A combination of hand-held instruments and sensors connected to a data logger (Data Taker 605) were used to make and record the measurements. The relative humidity were calculated from web bulb and dry bulb temperature using a psychometric chart. Solar radiation was measured with a pyranometer (CM 3 Kiipp & Zonen) with an sensitivity of 16.51 $\times$ 10^{-6} W/m^2 and accuracy of $\pm$ 5%. Air velocities were measured with a hot wire air anemometer (TA 400T) with an accuracy of $\pm$ 2.5%. The mass of the groundnuts was measured with an electronic balance (AND 2000) with an accuracy of 0.01g, while the biomass of woodfuel was measured with analog balance (TS 2777047) with accuracy of 0.1 kg. The dry mass of the dried samples were determined using air-oven method (Hall, 1980).

4. RESULTS AND DISCUSSION

4.1 Solar collector performance

From results of the experiments, the diurnal variation of temperatures of the solar collector outlet air, absorber, ambient, and solar radiation were plotted. One typical day of June is shown in Figure 2. It is observed that the rise in air temperature due to the generated air flow rate in the collector is sufficient for the purpose of most agricultural products drying, even the daily solar radiation was relatively low with an average of 350 W/m^2/day. During the 10 days, the solar radiation was fluctuating and varying from 200 – 900 w/m^2 along of the days. For the inlet air temperature of 40^{o}C, the maximum air temperature at the dryer inlet at no load conditions was recorded as 59^{o}C at the solar irradiance level of 960 W/m^2.The mass flow rate of the drying air in the thermosyphon mode of the collector depends on the prevailing wind conditions, ambient air temperature, incident solar radiation and the collector design (Pangavhane et al., 2002). It was observed that, when the wind velocity was more or less uniform throughout the day, the air velocity in the collector shows definite dependence on the stack temperature difference between ambient and collector outlet air.

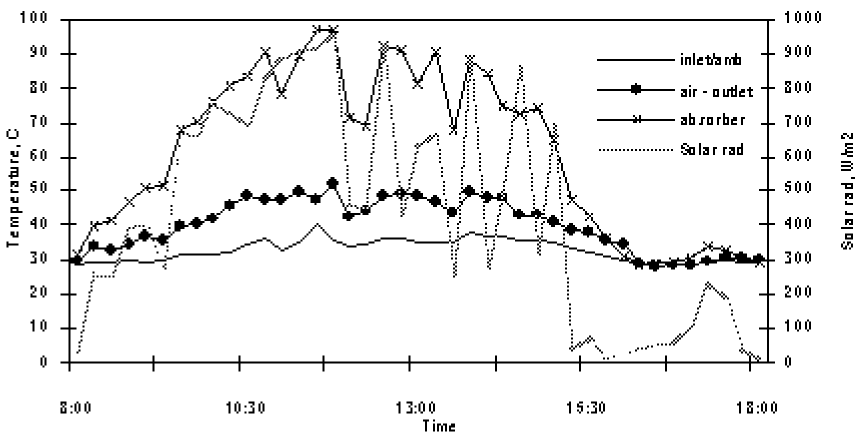


Figure 2. Variation of and temperatures of outlet air of collector, absorber, ambient, and solar radiation during test on June 26, 2005

4.2. Unloaded dryer performance

For unloaded test of the dryer, a continuously forty-eighth hours measurement (during June 26 – 28, 2005) was conducted with variation of heat sources. For the first 12 hours, i.e., during daytime on June 26, the source of heats was only solar energy. In the evening, starting at 17.30 p.m., about 50 kg of wood was burnt to supply heat for the night hours. The remaining of stored heats in the bricks, with combination of solar energy, were then used as heat source during the daytime on June 27. While, during the consecutive night time, the remaining of stored heats in the bricks was solely source of energy for the dryer. Diurnal variation of drying air temperatures at each tray, ambient temperature, and solar radiation during the experiment are shown in Figure 3.

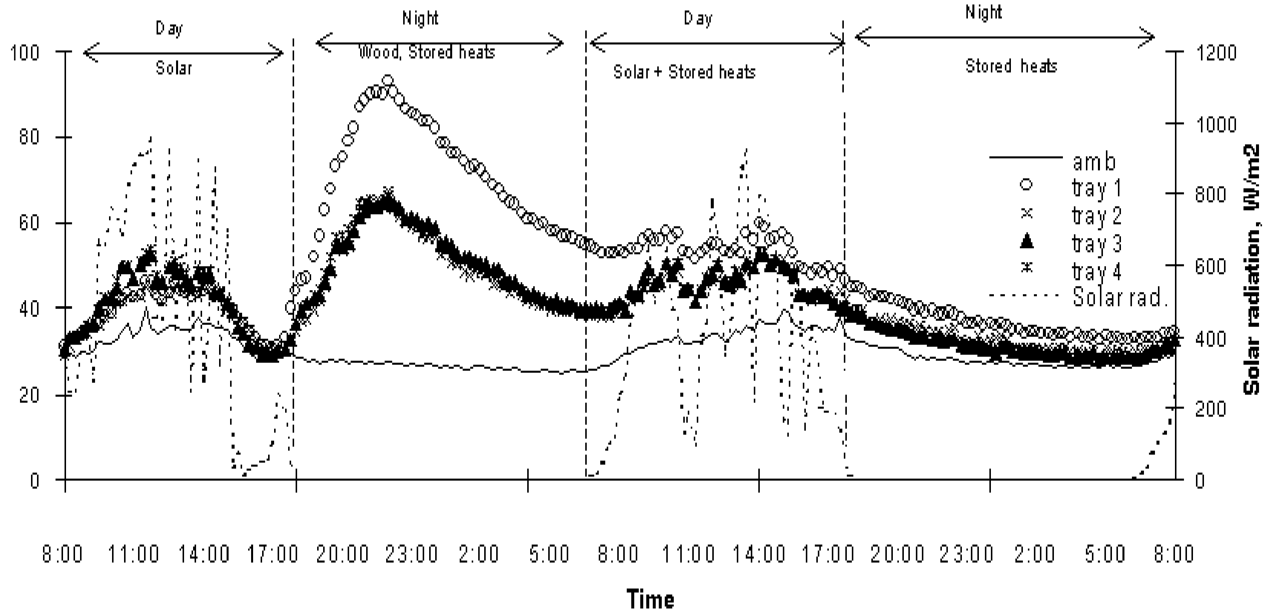


Figure 3. Variation of drying air temperatures on each tray, ambient temperature, and solar radiation during the unloaded experiment with variation of heat sources (June 26-28, 2005).

When using only solar radiation, it was observed that tray 4 has the highest temperature with maximum of 54^{o}C, i.e., when the solar radiation was 916 W/m^2. While for the three other trays, the air temperatures were relatively similar. The difference between temperature of air above tray 4 and the other three trays was significant, especially during the time with high solar radiation. For solar radiation higher than 550 W/m^2, the temperature difference was about 5 – 10^{o}C.

When burner was in operation in the night time, from initial of burning fuels the temperatures on the trays was increasing and reach maximum after 6 hours. This slowly temperatures raising indicated that apart of heats were stored in the bricks when exhaust gas and hot smoke pass through them. By burning about 60 kg of woods, combustion could be sustained about 3 hours without adding more fuel. However, using large pieces of slow burning hardwood enabled the fire to burn more slowly and for longer. The maximum temperatures that can be reached on tray 2, 3, and 4 were about 65^{o}C, which is suitable for drying most of agricultural products. In contrast, on tray 1 the maximum temperature reached 93^{o}C which is too high for drying. This excessive temperature probably due to the position of the tray was too close to bottom plate that positioned above and in contact with top surface of bricks. This problem should further be solved, otherwise tray 1 could not be used, particularly during first hours of burning wood.

Since fuel and combustion in the burner was over, the stored heats in the bricks obviously started to contribute to drying air, however the temperatures then gradually decreased. In the morning on consecutive day the temperatures on tray 4 and on the other three trays were about 55 and 37^{o}C, with ambient temperature of 25^{o}C. During this consecutive day the sources of heats were both solar energy and stored heats in the bricks. The bricks still continuously supplied heats until the second consecutive night, and it could keep the temperatures up to 8^{o}C above the ambient temperature. From this measurement, it can tentatively be concluded that the biomass burner and heat storage can improve the viability of solar dryer.

4.3. Capacity and drying times

Two separate of loaded tests were carried out, i.e., the first and the second experiments with load of 35 kg and 64 kg fresh unshelled groundnuts, respectively. With the layer of fresh unshelled groundnuts on each trays was about 0.03 cm thick, it was found that the capacity of the dryer was about 60-65 kg. During the experiments, the groundnuts samples located at the center and edges of each tray were used to determine the moisture content level of the crop during the drying process.

For the first experiment the fresh groundnuts were dried starting at 9:00 a.m., using only solar radiation until 17:00 p.m, then drying was continued by burning about 40 kg of woods. In this first experiment the lowest tray (tray 1) was not used to avoid over dry of the product, especially during drying by burning wood. The decreasing of moisture content of groundnuts during both daytime by solar energy and night time by burning woods are performed in Figure 4. It took about 16 hours to dry from moisture content of 135% to 13 % (d.b.) during the experiment. For the products on the upper tray (tray 4) approximately 70% of the moisture in the groundnuts were removed by solar energy and the remainder by the biomass burner. While for the product on other trays the moisture removed by solar energy was about 44%. Figure 4 also shows the decreasing of moisture content, at the same time, by open sun drying. The temperatures of drying air at each tray and ambient temperature during the experiment, day and night, are shown in Figure 5.

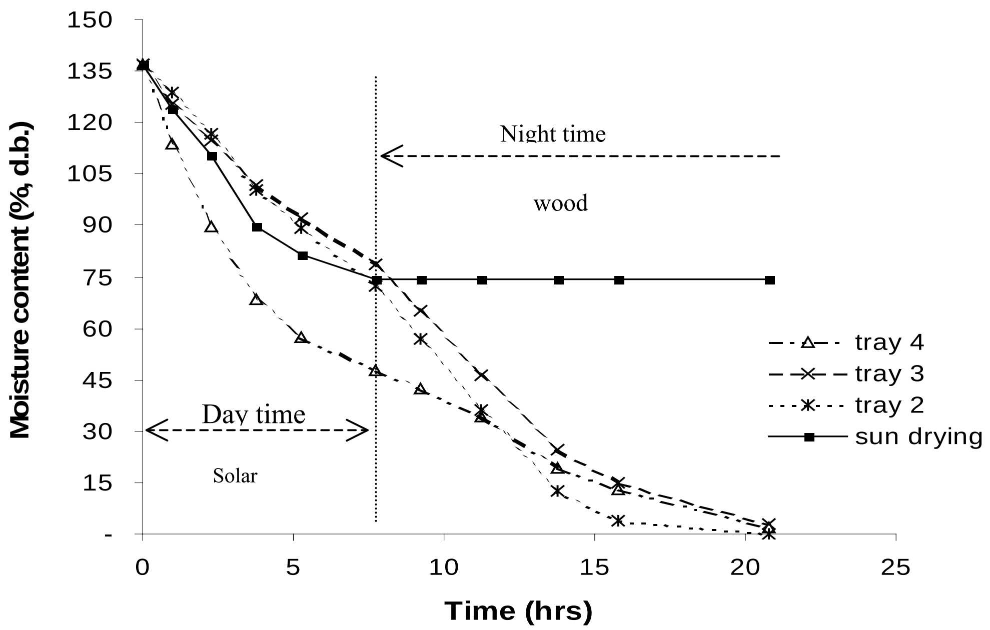


Figure 4. Decreasing of moisture content of groundnuts in the dryer during daytime by solar energy and night time by burning woods

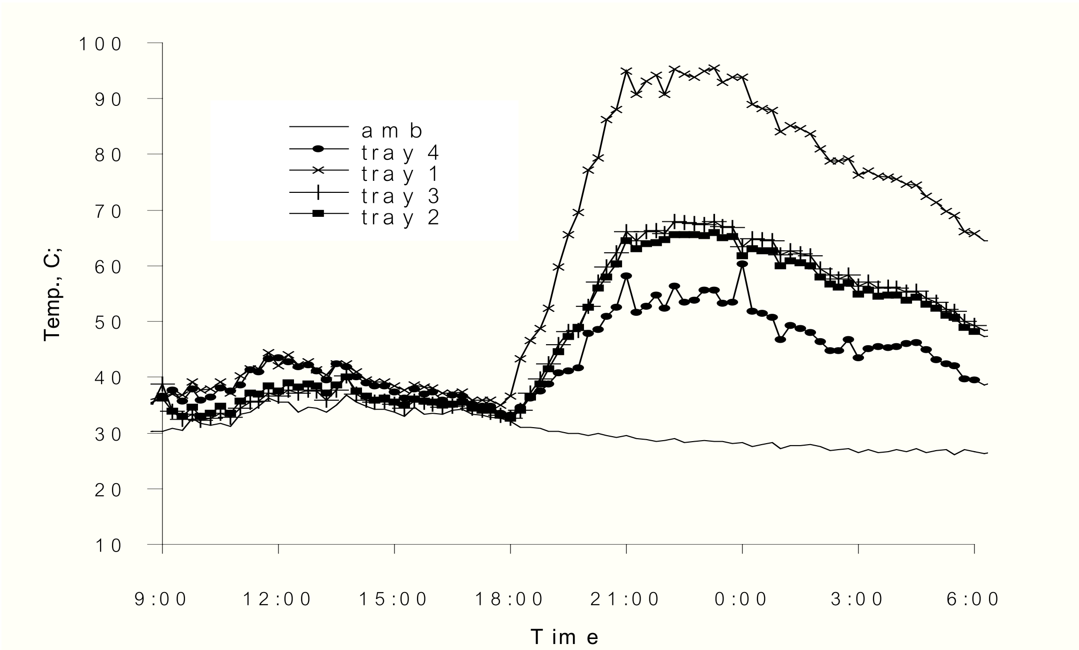


Figure 5. Variation of air temperatures in the dryer during drying of 30 kg fresh groundnuts

For the second experiment, solar energy was the only source of heat for drying about 60 kg of groundnuts (full loaded). The groundnuts were obtained from the farmers in the three different packages. Different initial moisture contents of groundnuts in each of the packages was found to be 100%, 80% and 70% (d.b.).This probably due to the difference of harvesting conditions. In the drying measurement, the groundnuts with initial moisture content of 100% and 80% were dried on tray 4 and tray 3, respectively. While the groundnuts with initial moisture content of 70% were dried on both tray 2 and tray 1. The decreasing of moisture content of groundnuts during for each of the trays is shown in Figure 6. It took about 3 days to reach moisture content about 13 % (d.b.) for groundnuts on each tray of the dryer. However, during the measurement, solar radiation was fluctuating and relatively low with an average daily radiation of 350 W/m^2/day. During the nighttime the groundnuts were just kept in the dryer, which means the dryer can also be used as storage.

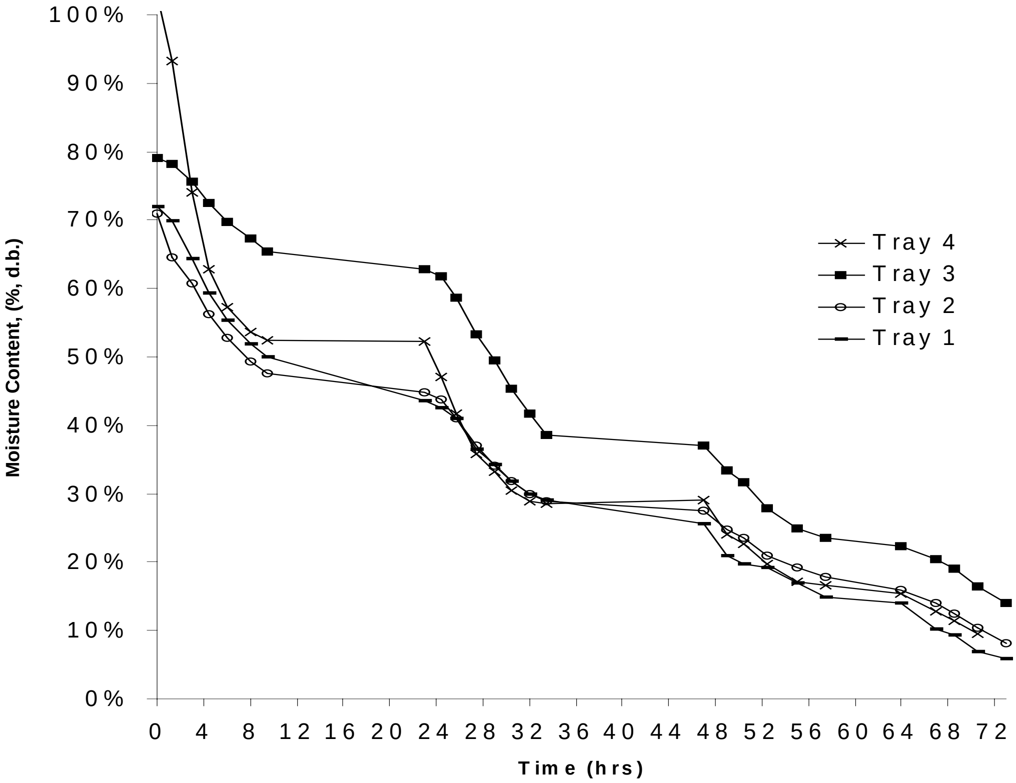


Figure 6. Decreasing of moisture content of groundnuts during for each tray of the dryer

4.4. Uniformity of drying and drying air temperatures

About 200 g samples located in the center of each tray were used to determine the variations in drying rates at different tray levels. The measurements indicated that there were significant variations in the moisture lost at different tray levels during the day where the crops on the top tray (tray 4) dried the fastest, while the crops on tray 1 dried the slowest. During the second day of full loaded test, the crops on tray 4 lost about 42% of the total moisture evaporated in the 12 h of of drying compared to 33 and 30% for those on tray 3 and the two bottom trays, respectively. The maximum temperature of the air measured just above the top tray was 43^{o}C on the first day and the average air temperatures just above the middle and bottom trays were, respectively, 7 and 108C below those at the top tray level. This trend of drying continued on sub-sequent days but the difference in the moisture lost between the trays reduces as the moisture from the partially dried slices becomes harder to remove. Similar phenomenon was reported by Bena & Fuller, (2002) as results of trial of a natural convection solar dryer.

When the burner was in operation, the crops on tray 2 dried faster compared to those on tray 3 and tray 4. (When the burner was in operation, tray 1 was not in use). In the first 6 hours of burning fuel, the crops on tray 2 lost 83% of the moisture compared to 68% and 59% for those on tray 3 and 4, respectively. The maximum temperature of the air measured just above the tray 2 on during the burning fuel was about 65°C, which was about 3 and 7°C above that at tray 3 and tray 4, respectively.

To determine the uniformity of drying across the trays, about 200 g samples of the groundnuts located at the four corners and in the center of each tray were used. The results of measurement indicates that when the dryer was operating, with either solar energy and burning biomass, most of the samples dried by the same degree. This agrees with the temperature distribution across the tray, which indicated that the maximum difference was only about 5 °C.

4.5. Airflow rates

The velocity of the drying air across the crop and the airflow through cabinet was estimated using a hand-held hot anemometer at several locations in the dryer. The measurements were taken above tray 2 when the outside wind speed varied between 0.2 – 3 m/s. The results of measurement indicated that, during loaded test with burning wood mode of operation, airflow through the dryer varied across the tray from 0.05 – 0.31 m/s. From these measurements it is estimated that airflow through the dryer in this mode of operation was about 0.04 m/s. When solar energy was the only heat source, it was found that velocities at the same positions were approximately half those values with burning wood mode. Little or no flow could be detected close to edges of the tray, while near the centre velocity were between 0.04 and 0.16 m/s. These measurments were taken when there was no wind, and it was found to be significant higher when a higher wind velocity.

4.6. Efficiencies

4.6.1. Solar dryer

The overall thermal performance of the drying system, including collector and chamber, is indicated by drying system efficiency. It measures the effectiveness of using input solar radiation for drying product in the dryer system. When solar energy was the only heat the drying, system efficiency can be written as (Leon et al., 2002)

$$\eta_{sys} = \frac{W \times L}{I \times A_p} \qquad (1)$$

where W is weight of water evaporated from the product (kg); I is solar insolation (J/m^2); A_p is area of solar collector (m^2); L = latent heat of vaporization of water (J/kg). Using Equation 1, the system efficiencies of the dryer for the first day of the first and second measurement were found to be 21.3% and 23%, respectively. However, it should be noted that the type of crop and its final moisture content level influences the thermal efficiency. The final moisture in a product generally requires more energy to extract than the initial moisture and the preparation of the crops prior to drying affects the thermal efficiency. These factors make it difficult to make comparisons with the thermal efficiencies of other solar dryers reported in the literature (Bena & Fuller, 2002).

4.6.2 Back-up heater

The overall thermal efficiency of the heater can be defined as the ratio of useful heat transferred to the drying air to the energy potential of fuel (Bena & Fuller, 2002). This efficiency is a product of the combustion efficiency and the efficiency of heat transfer to the air. In this project an overall efficiency of the back-up heater, burner and bricks heat storage, was calculated as:

$$\text{overall efficiency} = \frac{\text{heat transferred to air entering the drying cabinet}}{\text{calorific value of wood used}}$$

Using temperature data recorded during 36 hours of back-up heating operation, with approximately calorific value of wood of 13.1 MJ/kg, an overall efficiency of the back-up heaterheater was found to be 40 %.

5. CONCLUSIONS AND FURTHER RECOMMENDATIONS

A mixed mode natural convection solar dryer, designed for small-scale commercial producers of agricultural products in non-electrified locations, has been demonstrated which was combined with a simple biomass burner and bricks heat storage as back-up heating system. The back-up heating system which can be constructed with easily available materials, tools and skills, can improve the viability of the dryer. Certain key design features of the dryer contributed to produce an acceptable thermal efficiency and uniformity of drying air temperature across the trays. These features include the jacket and gap enclosing the drying chamber and arranging the bricks for storing heats.However, improvements in the performance of dryer could be achieved through further modifications, which include:

- increasing the distance between tray 1 and bottom plate of drying chamber to decrease the excessive temperatures on the tray, especially during burning fuels;
- using two layers of glazing to reduce the thermal losses from the cabinet.

In addition, performance test should be made with different kind of agricultural products and with different weather conditions.

6. ACKNOWLEDGEMENTS

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