Harnessing Solar Energy with Pebbles and Sand for Agricultural Drying Applications

Prem Kumar S
Assistant Professor
Seshadripuram Institute of Technology, Mysuru, Karnataka, India

***Abstract*—** In this work, a solar collector incorporating sensible heat storage materials was developed for solar crop drying applications. Pebbles and sand were employed as absorber materials, with experiments conducted under the meteorological conditions of Ujire, Karnataka, India. The bed thickness of the absorber was maintained at 20 cm, with air velocities of 4 m/s and 2 m/s for pebbles and sand, respectively. Measurements were taken hourly between 9:00 AM and 5:00 PM. Experimental and theoretical heat transfer analyses were conducted and the results were evaluated using characteristic curves.

The results showed that the collector with pebbles as an absorber performed better than the sand-based collector, due to surface roughness and higher Reynolds numbers. Maximum theoretical and experimental temperatures for pebbles were 344 K and 321 K, respectively, while for sand they were 334 K and 322 K. The average theoretical efficiency achieved with pebbles was 39%, compared to 28.5% for sand. Experimentally, pebbles yielded an efficiency of 25% versus 11% for sand. The developed system demonstrated moderate-temperature heat generation, suitable for crop drying.

Keywords: Solar Energy, Solar Collector, Solar Dryers, Heat Storage Materials, Heat Transfer Analysis.

1. Introduction

Solar energy is a clean and abundant energy source, with most parts of the Earth receiving over 280-300 sunny days annually, providing approximately 3,850,000 Exa-joules per year [1]. Solar drying is a crucial application of solar energy, enabling the dehydration of agricultural products to prevent bacterial and fungal growth, thereby facilitating long-term storage.

In developing countries, post-harvest losses are significant due to inadequate storage facilities. The Food and Agricultural Organization of the United Nations estimates annual food losses of up to 30% for cereals, 40-50% for root crops, fruits, and vegetables, 20% for oilseeds, and 35% for fish [2]. These losses result in wasted resources, including water, fertilizers, pesticides, labor, and energy [3].

Moderate temperatures of 40-75 °C, achievable using solar dryers, are essential for drying fruits and vegetables [4]. Solar collectors, critical components of indirect and mixed-mode dryers, capture and transfer solar energy as heat. Research has explored combining heat collection and storage in solar collectors, utilizing materials such as gravels [5,6], sand [7], SAE 20/40 oil [8], paraffin wax [9-18], lauric acid [19], and black-coated metal sheets [20-23]. This study aims to develop solar collectors with sensible heat storage materials for crop drying and to conduct a heat transfer analysis.

2. Materials and Methodology

The collector cabin was constructed from 5 mm thick GI-sheet with thermo-col insulation on all sides and the bottom. A 5 mm thick transparent glass cover was placed on top to minimize re-radiation losses. The collector's dimensions maintained a length-to-width ratio of 1.5 (L/W = 1.5) [24]. Preliminary experiments identified optimal bed thickness and air velocity: 20 mm thickness and 4 m/s velocity for pebbles, and 20 mm thickness and 2 m/s velocity for sand [25]. Figures 2.1, 2.2, and 2.3 illustrate the dimensional specifications of the collector and practical setups for pebble and sand absorbers. Incident solar radiation was absorbed by the materials and transferred to airflow. Temperature readings at the collector’s inlet and outlet were recorded hourly from 9:00 AM to 5:00 PM using calibrated thermometers, while incident radiation was measured with a pyranometer.

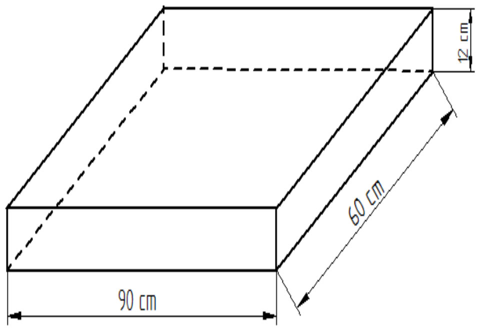

Fig. 2.1 Dimensional specifications of the collector

Fig. 2.2 Solar collector with pebbles absorber

Fig. 2.3 Solar collector with sand absorber

3. Experimental and Theoretical Analysis

To find the thermal efficiency of solar collectors two methods are used; the instantaneous method and the calorimetric method. For testing of solar collectors, instantaneous method is widely used [26]. The Eq. (3.1) represents the thermal efficiency of solar collector by instantaneous method.

$$\eta_{i} = \frac{m_a C_p \,(T2-T1)}{I_C \,(A_c)+W_p} \qquad (3.1)$$

In the Eq. (2.1), m_a is mass flow rate of air in kg/s, C_p is specific heat of air in J/kg K, T_1 and T_2 are air inlet and outlet air temperature in degree centigrade, I_c intensity of solar radiation in W/m^2, Ac is gross area of heat storage cabin in m^2, A_d is dryer gross area in m^{2}and W_P is power supplied blower.

In theoretical heat transfer analysis, the energy balance was applied to solar collector system with the assumptions that, the surrounding temperature, cover temperature and inlet air temperature are assumed to be same, the outlet temperature of air stream from collector cabin is equal to the surface temperature of the heat storage materials (plate temperature), the heat storage materials in the cabin are assumed to be a continuous medium and acts as solid surface and the flow takes place between absorber surface (heat storage material surface) and glass cover. The Figure 3.1 shows the energy balance of the collector system.

The analysis made method by following the procedure explained in the text on Heat Transfer [27] and Solar Energy [28]. The free and forced convection correlations are used in the analysis are referred from the Heat and Mass Transfer Data Hand Book [29]. The values of $(\alpha)_{sun}$ and $(\alpha)_{low\ temp}$ for pebbles are 0.29 and 0,85 [30], for sand 0.2 and 0.8 [31] respectively.

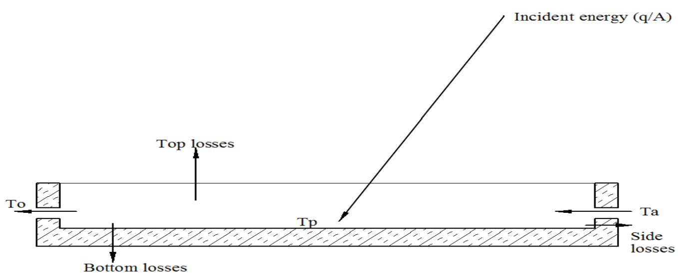

Fig. 3.1 Energy balance on the collector

The radiation absorbed from the sun must be equal to the long wave length radiation exchange.

$$(\alpha)_{sun} = (\alpha)_{low\ temp}\sigma(Tp^4 - T^4_{surrounding}) \quad (3.2)$$

In the Eq. (3.2), T_p is heat storage material bed temperature in degree centigrade and $T_{surrounding}$ is surrounding temperature in degree centigrade.

Characteristic length (L_C)

$$L_C = \frac{4A_C}{P} \quad (3.3)$$

In the Eq. (3.3), A_C is duct area in m^2, P is perimeter in m.

Reynolds number (R_e)

$$Nu = Re = \frac{L_C u}{\vartheta} \quad (3.4)$$

In the Eq. (3.4), u is air velocity in m/s, ϑ is kinematic viscosity.

Nussult number (Nu)

$$Nu = 0.023\ Re^{0.88}\ Pr^{0.33} \quad (3.5)$$

In the Eq. (3.5), Pr is Prandtl number.

Convective heat transfer coefficient (h)

$$h = \frac{Nuk}{L_C} \quad (3.6)$$

In the Eq. (3.6), k is thermal conductivity of air in W/m^0C, L_c is characteristic length in m.

Convective heat transfer coefficient between top most cover and the surrounding air (h_w)

$$h_w = 4.7 + 3.8\,V_w \quad (3.7)$$

In the Eq. (3.7), V_w is average wind speed in m/s.

Bottom loss coefficient (U_b)

$$U_b = \frac{k_i}{\delta} \quad (3.8)$$

In the Eq. (3.8), k_i is the thermal conductivity of insulating material and δ is the thickness of insulation in m.

Side loss coefficient (U_S)

$$Us = \frac{(L-w)Hk_i}{Lw\delta} \quad (3.9)$$

In the Eq. (3.9), L is length of the collector in m, w is width of the collector in m, H is the height of the collector in m and δ is the thickness of insulation in m.

Top loss coefficient (U_t)

$$Ut = A + B \quad (3.10)$$

$$A = \left[\frac{M}{\left(\frac{C}{Tp}\right)(Tp - Ta)(M+f)0.252} + \frac{1}{h_w}\right]^{-1}$$

$$B = \left[\frac{\sigma(T_p + T_a)(T_p - T_a)}{\frac{1}{\left(\varepsilon_p + 0.0425M(1-\varepsilon_p) + \left(\frac{2M+f+1}{\varepsilon_c}\right) - M\right)}}\right]^{1}$$

Where, ε_p is emissivity of the heat storage bed, ε_c is emissivity of glass cover and T_p is heat storage material surface temperature. The values of constants 'f' and 'c' are constants.

Overall loss coefficient (U_L)

$$U = Ut + Ub + Us \quad (3.11)$$

Radiative heat transfer coefficient (h_r)

$$hr = \frac{\sigma}{\left[\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1\right]} \frac{(T_p^4 - T_c^4)}{(T_p - T_c)} \quad (3.12)$$

In Eq. (3.12), ε_p and ε_c are emissivity of absorber and cover materials.

Equivalent heat transfer coefficient (h_e)

$$he = h + \frac{hh_r}{h + h_r} \quad (3.13)$$

Collector efficiency factor (F)

$$F = \left[1 + \frac{U_l}{h_e}\right]^{-1} \quad (3.14)$$

Collector heat removal factor (F_R)

$$FR = x\left(1 - e^{-\frac{1}{x}}\right) \quad (3.15)$$

In the Eq. (3.15),m_a is mass flow rate, C_p is specific heat of air in kJ/kg K,A_C is Collector area in$m^2$and the value of $x = \frac{m C_p}{U_L A_C}$

Useful heat gain (q_u)

$$qu = (FR)A[Ic(\tau \propto) - U_l(Tp - Ta) \quad (3.16)$$

In the Eq. (3.16), τ is transitivity of glass cover, $\propto$ is absorptivity of heat storage material.

Theoretical Instantaneous collector efficiency (η_2)

$$\eta_2 = \frac{q_U}{I_C A_C}$$

(3.17)

4. Results and Discussions

In this section, the results of the experiments are discussed with the help of characteristic curves. The pebbles and sand particles in the collector act as the absorber. The particles are closely packed in the collector, and thus the surfaces of pebbles and sand in the collector are assumed to behave as a single solid surface. When the solar radiation incident on the surfaces of pebbles and sand, a part of the incident energy is absorbed, and then the absorbed energy is transferred to the air flowing over the surface of the absorber. The amount of heat absorbed from incident solar radiation mainly depends on the properties of the absorber materials. The important properties on which the amount of heat absorption depends are absorptivity and surface emissivity. The absorber materials with good absorptivity result in better heat absorption. The value of absorptivity for pebbles is 0.85 and for sand is 0.8. The value of absorptivity for pebbles is slightly higher than that of sand. During the experiments, it has been observed that the higher temperature values are obtained with pebbles in both experimental and theoretical analysis. This is due to the fact that the surface of the sand particles acts like a plane surface, whereas the surface of the pebbles acts as a grooved surface. Therefore, the amount of heat transfer to the air stream with pebbles as an absorber is higher. Figures 4.1 and 4.2 represent the values of theoretical and experimental temperature during the experiments. The maximum theoretical and experimental values of temperature obtained for pebbles as an absorber are 344 K and 321 K, respectively. Similarly, for sand absorbers, the maximum theoretical and experimental values of temperature observed are 334 K and 322 K, respectively.

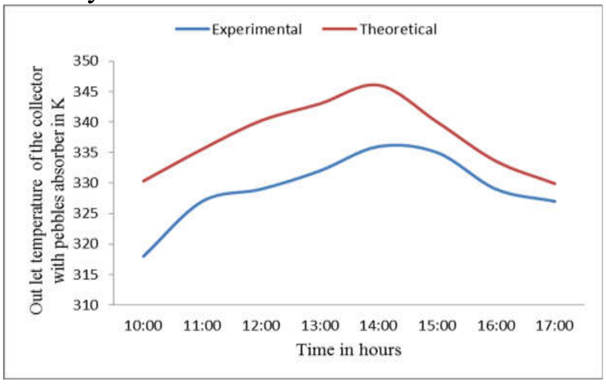

Fig. 4.1 The variation of air outlet temperature of collector with pebbles as absorber

The amount of heat absorbed by the absorber and transferred to the air stream is influenced by the equivalent heat transfer coefficient. The equivalent heat transfer coefficient, in turn, depends on the convective and radiative heat transfer coefficients. The convective heat transfer coefficient is primarily determined by the flow velocity and the temperature gradient between the absorber and the air stream. The radiative heat transfer coefficient depends on the emissivity of the absorber surface and the cover emissivity. Therefore, it is concluded that effective heat transfer is predominantly influenced by these parameters. Figure 4.3 represents the variation of the equivalent heat transfer coefficient during the experiments.

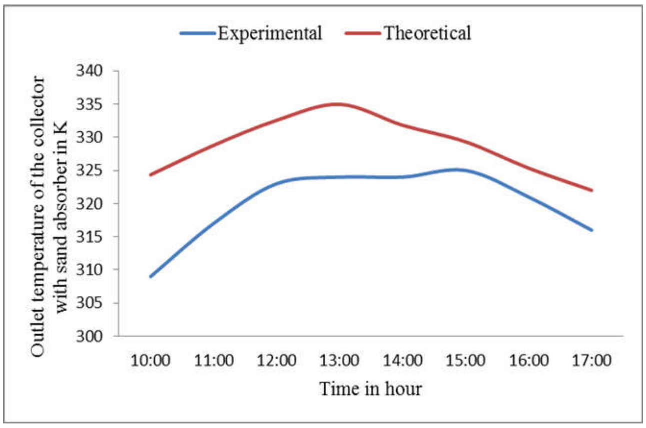

Fig. 4.2 The variation of air outlet temperature of collector with sand as absorber

The equivalent heat transfer coefficient is consistently higher for pebbles. The average equivalent value obtained with pebbles as the absorber is 21.2 W/m²K, while for sand, it is 13.2 W/m²K. The reason for the higher equivalent heat transfer coefficient with pebbles is the velocity maintained, which was 4 m/s compared to 2 m/s for sand. Higher convective heat transfer coefficients are achieved due to the higher Reynolds number. The surface of the absorber with pebbles consists of numerous grooves, which increase air turbulence and result in higher heat transfer rates. In contrast, for sand as the absorber, the surface acts like a plane plate, and there is no turbulence between the air stream and the absorber surface. Thus, higher equivalent heat transfer coefficients are achieved with rough surfaces at higher velocities.

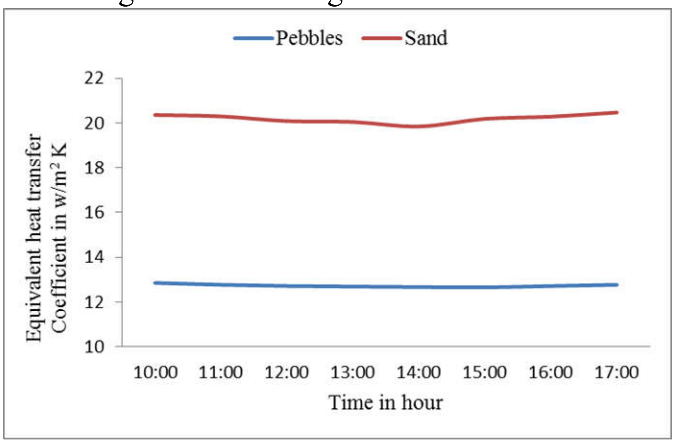

Fig. 4.3 Variation of equivalent heat transfer coefficient

Higher values of the equivalent heat transfer coefficient result in increased heat transfer rates between the absorber and the air stream. The amount of heat gained by the air stream is referred to as the useful heat gain. The variation of useful heat gain is represented by Figure 4.4. It has been observed that the useful heat gain is consistently higher for pebbles than for sand. The useful heat gain increases with time, reaches a peak value, and then begins to decrease. This variation follows the pattern of variation in solar radiation flux, as shown in Figure 4.5. Thus, the useful heat gain mainly depends on the availability of incident radiation. Other parameters that affect the heat gain include top loss, bottom loss, and side loss coefficients. The top loss coefficient depends on the gap between the absorber and the glass cover. The wind velocity over the glass cover also affects the top loss coefficient. The side and bottom loss coefficients depend on the properties of the insulation materials.

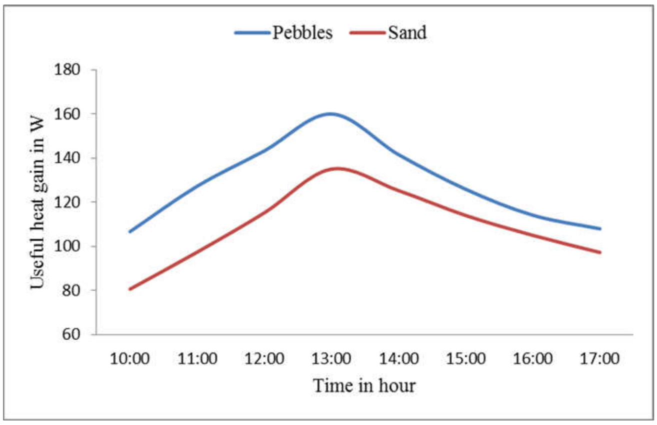

Fig. 4.4 Variation of useful heat gain

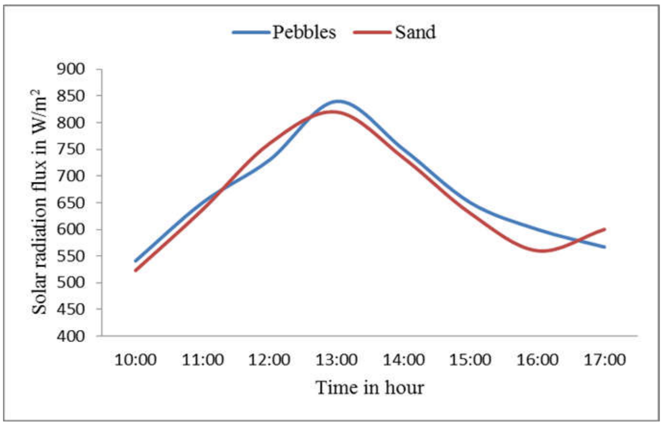

Fig. 4.5 Variation of solar radiation flux

The efficiency of the collector is defined as the amount of useful heat gained by the absorber plate relative to the total incident radiation flux. Figures 4.6 and 4.7 show the variation of theoretical and experimental efficiency values during the experiments. It has been observed that the efficiency value of the collector with pebbles as the absorber is always higher than that with sand as the absorber. The average theoretical efficiency obtained with pebbles as the absorber is 39%, and with sand as the absorber, it is 28.5%. The variation of theoretical efficiency values for both pebbles and sand follows almost a straight line, indicating minimal variation in efficiency. However, the experimental efficiency values do not follow a straight line. With pebbles as the absorber, the efficiency values increase gradually and then begin to decrease in the later stages. In contrast, for sand as the absorber, the efficiency increases initially and then continuously decreases. The average experimental efficiency with pebbles as the absorber is 25%, while with sand, it is 11%. The deviation of experimental efficiency from theoretical efficiency is greater for sand as the absorber compared to pebbles. This is because the higher surface roughness and air turbulence for the pebbles surface enhance heat transfer. Earlier sections of this research mentioned that the main objective of this study was to develop a low-cost solar collector for drying agricultural crops. The developed collector system, with pebbles and sand as absorbers, provides moderate temperature heat, which is ideal for crop drying applications.

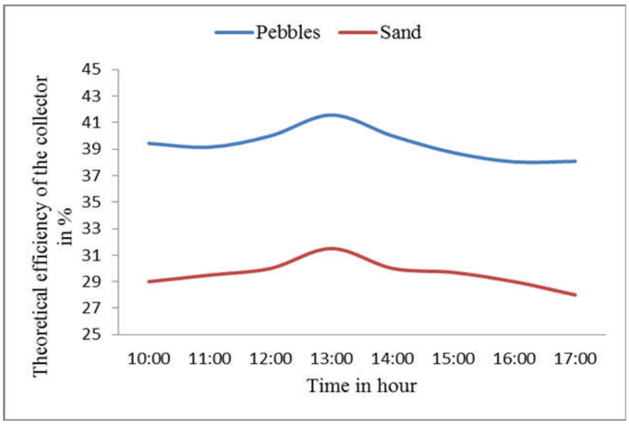

Fig. 4.6 Variation of theoretical efficiency of the collector

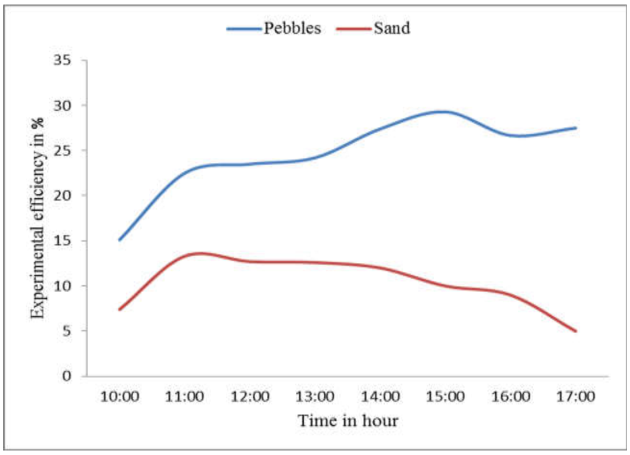

Fig. 4.7 Variation of experimental efficiency of the collector

5. Conclusions

The major conclusions of this research work are as below:

- The developed solar collector system with pebbles and sand as absorber materials provides the moderate temperature heat required for drying agricultural products. The maximum theoretical and experimental temperatures obtained with pebbles as the absorber are 344 K and 321 K, respectively. Similarly, for sand as the absorber, the maximum theoretical and experimental temperatures are 334 K and 322 K, respectively.
- The value of the equivalent heat transfer coefficient depends on the convective and radiative heat transfer coefficients. The convective heat transfer coefficient depends on the flow velocity and the temperature gradient between the absorber surface and the air stream. The radiative heat transfer coefficient mainly depends on the emissivity of the absorber and the glass cover emissivity. The average equivalent heat transfer coefficients are 21.2 W/m²K for pebbles and 13.2 W/m²K for sand as absorbers.
- The collector with pebbles as the absorber outperforms the collector with sand as the absorber due to higher Reynolds number and increased air turbulence caused by surface roughness.
- The average theoretical efficiency achieved with pebbles as the absorber is 39%, while

with sand as the absorber, it is 28.5%. The average experimental efficiency for pebbles as the absorber is 25%, compared to 11% for sand as the absorber.

References

[1] 2014 Key World Energy Statistics. International Energy Agency, 2014.

[2] Global Initiative on Food Loss and Waste Reduction (2015), Food and agricultural organization of United Nations

[3] M. Kummu, et al., Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertilizer use, Science of the Total Environment 438 (2012) 477–489, Elsevier

[4] Om Prakash and Anil Kumar, Historical Review and Recent Trends in Solar Drying Systems, International Journal of Green Energy, 06 May 2013.

[5] M. Mohanraj, P. Chandrasekar, Performance of a forced convection solar drier integrated with gravel as heat storage material for chilly drying, journal of Engineering Science and Technology, Vol. 4, No. 3 (2009) 305-314.

[6] Premkumar S,et al.,, An Experimental Study on Mixed Mode Solar Dryer with Heat Storage Materials, International Journal of Innovative Knowledge Concepts, ISSN : 2454-2415 Vol. 6, Issue 6, PP.124-129, June 2018.

[7] M. Shalaby, Effect of Using Energy Storage Material in an Indirect-mode Forced Convection Solar Dryer on the Drying Characteristics of Grapes, Journal of Medical and Bioengineering (JOMB) Vol. 1, No. 1, September 2012.

[8] Premkumar S, et al., Design and Development of Solar Crop Dryer Integrated with Oil Bath" International Journal of Mechanical And Production Engineering Research and Development (IJMPERD), ISSN (P): 2249-6890; ISSN (E) : 2249-8001, Vol. 9, Issue 2, PP. 375-386, April 2019.

[9] Shalaby, S. and M. Bek, Experimental investigation of a novel indirect solar dryer implementing PCM as energy storage medium. Energy conversion and management, 2014. 83: p. 1-8.

[10] Shalaby, S. and M. Bek, Drying Nerium Oleander in an Indirect Solar Dryer Using Phase Change Material as an Energy Storage Medium. Journal of Clean Energy Technologies, 2015. 3(3).

[11] El-Sebaii, A. and S. Shalaby, Experimental Investigation of Drying Thymus Cut Leaves in Indirect Solar Dryer With Phase Change Material. Journal of Solar Energy Engineering, 2017. 139(6): p. 061011.

[12] Bhardwaj, A.K., R. Kumar, and R. Chauhan, Experimental investigation of the performance of a novel solar dryer for drying medicinal plants in Western Himalayan region. Solar Energy, 2019. 177: p. 395-407.

[13] Vásquez, J., A. Reyes, and N. Pailahueque, Modeling, simulation and experimental validation of a solar dryer for agro-products with thermal energy storage system. Renewable Energy, 2019. 139: p. 1375-1390.

[14] Applied Thermal Engineering, 2019. 146: p. 910-920.

[15] El Khadraoui, A., et al., Thermal behavior of indirect solar dryer: Nocturnal usage of solar air collector with PCM. Journal of Cleaner Production, 2017. 148: p. 37-48.

[16] Agarwal, A. and R.M. Sarviya, An experimental investigation of shell and tube latent heat storage for solar dryer using paraffin wax as heat storage material. Engineering Science and Technology, an International Journal, 2016. 19(1): p. 619-631.

[17] Jain, D. and P. Tewari, Performance of indirect through pass natural convective solar crop dryer with phase change thermal energy storage. Renewable Energy, 2015. 80: p. 244-250

[18] Reyes, A., A. Mahn, and F. Vásquez, Mushrooms dehydration in a hybrid-solar dryer, using a phase change material. Energy Conversion and Management, 2014. 83: p. 241-248

[19] Srivastava, A.K., S.K. Shukla, and S. Mishra, Evaluation of Solar Dryer/Air Heater Performance and the Accuracy of the Result. Energy Procedia, 2014. 57: p. 2360-2369.

[20] Bukola O. Bolaji and Ayoola P. Olalusi, Performance Evaluation of a Mixed-Mode Solar Dryer, Technical Report, AU J.T. 11(4): 225-231.

[21] Premkumar and Dr.E.S. Prakash, Study on Solar Dryer Coupled With FPC, Proc. Of 1st National Conference on Trends and Innovations

in Automation, Materials and Thermal Engineering (TIAMTE-2015).

[22] Mehdi Moradi and Ali Zomorodian, Thin Layer Solar Drying of Cyminum Grains by Means of Solar Cabinet Dryer, American-Eurasian J, Agric& Environ. Sci., 5(3): 409-413, 2009.

[23] Ahmed Abed Gatea, Design and construction of a drying system, a cylindrical section and analysis of the performance of thermal drying system, African journal of Agricultural Research Vol. 6(2), pp. 343-351, 18 January, 2011.

[24] F.K. Forson, M.A.A. Nazha, F.O. Akuffo,and H. Rajakaruna, Design of mixed-mode natural convection solar crop dryers, www.science direct.com, Received 9 August 2006; accepted 15 December 2006,Available online 22 February 2007.

[25] Premkumar S et al.,An Experimental Study to Select Optimum Heat Storage Materials Bed Thickness and Optimum Air Velocity for a Designed Solar Dryer, International Journal of Engineering Research and Application, ISSN: 2248-9622, PP 47-51, 2018.

[26] Treatise on Solar Energy, H.P.Garg, Jhon Wiley, 1892.

[27] J.P Homan and Soouvik Bhattacharya, Heat and Mass Transfer, Tata Meghra Hill Publication, New Delhi, India.pp.451.

[28] Solar energy, 2nd Edition, S.P.Sukathme, Tata Megrahill Company, New Delhi, India.pp.171.

[29] Heat and Mass Transfer Data Hand Book,8th Edition, C.P. Kondandaraman and S. Subramanyan, New Age International Publishers, New Dehli, India. pp113-149.

[30] J.P Homan and Soouvik Bhattacharya, Heat and Mass Transfer, Tata Meghra Hill Publication, New Delhi, India.pp.450.

[31] Tables of Emissivity of Various Surfaces for Infrared Thermometry, MIKRON Vertretung Schweiz, www.transmetra.ch.