Solar Energy
And Sustainable Development
Refereed, biannual scientific journal issued by
Center for Solar Energy Research and Studies

Numerical Simulation of Rock-bed Solar Thermal Storage Energy

Ebangu Orari Benedict[1, 2, *], Dintwa Edward[1], Motsamai Seraga Oboetswe[1], Okiror Grace [2]

[1]Department of Mechanical Engineering, University of Botswana
Gaborone, Botswana.

[2]Department of Biosystems Engineering Gulu University, Gulu, Uganda

e-*mail:* [1*] *benebangu@yahoo.com*

Abstract: Solar dryers are increasingly being applied to dry fruits and vegetables in order to increase their shelf-lives. In the sunny-belt countries, the availability of solar irradiance is taken for granted and the mean daily solar irradiation is often used as the design basis for a solar dryer. The predicted performance of the solar irradiance is therefore inherently inaccurate. Contemporary solar dryer designs incorporate thermal energy storage (TES) systems for application after sunset. The performance of such TES systems is often determined experimentally. In this study, mathematical models have been developed and by numerical simulation using the technique of Finite Differential Method (FDM) and MATLAB programming, the performances of solar irradiance as well as that of the TES system have been predicted. The simulation results were secured to inform the design of the solar dryer for fruits and vegetables in the sun-belt countries.

المحاكاة العددية لتخزين الطاقة الشمسية الحرارية باستخدام السرير الصخري

ايبانجوا اوبراري بينيدكت [1,2,*]، دينتوا ادوارد [1]، موتساماي سيراجا ابوتسوا [1]، اوكيرور جريس [2]

[1]قسم الهندسة الميكانيكية - جامعة بوتسوانا - جابورون - بتسوانا

[2] قسم هندسة الانطمة العضوية - جامعة جولو - جولو - اوغندة

ملخص: يتم استخدام مجففات الطاقة الشمسية بشكل متزايد لتجفيف الفواكه والخضروات من أجل زيادة فترة صلاحيتها. في

* *Corresponding author*

البلدان ذات الحزام المشمس ، يعتبر توفر الإشعاع الشمسي أمرًا مسلمًا به ، وغالبًا ما يستخدم متوسط الإشعاع الشمسي اليومي كأساس لتصميم المجفف الشمسي. وبالتالي ، فإن الأداء المتوقع للإشعاع الشمسي غير دقيق بطبيعته. تشتمل تصميمات المجففات الشمسية المعاصرة على أنظمة تخزين الطاقة الحرارية (TES) للتطبيق بعد غروب الشمس. غالبًا ما يتم تحديد أداء أنظمة TES التجريبية. في هذه الدراسة ، تم تطوير النماذج الرياضية ومن خلال المحاكاة العددية باستخدام تقنية الأسلوب التفاضلي المحدود (FDM) باستخدام برنامج MATLAB ، تم التنبؤ بأداء الإشعاع الشمسي بالإضافة إلى أداء نظام TES. اثبتت نتائج المحاكاة يجدوى تصميم المجفف الشمسي للفواكه والخضروات لاستخدامه في بلدان الحزام الشمسي.

Keywords: ***Solar irradiance, MATLAB programming, Predicted, Simulation, TES, Solar dryer, FDM***

1. INTRODUCTION

It is important to predict the performance of the design of a solar dryer before construction of the prototype by using numerical techniques that can be applied to solve an engineering problem [1]. The design is described by a set of differential equations and boundary conditions. These equations are then discretized to algebraic equations. Using computer algorithms and computer codes, the generated sets of algebraic equations are solved to obtain the numerical solution. Finally, the numerical solution is visualized and evaluated for accuracy against experiment or any other model that has proven accuracy, including analytical equations or phenomenological equations, before being used as a validated model. Modelling and simulation of solar dryers are critical steps in developing and predicting their performances while saving on the costs of testing by experimental set-ups [2].

Prediction of solar irradiance for solar drying based on the solar constant and location angles of the sun during day is important for determining the size and drying capacity of a solar dryer during the development stage [3]. It has apparently become common practice to use thermally stored energy for drying fruits and vegetables after sun set for cost effectiveness and thus the need to predict the performance of such thermal storage systems.

Solar energy is absorbed and stored as thermal energy by materials such as rocks or pebbles. The pebble bed or rock pile consists of bed of loosely packed rock material through which the heat transport fluid can flow. Thermal energy is stored in the packed rock bed by forcing in heated air to charge the rock bed. The stored energy is discharged by recirculating air at ambient temperature in the rock bed [4].

Many researchers have developed and performed simulations of models of a variety of dryer types. The mathematical model of the thin layer drying behaviour of tomato slices dried by a solar dryer in a hybrid drying mode, as well as indirect solar and open sun modes was developed by [5]. The thin layer drying models are commonly used to optimise the goodness of fit to experimental data. Experiments and simulations of the performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana [6,7]. The numerical solution was used to predict the performance of the dryer using the finite difference method (FDM) and simulated using Compaq Visual FORTRAN version 6.5. The results of simulation of performance of the dryer reasonably agreed with the experimental data for solar drying of peeled longan and banana and were useful for optimal design of the dryer.

A numerical investigation of a solar greenhouse dryer was performed by [8]. The mathematical model was formulated and solved using the finite difference method FDM. The numerical solution was simulated in Compaq Visual FORTRAN version 6.5. The simulated results reasonably agreed with the experimental data for solar drying copra.

A solar heat pump dryer driven by photovoltaic module was investigated by [9]. They developed mathematical model was simulated using MATLAB to describe the whole drying system including heat and mass transfer phenomena

This study aims at developing the simulation models using numerical analysis for predicting the performance of the solar irradiance and the TES system using MATLAB programming in order to design an appropriate solar dryer for drying fruits and vegetables.

Literature review on the rock-bed type thermal storage indicates that it is used very often for temperatures up to 100 ^{0}C in solar air heater applications. Typically, the characteristic size of rocks for optimum energy storage varies from 1-5cm. The rule of thumb for sizing of rock bed is to use 300-500kg of rock in a unit square meter of solar collector area for space heating applications [10].

A theoretical investigation of a dryer-cum-air-heater with heat storage was performed by [11]. They analysed the drying characteristics of coriander in a deep bed dryer coupled with a solar air heater and a rock bed storage unit. The rock bed storage device was charged during the sunshine and discharged during off-sunshine hours. The theoretical investigation was made by writing the energy and mass balance equations for different components of the system and adopting a finite difference approach for simulation to reduce the moisture content from 28.2% db to 11.4% db. It took 27 cumulative sunshine hours (about 3 sunshine days) for an air heater alone to complete the drying, while with the air heater combined with the rock bed storage it took 31 cumulative sunshine hours (in a period of about 2 sunshine days and 2 nights). It is therefore clear that with the rock bed storage device the drying time decreased by 1 sunshine day. The completion period was shorter because drying was performed during the two nights using the energy from the thermal energy source in the combined bed setting. However, the literature on the application of the rock bed thermal storage system as an energy source is scarce in Botswana, hence the research gap to predict the discharging characteristics using local thermal storage rock bed.

2. METHODOLOGY

In this study, a mathematical model was formulated for horizontal solar irradiance on rock-bed thermal energy storage (TES) system. This solar energy was absorbed by the rock-bed as thermal being thermal energy storage material. The stored thermal energy was later released to a convectional air during discharge cycle for application in solar drying of fruits and vegetables. The mathematical model describing the energy discharge depicted by the thermal performance of the outgoing air was also formulated. By invoking numerical analysis techniques, specifically, the Finite Difference Method (FDM), simulation models were developed for solar irradiance and the TES system and coded using MATLAB programming.

2.1 Model of solar irradiance on the dryer

The days of the year are numbered from the first day being the first of January to the 365th or 366th day of the year being the last day of December in a year. The Nth day can be obtained as the sum of the cumulative total number of days of the year plus the current date number (i) of the given month as detailed in Table 1.

The extra-terrestrial radiation measured on the plane normal to the radiation on the nth day of the year is given by [3]

$$Gon = Gsc\left[1+0.033\cos\frac{(360N)}{365}\right] \tag{1}$$

where, the solar constant G_{SC} is 1.3661 W/m^2, and G_{on} is the horizontal terrestrial solar irradiation.

The horizontal irradiance on a terrestrial horizontal surface is given by

$$GoH = Gon\cos\Phi \tag{2}$$

where $Cos\Phi = Cos(L)Cos(\delta)Cos(h) + \sin(L)\sin(\delta)$ and where L is the latitude of insolation location and δ is the angle of declination given by [12]

$$\delta = 23.45\sin\left[\frac{360}{365}(284+N)\right] \tag{3}$$

The hour angle h is calculated by

$$h = \pm 0.25\min \tag{4}$$

The solar irradiance on any day can be simulated for the global horizontal terrestrial irradiance as well as the irradiance received by the cover of the solar dryer in Gaborone.

Table (1). Determination of day number N of the year

Month	Day N	Month	Day N
January	0+i	July	181+i
February	31+i	August	212+i
March	59+i	September	243+i
April	90+i	October	273+i
May	120+i	November	304+i
June	151+i	December	374+i

2.2 Model of thermal energy storage system

The fabricated solar collector is fundamentally a double pass solar collector design with the thermal energy storage, TES, system comprising of rock-bed using granite pebbles as the TES medium in the second pass section of a double ass solar collector. When solar radiation is available, heated air from the collector enters the top of pebble bed energy storage system and heats the rocks. As the air flows downward, heat transfer between the air and the rocks results in a stratified distribution thermal energy storage resulting into pebble-bed having high temperature at the top and low at the bottom. This is the charging mode of the bed. The discharging mode on the other hand happens when there is a heating demand. Hot air is drawn from the top of the unit and cooler air returned to the bottom of the bed causing the bed to release energy. This shows that the two modes cannot happen at the same time. In the analysis of rock bed storage, both air and rocks are changing temperature in the direction of air flow and there is temperature differential between the air and the rocks. Therefore, separate energy balance equations are required for the rocks and air. The following were the assumptions made for the analysis:

- Forced airflow is one-directional.
- System properties are constant.
- Conduction heat transfer along the bed is negligible.

- Heat loss to the environment was negligible.
- Energy stored in the air within the rock-bed is negligible.

The thermal behaviour of the rock-bed and air during the discharging cycle were described by the two coupled partial differential equations by [13] as:

$$\rho_b c_{pb}(1-\varepsilon)\frac{\partial T_b}{\partial t} = h_v.(T_a - T_b) \quad (5)$$

$$\frac{\dot{m}\, c_{pa}}{A}\frac{\partial T_a}{\partial x} = hv(T_b - T_a) \quad (6)$$

where, A is cross-sectional area of the storage bed normal to flow, m^2, T_b is temperature of the bed material, °C, T_a is temperature of the air °C, ρ_b is density of the rock bed, kg/m^3, ρ_a is density of air, kg/m^3, C_{pb} is specific heat capacity of the bed material, J/kg K, C_{pa} is specific heat capacity of air, J/kg K, ***t*** is time, s, ***x*** is position along the bed in the flow direction in m, $\dot{m}$ is mass flow rate of air, kg/s, ε is void fraction of packing of pebble bed in dimensionless units, and h_v is volumetric heat transfer coefficient, W/m^3 K.

An empirical equation for the determination of the volumetric heat transfer coefficient, h_v in W/kg K is given by:

$$h_v = 279.6(G / D_p)^{0.7} \quad (7)$$

where, ***G*** is air mass velocity per square meter of bed frontal area, kg/hr-m^2

D_p is rock equivalent diameter, mm.

Equation 8 can be expressed as

$$\frac{dT_a}{dx} = \frac{h_v A}{\dot{m} c_{pa}}(T_b - T_a) \quad (8)$$

And if we let the number of transfer units to be NTU,

$$NTU = \frac{h_v A}{\dot{m} c_{pa}} \quad (9)$$

Then $\frac{dT_a}{dx} + NTU \text{ x } T_a = NTU \text{ x } T_b$, and using the integrating factor $I = e^{\int NTU dx}$ the solution is

$$T_a e^{NTUx} = \int e^{NTUx} NTU T_b dx + C$$
$$= e^{NTUx} T_b + C \quad (10)$$

When x=0, ***Ta=Ta,n*** and ***Tb= Ta,n*** or C= ***Ta,n -Tb,n*** when x=Δx, Ta=Ta, n+1 and ***Tb= Tb,n***

Thus, $T_{a,n+1} \text{x} e^{NTU\Delta x} = e^{NTU\Delta x} T_{b,n} + T_{a,n} - T_{b,n}$ from which we get

$$\frac{Ta_{(n+1)} - Tb_{(n)}}{T_{a(n)} - T_{b(n)}} = \exp\left(\frac{-h_v A}{\dot{m} c_{pa}}\Delta x\right) \quad (11)$$

By using Finite Difference Method, the Equation 11 is discretised and given in temporal and spatial implicit forms as follows.

$$T_{a(n+1)} = T_{a(n)} + \left(1 - \exp\left(\frac{-h_v A}{\dot{m}_a c_{pa}}\Delta x\right)\right)\left(T_{b(n)} - T_{a(n)}\right) \quad (12)$$

$$T_{a(n+1)} = T_{a(n)} + \left(1 - \exp\left(\frac{-h_v A}{\rho_a c_{pa}} \Delta t\right)\right)\left(T_{b(n)} - T_{a(n)}\right) \quad (13)$$

3. RESULTS AND DISCUSSIONS

3.1 Prediction of solar irradiance onto the greenhouse solar dryer

Figure 1 shows the prediction of a typical hourly simulated horizontal solar irradiance in Gaborone. The solar irradiance in Gaborone indicated that sufficient sunshine was available for effective drying for 8 hours on a typical day of June 2018 with a peak value of 1200W/m^2 and average of 600 W/m^2. The measured results had peak value of 760 W/m^2. Using hourly sampled irradiance gives better accuracy than using the daily average value of 600 W/m^2 of solar irradiance.

Mathematical models were formulated for solar irradiance on the dryer cover, the outlet temperature of the TES system, the temperature of dryer cover, the temperature of the drying air, the temperature of the drying tomatoes, and the heat transfer coefficients. Using the numerical analytical method, the mathematical models were discretized into algebraic expressions that were used as simulation models to predict the performance of the solar dryer.

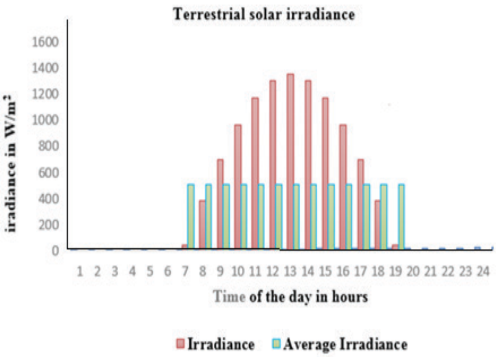

Figure (1). The numerically simulated and average values of typical horizontal terrestrial irradiance in Gaborone

Figure 2 shows the predicted performance of the solar irradiance in Gaborone in the month of June. The global horizontal irradiance is presented with a peak of 1370 W/m2 while the irradiance on the dryer cover was peaked at 1180 W/m2 due to solar fraction phenomenon of the cover material where some irradiance is lost at absorption.

3.2 Prediction of performance of the thermal energy system (TES)

Figure 3 shows the predicted performances of the thermal energy system (TES). The ambient air temperature was 25 ^{o}C and gets heated as it passes through the rock-bed which was charged by solar energy and 35 ^{o}C after 5 hours of discharge is achieved. The rock bed type storage is used very often for temperatures up to 100 ^{o}C in solar air heater applications. Typically, the characteristic size of rocks for optimum energy storage varies from 1-5cm. The drying air then gradually drops until ambient temperature of 25 ^{o}C extrapolated to occur after 10 hours, whereby the TES system is utilised for drying .before sunrise.

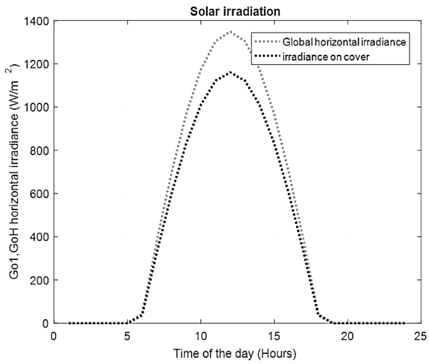

Figure (2). The typical solar irradiance in Gaborone

3.3 Experimental procedure

Figure 4 illustrates the charging at day time and discharging at night of a rock-bed Thermal Energy Storage (TES) system. Figure 4(a) shows the charging cycle and Figure 4(b) shows the discharging cycle.

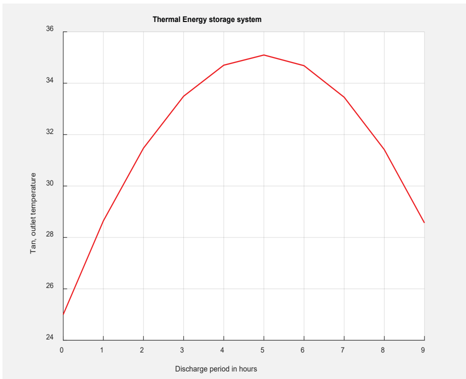

Figure (3). Typical outlet temperature of the Thermal Energy Storage (TES) system

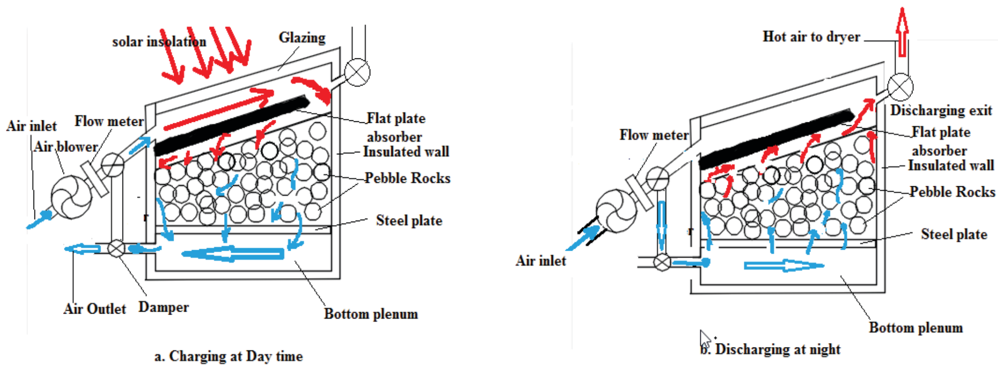

Figure 4 Schematic drawing of the rock-bed TES depicting: (a) charging at daytime, and (b) discharging at night time cycles

Figure 5 is the photograph of the test rig that was used to carry out performance data. On the left-hand side, the pyranometer placed on the top surface) connected to its logger was used for recording the irradiance on the rock-bed TES system. Similarly, shown on the front side, is the calibrated NiCr-Ni thermo-couples connected to 6-port Easy Sense Advanced Data logger that was probed into the system for temperature measurement. The Pyranometer CM3-025778 sensitivity 23.89x10-6V/Wm-2 from Kipp & Zonnen BV, Delt Holland was installed besides the glass cover connected to a digital reader to measure solar intensity. One thermocouple measured the ambient temperature and the other measured the hot heated air at the exit end of the rock-bed TES system. Figure 6 gives the performance of the rock-bed TES system. It shows the solar irradiance (I), ambient air temperature and Outlet air temperature measured between 10.00 and 22.00 hours in Gaborone, Botswana on 16/6/2018. The plot of the Outlet air temperature clearly shows that the discharged energy from the TES system is capable of drying material at ambient temperature

Figure (5).Test-rig for validation of simulation of performance of the pebble bed thermal storage system

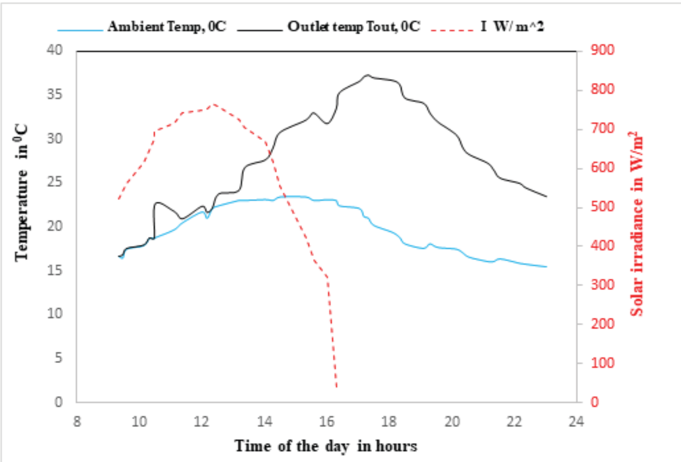

Figure (6). Performance of the TES system showing temperature Tout, and ambient temperature Tamp, and soar irradiance on 16/6/2018.

3.4 Validation of Solar irradiance model

In order to validate the Solar irradiance mathematical model, measurements of solar irradiance on the dryer top cover were taken hourly for seven hours from 10:00 hours on 16/6/2018. The pyranometer instrument of +-5% accuracy was used. The formulated mathematical model of global solar irradiance for the same date was evaluated and results in respect of the corresponding hours of observed irradiance were obtained. These results are given in Table 2.

Figure 7 gives the display of the graphical comparisons of experiment and simulated results of solar irradiance. It shows good agreement with the regression coefficient R2=0.9194. However, the difference between the simulated and measured irradiance data was attributed to the cloudy weather that prevailed during the experiment which was not factored in the ideal irradiation model

Table (2). Results of experimental and the expected solar irradiance

Time of the day	I-Experiment	I-Simulated
10:00	563	763.23
11:00	695	848.055
12:00	750	876.98
13:00	759	848.055
14:00	669	763.23
15:00	556	628.29
16:00	321	452.465

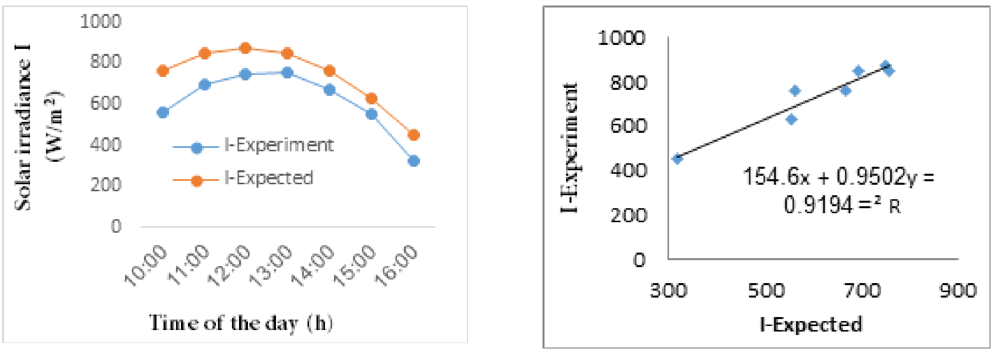

Figure (7). The comparison of experiment and expected solar irradiance on the dryer cover

3.5 Validation of TES system model

These readings were compared with the results obtained from the model simulation as presented in Table.3 and Figure 8. These results were in good agreement with the regression coefficient of R2=0.9116, thus, validating the TES system model.

4. CONCLUSIONS

The outcome of simulation using MATLAB code on the thermal performance of the solar irradiance and the TES system were: i) Solar irradiance in Gaborone indicated that sufficient sunshine was available for effective drying of materials for 8 hours on a typical day of

June 2018, and ii) The performance of the TES system during discharging cycle clearly showed that the rock-bed thermal storage unit is capable of providing thermal energy for drying after sunset.

Table (3). Results from experiment and simulation of the TES systems.

Hours of discharge	Tout-Experiment	Tout-Simulation
1	24	25
2	31	28.64
3	33	31.47
4	34	33.49
5	37	34.7
6	37	35.09
7	34	34.68

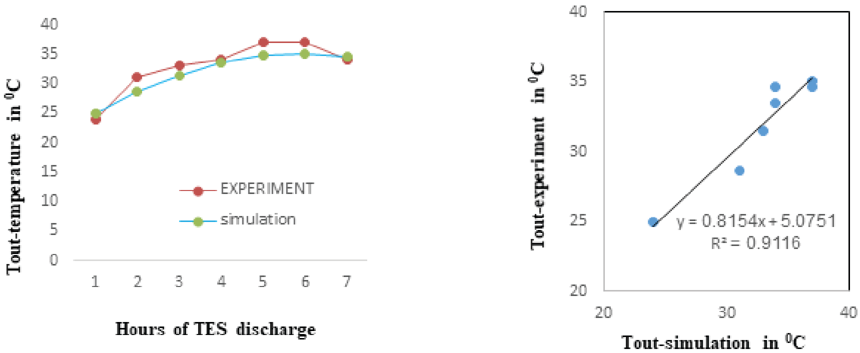

Figure (8). The comparison of the experimentally measured and simulated outlet temperatures of TES system

5. RECOMMENDATION

The sensible heat storage material used in this study was the granite rock that is bulky by volume and is also limited by its heat storage capacity. The authors recommend a study to improve the performance of a TES system by combining rock-bed and latent thermal storage media for commercial drying of fruits and vegetables.

6. ACKNOWLEDGMENT

The authors gratefully acknowledge the funding by Education, Audio-visual and Culture Executive Agency, EACEA of the European Commission, which is the sponsor of the project entitled Mobility to Enhance Training of Graduate Engineers in Africa, METEGA for providing the scholarship for the PhD research. Additional support by RUFORUM, University of Botswana and Gulu University is highly appreciated.

7. REFERENCES

[1]. Schäfer, M. (2006). Computational engineering: Introduction to numerical methods (Vol. 321): Springer.

[2]. Amer, B., Hossain, M., and Gottschalk, K. (2010). Design and performance evaluation of a new hybrid solar dryer: for banana. Energy Conversion and Management, 51(4), 813-820.

[3]. Kalogirou, S. A. (2013). Solar energy engineering: processes and systems: Academic Press

[4]. Dincer, I. (1999). Evaluation and selection of energy storage systems: for solar thermal applications. International Journal of Energy Research, 23(12), 1017-1028.

[5]. Hussein, J., Filli, K., & Oke, M. (2016). Thin layer modelling of hybrid, solar and open sun drying of tomato slices. Research Journal of Food Science and Nutrition, 1, 15-27.

[6]. Janjai, S. (2012a). A greenhouse type solar dryer for small-scale dried food industries: development and dissemination. International Journal of energy and environment, 3, 383-398.

[7]. Janjai, S. (2012b). A greenhouse type solar dryer for small-scale dried food industries: development and dissemination.

[8]. Sadodin, S. and Kashani, T. (2011). Numerical investigation of a solar greenhouse tunnel drier for drying of copra arXiv preprint arXiv: 1102.4522

[9]. Houhou, H., Yuan, W., & Wang, G. (2017). Simulation of Solar Heat Pump Dryer Directly Driven by Photovoltaic Panels, a paper presented at the IOP Conference Series: Earth and Environmental Science.

[10]. Gordon, C. and Thorne, S. (1990). Determination of the thermal diffusivity of foods: from temperature measurements during cooling. Journal of Food engineering, 11(2), 133-145..

[11]. Chauhan, P. S., Kumar, A. and Tekasakul, P. (2015). Applications of software in solar drying systems: A review. Renewable and Sustainable Energy Reviews, 51, 1326-1337.

[12]. Handbook, A. (2007). Heating, ventilating, and air-conditioning applications. Atlanta (GA): ASHRAE, 359.

[13]. Leon, M. A., Kumar, S., & Bhattacharya, S. (2002). A comprehensive procedure: for performance evaluation of solar food dryers. Renewable and Sustainable Energy Reviews, 6(4), 367-393.