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PREFACE

After the four successful International Symposiums on Agricultural Engineering – ISAE, that were held in Belgrade at the Faculty of Agriculture, thanks to our colleagues we are organizing The Fifth International Symposium on Agricultural Engineering – ISAE 2021. Together with the University of Basilicata, School for Agricultural, Forestry, Food and Environmental, Sciences (Potenza, Italy), University of Sarajevo, Faculty of Agricultural and Food Sciences (Sarajevo, Bosnia and Herzegovina), Aristotle University of Thessaloniki Faculty of Agriculture, Thessaloniki (Greece), University of Belgrade, Faculty of Mechanical Engineering, Department of Agricultural Engineering, Belgrade (Serbia), Vinča Institute for Nuclear Science, Belgrade, Serbia, and thanks to the Ministry of Education, Science and Technological Development, Republic of Serbia, support of the AMAPSEEC, RebResNet and BENA, and sponsor and donors, we have managed to organize the presentations of the 29 papers that were submitted to the Scientific Committee of the ISAE 2021 Symposium. We have arranged them in to four sections and categorized them as Original scientific papers, Scientific review papers, Firs (short) communications, Case studies, Professional (Expert paper) and Popular papers. All papers within the Proceedings of the ISAE 2021 were reviewed by the members of the Scientific Committee and kind assistance of some members of other Conference bodies.

The Proceedings of the ISAE 2021 International Symposium is organized in four thematic sections. Section I – Sustainable agriculture and biosystems engineering; Section II – Soil tillage and agroecosystems protection; Section III – Energy and energy efficiency in agriculture and Section IV – Economics in agricultural engineering.

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ISAE-2021 Proceedings

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Section I: Sustainable Agriculture and Biosystems Engineering

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RECENT ADVANCEMENTS OF SOLAR DRYERS WITH IMPLEMENTED PHASE CHANGE MATERIALS

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Abstract *Using solar energy for drying agricultural products is one of the oldest methods of preserving food. Excellent results are obtained by using solar dryers, both in the quality of dried products and in energy-efficient drying procedures. The problem occurs when the solar radiation is low intensity or absent, which makes it impossible for the solar dryer to work. This problem can be solved by implementing phase change materials (PCM) which improve the efficiency of the system and allow the dryer to work in a period during off sunshine hours. This review provides insight into the progress in the field of solar dryers in which PCM is implemented. The impact of using PCM on the quality and efficiency of product drying compared to solar dryers without PCM and open sun drying is shown. It has been noticed that the use of PCM improves the global thermal efficiency of the system. The temperature and the percentage weight of moisture removal was increased and the drying time of the product was reduced. Various cases of drying apples, tomatoes, basil, bitter melons, strawberries and medicinal herbs have been considered. Different positions of PCM in flat solar collectors increased the thermal efficiency of the flat plate collector in the range from 5.02% to 10.13%, and the overall efficiency varied from 21.92% to 25.72%. The use of hybrid systems consisting of two or more synchronized systems also have been considered. The hybrid solar dryer with implemented PCM and integrated geothermal system showed an improvement in performance efficiency of 20.5% compared to a flat plate solar collector. The progress of solar dryers with the implementation of PCM is given with the aim of further developing the application of renewable energy sources in food preservation.*

Keywords: *food, solar dryer, PCM, renewable energy*

1. INTRODUCTION

Drying is one of the oldest ways of preserving food by removing moisture. By drying, the process of product decay and the growth of microorganisms is slowed down, and the lifespan is extended without reducing the quality. The oldest procedures for drying food were based on the use of solar and wind energy. In this drying process, the product is exposed to direct sunlight, where part of the radiation is absorbed and converted into thermal energy. As a result, the temperature rises, and at the same time moisture is released from the product. Open sun drying causes large losses of thermal energy, so this method is not energy efficient. This drying process takes place in uncontrolled conditions. Product is exposed to open space for a long time, which can lead to contamination due to dust, birds, insects, and rodents and can cause a significant drop in the quality of the drying product.

Modern drying systems perform drying in controlled conditions, and the quality of the dried product is significantly better. However, such systems are expensive, their energy consumption is very high and they pollute the environment. Due to large increase in the price of fossil fuels and the harmfulness of gas emissions, it will be necessary to use renewable energy sources such as solar energy, wind energy, geothermal energy, and biomass in the near future 1..

Therefore, solar dryers that use solar radiation to extract moisture from the product could be used as an alternative. In typical solar dryers, solar radiation reaches the surface of the collector where it is absorbed and converted into thermal energy. The air in the collector is heated and as such enters the drying chamber and removes moisture from the product and then leaves the chamber. The problem occurs in hours when the intensity of solar radiation is very low or absent, which makes it impossible for further operation of the dryer. One way to solve this problem is to store the excess energy obtained in sunshine hours and use it later. Sensitive and latent heat storage are the most often used methods for storing energy. PCMs are proving to be the most promising materials for latent heat storage. Paraffin has proven to be one of the better PCMs 2.. It is not corrosive, chemically stable below 500 °C, has small changes in volume when changing phase, and is less expensive.

2. SOLAR DRYERS

A solar dryer is a device that converts solar energy into heat and is used to remove moisture content from the product being dried in it 3.. Solar dryers can be used for drying agricultural products 4., fruits 5., vegetables, and medicinal plants 6.. They can also find their role in the marine 7., automobile, rubber, paper, sugarcane, and tea industries 8.. The classification of solar dryers based on the construction and method of using solar energy 9. is given in Fig. 1. The basic classification of solar dryers according to the exposure of the product to solar radiation is into direct, indirect, and mixed solar dryers.

2.1. Direct solar dryers

The construction of a direct solar dryer is simple. It consists of housing whose side walls and top are covered with transparent glass and small holes through which air enters and exits. The product to be dried is exposed to incident sunlight and with the incidence of solar radiation the temperature of the food rises. The glass cover prevents the release of solar radiation into the atmosphere and increases the thermal efficiency of the dryer. In this way, the air temperature in the chamber rises and moisture removes from the product. Direct type solar dryers are being used for drying red peppers, mangoes, and meat.

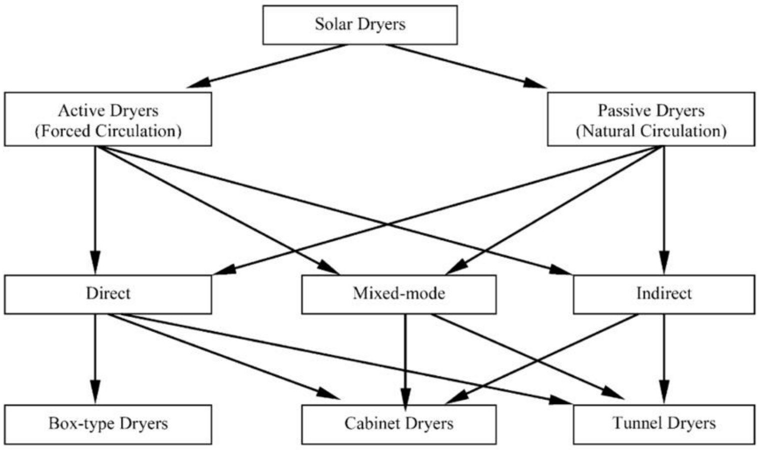


Fig. 21 The classification of solar dryers 9.

2.2. Indirect solar dryers

Indirect solar dryers 10. consist of a thermal solar collector and a drying chamber that are connected. Air heating takes place in the solar collector. Heated air enters the drying chamber and flows over the product, resulting in the release of moisture, and exits through the chimneys into the atmosphere. Airflow can be achieved by natural convection or forced by a fan. This type of dryer is used for drying beans, bananas, mangoes, chilies, and meat.

2.3. Mixed-mode solar dryers

Mixed-mode solar dryer is a combination of direct and indirect solar dryer. The dryer consists of a thermal solar collector and a drying chamber 11.. The top of the drying chamber is covered with transparent glass. This type of dryer has two heat sources. Solar radiation reaches the dried product in the drying chamber through the glass located at the top, and the heated air from the thermal solar collector enters the drying chamber. A mixed solar dryer is used to dry products such as tomatoes, bananas, coconut, pears, and seafood.

2.4. Hybrid solar dryers

The hybrid solar dryer consists of several synchronized systems and uses multiple heat sources. Solar energy is used as a primary source of heat, while wind energy, geothermal energy, photovoltaic modules, biomass, etc. are used as additional sources. This dryer can be used in direct and indirect mode or both.

3. PCMS USED FOR THERMAL ENERGY STORAGE

PCMs are used for latent heat energy storage and have the ability to absorb and release heat during a phase change cycle 12.. During the solidification process heat is released, while in the melting process heat is absorbed. Latent heat energy storage has the ability to provide a high-energy storage density per unit mass and per unit volume in an almost isothermal process 13.. Important physical capabilities of PCM are high specific heat and heat of fusion, high density and thermal conductivity, stable composition, and non-toxicity 14.. The use of PCMs for heat energy storage in solar dryers is becoming increasingly popular. The characteristics of some of the most commonly used PCMs for drying agricultural products are shown in Table 1.

Table 3 PCMs used for drying agricultural products

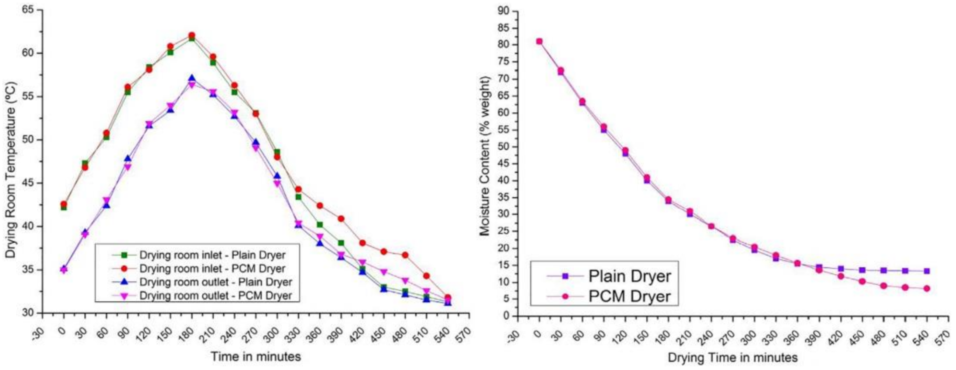
material	Melting temperature in °C	Density in kg/m^3	Specific heat in kJ/kgK	Thermal conductivity in W/mK	Ref.
Paraffin wax	35-60	775^l-786^l 833^s-861^s	2.44^l-3.89^l 2.35^s-2.94^s	0.15-0.4	15.
Calcium chloride hegzahidrat	30	1710	-	1.28	16.
Rubitherm RT 42	38-43	760^l, 880^s	-	0.2	17.
Rubitherm RT54HC	53-54	800^l, 850^s	2	0.2	18.
Paraffin wax 45	60	934	2.5	0.9	19.
Paraffin wax 60	41-46	880	2	0.2	19.
Octacosane	50	803	1.9	0.23	20.

^{s} solid phase
^{l} liquid phase

4. SOLAR DRYERS WITH PCM

The main disadvantage of solar dryers is the inability to work after sunset and low efficiency. All of this can be improved by integrating a PCM that can be integrated into three different ways: into a solar collector, heat exchanger, or drying chamber. Various improvements of solar dryers, as well as the results of drying different food materials are presented in this paper.

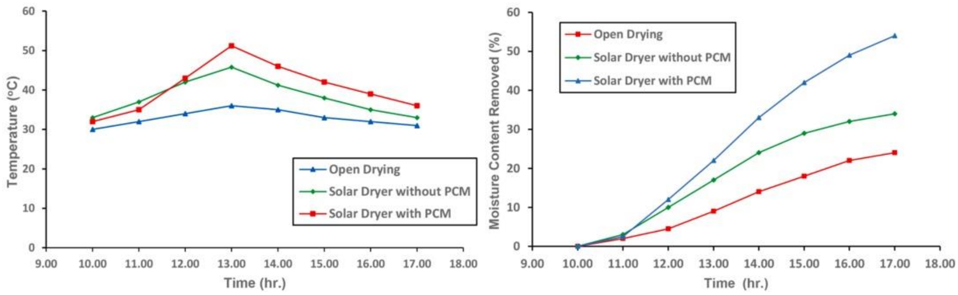
Vigneshkumar et al. 21. performed experimental research of drying sliced potatoes in an indirect solar dryer with and without PCM. Paraffin in the form of white-colored pellets with a melting point of 45 °C and a latent heat capacity of 180 kJ/kg was used as PCM. The PCM was placed under the absorber plate inside the flat solar collector. The experiment was performed for 9 hours from 10.00 a.m. to 7.00 p.m. and the average solar radiation in that period was recorded as 700 ± 10 W/m^2. The obtained results showed that the implementation of PCM inside the collector contributed to maintaining a significantly higher temperature in the dryer for another two hours after the sunshine period (Fig. 2a). The moisture content in the potato slices at the beginning of drying was 81%. Drying in a dryer without PCM the moisture content was reduced from 81% to 13.3%. Drying in a dryer with implemented PCM the moisture content was reduced to 8.2%, which is 5.1% more than in a solar dryer without PCM (Fig. 2b).



a) b)

Fig. 2 Comparison of (a) Drying room inlet and outlet temperature (b) moisture content of potato slices during drying period with and without PCM 21.

Rakshamuthu et al. 22. developed a greenhouse solar dryer consisting of a small rectangular drying chamber with the specifications of 100 (L) x 60 (D) x 20 (H) cm. Zinc nitrate hexahydrate with a melting point of 35 °C placed in a detachable tray was used as PCM. A comparative study of drying 1 kg of gooseberry was conducted to evaluate the performance of open sun drying, solar dryers without, and solar dryers with PCM. Experimental data showed that the drying air temperature in the solar dryer without PCM was increased by 27% compared to atmospheric temperature, while in the solar dryer with PCM it was increased by 43% (Fig. 3a). This indicates that the drying period in a dryer without PCM can be reduced by 27%, and with PCM by 43% compared to open sun drying. With open sun drying maximum of 25% moisture was removed in the period of 7 hours. During the same time, 34% of the moisture was removed in the solar dryer without PCM and 54% in the solar dryer with PCM (Fig. 3b). Open sun drying will take four days to completely dry the gooseberries, solar dryer without PCM will take three days and solar dryer with PCM will take less than two days.



a) b)

Fig. 3 Comparison of (a) Drying air temperature (b) moisture content removal of 1 kg goosebery during drying period with and without PCM and open sun 22.

Bhardwaj et al. 23. have developed a solar drying system that includes solar collectors with the integrated sensible heat storage medium and paraffin RT-42 (PCM) as a latent heat storage medium that is placed in a drying chamber (Fig. 4). During the experiment, 9 kg of Valerian rhizomes were dried. The initial moisture content was 89%. Drying to the final product with 9% moisture content in the open sun took 336 hours, in the dryer without PCM 216, and with PCM 120 hours. The mean value of energy efficiency of solar air collector without PCM was 9.8% while with PCM it was 26.1%. The mean value of exergy efficiency without PCM was 0.14% and with PCM 0.81%. The overall drying rate without PCM was 0.028 kg/h, and with PCM 0.051 kg/h. The mean value of exergy efficiency of the drying units was 30.28% and the overall efficiency of the drying system was 10.53%.

Fig. 4 Experimental setup 23.

Madhankumar et al. 15. analyzed and compared the performance of an indirect solar dryer in three different cases: without thermal energy storage (TES), with TES unit having PCM and with TES having fins inserted PCM, during spring and summer seasons (Fig. 5). Paraffin wax with a melting temperature of 52 °C was used as PCM, latent heat of fusion is 196.05 kJ/kg and specific heats for liquid and solid phases are 2.44 kJ/kgK and 2.35 kJ/kgK respectively. During the experiment, 2 kg of Momordica charantia with an initial moisture level of about 92% was dried until the moisture level of the final product was around 12%. Drying in the open sun required 17.1 h, while in test 1, 2, and 3 during the spring it took 15, 12, and 11 h respectively. Drying in test 4, 5 and 6 during the summer took 14.5, 11, and 10.5 h respectively. The maximum thermal efficiency of 19.41% was achieved in test 6 during the summer, and 19.37% in test 3 during the spring.

Hana Ebrahimi et al. 24. performed numerical and experimental research of drying tomato slices in a solar dryer with flat solar collectors with and without PCM. Paraffin wax was used as PCM. The results for four different PCM positions inside the collector were analyzed: a: the tube aligned with equal distances through the plate, b: the tube aligned with different distances through the plate, c: the tube aligned with equal through

2/3 of the plate, d: the tube aligned with equal distances through half of the plate (Fig. 6). It was concluded that the use of PCM contributes to a reduction in drying time of about 6.25–21.87% (Fig. 7). In case d, the highest average thermal efficiency of 40.20% and the total drying efficiency of 25.72% were achieved. The use of PCM had the effect of reducing energy consumption in the range of 7.29–18.97% compared to drying without PCM.

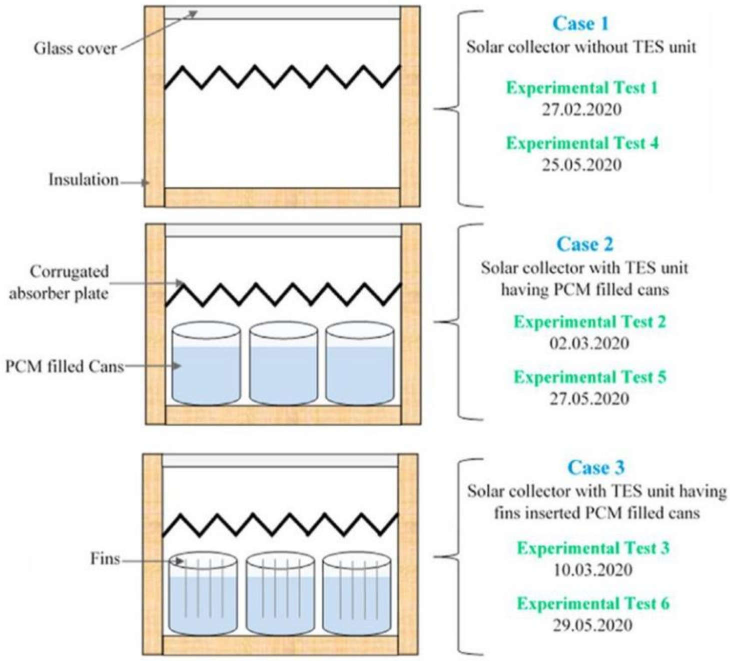


Fig. 5 Schematic representation of experimentation plan 15.

Lakshmi et al. 25. developed two types of solar dryers (mixed mode and indirect mode) integrated with an energy storage system based on paraffin wax. The TES is made up of galvanized iron sheet (shell and tube heat type). The air passes through the tubes of TES from the collector to the drying chamber. In the heat exchanger was poured 38 kg of Paraffin wax. During the experiment, 30 kg of black pepper from an initial moisture content of 3.46 (d b) to a moisture content of 0.14 (d b) was dried. In the first case, the upper part of the dryer is transparent and the product receives thermal energy from solar air heaters as well as through the upper transparent cover (mixed mode). In the second case, the upper part of the chamber is completely insulated and the dried product receives heat only from solar air heaters (indirect mode). In the first case, the drying process was completed after 14 h, in the second case after 23 h, while open sun drying took 59 hours. The first case proved to be a better solution due to the higher overall dryer efficiency of 53.1% compared to the second case of 42.5%. Medicinal qualities attributes (TPC, TFC, and anti-oxidants) of dried black pepper are found to be better in the first case.

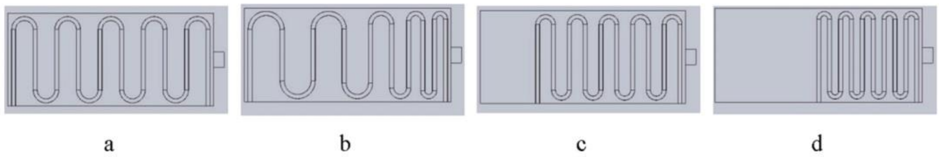


Fig. 6 PCM positions inside the collector 24.

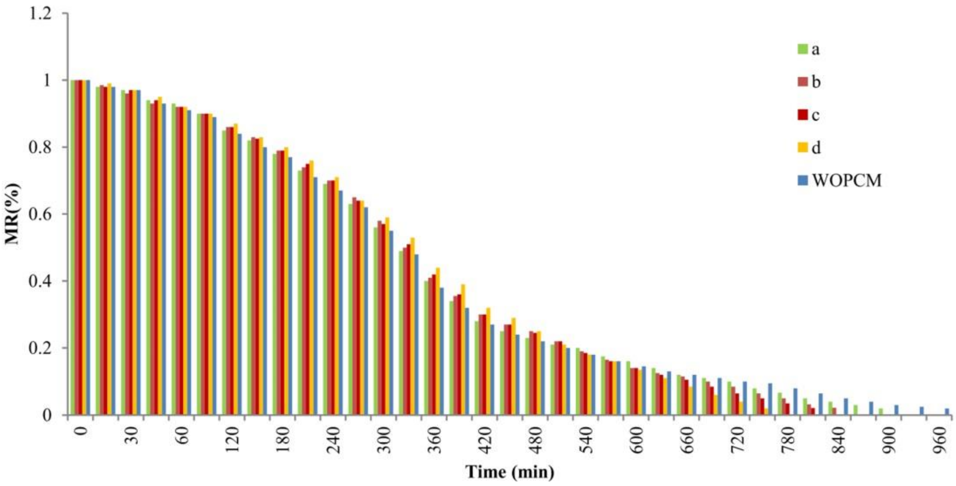


Fig. 7 Variations of drying process vs. drying time at various PCM conditions (a, b, c, d and WOPCM). 24.

Ananno et al. 26. performed a numerical analysis of a hybrid geothermal PCM flat plate solar collector dryer. The analysis showed that this hybrid system has much higher efficiency than the existing stand-alone systems. The air outlet temperature from the hybrid geothermal PA-FPSC dryer is 18.79-16.55 °C higher than the ambient temperature during 5 h after sunset and 15.9-13.4 °C higher during 12 hours after sunset. In theory, a hybrid system can achieve 20.5 times greater efficiency than a flat solar collector, or 6% more efficiency than a v-corrugated solar air heater when drying food for 20 hours a day.

Atalay and Cankurtaran in 27. developed a large solar dryer with implemented PCM (paraffin wax) as an energy storage medium. During the experiment, 5, 10, and 15 kg of strawberries were dried. The drying rate was 0.953, 1.834, and 2.391 kgw/h, and the total drying time was 225, 261, and 300 min respectively. In the experiment that was conducted for three days during the day and night, the highest and lowest energy efficiency were 70% and 76%, and exergy efficiency were 69.59% and 62.80%, which is a significantly high result. The results showed that the change in the amount of product to be dried does not greatly affect the energy and exergy efficiency. Fans were found to have the highest exergy destruction cost of $ 0.2286/h and the lowest exergy efficiency of 55.96% and therefore those components needed to be improved the most. It is calculated that the CO_2 mitigation for the expected service life of the system is 99.60 tons.

5. CONCLUSION

The use of solar dryers for drying products contributes to large energy savings and reduction of harmful gas emissions. Improvements of solar dryers can be achieved by integrating PCM and due to its characteristics, paraffin wax is the most commonly used PCM. The integration of PCM in the solar dryer allows it to work for several hours after sunset, which greatly reduces the time required for the product to dry. Also, the integration of PCM reduces the temperature fluctuation in the drying chamber, which results in a dried product of much better quality. It is necessary to carefully choose the place of installation of PCM because its position has a significant effect on the drying rate, thermal efficiency, and total drying efficiency. The overall efficiency of a solar dryer with PCM can be further increased by the additional use of sensitive energy storage or an additional source of renewable energy (geothermal, photovoltaic, biomass). Although the initial investments in solar dryers with PCM are large, the operating costs are small and the saving rate will grow with the increase in energy costs.

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