International Journal of Scientific and Research Publications, Volume 7, Issue 7, July 2017
ISSN 2250-3153

Solar rack dryer with supplementary heat storage and evaluation of dried food quality

[1]P. N. R. J. Amunugoda, [2]N. S. Senanayake, [2]K. D. G. Kulathunga

[1] Food Technology Section, Industrial Technology Institute, Sri Lanka
[2]Faculty of Engineering Technology, The Open University of Sri Lanka

Abstract- Performance of a solar rack dryer augmented with heat storage materials was evaluated in terms of temperature and humidity developments as well as quality characteristics of dried foods. Granite chips and granite rubbles were used as sensible heat storage materials. Also paraffin wax in aluminum trays and enclosed in PVC pipes were integrated into the collector as sensible and latent heat storage. Trials were carried out under natural and forced air draft conditions. Results showed that the solar rack dryer coupled with flat a plate collector containing granite rubbles, granite chips and paraffin wax collectively stabilized drying air temperature during the day time at 50^{o}C, thus increasing the effective drying hours. However, marginally acceptable organoleptic quality of dehydrated foods indicated that the dryer further requires additional heat source to supply necessary heat during nights, and whenever necessary during daytime to obtain optimum product qualities.

Index Terms- Solar rack dryer, heat storage, effective solar drying hours

I. INTRODUCTION

Inclined solar collector is one of the favorable design features of a solar rack dryer to harness solar energy [1,2]. A certain amount of energy savings could be possible in a solar rack dryer because of natural draft is made use to provide air flow through the insulated drying cabinet. It prevents direct solar radiation, thereby bleaching of products; however, it causes a lower temperature inside the drying chamber compared to that of a solar tunnel dryer due to no direct radiation to the drying chamber [4], which results in slow rates of drying. The rate of drying is mainly controlled by the rate of surface moisture evaporation and is highly influenced by the velocity and the humidity of the airflow. At the early stage of drying, since the trays are fully filled with the layers of products, airflow is obstructed to a certain extent.

The reduced rate of airflow gives rise to relatively high humidity build up in the air stream which results in low drying rates. As drying progresses, the food material shrinks creating more void spaces for free air flow resulting in reduced humidity in the drying air. Usually solar drying process cannot be completed in a single day due to the short time duration of solar radiation. Under these circumstances, when the half-dried food is left in the dryer overnight, moisture re-absorption occurs which extends the total period of drying. With these limitations, solar rack dryer usually takes three to five days for the completion of drying process. Further, leaving semi-dried products in the dryer in the absence of drying air lead to spoilage, hence adversely affect the final product quality. This becomes crucial in the tropics due to the intermittent solar radiation and low radiation intensity during morning and evening times. To rectify this problem and to ensure continuous and effective drying, solar dryers require supplementary heat during night. One of the solutions would be to use direct solar energy as the major energy source during day time and supplementary heat by stored solar energy during night. The cheapest and easily available materials that can store energy from solar radiation in the form of sensible and latent heat are granite and paraffin [5] to maintain the drying temperature during night time and in the evening. Other option is to use paraffin wax. The melting point of paraffin wax is between 50^{o}C and 60^{o}C, and lies in the temperature range required for optimum drying of many crops. Paraffin wax shows slow rate of absorbance and release of heat due to its low thermal conductivity compared to granite. Similar studies aimed at increasing effective drying period in solar dryers have been reported for instance, the incorporation of basalt chippings into the collector for energy storage [6], and the use of rock bed collector cum storage, and augmented integrate rock bed storage air heater [7]. Similarly, heat required to prevent moisture re-absorption in the beans during the periods of non solar radiation has been adequately obtained by the integration of suitably black painted glazed gravels in development of an intermittent solar dryer [8] and reversed absorber with a packed bed thermal storage natural convection solar dryer [9]. A system that combines all heat storage materials with different thermal properties would enhance heat storage more than single a material used separately. Further, the presence of wax offers a more controlled rate of heat release.

Another possibility is to use a heat pump that provides high-grade energy from a low-temperature source through a condenser [10] which can be used if appropriately incorporated into a solar rack dryer during the operation. The ways of operating solar drying systems day and night are being constantly investigated which largely depends on the local conditions as well as availability of alternative sources of energy.

The objective of the present work was to investigate the possibility of integrating granite rubbles, granite chips and paraffin wax as heat storage materials into the solar rack dryer and thereby to improve the temperature development and stability with favorable relative humidity for continuous and accelerated drying.

II.METHODOLOGY

A. Modified rack dryer for heat storage

Several drying trials were carried out using a rack type solar dryer. The size of drying chamber was 0.8m x 0.7m x 1.6 m. The flat plate collector was made using black corrugated galvanized sheets as absorbance bed, with clear glass top. The size of the collector was 1.8m x 0.7m and the angle of inclination was 7^{o} facing the south. In order to contain the heat storage materials, the solar rack dryer was modified by extending the collector area to have an extra area of approximately 1.3m^{2} as shown in Figure 1. The temperature and humidity measurements were made by using EL008 Enviro Mon Data Logger equipped with EL 026 temperature humidity converters and EL030 temperature/humidity sensors. During the drying trials, the air velocity was measured using a turbo air-flow meter (range: 0- 44.8 ms^{-1}, accuracy: ± 0.1ms^{-1}). The moisture content of the samples was determined by the oven-dry method. All drying trials were carried out to test the performance of the prototype and modified system using 6mm thick circular pineapple slices (rings). The slices of pineapple were dipped in a solution of 30% ^{o}Brix sugar, 0.1%Sodium metabisulfite and 0.3% Citric acid for 10 minutes before placing in the dryer.

The first drying trail was carried out without any heat storage materials. In the second trial, the extra area of the collector was filled with an approximately 10cm thick layer of granite chips and 25cm thick layer of granite rubbles as shown in Figure 1. In the third trail, 5 aluminum trays and 4 PVC pipes of length 1m each filled with a total of 30kg paraffin wax were added to the bed of the granite rubbles as additional heat storage. For each trial, temperature, humidity and airflow rate were measured. The temperature and humidity sensors were located at the points as shown in Figure 1. The sensor at point 1 measured the ambient air conditions. Additionally, during trial 3, the moisture content of the samples was measured each day in the morning at the beginning of drying and in the afternoon (at 6.00pm) until the drying was completed. In the afternoon of the third day a sample was taken off the dryer and kept under room condition of 26-28^{o}C and 70 -95% RH. In the morning of the fourth day, the moisture content of the sample kept in the room and a sample taken from the solar dryer were measured to compare the moisture re-adsorption during 12h period. A sample of pineapple was dehydrated using an electrical dryer to compare the products characteristics

B. Water sorption and Organoleptic characters

Static gravimetric technique was used for the equilibrium moisture determination of dehydrated pineapple. Varieties of salt solutions were used according to their ability to develop temperature dependent equilibrium humidity values. The initial moisture content of the dehydrated pineapple sample was also determined. Five grams of dehydrated sample was placed in the cup made by aluminum foil (Figure 2) and glass jar was closed tightly. Airtight glass jars containing saturated salt solutions were placed in temperature-adjusted incubators for 15^{o}C, 30^{o}C, 40^{o}C and 50^{o}C to provide constant equilibrium humidity and constant temperatures. In order to prevent mould growth at high relative humidity levels small pieces of cotton containing toluene were placed inside the sealed glass jars. Apparatus were allowed to equilibrate with the environment of temperature and humidity for 14 –21 days. The sample weights were determined at three day intervals until a constant or nearly constant weight was achieved using an analytical balance. Equilibrium moisture content was plotted against the relative humidity.

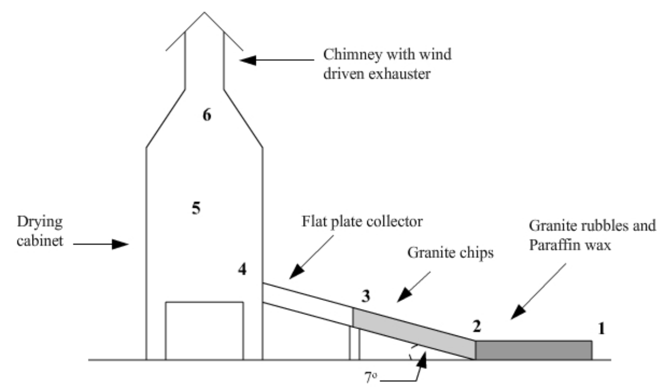

Figure 1 - Sensor location diagram of the solar rack dryer

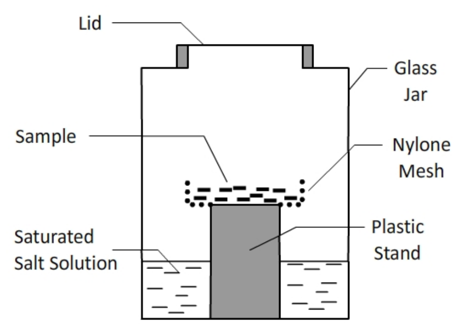

Figure 2 - Apparatus for equilibrium moisture content determination.

Organoleptic characters were evaluated based on color, odor, taste, texture and overall acceptability by a trained taste panel comprising of 10 persons. A nine point hedonic scale (1-2 = very poor, 3-4 = poor, 5-6 = fair, 7-8 = good, 9 = excellent) was used to evaluate each parameter. Results of the sensory tests were analyzed by Friedman Non Parametric method and Mann-Whitney Confidence Interval and Test. Statistical analysis was conducted using the applicative software SAS 6.12 and Minitab. Mean separation of sensory analysis was compared with LSD (Least Significance Difference) at $p < 0.05$.

III. RESULTS

A. Temperature developments in the dryer

The maximum and minimum values of solar radiation intensity of the trial date were reported as 3214 MJm^{-2}and 19MJm^{-2} respectively. The maximum and minimum temperatures of the trial days were recorded as 30.2^{o}C and 25.1^{o}C respectively. The average humidity during day time was 82% whereas that of night was 99%. Temperature variation in the drying cabinet and collector during the first trial, with the flat plate collector without heat storage materials, are given in Figure 3. Results indicated that temperature development was below the required level of 50 – 60 ^{o}C range during the trial period from 10.00 am to6.00 pm. Air velocity measured across the drying cabinet was in the range of 0.1 - 0.12ms^{-1}. Results of the drying trial of pineapple showed that dryer was unable to reduce the moisture content of products below 20% for five days, thus resulting in poor product quality.

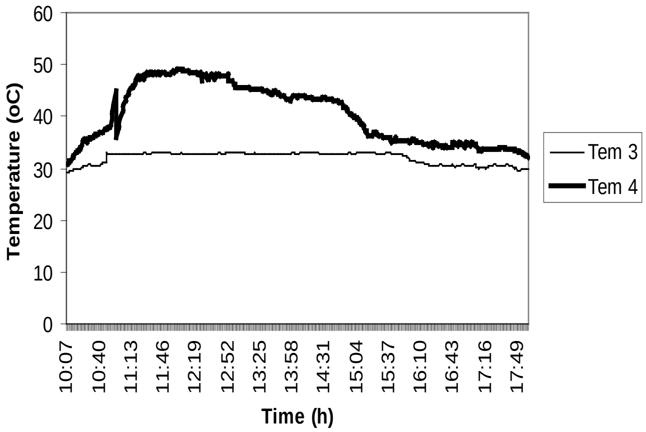

Figure 3 - Temperature variations at different locations with flat plate solar collector during no load trial period

According to the studies of Minaka (1986) no difference observed between open sun dryers and natural convection direct dryers as far as drying time is concerned due to low air movement across the dryer [11]. It has been reported that low airflow rate of natural convection dryers was the main reason for longer drying durations and their failures in practice [12]that was confirmed by the findings of the present study. In order to increase the airflow rate using forced air draft or using any other mechanism, adequate energy supply must be available.

The intention of using granite chips in this study was to investigate the possibility of providing a low-cost flat plate collector, with energy storage material for a short time period. The granite rubble stores heat and keeps it for a longer period as heat energy is released slowly. Further, laying of these two heat storage materials increased the collector area in trial 2 that gave encouraging results. As shown in Figures 4, the temperature of drying air was found to be greater than those of trial 1, that was carried out without heat storage materials. This naturally resulted in an increase in the effective drying period.

A significant reduction of temperature was observed, after 12.30 pm and prevailed till 6.00 pm, in the flat plate section. Temperature reduction rate was little slow till 3.40 pm and it followed the same pattern till6.00 pm in the granite chips section of the flat plate collector. Rate of temperature reduction was slow in granite rubbles under the air velocity of 0.10 to 0.15 ms^{-1} across the drying cabinet similar to the trial 1.

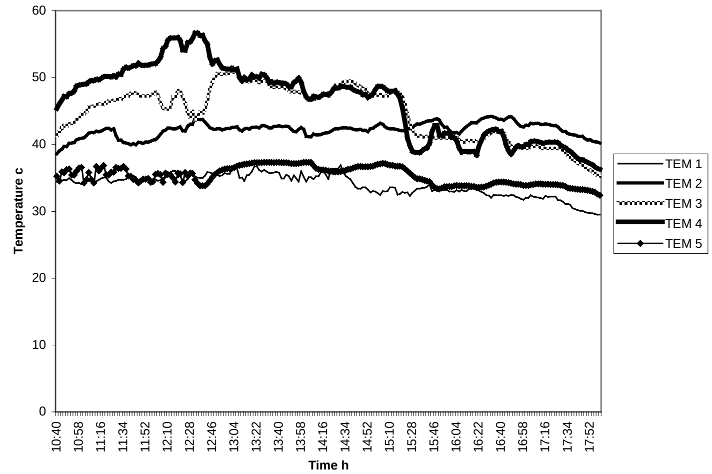

Figure 4 -Temperature variation at different locations when granite is used with flat plate solar collector during the drying trial.

The maximum and minimum of solar radiation intensity of the date of trial 3 were 1770MJm^{-2}and 30MJm^{-2} respectively. The maximum and minimum temperatures of the trial days were recorded as 30^{o}C and 21^{o}C, respectively. The average day time humidity was recorded as 79% whereas average night time humidity was 96%.The temperature built up in the drying chamber in trial 3 reached a peak in the range of 50^{o}C – 55^{o}C, after 1.30 p.m. as shown in Figure 5. Thereafter, this temperature level was maintained till afternoon.

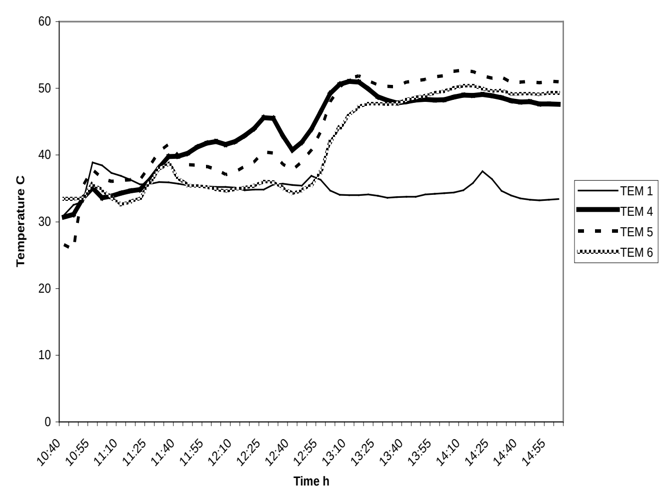

Figure 5-Temperature variation at different locations when granite and paraffin wax is used with flat plate solar collector during the drying trial

A more stable temperature for optimum dehydration of fruits and vegetables was observed in this trial. This favorable performance was due to the incorporation of the additional heat storage material i.e. paraffin wax and the combined effect of flat plate collector with granite chips and granite rubbles. During the trials 1 and 2, a sunny weather prevailed and the dryer received relatively high amount of solar radiation throughout the day compared to the bad weather of the day of trail 3. This resulted in a low temperature development in the drying chamber in the early hours and in the evening thus deviating from the full potential of using heat storage materials. During trial 3, it was possible to double the air flow rate using an air blower after 1.30pm from the starting range of 0.10 to 0.15 ms^{-1}, to 0.25 to 0.30ms^{-1} owing to the supply of more heat energy through increased collector area and due to additional heat storage materials than in trial 1 and 2. This increase in airflow rate did not cause a temperature drop that one would expect inside the drying chamber.

Use of wax as a heat storage material is an important area for new development. Some problems were encountered when wax came out of the end caps of the PVC pipes during melting due to expansion of volume. This difficulty of change in volume can be overcome by providing an additional space within ducts to allow for change in volume when wax melts. However, temperature development at location 4 (Figure 1) of the dryer during trial 2 (Figure 4) and trial 3 under given solar radiation, indicated that incorporation of wax to the collector in trial 3 has a significant effect to increase and stabilize the temperature at 50^{o}C.

When wax is used as heat storage material it is possible to control the rate of heat release by suitably sizing the containers that enclose wax and by mixing wax with high conductivity materials to improve the rate of heat transfer. A similar study has indicated and reviewed by Garg (1987) in which micro encapsulation, metallic and powdered filler wire structures were used [5]. The findings of this research contribute to series of investigations conducted to develop a viable and low-cost dehydration system using solar dryers.

B. Characteristics of dried products

Fruit like pineapple and other foods consist of water, carbohydrates, protein and fractions of lipids. These compounds are easily modified in longer drying durations, high temperatures, and high and very low humidity conditions. The moisture desorption and sorption results in degradation in sensory quality such as appearance, color, texture, flavor, shrinkages, and the product desirability for consumption is affected. Browning of pineapple can also occur by enzymatic and non-enzymatic reactions, which usually impairs the sensory properties of products due to associated changes in color, flavor, and texture, and the nutritional properties. During drying, significant changes in structural properties can be observed as water is removed from the moist material. Shrinkage occurs because food polymers cannot support their weight and, therefore, collapse under gravitational force in the absence of moisture. The collapse of structure and the resulting changes in porosity, including texture, during drying are key sensory properties perceived by consumers.

Soluble substances present in foods may undergo phase transformation. The occurrence of these phase changes depends on the presence of water. The physicochemical and microbial stability of foods under different temperatures and humidity during storage therefore can be predicted through moisture adsorption isotherms [13].

Moisture sorption studies of dehydrated pineapple at four different storage temperatures showed that sorption increased with the increase of temperature (Figure 6). Thus the marked increment is shown at 50^{o}C. The study shows that the curves are sigmoid in shape. In general, most of the food products show a decrease in EMC values with increasing temperatures at a constant water activity. The reasons for this phenomenon are the loss of hygroscopy at higher temperatures, increase in thermal motion of water molecules causing them to become less stable and break away from the water binding sites of the food, irreversible change in the substrate such as protein damage, and sugar caramelization. It has also been pointed out that the excitation of molecules and the distance and attraction between molecules are the reasons for adsorbed water to change with change in temperature at a given water activity [15, 16].At higher temperatures and higher water activities increased hygroscopes are observed in pineapple which has less starch and protein content and more reducing and non reducing sugars such as sucrose, glucose and fructose. Crystalline sucrose contained foods adsorbs very little water until water activity reaches approximately 0.8 and the sucrose begins to dissolve when the drying is sufficiently rapid to produce amorphous sucrose as observed in the present study. This water uptake resulting in sorption levels was far higher than the initial level in pineapple, due to the greater internal area available for water sorption in the amorphous material and the greater ability of water to penetrate in to the H-bonded structure.

The stability of dehydrated pineapple decreases at very low humidity and high temperature as it can tolerate less water with the increase of temperature which leads to higher shrinkage, formation of hard texture and occurrence of browning reactions. Under high humidity and high temperature the stability of dehydrated pineapple decreases by way of softening due to the availability of more liquid water.

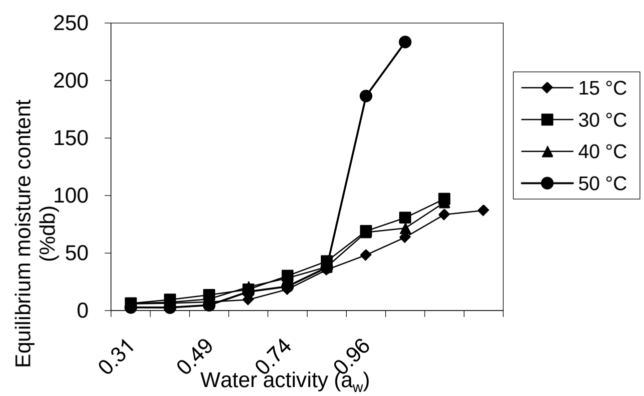

Figure 6-Moisture sorption isotherms of dehydrated pineapple at four different storage temperatures

Equilibrium moisture content of dehydrated pineapple corresponding to 75% and 96% relative humidity and under 15^{o}C, 30^{o}C, 40^{o}C and 50^{o}C are given in Table 2and shows how large the sorption of water at increased relative humidity and increased temperatures. The equilibrium moisture content corresponding to a relative humidity of 75% is close to the average relative humidity value and ambient temperature in Sri Lanka. Results indicated that at ambient temperature (30 ± 2^{o}C) dehydrated pineapple showed 21% EMC and which shifted to 71 % EMC under 96% relative humidity level. On the other hand the relative amount of sorption of moisture could be observed under low temperature and high humidity development.

Table 2 - Equilibrium moisture content (%db) of pineapple, corresponding to 75% and 96% relative humidity

Relative humidity	Temperature °C			
	15	30	40	50
75%	18	21	28	30
96%	66	71	80	186

Laboratory tests under ideal conditions clearly indicated how moisture pick up happened under low temperature and saturated conditions as against high temperature and saturated conditions. Similar environment existed in the drying chamber of solar rack dryer under night time and daytime at low airflow rates. Therefore, measures should be taken to reduce high humidity development during the actual drying process (water desorption process) both at low temperature and high temperature in the solar rack dryer.
Results of the moisture measurements of pineapple slices are shown in Table 2.The sample that was kept under ambient conditions at the end of the third day reduced to 10.8% (wb) moisture content. The same sample showed 14.8% (wb) moisture content on the following morning, indicating a 4% moisture adsorption. The sample that was in the dryer having 10.8 % moisture content showed no significant change in the following morning. Thus no change of moisture content can be attributed to the presence of granite rubble, granite chips and paraffin wax which release heat energy to prevent moisture re-absorption in the night. This indicates that use of heat storage materials not only contributes to stabilize the optimum temperature during the daytime but also prevents nighttime moisture absorption when food was left in the dryer overnight.

Table2-Results of the moisture determination using solar rack dryer with granite rubbles, granite chips and paraffin wax as heat storage materials

Day	Time	Sample	Moisture Content (wb)
1	10 am	Inside the dryer	85.5 % ± 0.2
	6 pm		65.2 % ± 0.2
2	7 am	Inside the dryer	51.0% ± 0.2
	6 pm		60.2% ± 0.2
3	7 am	Inside the dryer	14.9% ± 0.2
	6 pm		10.8% ± 0. 1
	6 pm	Room at ambient conditions	10.8% ± 0.1
4	7 am	Inside the dryer	9.2% ± 0.1
		Room at ambient conditions	14.8% ± 0.2

Permissible temperature, relative humidity and air velocity are three interrelated parameters, under which the dryer has to be operated for obtaining optimum quality. In most cases, drying processes that use maximum temperature for short time do less damage to food than drying with lower temperatures for longer drying times. In most food products the drying process occurs in longer falling rate periods due to their structural and chemical composition. The prolonged period of drying coupled with the falling rate period could enhance the formation of unfavorable physicochemical changes in the food material. The rate of most browning reactions is greatly dependent on the combined effect of time, temperature and the intermediate moisture content of the food material. In solar rack dehydration (no direct solar radiation to the drying cabinet) product quality is greatly affected by the absence of optimum drying environment during the cloudy weather and in the nights.
Even though we were able to stabilize the temperature the effective drying period in trail 3 was extended and the extended drying period will have unfavorable effects on the organoleptic qualities. Therefore, we need to assess the dryer performance by analyzing product characteristics. In the dryer performance assessment we used pineapple rings of 6mm thick which is a relatively hard material thus being difficult to dehydrate. So it requires ideal drying environment for the completion of dehydration process. Sensory quality assessment of dehydrated pineapple obtained at 6 pm of the third day (Table 3) showed that sensory quality attribute of color is low due to browning reaction. Three days of prolonged drying environment of the solar rack dryer has been more favorable to accelerate these non- enzymatic and other browning reactions, that was indicated by poor color development and poor organoleptic quality attributes of appearance, taste and overall quality compared to those of electrical dryer.

Table 3- Sensory quality attributes of dehydrated pineapple

Sensory parameter	Sensory attributes (solar rack dryer)	Sensory attributes (electrical dryer)
Appearance	$5.5^{b} \pm 2.2$	$7.8^{a} \pm 1.4$
Color	$5.2^{b} \pm 1.3$	$7.4^{a} \pm 1.2$
Taste	$6.1^{b} \pm 1.0$	$7.2^{a} \pm 1.3$
Overall	$5.4^{b} \pm 1.5$	$7.7^{a} \pm 1.5$

Means followed by same superscript letters are not significantly different at 0.05% LSD

IV. CONCLUSIONS

Drying duration of solar rack dryer attached with flat plate collector is highly variable. Flat plate collector equipped with supplementary heat storage composed with granite chips, granite rubbles and paraffin wax stabilized the temperature at 50°C and increased the effective drying hours, thereby reducing the duration of drying in solar rack dryer. Moisture sorption analysis both at in vivo and in vitro indicated that the necessity of high air flow in the drying chamber of the solar rack dryer. The use of correct amounts of heat storage material and the location for the best temperature distribution needs further study.
Marginally acceptable organoleptic quality of dehydrated pineapple due to prolonged drying duration of the improved system indicated the dryer further requires an additional heat source to supply necessary heat during nights, and whenever

necessary during day time to reduce drying duration and optimize products qualities. In order to induce air flow and to have a better temperature control, a blower powered by solar PV panel could be used.

REFERENCES

[1] Bari, S., Lim, T. H. and Yu, C. W. (2001). Slope angle for seasonal application of solar collectors in Thailand. International Energy Journal, Vol. 2. No. 1. June 2001. pp 43-51

[2] Das, P. and Sharma, S. K. (2001). Drying of Ginger using solar cabinet dryer. Journal of Food Science and Technology, 38 (6): 619-621

[3] Kumara, M. A. S. U., Jayawardene, H. S., Jayathunga, K. G. L. R., Senanayake, D. P., Palipana, K.B., Development and performance evaluation of a dual heat dryer technology for sustainable processing of agro. Engineer – Vol. XXX.01, pp 1- 9, 2006

[4] Esper, A. and Muhlbauer, W. (1996). Solar tunnel dryer for fruits. Plant research and development, Vol. No. 44, Institute for scientific cooperation, Federal Republic of Germany, pp 61-81

[5] Garg, H. P. (1987). Advances in Solar Energy Technology: Collection and Storage System. In: Storage of Solar Energy. Vo. 1, De Reidel Publishing Company, pp 361- 504

[6] Oosthuizen, P. H. (1986). A numerical model of a natural convection solar grain dryer, Development and Validation. Solar drying in Africa. Editors: Bassey, W. M. and Schmidt. Proceedings of a workshop held in Dakar, Senegal, 21-24 July, 1986. International Development Research Center, Ottawa

[7] Garg, H. P., Bandyopadhaya, K. K., Sharma, V. K. and Bhargava, A. K. (1983). Development an inexpensive solar collector cum storage system for agricultural requirements. pp. 5-10, 88-109.

[8] Fagunawa, A.O., Koya, O.K. and Faborode, M. O., (2009). Development of an Intermittent Solar Dryer for Cocoa Bean. Agricultural Engineering International : the CIGR e- journal. Manuscript No. 1292, Vol XI. July 2009

[9] Jain, D. (2007). Modeling the performance of the reversed absorber with packed bed thermal storage natural convection solar crop dryer. Journal of Food Engineering, 78 (2007) 637-647.

[10] Kivelle, T, and Huan, Z. (2014) A review on opportunities for the development of heat pump drying system in South Africa. South African Journal of Science, 2014, 110 (5/6), pp. 1-11

[11] Minka, J. C. (1986). Results of potential improvements to traditional solar crop dryers in Cameroon, Editors: Bassey, W. M. and Schmidt. Solar drying in Africa. Editors: Bassey, W. M. and Schmidt. Proceedings of a workshop held in Dakar, Senegal, International Development Research Center, Ottawa 21-24 July, 1986

[12] Othieno, H. (1986). Circulation of air in natural convection solar dryers.Solar drying in Africa. Editors: Bassey, W.M. and Schmidt. Proceedings of a workshop held in Dakar, Senegal 21-24 July, 1986. International Development Research Center, Ottawa

[13] Lee, H. J. and Lee, J. M. (2008). Effect of drying method on the moisture sorption isotherms for Inontusobliquus mushroom. Food Science and Technology, 41 (2008) 1478 – 1484

[14] Shatadal, P. and Jayas, D.S. (1990). Moisture sorption isotherm for grains and oil seeds.Post harvest news and information. 1, 447 – 451.

[15] Palipana, K. B. and Droscoll, R. H. (1992). Moisture sorption characteristics of in –shell Macadamia nuts. Journal of Food Engineering. 18, 63-76

[16] Kumar, K.R. &Balasubramanym, N. (1986). Moisture sorption and the applicability of the Brunaur-Emmett-Teller equation for some dry food products. Journal of Stored Product Research, 22, 205-209