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Evaluation of Phase Change Materials (PCMs) Applications in a Small Scale Solar Dryer by Using Mathematical Model

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Abstract

Solar dryers have been developed for drying agriculture products as preserved food. The sun's irradiation generates heat energy to drive moisture out of the products. However, the effectiveness of solar dryers is dependent on sunlight availability during the day which in turn is seasonal. The temperature inside the solar dryer is sensitive to weather conditions. The researchers did not only use Phase Change Material (PCM) to store and retain the heat during charging cycle, but also maintained suitable temperature inside the dryer during discharging cycle for a longer period of time after sunset. There are two key parameters related to the required performance of the solar dryer during charge and discharge periods: the rate constant (k) and the retaining time (t). Since k is very sensitive to how the PCM is used, the researchers investigated the suitable composition of PCM and the quantity of PCM used in the solar dryer to meet the performance targets established for the study. They used mathematical modeling based on the first order equation to determine the suitable composition and amount of PCM in a small scale solar dryer to achieve overall performance targets. The results on evaluation of PCMs applications in a small scale solar dryer with the use of a mathematical model were reported in this paper.

Keywords: *Solar dryer, Phase Change Material (PCM), charging/discharging period, retaining time, the rate constant (k), Mathematical modeling for PCM*

1. Introduction

Energy production using fossil fuels is a major contributor to anthropogenic greenhouse gas emissions which results in global warming and accelerating climate change. In this regard, the diversification of the fuel base and adoption of emerging clean and green alternative for energy production may provide solutions for sustainable energy production to meet the current and future energy requirements (Fudholi et al., 2010). The use of renewable non-conventional energy such as solar energy is promising. In particular, the solar dryer application for drying agriculture products (Ekechukwu, 1999; Ekechukwu & Norton, 1999a; Ekechukwu & Norton, 1999b) is to accelerate the use of cleaner technology in Thai small/ medium enterprises (SMEs) in the near future (Srisang et al., 2004).

Solar energy is clean and has very little impact on the environment (Ekechukwu, 1999). The intermittent and variable nature of solar energy generally results in a mismatch between the supply and demand of solar energy (Mondal, 2008). As a result, it is often necessary to incorporate an energy storage system to meet the energy requirements during non-solar hours. Among different solar thermal energy systems, latent heat thermal energy storage in the form of Phase Change Material (PCM) (Shama et al., 2009; Zhou et al., 2012; Soares et al., 2013) has an advantages of high energy density.

Solar-drying technology offers an alternative which can process agriculture products in clean, hygienic and sanitary conditions. It saves energy, time, occupies less area, improves product quality, makes the process more efficient and reduces environment impacts. Generally solar dryers can be classified into three types: (1) Passive solar dryers using natural convection in solar dryers to drive moisture out of products. Some types of passive solar dryers incorporated a solar chimney to increase air velocity in solar dryers for more efficiency in drying (Ekechukwu & Norton, 1999b). (2) Active solar dryers enhancing convection with the use of a fan or blower to increase air velocity to drive moisture out of products (Ekechukwu & Norton, 1999a). (3) Hybrid solar dryers having an additional heat source such as electric heater or biomass burner to compensate the solar energy when the sun is not available (Ekechukwu & Norton, 1999a; Taworn et al., 2007).

Phase Change Materials (PCMs) are materials with a high latent heat capacity which melt and solidify at a certain temperature range appropriate to thermal storage and temperature requirement of each application. Generally, PCMs can be classified into three types: (1) organic compound, such as fatty acid, (2) inorganic compound, such as salt hydrate and metallic, and (3) eutectic compound which can be a mixture of organic and organic, inorganic and inorganic, organic and inorganic (Soares et al., 2013). The use of PCM provides higher heat storage capacity and lower temperature variation during charging and discharging cycles and maintaining relatively constant heat transfer during the discharge process (Mondal, 2008). With a suitable melting point of PCM, for example in building, the room temperature can be controlled for human comfort by incorporating micro-encapsulated PCM in wood-based flooring application in the comfort zone of the building (Taworn et al., 2007; Jeong et al., 2013). In solar dryer applications, PCM can facilitate the control of temperature inside the solar dryers, and increase retaining time of a suitable amount of thermal energy required in drying the products (Jeong et al., 2012; Pakorn & Suthathit, 2012).

Paraffin has been widely used as heat storage material in solar dryers(Holasut et al., 2009; Holasut & Kumwachara, 2010; Holasut et al., 2015; Malasai & Holasut, 2016; Malasai, 2016), because the paraffin is cheap and nontoxic (Devahasdin & Pitaksuriyarat, 2006; Reyes et al., 2014), but the melting point of paraffin may not be suitable for all requirement conditions in a solar dryer (Pakorn & Suthathit, 2012). The maximum of average temperature in the prototype solar dryer with no PCMs is between 60-85 degree Celsius (Taworn et al., 2007; Holasut et al., 2009; Pakorn & Suthathit, 2012) been widely used as heat storage material in solar dryers (Holasut et al., 2009; Holasut & Kumwachara, 2010; Holasut et al., 2015; Malasai, 2016) in Thailand. Taworn et. al.(2007) studied paraffin-kerosene mixer PCMs with the aim to control the melting point of paraffin-kerosene mixer PCMs and using the mixed PCM with a ratio paraffin to kerosene at 2:1 by weight and installed 2% by volume of PCM in the 1.6 cubic meters capacity of the prototype solar dryer. The 150 ml aluminum cans were used to contain the PCM. Their results showed that PCM could retain temperature above the ambient temperature in solar dryers for two hour after sunset (after 6:00 pm). Later Pakorn and Suthathit (2012) studied the variation of the composition of PCM (paraffin-kerosine in 3:1, 2:1 and 1:1) and the % by volume of PCM up to 10% in the small scale of solar dryer to maintain temperature above environment for certain time. The relation of retaining temperature for certain time and PCM in solar dryer has been approximated by the empirical equation (Pakorn and Suthathit (2012). This can be used to facilitate the design of the composition of PCM and % volume of PCM in the specific small scale solar dryer. However, the use of kerosene causes bad smell. To overcome this problem, one can use vaseline instead of kerosene.

This research aimed to study the effect of installed PCM in a small scale solar dryer on the average temperature inside the dryer during (heat) charging and discharging periods, and to develop a mathematical model to predict or estimate the suitable PCM at the temperature required for the drying process in the solar dryer. In order to avoid the kerosene smelling problem, vaseline was used in this research (Malasai, 2016). A paraffin-vaseline mixture was used as PCM with the ratios of paraffin to vaseline at 3:1, 2:1 and 1:1 by mass. The effects of the amount of PCM used in a solar dryer were also investigated by varying the amounts of PCM volume at 10% 20% and 30% in a solar dryer.

2. The Experiment

In order to develop a meaningful and practical mathematical model, the researchers set an experiment in three steps: (1) the basic properties of paraffin-vaseline mixtures which would be used as PCMs were determined by using DSC, (2) the melting rate of designed PCMs being investigated, and (3) the temperature responding in the solar dryer with PCMs during 4 hours of charging and then discharging to be recorded as data for the development of a mathematical model. The experiment steps were as follows:

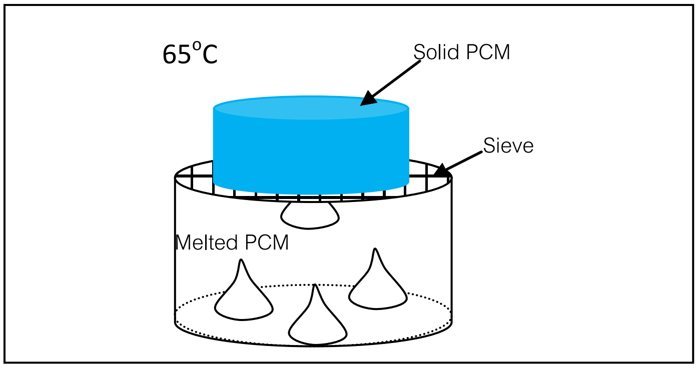
2.1 Preparation and the Melting Point Measurement

The PCMs were prepared by property mixed paraffin and vaseline with the ratio P:V 3:1, 2:1 and 1:1 by weight in a 70^{o}C heated container and later allowed to cool down to the room temperature. The melting point and latent heat of each mixed PCM was determined by using the Differential Scanning Calorimetry (DSC).v The results are shown in **Table 1**

2.2 Melting Test

The melting test was performed by putting a 100 g. of solid sample of each PCM on a grill or a sieve plate of the melting test container as shown in **Figure 1**, and then placed in the container in the control temperature 65-85^{o}C dryer (the test temperature of 65-85^{o}C was referred to the previous experiment for the average solar energy each day (Taworn et. al.,2007; Holasut et al., 2009; Holasut & Kumwachara, 2010; Pakorn & Suthathit, 2012; Holasut et al., 2015). At each hour interval the test container was removed from the dryer and the lower part of the container was weighed to determine the mass of melted PCM until 4 hours exhausted. The PCM of each mixed ratio (P:V at 3:1, 2:1 and 1:1) was tested with the same procedure, and the test results are shown in **Figure 3.**

Figure 1: Melting test PCM in Control Solar Dryer System at Temperature at 65 °C



2.3 Testing the effect of PCM on the charging and discharging performance of small scale solar dryer

Figure 2: Charging and Discharging of Each Composition of PCM in Small Scale Solar Dryer

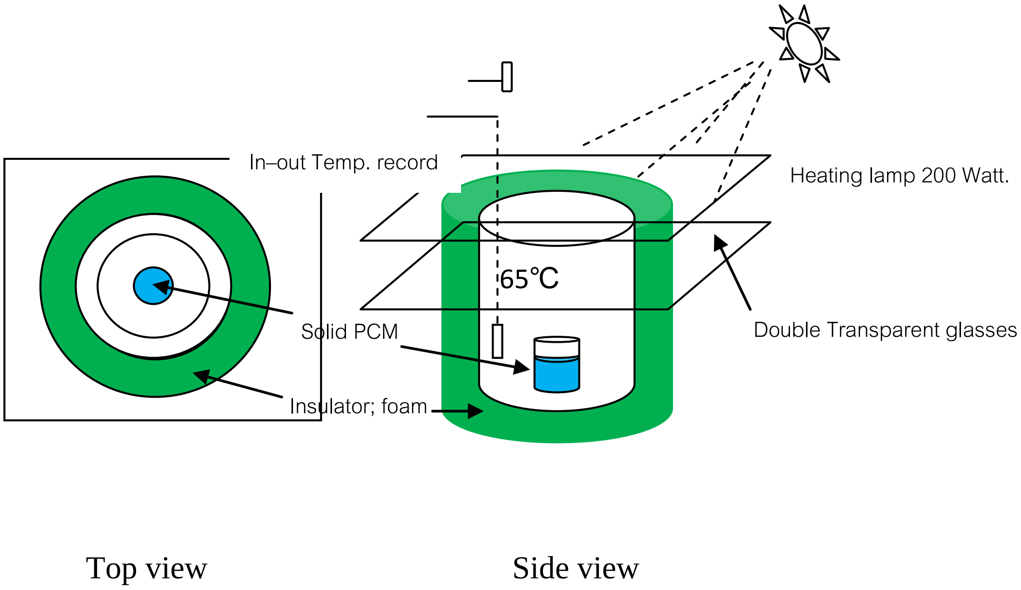


Figure 2 shows the small scale solar dryer which was modified to use in the test (Pakorn & Suthathit, 2012). It was made from metal can with internal volume of 1.3 liters. The exterior of the can was insulated with thick polystyrene foam, while the inside was lined with the black-painted aluminum sheet with a translucent glass plate acting as a cover at the top. The 200 watts heating lamp was used as a charging energy source. The distance between the cover and the lamp could be adjusted to obtain the average temperature inside the dryer to be in the range of 65-85°C when the dryer was empty (no PCM). Both the dryers and the PCM test sample were allowed to settle at the room temperature before the test started. Then the PCM was placed in the dryer, the distance of the lamp was set and then the lamp was timed for 4 hours (charging) before being switched off. The procedure let the PCM to discharge for another 4 hours; data on temperatures were recorded both inside and outside the dryer for 8 hours in total. The experimental set up is shown in **Figure 2.**

3. Results and Discussion

3.1 Result of DSC

The results of DSC for thermal testing to measure melting points and thermal properties of PCM are shown in **Table 1**

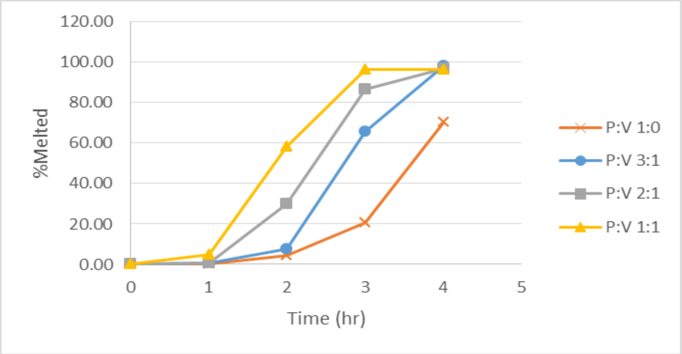
Table 1: Thermal Properties of PCM Measured by DSC

PCM Ratio Paraffin:Vaseline	Melting Point (°C)	Latent Heat of Fusion (kJ/kg)
P:V 1:0	54.06	132.675
P:V 3:1	51.26	99.149
P:V 2:1	49.56	79.866
P:V1:1	48.99	77.056
P:V 0:1	40.09	17.594

The melting point and latent heat of PCM decreased with the increase of vaseline in PCM because vaseline had lower melting point and latent heat.

3.2 PCM Melting

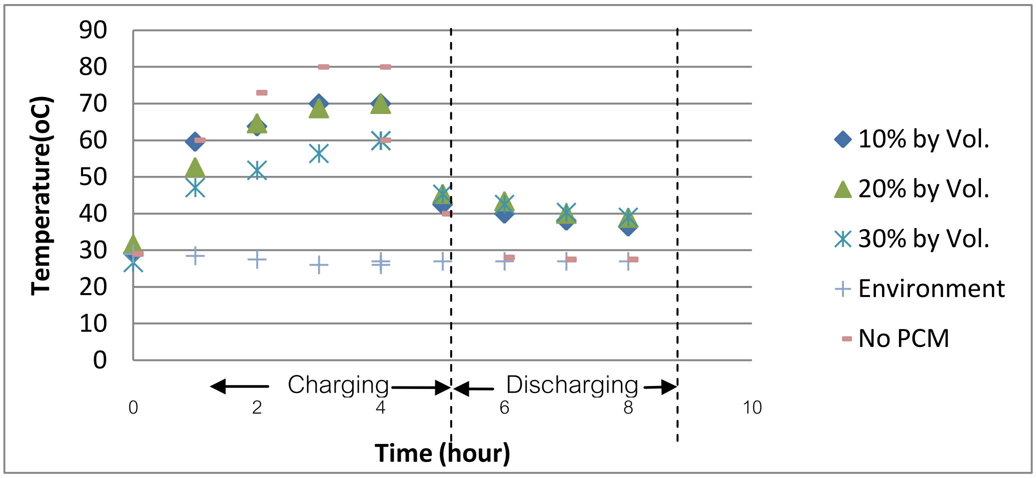
Figure 3: Percentage by Mass in Melting of Various Compositions (P:V) of PCM.



All tested PCM showed varied melting points shown in **Table 1**, lower than 65^{o}C; all of them completely melted after 4 hours in 65^{o}C test chamber, apart from the pure paraffin specimen which did not completely melt. This seemed to suggest that the ability to store heat energy of any substance only depended upon the specific heat, the melting point and the latent heat, but also the surface area and the heat conductivity at the interface between melting liquid and remaining solid. As seen in **Figure 3,** the charging period of 4 hours at 65^{o}C with the use of PCM in various compositions at the mixing ratio P:V of 3:1, appeared to offer the best alternative for its complete melting in 4 hours.

3.3 PCM in Small Scale Solar Dryer (Charging and Discharging)

Figure 4: Variation temperatures in a small scale solar dryer during charging and discharging with PCM P:V (3:1) with 10%, 20% , 30% volume fraction and without PCM



The temperatures responding in dryers were in two periods: (1) the first or charging period in which the heat energy was accumulated and stored in the PCM, resulting in the rise of temperature, and (2) the second or discharging period in which the stored heat energy was released, resulting in a temperature drop.

During the charging period, PCM addition reduced the peak temperature with a suitable amount of PCM—reducing or eliminating the possibility of over heat in the dryer, and therefore maintaining a stable temperature in the charging period. During the discharging period, the PCM helped to maintain the temperature inside the dryer better than without PCM as shown in **Figure 4**.

3.4 Analysis of Experimental Results

The average temperature inside the dryer at a particular time (t) was estimated using a mathematical model proposed by Malasai (Malasai, 2016; Malasai & Holasut, 2016). The model is based on the assumption that the rate at which the average temperature increasing inside the dryer at time t during charging period will reduce as this average temperature

$\left(T_{est}\right)$ approaching the maximum possible temperature $\left(T_{\max}\right)$ under a certain thermal energy input is governed by the first-order equation of the form:-

$$\frac{d(T_{\max}-T_{est})}{dt}=-k(T_{\max}-T_{est}) \qquad \ldots(1)$$

Which k is the rate constant, Equation (1) can be solved with the initial temperature at the start (i.e. $t=t_o$ hours) to be T_o (°C) to obtain the relations:-

$$T_{est}=T_{\max}-e^{-kt}.(T_{\max}-T_o) \qquad ...(2) \quad \textbf{for charging period}$$

and

$$T_{est}=e^{-kt}.(T_p-T_e)+T_e \qquad ...(3) \quad \textbf{for discharging period}$$

where T_p = Peak temperature, temperature at the start of the discharging period or a final temperature of the charging period (°C)

T_e = Temperature of the environment (°C)

The rate constant (k) can be used to indicate the characteristics of any solar dryer, since it reflects both the thermal capacity and the heat transfer properties of the dryer. In general an average temperature inside a solar dryer which has a high value of k will respond more rapidly than the dryer which has lower value of k under the same heat input or output.

The rate constant k was obtained by fitting the Equations (2) and (3) for charging and discharging periods, respectively, to the corresponding experimental results using Excel SOLVER, as shown in **Table 2**.

Table 2: The Constant (k) of Each Dryer with Different Compositions (P:V) and % by Volume PCM in the Dryer

P:V	Constant (k) of dryer with different composition (P:V) and % by Vol					
	Vol 0%	Vol 10%	Vol 15%	Vol 20%	Vol 25%	Vol 30%
1:1	3.041	1.510	1.008	0.781	0.603	0.383
2:1	3.041	1.020	0.711	0.549	0371	0.287
3:1	3.041	0.842	0.563	0.460	0.285	0.267

The effects of incorporating PCM with various ratios of paraffin:vaseline into the solar dryer and different volumes (in terms of volume fraction or % of PCM volume or heat storage capacity) on the values of the rate constant k are shown in **Table 2**. As seen in **Figures 5** and **Table 2,** the value of the rate constant k reduced the responding rate and the fluctuations of the average temperature inside the dryer also reduces. When the rate constant k was high, the temperature rose or dropped quickly, hence maintaining required temperature sufficiently long after heat energy input being removed and the rate of constant k remaining sufficiently low. The accuracy of estimated temperatures as given by the model was acceptable when comparing with the experimental measured temperatures, as shown in **Figure 5.**

Figure 5: Temperature response in solar dryer with various (P:V) PCM at 10%, 20% and 30% volume fractions during charging and discharging periods**.** (P:V in **Figure 5a**, **5b** and **5c** are 1:1, 2:1 and 3:1 respectively) by using **Equation (1)** for charging and **Equation (2)** for discharging.

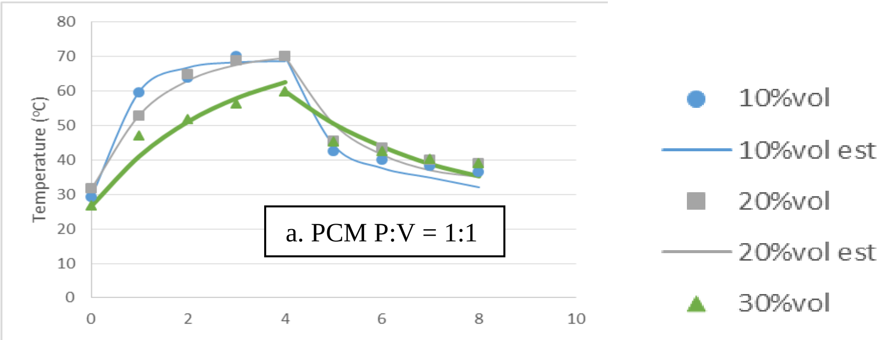


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Fig. 5a

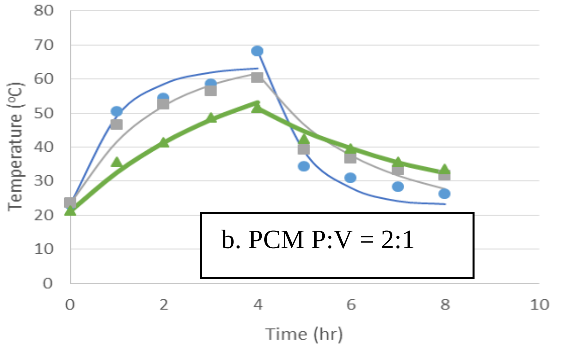


Fig. 5b

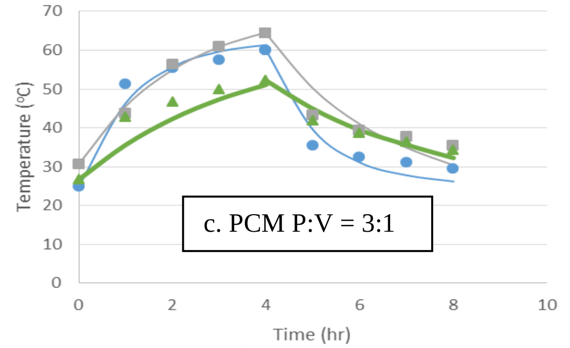


Fig. 5c

The experimental results indicated that the solar dryer with a lower rate constant k was able to retain required temperature for a longer period during discharging. This seems to suggest that the larger volume fraction of PCM, the better the result. However, in the plots of the volume fraction of PCM against the value of the rate constant k as shown in **Figure 6**, showed the effect of increasing volume fraction of PCM being diminished as indicated by the slope of the curve approaching zero, as the percentage of volume fraction increased. Any addition of volume fraction of PCM above 30% had a very little effect on the value of the rate constant k, but it was likely to reduce the working space inside the dryer to the point at which it appeared impractical. This diminishing effect was due to the fact that the extra PCM added had no chance to completely melt during the charging period—being caused by either insufficient heat energy input or the short charging period. In such a case, the PCM was not fully utilized to its full capacity.

The effect of incorporating the PCM into the dryer on the rate constant k can be approximated by the empirical **Equation (4)** which is obtained by equation fitting to the experimental results as given in **Table 2**.

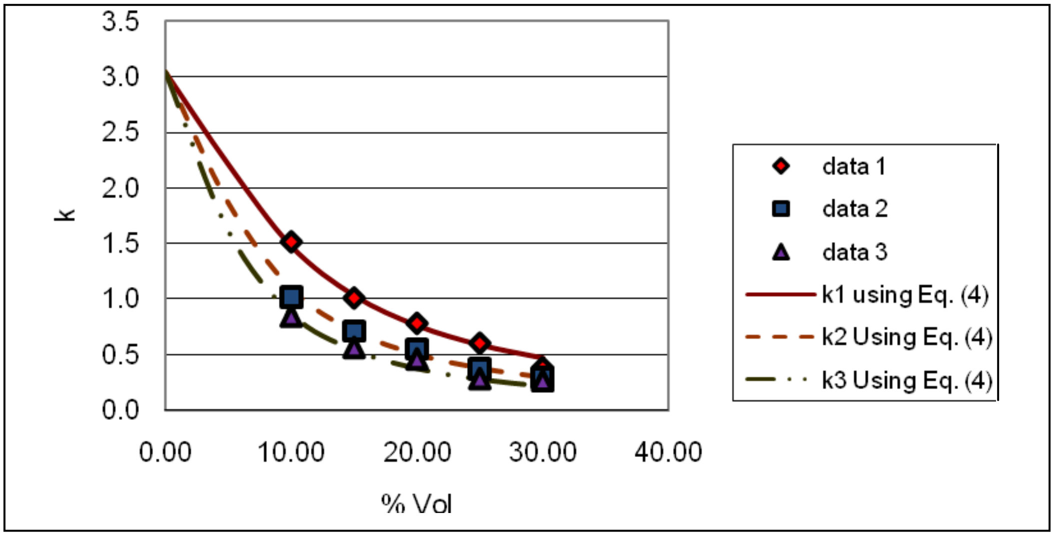
$$k/k_o = 1 - \frac{(1.645m + .784)R^{3/2}}{(1.645m + .784)R^{3/2} + 0.072} \qquad \ldots(4)$$

By k_o = rate constant without PCM (in this case k_o = 3.041)

m = P:V of PCM by using 1, 2 and 3 to substitute for 1:1, 2:1 and 3:1 respectively

R = % volume of PCM in the solar dryer

Figure 6: Rate constant (k_1, k_2, k_3) and percent by volume of PCM for various mixing ratio P:V 1:1, 2:1 and 3:1, respectively



The plot of the empirical **Equation (4)** in comparison to the experimental data is shown in **Figure 6**. It is obvious that the first 15% addition of PCM was effective in reducing the value of the rate constant (k): the reduction to about 1/3 to 1/4 of the k_o.

3.5 Implications of the Model for Solar Dryer

The model developed in this study can be used as a guide to improve the solar dryer design by incorporating the PCM to the dryer. If the target temperature inside the solar dryer is about 50 to 60 °C which is the most appropriate range for many agriculture products, the equation (4) can be used without any modification. The required rate constant k can be determined by using equation (2) with (T_{est}) set to target temperature for the required charging period . The suitable P:V mixing ratio and the % volume of PCM required can be solved using **Equation (4)**.

Table 3 shows the results of this approach. When the average temperature inside the dryer without PCM was allowed to settle at the equilibrium temperature for a given heat input at the end of 4 hours charging period, and if the target temperatures after 4 hours of charging was in the range of 50 to 60 ^{o}C, the amount of PCM (% by volume) of three mixing ratio were required to maintain the target temperature, as shown in three columns.

Table 3: Amount of PCM in volume fraction required to provide target temperature within the range of 50-60 ^{o}C for 4 hours of charging

Temperature in Dryer (^{o}C) (No PCM)	Volume PCM in Dryer (%)		
	P:V 3:1	P:V 2:1	P:V 1:1
51 - 60	-	0 – 5	5 - 10
61 – 70	5 - 10	10 – 15	15 - 20
71 – 80	15 – 20	20-25	25-30
81 - 90	30	35	40

For example, if the temperature inside the dryer without PCM reaches 85^{o}C, then the 30% volume fraction of PCM with P:V 3:1 mixing ratio can be used to reduce the temperature down to the target 50 -60^{o}C and to retain sufficient temperature during the discharging period.

4. Conclusions

Thermal properties of PCM can be designed by selecting substances or compounds which have thermal properties close to the requirement, and combining or mixing the compounds to form the required PCM. By mixing paraffin and vaseline with various ratios, the melting point of designed PCM can be adjusted to be between the melting point of paraffin and vaseline.

The ability of PCM to melt at a target temperature is very important in controlling the temperature inside the dryer. However, the percentage of melting PCM at the end of discharging period may not have a good effect on the performance of the dryer. It was found that the PCM with a maximum ratio of 3:1 has a melting point at 51.23^{o}C and latent heat at 99.149 kJ/kg; this appeared to be a practical combination. It is possible, as shown in this research, that the experiment with PCM in a small scale solar dryer can generate the sufficient test data to verify the accuracy of the mathematical model to estimate the average temperature during the charging period in **Equation (2)** and the retained temperature during the discharging period in **Equation (3)**.

The rate constant (k) reflects the general temperature behavior in the sense that the rapid response of temperature inside the dryer indicated by the high value of k whereas the low value of k is corresponding to the more stable response as shown in **Equation (4)**. The experimental data and the mathematical model were used to construct a guide line, as shown in Table 3, for selecting the right amount of P:V of PCM required for a solar dryer to maintain its target inside temperature in the range 50 to 60^{o}C.

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