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A review of phase change material based thermal energy accumulators in small-scale solar thermal dryers

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Solar thermal energy is usually of intermittent and dynamic character and the possibility to use it during non-sunshine periods is one of the current interest of researchers. Phase change materials as thermal energy accumulators are attractive because of their high storage density and ability to release thermal energy at a constant temperature corresponding to the phase transition temperature.

This paper reviews the recent state-of-the-art small-scale solar thermal dryers integrated with phase change material as energy accumulators. This is an intensive field of investigation for more than 30 years with importance for the agriculture and the food industry, especially in hot climate. A variety of commercial small-scale solar dryers are offered as a low-cost, zero-energy solution for small farmers. And yet, there are no commercial systems using latent thermal storage because at the present level of development this unit will increase unacceptably the price of the system. The solution needs a very simple design, accessible materials and optimal conditions for operation.

The aim of the present work is on the basis of the recent developments to identify the requirements for this new solution. Among the great number of designs, devices and materials, it compares the most cost and energy effective solar dryer systems with thermal storage. At the same time it makes an overview of the methods for theoretical evaluation and prediction, which are used to design and assess them. The resulting conclusions from the collected and compared information will serve as prerequisites for a novel solution of a cost-effective thermal energy storage for a small-scale solar dryer, which will lead to improved efficiency of the drying process due to controlled temperature and longer operation time. This information might serve also in the development of the wider field of thermal energy storage, which is an important part of the technologies of renewable and waste energy conversion.

Keywords: Solar energy, thermal energy accumulator, solar dryer, latent heat, phase change, energy efficiency, exergy efficiency, computational fluid dynamics

INTRODUCTION

The continuing increase in energy demand in the world creates deficiencies globally. That is why the efforts in science and technology are directed towards more effective utilization of renewable energy sources. The objectives are higher yields of product per device and lower ecological risk combined with lower cost of the devices.

Solar energy is one of the most prospective sources of renewable energy. Its intermittent nature is a drawback which can be overcome to some extent by thermal energy storage (TES) for heat supply during the non-sunshine hours. A thermal energy accumulator, integrated with a solar dryer, diminishes the fluctuation in the inlet temperature and supplies heat flow near constant temperature.

The constant temperature regulation helps to prevent the degradation of product quality. The effect on the environment is reducing harmful emissions in the atmosphere.

Solar energy can be stored by thermal, electrical, chemical, and mechanical methods, [1]. TES includes three principles of heat accumulation, by using sensible heat, latent heat and chemical heat (Fig.1). Typical examples of each principle are presented in the figure.

The rock bed is the most common material for sensible storage used in solar dryer systems. Drying of peanuts was investigated [2] using solar energy stored in a rock bed. The drying time ranged from 22 to 25 h reducing the moisture content to the safe storage moisture level of 20% with an air flow rate of 4.9 m^3/s.

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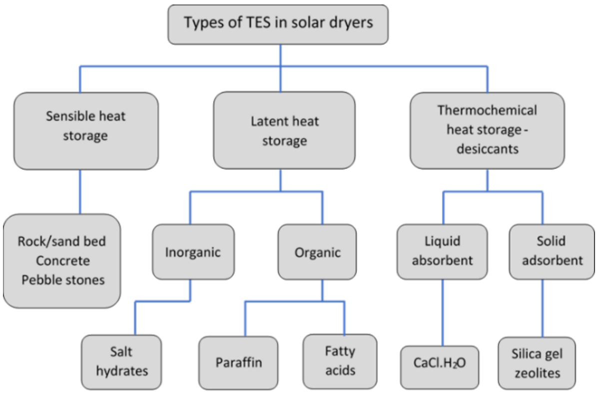

Fig.1. Types of TES integrated in solar dryer systems

It should be noted that the high energy storage density of the phase change material (PCM) is an advantage, but does not guarantee higher efficiency of the system. Surprising is the conclusion in [3] that using sensible heat storage with pebble stones is more advantageous for drying process compared to latent heat storage (LHS) with paraffin wax, with regard to performance and cost. The study presented experiments for comparison of two systems for heat storage in a solar air dryer. One of the systems was a packed bed of pebble stones and the other was paraffin wax with a melting temperature of 55-60°C, placed in heat resistant bags. One and the same quantity of 500 kg of each material was used to dry 10 kg of 5 mm thick lemon slices. The drying process lasted an average of 6.23 h (paraffin) and 6.27 h (pebble stones). The total discharge time of the two systems was 7 h on average. The presented data demonstrate the importance of the design of the LHS. The advantage of the PCM can be wasted because of hindered air flow and poor heat transfer provided by the bags containing the PCM.

The chemical heat storage is characterized by the highest energy storage density of the material, but this technology is less mature than the previous two in respect to commercialization. It uses reversible reactions which involve absorption and release of heat. In solar dryers, an example of this technology is liquid or solid desiccant material used for reducing the humidity of the drying air in off-sunshine hours.

Intensive research is carried out recently on LHS with paraffin in combination with a solar dryer. A variety of solar dryers for different food and agricultural products are suggested, tested, modified and simulated. The wide interest in these systems is due to the increasing need for preservation of food at low energy consumption with high quality of the product. One modern trend is drying of medicinal plants [4]. The heat is stored when paraffin changes its phase from solid to liquid and the heat is released at a constant temperature when paraffin cools down and solidifies again. The phase change temperature of paraffin corresponds to the drying temperature range appropriate for most of the food products to retain their valuable components.

The low thermal conductivity of paraffin is still a problem for its worldwide application and further research and development is carried out in this regard [5].

The aim of the present review is to reveal the current level of development of LHS in solar air dryers, which is an area offering many engineering solutions, experimental data and mathematical approaches for prediction and evaluation of the systems. The particular task is on the basis of the collected and compared solutions and data on LHS with a focus on paraffin as PCM to evaluate the perspectives for cost and energy-efficient design of LHS for solar dryers of small capacity (for households and small producers). The increasing of the costs of the dryer, when integrating a thermal energy accumulator, with the currently available constructions and materials, still hinders commercialization. The present overview is a step towards solving this problem, by identifying the most important conditions which will ensure a cost and energy-efficient system. It points out the characteristics of TES, proper for integration with a small-scale solar dryer, designed as a low-cost zero-energy system.

SMALL-SCALE SYSTEMS FOR SOLAR AIR DRYING WITH PARAFFIN

Conditions for successful solar drying

The drying temperature range of 40°C to 60°C is found to be sufficient for most of the food products to retain their flavor, aroma, texture and nutrition values. Therefore, the minimum melting temperature of the PCM should be 5–10°C higher than the desired temperature of the heat transfer fluid (HTF) [6]. The good design of a solar dryer has to ensure the continuously stable temperature of the drying air in the order of 10–25°C above the ambient temperature [7]. This is necessary to avoid the dried object from re-absorbing the moisture during the night, when in absence of solar energy, the air temperature drops and its humidity increases. Initial and final moisture content and maximum allowable temperature for drying of some crops are summarized in [8]. Literature review of solar drying of some medicinal plants and herbs is presented in [9]. It reveals the conditions for good quality of these heat sensitive products.

The focus of the present work is on the integration of a solar dryer with latent TES to prevent the interruption of the drying process at night. The development of a latent heat TES system involves the understanding of three essential subjects [10]: kind of phase change materials, containers' material and form of HEs.

Waxes were distinguished [1] among other LHS materials due to their availability in a wide temperature range.

Paraffin as phase change material

Paraffins are tabulated in [10] with their number of carbon atoms (from 14 to 34) and categorized as more or less promising according to their characteristics. Paraffin consists of a mixture of n-alkanes CH_3-(CH_2)-CH_3 into which the crystallization of the (CH_3) - chain is responsible for a large amount of energy absorption [10]. The melting point and heat of fusion increase with molecular weight. The latent heat of fusion of paraffin varies from nearly 170 kJ/kg to 270 kJ/kg with the temperature of phase change between 5^{o}C to 76^{o}C [10] which makes them suitable for solar applications. Paraffin as PCM is characterized in [10] with its advantages: it is safe, reliable, predictable, less expensive and non-corrosive; and disadvantages: low thermal conductivity, possible non-compatibility with the plastic container and moderate flammability. The following recent studies on paraffin wax in solar air dryers show the important preferred characteristics for that application.

Five paraffin waxes and a wood resin were compared [11] by studying their thermo-physical properties. The investigation aimed at selection of a PCM, for its potential use as a TES in a solar dryer. The selected paraffin had maximum density of 932.9 kg/m^3 in liquid state, and maximum latent heat of fusion and solidification 383.87 kJ/(kg K) and 320.26 kJ/(kg K), respectively. The selected PCM was used in the flat plate collector (FPC) of the solar dryer to identify the thermal zones and to validate its capability as a thermal storage. The maximum temperature achieved at outlet of the FPC was 50°C. It was found that after 18:00, the average temperature of the collector chamber with the selected paraffin was found to be 23.5% higher than that without using PCM.

In [12] paraffin with melting point 45-48°C was found more suitable compared to paraffin with melting point 68-70°C for application in fish drying with maximum temperature at the inlet of up to 75°C. The use of PCM to control the temperature inside the chamber was an important aspect as fish could not sustain a temperature of more than 62^{o}C.

Thermal conductivity enhancement of paraffin

Multiple techniques are used to increase the charging/ discharging rate of paraffin by increasing its thermal conductivity. They include dispersion of high conductivity particles in the PCM [13, 4], using extended surfaces, and porous material embedded in the PCM. As a result the effective thermal conductivity of the PCM can be increased up to five times leading to higher rate of the heat transfer [14].

1. Additives

Novel materials were categorized in [15] for preparation of high performance PCM as 3D, 2D, 1D and 0D additives. Examples of these groups of additives used with paraffin are: graphene– nickel foam, graphite and metal foams (3D); expanded perlite, kaolin, expanded graphite (2D lamellar structure); graphite fiber (1D); and graphite-based nano-particles, nano-Al_2O_3 (0D). Improvement of 2 to over 10 times of the thermal conductivity of paraffin wax by additives is reported in [15].

2. Encapsulation of paraffin

The main advantages of PCM encapsulation are providing large heat transfer area, reduction of the material reactivity towards the outside environment and controlling the changes in volume of the storage materials as phase change occurs [16]. Based on size, the PCM encapsulation is classified into nano (0–1000nm), micro (0–1000 µm), and macro (above 1mm) encapsulation. The cheapest containers used for macro-encapsulation are tin cans and plastic bags or bottles. Typical shapes of containers for PCM are discussed in a review [17] with an emphasis on the type of the geometric configuration and orientation of the container. The shapes include spherical, rectangular, cylindrical (both horizontal and vertical) and annular containers. It was concluded there that increasing the height/width ratio of the container of the same volume decreases the time for the melting process due to the stronger buoyancy effect. Usually the material of the shell is plastic or metal (copper, aluminum and steel) when higher heat transfer rates are desirable.

Results in [18] had shown that a rectangular container needed nearly half of the melting time of a cylindrical container with the same volume and heat transfer area. The duration of the heat discharge increased with increasing PCM container diameter in the order of sphere, cylinder, plate and tube [19].

3. Extended surfaces

Experimental measurements and theoretical predictions for different fin heights and thicknesses [20, 21] showed that the use of fins enhanced significantly the heat transfer rate in and out of the element containing the PCM.

Paraffin wax was investigated [22] (phase change temperature 35–54°C, heat of fusion 196.05 kJ/kg) in a solar dryer for sweet potato coins. The TES tank was a cylindrical acrylic vessel, where HTF flowed in a tube with 18 copper fins (Fig.2). It was found that melting was dominated by heat conduction followed by free convection; charging time decreased with the increase in the inlet air temperature and air velocity.

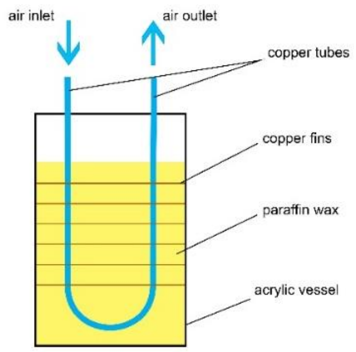

Fig.2. A scheme of a TES vessel with fins [22]

The discharging time of the LHS at an air velocity of 1 m/s was 180 min, while it was 165 min at an inlet velocity of 2 m/s. The results indicated that the air velocity did not affect much the discharging time since heat conduction was dominant during solidification.

PCM-BASED THERMAL ENERGY ACCUMULATORS IN SMALL-SCALE SOLAR THERMAL DRYERS

For solar dryers with integrated thermal energy accumulators the classification of [8] can be adopted as follows (Fig.3).

The development of a solar air drying system with paraffin includes solving several essential problems leading to energy and cost efficiency of the system: location and volume occupied by PCM; intensification of heat transfer between PCM and HTF; low energy consumption and heat loss in the systems.

It was shown [23] that the flow rate of the drying air had a significant effect on the performance of the system.

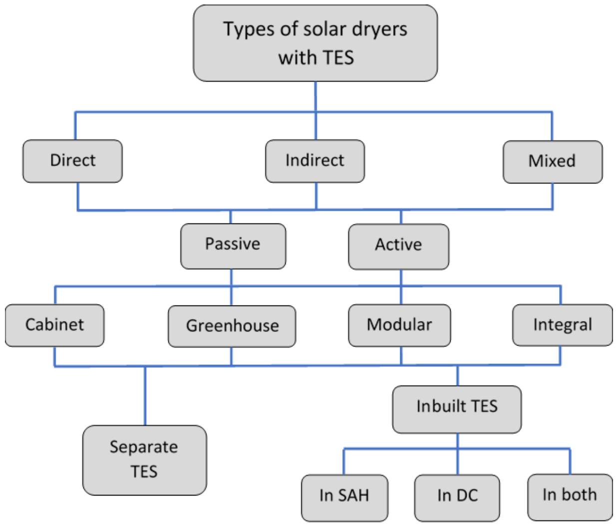

Fig.3. Types of solar dryer system with TES

The heated air for drying can be driven by buoyancy forces, or a fan, or both. Natural convection solar dryers are suitable for the rural sector and remote areas as they do not require external energy source. But it is generally agreed that well designed forced-convection distributed solar dryers are more effective and more controllable than the natural circulation types. The following dependences have been observed: the higher the mass flow rates, the higher the efficiency of the collector; the electrical energy of the fan increases with the increase in the mass flow rate of air; the effect of leakages increases with the increase in the air flow rate. The usage of forced convection in the drying system can reduce the drying time tree times and can decrease by 50% the necessary collector area [24]. Fans may be powered with utility electricity, if it is available, or with a solar photovoltaic panel.

The types of TES with PCM and their possible location in solar dryers are shown in Fig.4.

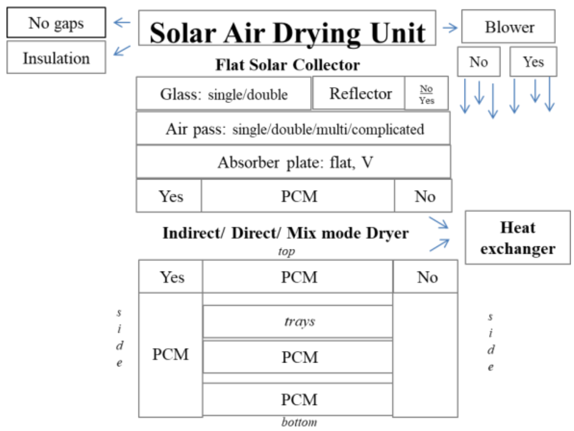

Fig.4. Solar air drying unit and possible location of PCM

A thermal energy accumulator can be integrated in the dryer system as a *separate unit*, connected outside the solar air heater (SAH) or *inbuilt* in the SAH or in the drying chamber (DC) (at the top, bottom, side walls), Fig.4.

The PCM can fill part of the volume of the unit, or can be encapsulated in containers with different form, size and material, arranged or dumped in a packed bed.

Separate TES unit with PCM

In [25] the performance of a PCM-based solar dryer is analyzed for drying black turmeric. The DC is of a mixed-mode type with hot air entering from one side and a glass top cover allowing the direct sun radiation to pass into it. Paraffin wax is used as PCM. The TES system is a shell-and-tube heat exchanger (HE) and the paraffin wax (35 kg) is placed in the shell side (Fig.5). The air from the collector passes through the tubes made of copper; one tube at the center and the other nine tubes at the periphery.

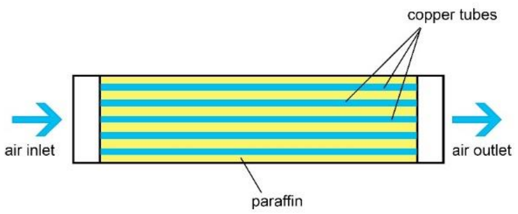

Fig.5. Shell-and-tube TES [25]

Results obtained for a solar dryer with PCM where compared to open sun drying and there was 60.7 % saving of time. The discharging of paraffin wax maintained the temperature 4-5 ^{0}C higher than the ambient temperature for 6 hours after sunset.

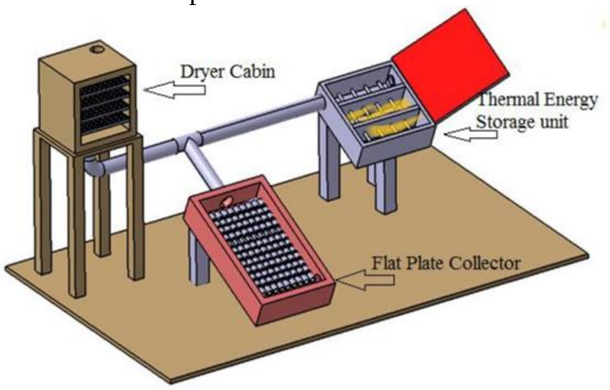

Fig.6. Solar air dryer with a separate TES unit [26]

The performance enhancement of a solar air dryer with a FPC was focused in [26], Fig.6. The FPC provided outlet air temperature up to 100°C at natural convection mode during sunshine hours, when the TES was disconnected from the system. Direct solar radiation was incident on the TES unit during the charging period. At off-sunshine hours the solar TES was connected to the dryer cabin and the FPC was disconnected. A fan was located at the base of the dryer cabin to maintain the air flow at night. The TES unit consisted of an absorber plate, a reflective mirror, and heat pipes with fins as a vapor-liquid phase change device, dipped in paraffin wax as PCM, Fig.6. The efficiency decreased with the increase in air velocity. The increase in temperature gradient led to an increase in the efficiency.

Inbuilt thermal energy accumulator in the SAH and/or the DC

The most common solution for integration of the thermal energy accumulator in the SAH is to place the PCM in the volume under the absorber plate. This construction (Fig.7) was adopted in the study [27]. Part of the heat from the solar radiation heated the air for the drying process and the rest of it charged the PCM. These two processes were separated in two solar air collectors. The solar energy accumulator in [27] comprised a PCM cavity (with dimensions 2.04 m x 1.04 m and total volume of 0.33 m^3,) with insulator and a cover glass. Experiments were conducted in no-load conditions (without material for drying) to evaluate the charging and the discharging characteristics of the latent heat unit. The daily energy efficiency of the solar energy accumulator reached 33.9%, while the daily exergy efficiency reached 8.5%.

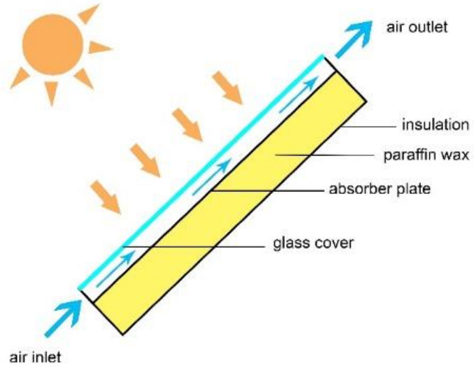

Fig.7. PCM placed below the absorber plate of the SAH [27]

The solar dryer of 0.7 m^3 with 60 kg of paraffin wax kept the relative humidity inside the DC of 0.768 m^3 between 17 and 34.5% lower than the ambient relative humidity and maintained the DC temperature 4-16 °C higher than the ambient temperature all the night.

The absorber plate shape factor (the ratio of the total collector area to the absorber area normal to the solar radiation) is one of the most important parameters in the design of a SAH. The increase in the total absorber area intensifies the heat transfer to the air flow, but leads to an increase in the pressure drop, therefore increase in the power consumption [28]. There is an optimal range of the shape factor for maximal efficiency.

A widely employed configuration is a double-pass SAH, where the air flows over and under the absorber plate. An experimental investigation [29] was carried out on an asymmetric double-pass air heater containing paraffin macro-encapsulated in rectangular or cylindrical metallic containers (Fig.8).

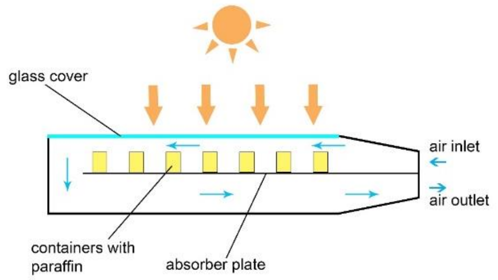

Fig.8. Double-pass SAH with containers with paraffin [29]

It was found [30] that the poor thermal conductivity of PCM had negligible effect on the heat transfer due to high surface convective resistance provided by the air in a packed bed storage unit.

A solar air HE was studied [31] with paraffin wax encapsulated in aluminum cans filled with 5% w/w aluminum wool (Fig.9), which doubled the thermal conductivity of the paraffin wax.

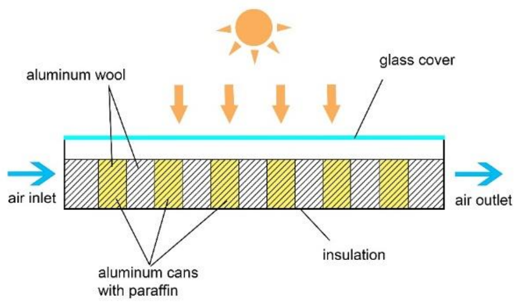

Fig.9. Paraffin wax in aluminum containers inside the SAH with aluminum wool inside and outside the containers [31]

The usage of aluminum wool outside the PCM containers reduced the conductive resistance of air and increased the HE efficiency in charging stage from 46.8% to 48.9% and in discharging stage from 64.4% to 80%.

An example of LHS inbuilt in the DC is shown in [12]. The PCM is placed in boxes inside the DC in a fish dryer (Fig.10). 3 boxes of 3 kg paraffin are placed at the three sides of the DC.

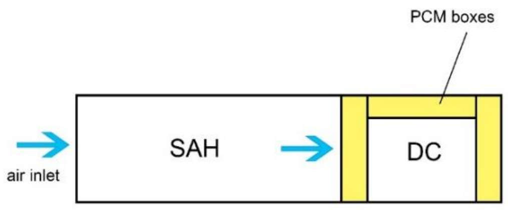

Fig.10. Boxes with PCM in the DC [12] - top view

PREDICTION OF THERMAL BEHAVIOR AND EFFICIENCY ESTIMATION OF A SOLAR DRYER WITH PCM

A variety of mathematical models are employed in order to compare storage systems and to optimize their design. They predict the thermal behavior of the systems and calculate their efficiency. Two types of models are distinguished [32], based on the first law of thermodynamics (FLT) and the second law of thermodynamics (SLT). An overview of the first type models, FLT, in [10] shows different analytical and numerical techniques to solve the energy equation at the moving solid–liquid interface (Stefan problem) of the PCM [33]. The difficulty with the moving interface is avoided by the enthalpy method [10]. It assumes a mushy zone between the two phases and introduces the total volumetric enthalpy as the sum of sensible heat and latent heat of the PCM. The energy conservation for the phase change process is expressed in terms of that enthalpy. This approach is widely exploited in the Computational Fluid Dynamics (CFD) models.

Energy analysis

The energy analysis of a system with a thermal energy accumulator is based on the FLT. It calculates the energy efficiency, denoted also as first-law efficiency.

The energy analysis presumes that energy efficiency η_I is defined as the ratio of the output energy E_{out} to the input energy E_{in}, part of which is lost as energy loss, E_{loss}

$$E_{in} = E_{out} + E_{loss} \tag{1}$$

$$\eta_I = \frac{E_{out}}{E_{in}} = \frac{E_{in} - E_{loss}}{E_{in}} \tag{2}$$

Energy efficiency equations, used by different authors for the constituent units in solar dryer systems with PCM storage are listed below.

1. SAH efficiency

The SAH efficiency is defined as a ratio of the heat flow rate extracted by the SAH to the solar radiation incident on the absorber surface.

$$\eta_{SAH} = \frac{\dot{Q}_{sah}}{A_{abs}\, I_{SAH}}, \quad (3)$$

where, $(\dot{Q}_{SAH})$ [W], is the heat flow rate, extracted by the SAH and can be calculated [27, 34] as:

$$\dot{Q}_{SAH} = \dot{m}_{SAH}\, c_{p,SAH}\, (T_{SAH,o} - T_{SAH,i}) \quad (4)$$

2. Stored/ recovered thermal energy

The amount of energy stored inside the PCM during charging cycle Q_{ch} [J],

$$Q_{ch} = m_{PCM}[c_{PCM,s}\,(T_{PCM,F} - T_{PCM,i\_ch}) + L + c_{PCM,l}\,(T_{PCM,f\_ch} - T_{PCM,F})]\,. \quad (5)$$

Similarly, the amount of energy recovered from the PCM during discharging cycle Q_{dis} [J]

$$Q_{dis} = m_{PCM}\,[c_{PCM,l}\,(T_{PCM,i\_dis} - T_{PCM,F}) + L + c_{PCM,s}\,(T_{PCM,F} - T_{PCM,f\_dis})]. \quad (6)$$

3. Efficiency of the PCM modules

The efficiency of the PCM modules is calculated by the ratio of the thermal energy extracted in discharging cycle to the thermal energy stored in charging cycle for a specific period of time [35, 36].

$$\eta_{PCM} = \frac{Q_{dis}}{Q_{ch}} \quad (7)$$

4. Efficiency of the solar drying system at natural convection of air through the SAHs without PCM modules

The system efficiency is the ratio of the thermal energy used to evaporate the moisture from the sample to the global solar radiation incident on the absorber surface of the SAHs [37].

$$\eta_{sys,1} = \frac{\int_0^{t_{end}} m_e\, h_{fg}\, dt}{\int_0^{t_{end}} I_{SAH}\, A_{abs}\, dt} \quad (8)$$

5. Efficiency of the solar drying system at forced convection of air through the SAHs without PCM modules

The system efficiency is the ratio of the thermal energy used to evaporate the moisture from the sample to the sum of the global solar radiation incident on the absorber surface and the energy consumed by the fan [37].

$$\eta_{sys,2} = \frac{\int_0^{t_{end}} m_e\, h_{fg}\, dt}{\int_0^{t_{end}} I_{SAH}\, A_{abs}\, dt + \int_0^{t_{end}} P_{fan}\, dt} \quad (9)$$

6. Efficiency of the solar drying system at forced convection of air through the SAHs with n PCM modules

The system efficiency is the ratio of the thermal energy used to evaporate the moisture from the product plus the thermal energy stored in the modules to the sum of the global solar radiation incident on the absorber surface and the energy consumed by the fan

$$\eta_{sys,3} = \frac{\int_0^{t_{end}} m_e\, h_{fg}\, dt + \sum_o^n \int_0^{t_{end}} Q_{ch}\, dt}{\int_0^{t_{end}} I_{SAH}\, A_{abs}\, dt + \int_0^{t_{end}} P_{fan}\, dt}\,. \quad (10)$$

Exergy analysis

The second-law models are introduced as a more correct approach to find the potential for improvement of the thermodynamic behavior of the TES [32]. According to them, not energy is important, but the thermodynamic availability of this energy. Unlike first-law energy analysis, they take into account the loss of energy because of irreversibility of the process. They formulate second-law efficiency based on entropy number [38] or exergy analysis.

Exergy is the maximum amount of work which can be produced by a system or a flow of matter till the system or the flow comes to equilibrium with a reference environment [39].

Second-law efficiency η_{II} [40] can be expressed as the ratio of the exergy output Ex_{out} to the exergy input Ex_{in}.

$$\eta_{II} = \frac{Ex_{out}}{Ex_{in}} = \frac{Ex_{in} - Ex_{loss} - Ex_{des}}{Ex_{in}} \quad (11)$$

Ex_{des} is the exergy destruction due to the irreversibility of the process, Ex_{loss} is the exergy lost to the environment.

The exergy analysis in [37] of the units of a solar dryer with PCM uses the following equations taken from literature:

1. Exergy analysis of the SAH

The exergy analysis employs the steady flow exergy equation expressed as follows [41]:

$$\dot{E}x = \dot{m}_a \left\{ c_{pa}(T - T_r) - T_r \left[c_{pa} ln\left(\frac{T}{T_r}\right) - R\, ln\left(\frac{P}{P_r}\right) \right] \right\} \quad (12)$$

The exergy efficiency of the SAH $\eta_{Ex,SAH}$ is expressed as the ratio between the exergy received by the working fluid (air) $\dot{E}x_{re,air}$ to the exergy inflow $\dot{E}x_{in,SAH}$

$$\eta_{Ex,SAH} = \frac{\dot{E}x_{re,air}}{\dot{E}x_{in,SAH}}, \quad (13)$$

where the exergy inflow into the air heater is expressed as

$$\dot{E}x_{in,SAH} = \left[1 - \frac{T_r}{T_{sun}}\right]\dot{Q}_{in}, \quad (14)$$

T_{sun} denotes the apparent sun temperature and it is assumed to be 4500 K, T_r - reference temperature of the ambient, $\dot{Q}_{in} = \alpha\tau' I A_{SAH}$ is the energy input to the solar heater. $\dot{E}x_{re,air}$ is expressed using the steady flow exergy equation (Eq.12):

$$\dot{E}x_{re,air} = \dot{m}_a c_{pa}\left[\left(T_{o,SAH} - T_{i,SAH}\right) - T_r \ln\left(\frac{T_{o,SAH}}{T_{i,SAH}}\right)\right] \quad (15)$$

2. Exergy analysis of energy storage

The exergy efficiency of energy storage is the ratio of the net exergy recovered from the energy storage during the discharging period Ex_{dis} to the net exergy input to the storage during the charging period Ex_{ch}

$$\eta_{Ex,es} = \frac{Ex_{dis}}{Ex_{ch}} \quad (16)$$

$$Ex_{ch} = \int_0^t \dot{m}_a c_{pa}\left[\left(T_{i,es} - T_{o,es}\right) - -T_r \ln\left(\frac{T_{i,es}}{T_{o,es}}\right)\right] dt \quad (17)$$

$$Ex_{dis} = \int_0^t \dot{m}_a c_{pa}\left[\left(T_{o,es} - T_{i,es}\right) - -T_r \ln\left(\frac{T_{o,es}}{T_{i,es}}\right)\right] dt. \quad (18)$$

3. Exergy analysis of the DC

The exergy efficiency of the DC, $\eta_{Ex,d}$, is defined as the ratio of the exergy outflow $\dot{E}x_{od}$ to the exergy inflow $\dot{E}x_{id}$ of the DC

$$\eta_{Ex,d} = \frac{\dot{E}x_{od}}{\dot{E}x_{id}} \quad (19)$$

$$\dot{E}x_{id} = \dot{m}_{da} c_{pa}\left[\left(T_{id} - T_r\right) - T_r \ln\left(\frac{T_{id}}{T_r}\right)\right] \quad (20)$$

$$\dot{E}x_{od} = \dot{m}_{da} c_{pa}\left[\left(T_{od} - T_r\right) - T_r \ln\left(\frac{T_{od}}{T_r}\right)\right]. \quad (21)$$

Examples of efficiency evaluation of solar dryers with PCM

The article [37] presents performance studies of a forced convection solar dryer of chili, integrated with a shell-and-tube TES unit, based on paraffin wax. The performance of each component of the drying system was evaluated in terms of energy and exergy efficiency. The average instantaneous heat input and heat recovered during the charging and discharging processes of the energy storage were in the range of 105–130 W and 89–116 W, respectively. The net heat input and heat recovered varied from 2.5 MJ to 3.2 MJ and from 1.2 MJ to 1.5 MJ, respectively. The average energy efficiency or the percentage of the energy recovered (Eq.7) was in the range of 43.6–49.8%. No heat energy was retrieved from the storage after 18:00 h as the air coming out of the storage at the temperature below 36 ºC was not much effective for drying the chili. The drying time was reduced by 55% of the drying time in open sun drying. The TES provided an extended drying time of 2 h after sunset and the overall efficiency of the drying system was 10.8%. The net exergy input and recovered were in the range of 0.2–0.3 MJ, and 0.04–0.05 MJ, respectively. The overall exergy efficiency ranged from 18.3% to 20.5%.

Pebble stones and paraffin wax (as TES) were used in drying of lemon slices [3] Considering that the drying time increased with increasing the product amount, it was concluded that maximum 11.3 kg of lemon slices could be dried with each of the energy storage systems. As a result of the experimental studies, the average energy efficiencies were obtained as 68.2% and 68.55% for pebble stones and paraffin, respectively. When the systems were evaluated economically, it was observed that the TES based on pebble stones had a 10.47% lower initial investment cost compared to the TES based on paraffin. Pebble stone unit price used in the system was $ 0.0725/kg. The unit price of paraffin wax used in the PCM system was $ 2.483/kg. Moreover, paraffin wax loses its ability to store energy since its properties deteriorate after a certain period of time (approximately 4 years) and should be replaced.

CFD predictions of thermal behavior of solar dryers with PCM

CFD is a useful tool in designing drying systems. The commercial numerical packages for CFD most often used to improve the performance of a solar dryer with TES are COMSOL Multiphysics, ANSYS CFX, Fluent, FORTRAN and OpenFOAM [42]. CFD reveals a detailed picture of flow velocity and temperature and humidity distribution pattern inside the units of the solar dryer.

A low-temperature latent heat TES device was studied [43] for drying of agricultural products in an indirect-type solar dryer. A 2D geometry was created. It had an inner copper tube and outer plastic tube assembly. The air flowed into the copper tube and the PCM was in the outer plastic tube. Transient simulations were conducted by ANSYS Fluent 2015 to capture the velocity, temperature, melting and solidification fractions.

The enthalpy-porosity model of phase change is employed in ANSYS Fluent. It adopts the following equations for describing the processes in charging/discharging of the PCM:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \boldsymbol{v}) = 0. \tag{22}$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla(\rho \boldsymbol{v}\boldsymbol{v}) = -\nabla p + \nabla \boldsymbol{\tau} + \rho \boldsymbol{g} + \boldsymbol{S}, \tag{23}$$

where $\boldsymbol{v}$ is the velocity vector, p is the static pressure, $\boldsymbol{\tau}$ is the stress tensor and $\rho \boldsymbol{g}$ and $\boldsymbol{S}$ are the vectors of gravitational and external body forces.

The momentum sink due to the reduced porosity in the mushy zone takes the following form:

$$\boldsymbol{S} = \frac{(1-\beta)^2}{(\beta^3+\varepsilon)} A_{mush} \boldsymbol{v}, \tag{24}$$

where β is the liquid volume fraction, ε is a small number (0.0001) to prevent division by zero, $A_{mush} = 10^5$ is the mushy zone constant.

Energy equation:

$$\frac{\partial}{\partial t}(\rho H) + \nabla(\rho \boldsymbol{v} H) = \nabla(k \nabla T). \tag{25}$$

The enthalpy H consists of sensible enthalpy h and latent heat ΔH

$$H = h + \Delta H, \tag{26}$$

where $h = h_r + \int_{T_r}^{T} c_p dT$, $\Delta H = \beta L$.

The latent heat content can vary between 0 for solid and L for liquid. The liquid volume fraction can be defined as:

$$\beta = 0 \text{ if } T<T_s$$
$$\beta = 1 \text{ if } T>T_l$$
$$\beta = \frac{T-T_s}{T_l-T_s} \text{ if } T_s<T<T_l,$$

where T_s and T_l are solidus and liquidus temperatures respectively.

The CFD simulations of the TES in [43] were run from 8.00 am to 10.00 pm. The inlet air temperature was gradually increased and reached a maximum value of 349 K at 2.00 pm. The model helped to analyze the potential of PCM to store excess solar energy and to estimate the temperature distribution in radial direction of the TES device.

Different configurations of a solar dryer integrated with thermal storage medium were analyzed in [44] by means of a CFD software to study temperature and humidity distributions in the system. Paraffin wax was used as PCM. It was assumed that at the inlet the temperature was 303.00 K, the pressure was 101325.00 Pa and the air velocity was 1.2 m/s. Maximum fluid temperature of 346.56 K was obtained at the chimney of the solar dryer. The results of the study showed that maximum temperature loss occurred due to the metallic components of the solar air dryer, where suitable insulation material should be used.

A 2D numerical study was conducted in [45] (by ANSYS Fluent) for a TES device of an indirect type solar dryer. Two cases were considered: Case-I without fins and Case-II with fins. The TES dimensions of both cases were the same. Fin dimensions were 0.5 mm tip diameter, 5 mm length 14.86 mm fin spacing. Paraffin wax was used as a PCM material for both cases. CFD simulations were carried out for four air velocity conditions (1m/s, 2m/s, 3m/s, 4m/s). It was found that both cases worked best with an air velocity of 1 m/s compared to higher air flow velocities. Higher air flow velocity did not exercise much impact on the DC temperature compared to lower velocity. Also, lower air flow velocity maintained the uniformity of drying over a longer period of time. At the same time, higher air flow velocity carried more moisture from the food product, so the drying time could be reduced. Melting fraction was higher in Case-II compared to Case-I as the fins transferred more heat to the PCM. For all the velocities considered in this work, the heat gained by the air was higher for Case-II compared to Case-I. The maximum heat gained by the air for Case–II was 55.2% more in comparison to Case–I at an air velocity of 1 m/s.

CONCLUSIONS

The rate of drying depends on various parameters such as solar radiation, ambient temperature, air flow velocity, relative humidity, initial moisture content, wind speed, type of goods, absorptivity and mass of product per unit exposed area. The conditions for heat transfer in the units of the solar dryer with paraffin (containers' materials and surface area, insulation, desiccants, air flow rate and velocity, arrangement of the grids for the drying material, etc.) which lead to good results of the drying process are considered in order to determine the important performance characteristics of a successful simplified small-size solar dryer with paraffin.

The main requirements in the design of a thermal energy accumulator are:

- Continuously stable temperature of the drying air at least 10-25°C above the ambient temperature. This is necessary to avoid the dried object to re-absorb the moisture during night, when the air temperature drops and its humidity increases.
- Choice of proper PCM according to the drying regime; the minimum melting temperature of the PCM should be of 5–10 ºC higher than the desired temperature of the HTF.
- Minimal heat loss by effective thermal insulation.
- Intensive heat transfer (measures for reduction of air convective resistance and enhancement of thermal conductivity of PCM.)
- Metal lamellae structures are a good solution for increasing paraffin thermal conductivity more than 2 times.
- Macro-encapsulation is recommended for providing large heat transfer area, reduction of the paraffin reactivity towards environment and controlling the changes as phase change occurs. Increasing the height/width ratio of the container for the same volume decreases the time for the melting process due to the stronger buoyancy effect. Usually the material of the shell is plastic or metal (copper, aluminum and steel) when higher heat transfer rates are desirable.
- Metal fins enhance significantly the heat transfer rate in and out of the element containing the PCM.
- The thermal storage should not create additional pressure drop, especially in natural convection units. It can also serve as an obstacle to the air flow that increases the heat transfer area and enhances the air flow conditions, by creating turbulence and eliminating stagnant zones.
- The second-law models are a more informative approach to find the potential for improvement of the thermodynamic behavior of the thermal energy accumulator, since they evaluate the thermodynamic availability of energy.
- CFD simulation of the TES is useful for analyzing the potential of PCM to store excess solar energy during sunshine hours and to release the same at night. It enables to compare different device configurations by revealing the picture of temperature, humidity and velocity distribution.

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NOMENCLATURE

A - area, m^2;
c_p - specific heat, J/(kg K);
$c_{p,SAH}$ - average specific heat of air between $T_{SAH,i}$ and $T_{SAH,o}$, J/(kg K);
$c_{PCM,s}$- average specific heat of solid PCM, J/(kgK);
$c_{PCM,l}$ - average specific heat of liquid PCM, J/(kg K);
Ex - exergy, J;
$\dot{Ex}$ - exergy flow rate, W;
$\boldsymbol{g}$ - gravitational acceleration vector, m/s^2;
h - sensible enthalpy, J/kg;
H_{FG} - latent heat of vaporization, J/kg;
H - enthalpy, J/kg;
ΔH - latent heat, J/kg;
I - solar intensity, W/m^2;
k - thermal conductivity, W/(mK);
L - heat of fusion per unit mass, J/kg;
m - mass, kg;
$\dot{m}$ - mass flow rate, kg/s;
p - static pressure, Pa;
P_{fan} - power consumption of fan, W;
Q - thermal energy, J;
$\dot{Q}$ - heat flow rate, W;
R - gas constant, J/(kgK);
t - time, s;
T - temperature, K;
$\boldsymbol{v}$ - velocity vector, m/s;

Greek letters

α - absorptivity;
η - thermal efficiency;
β - liquid volume fraction;
Δ- difference;
μ - dynamic viscosity, Pa.s;
ρ - density, kg/m^3;
$\boldsymbol{\tau}$ - stress tensor, Pa;
τ' – transmissivity.

Subscripts

a - air;
abs - absorber;
ch - charging;
d – dryer;
dis - discharging;
des - destruction;
e - evaporated moisture;
es - energy storage;
f - fluid;
f_ch - final in charging;
f_dis - final in discharging;

F - fusion;
i - inlet;
i_ch - initial in charging;
i_dis - initial in discharging;
in - input;
l - liquid;
o - outlet;
out - output;
PCM - phase change material;
r- reference;
re - received;
s - solid;
SA - solar accumulator;
sys - drying system;
SAH - solar air heater.

Abbreviations

CFD - computational fluid dynamics;
DC - drying chamber;
FLT - first law of thermodynamics;
FPC - flat plate collector;
HE - heat exchanger;
HTF - heat transfer fluid;
LHS - latent heat storage
PCM - phase change material;
SAH - solar air heater;
SLT - second law of thermodynamics;
TES - thermal energy storage.

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