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Mathematical Modeling for Phase Change Materials in a Small Scale Solar Dryer

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Abstract: **Solar dryer has been developed for drying agriculture products with aims for preservation of food. It takes the advantages of greenhouse effect which turns the sun irradiation energy into heat energy to drive moisture out of the products, and the addition advantage of using solar energy for solar dryers is that it comes without cost. However, the effectiveness of solar dryers is depending upon the available of the sunlight during the day which in turn is seasonal. The temperature inside the solar dryer is sensitive to weather conditions. The use of Phase Change Material (PCM) is not only to store and retain the heat during charging cycle, but also to maintain the suitable temperature inside dryer during discharging cycle for longer period of time after the sun is out in the evening. There are 2 key parameters related to the required performance of solar dryer which are the rate constant (k) and the retaining time (t) both during charge and discharge periods. Since k is very sensitive to how the PCM used, therefore the aims of this are to investigate the suitable composition of PCM and the quantity of PCM used in the solar dryer to meet the performance targets. The mathematical modeling based on the first order equation developed is sufficient to determine the suitable of PCM in a small scale solar dyer to achieve overall performance targets.**

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

I. 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 [1]. The use of renewable non-conventional energy such as solar energy is promising; especially in the solar dryer application for drying agriculture products [2-4] to accelerate the adopting of the cleaner technology in Thai small medium enterprise; SME’s in the future [5].

Solar energy is clean and has very little impact on the environment [2]. The intermittent and variable nature of solar energy generally results in a mismatch between the supply and demand of solar energy [6]. 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) [7-9] has the 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 dryer: Solar dryer uses natural convection in solar dryer to drive moisture out of product. Some types of passive solar dryer incorporated a solar chimney to increase air velocity in solar dryer for more efficiency of drying [4]. 2) Active solar dryer: Solar dryer enhances convection by using fan or blower to increases air velocity to drive moisture out of products [3]. 3) Hybrid solar dryer: Solar dryer that has an addition heat source such as electric heater or biomass burner to compensate the solar energy when the sun is not available [3,10].

Phase Change Materials (PCMs) are materials with a high latent heat capacity which melt and solidify at certain temperature range that is appropriate to thermal storage and temperature requirement of each application. Generally, PCMs can be classified into three types which are: 1) Organic compound such as fatty acid, 2) Inorganic compound such as salt hydrate and metallic, 3) and Eutectic compound which can be a mixture of organic and organic, inorganic and inorganic, organic and inorganic [7]. 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 [6]. By choosing 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 the building for the comfort zone [10-11]. In solar dryer applications PCM have been employed to facilitate the control of temperature inside the solar dryers, and increase retaining time of suitable amount of thermal energy required to dry the products [12-13].

Paraffin has been used as heat storage material in solar dryers widely [14-18], because the paraffin is cheap and nontoxic [19-20], but the melting point of Paraffin may not suitable for all requirement conditions in a solar dryer [13]. The maximum of average temperatures in the prototype solar dryer with no PCMs are between 60-85 degree Celsius [10, 13, 15-17] for Thailand. Thaworn et. al. [10] 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 of 2:1 by weight and installed 2% by volume of PCM in the 1.6 cubic meters capacity of prototype solar dryer. The 150 ml aluminum cans were used to contain the PCM. Their results have shown that PCM could retain temperature above the ambient temperature in solar dryer for 2 hour after sunset (after 6 O'clock). Later Pakorn and Suthathid [13] 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 [13]. 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 used of kerosene cause for the smell problem.

This research aims 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 dying process in the solar dryer. In order to avoid the kerosene smelling problem the Vaseline has been used in this research [14]. A Paraffin-Vaseline mixture is used as PCM with the mixer ratio of Paraffin to Vaseline are 3:1, 2:1 and 1:1 for the experiments. The effects of amount of PCM used in a solar dryer are also investigated by varied the amount of PCM volume at 10% 20% and 30% of the volume of a solar dryer.

II. EXPERIMENT

In order to develop a meaningful mathematical model which can be used in practice. The experiment was divided into three steps, in the first step the basic properties of paraffin-Vaseline mixtures which would be used as PCMs were determined by using DSC, in the second step the melting rate of designed PCMs was investigated, and lastly in the third step the temperature respond in the solar dryer with PCMs during 4 hours of charging and then discharging immediately for another 4 hours were recorded and used as data for the developing of the mathematical model. The details of each experiment step will be explained as follows:

2.1 Preparation and the melting point measurement:

The PCMs are 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 were shown in **TABLE 1**

2.2 The Melting test:

The melting test has been performed by putting a 100 g. of solid sample of each PCM on a grille or a sieve plate of the melting test container as shown in **Fig. 1**, and then placed in the container in the control temperature 65-85^{o}C dryer (the test temperature of 65-85^{o}C is refer in the previous experiment for the average solar energy each day [10,13, 15-17]). At each hour interval the test container was removed from the dryer and the lower part of the container was weight to determine the weight of melted PCM until the 4 hours is reached. The PCM of each mixing ratio (P:V at 3:1, 2:1 and 1:1) was tested by the same procedure, and the test results are shown in **Fig. 3.**

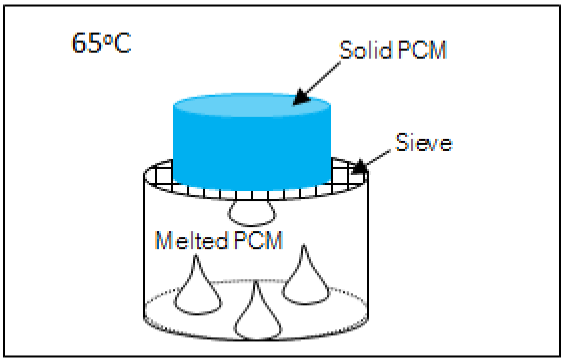

Fig. 1 Melting test PCM in control solar dryer system at temperature at 65 °C.

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

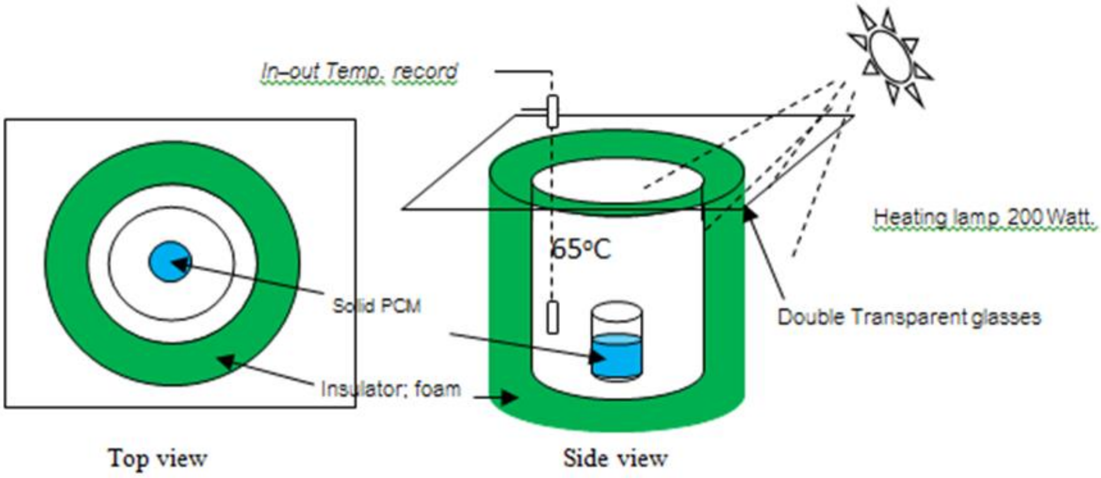

Fig. 2 Charging and discharging of each composition of PCM in small scale solar dryer

Fig. 2 shows the small scale solar dryer which is modified to use in the test [13]. It 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 has lined with the black-painted aluminum sheet with a translucent glass plate acts 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 can be adjusted to obtain the average temperature inside the dryer to be in the range of 65-85°C when the dryer is empty (no PCM). Both the dryers and the PCM test sample are allowed to settle at the room temperature before the test start. Then the PCM was placed in the dryer, set the distance of the lamp and then switch on the lamp on for 4 hours (charging) before switch off and allowed the PCM to discharge for another 4 hours, record the temperatures both inside and outside the dryer for total 8 hours. The experimental set up is shown in **Fig. 2.**

III. RESULT AND DISCUSSION

3.1 Result of DSC:

TABLE 1 THE THERMAL PROPERTIES OF PCM MEASURED BY DSC

PCM Ratio Paraffin :Vaseline	Melting Point (°C)	Latent Heat (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

Result of DSC for thermal testing to measure melting point and Thermal properties of PCM has shown in **TABLE 1**. The results form DSC are show in **TABLE 1** the melting point and latent heat of PCM decrease with the increasing of Vaseline in PCM because Vaseline has lower melting point and latent heat.

3.2 PCM Melted:

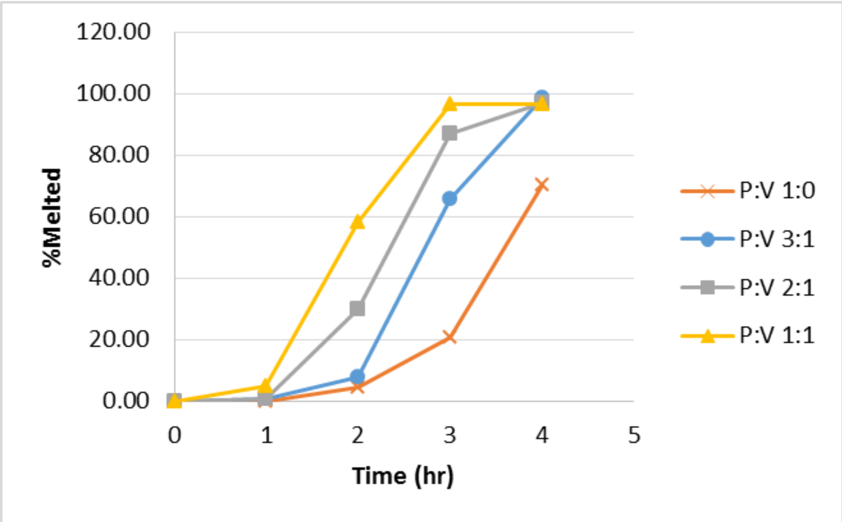

Fig. 3 The Percentage by mass in Melting of various compositions (P:V) of PCM.

All PCM tested have melting points (as shown in **TABLE 1**) lower than 65^{o}C, all of them completely melt after 4 hours in 65^{o}C test chamber apart from the pure Paraffin specimen which did not completely melt. This seems to suggest that the ability to store heat energy of any substance is not only depending 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 remain solid. From the **Fig. 3** for the charging period of 4 hours at 65^{o}C the PCM with the various compositions (mixing ratio P:V) of 3:1 seems to offer the best alternative since it just melted completely at 4 hours.

3.3 PCM in small scale solar dryer (Charging and discharging):

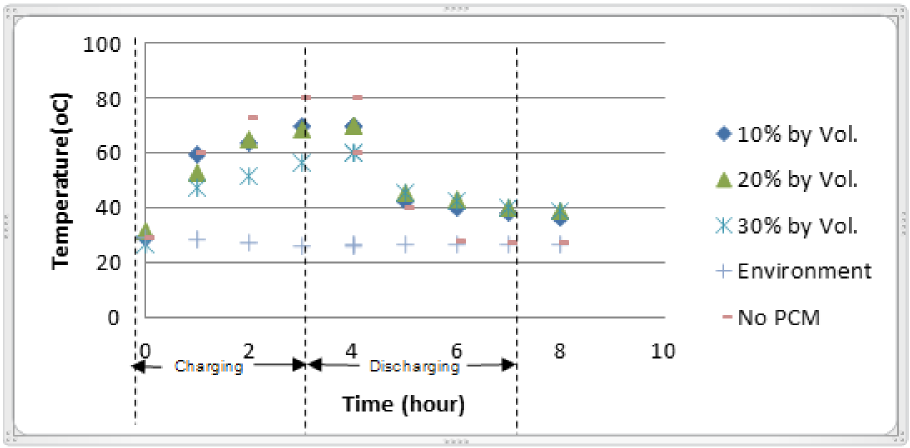

Fig. 4 Variation temperatures in a small scale solar dryer during charging and discharging with PCM P:V (3:1) with 10%, 20% , 30% volume fraction and without PCM.

The temperatures respond in dryers can be divided into two periods. In the first or charging period the heat energy is accumulated and stored in the PCM results in the rise of temperature, and the second or discharging period the heat energy which has been stores is released results in temperature drops.

During the charging period adding PCM will reduce the peak temperature with suitable PCM the possibility of dryer over heat is reduced or eliminated, the temperature with in this charging period will be more stable. While during the discharging period the PCM will help to maintain the temperature inside the dryer better than the case of no PCM as shown in **Fig. 4**.

3.4 Analysis experimental results:

The average temperature inside the dryer at a particular time (t) is estimated using mathematical model proposed by Malasai [14, 18]. 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 (T_{est}) approaching the maximum possible temperature $(T_{\max})$ under a certain thermal energy input is governed by the first-order equation of the form:-

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

The rate constant k differs per dryer; 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:-

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

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

where T_p = Peak temperature, temperature at the start of the discharging period or a final temperature of the charging period (°C) and 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 can be obtain by fitting the Equations (2) and (3) for charging and discharging periods respectively to the corresponding experimental results using Excel SOLVER as showed in **TABLE 2**.

TABLE 2 THE CONSTANT (k) OF EACH DRYER WITH DIFFERENT COMPOSITION (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 incorporate PCM with various ratio of Paraffin:Vaseline into the solar dryer but with a different volume(in term of volume fraction or % of PCM volume or heat storage capacity) on the values of the rate constant k are shown in **TABLE 2**. From **Fig. 5,** it can be noticed that as the value of the rate constant k reduces the responding rate and the fluctuations of the average temperature inside the dryer also reduces. When the rate constant k is high the temperature can rise or drop quickly, hence in order to maintain required temperature sufficiently long after heat energy input is removed the rate constant k needs to be sufficiently low. The accuracy of estimated temperatures as given by the model is acceptable as seen in **Fig. 5** when comparing with the experimental measured temperatures.

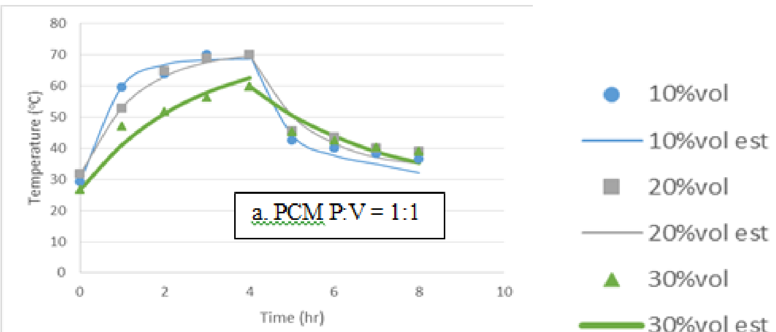

Fig. 5a

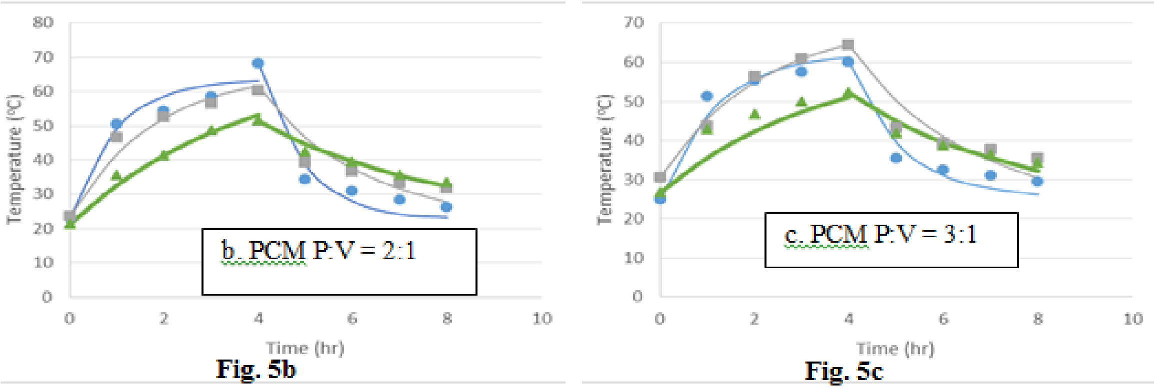

Fig. 5 Temperature response in solar dryer with various (P:V) PCM at 10%, 20% and 30% volume fractions during charging and discharging periods**.** (P:V in **Fig. 5a**, **5b** and **5c** are 1:1, 2:1 and 3:1 respectively) by using **Equation (1)** for charging and **Equation (2)** for discharging.

The experimental results indicated that the solar dryer with a lower rate constant k can retain required temperature for a longer period during discharging. This seems to suggest that the larger volume fraction of PCM used is better. However in the plots of the volume fraction of PCM against the value of the rate constant k as shown in **Fig. 6**, it can be seen that the effect of increasing volume fraction of PCM is diminished. Any addition of volume fraction of PCM above 30% has very little effect on lower the value of the rate constant k, but it is likely to reduce the working space inside the dryer to the point of impractical. This diminishing effect is due to the fact that the extra PCM added has no chance to completely melt during the charging period which can be caused by either the heat energy input is not sufficient or the charging period is to shot, if this allowed to happen then the PCM is 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 = The 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

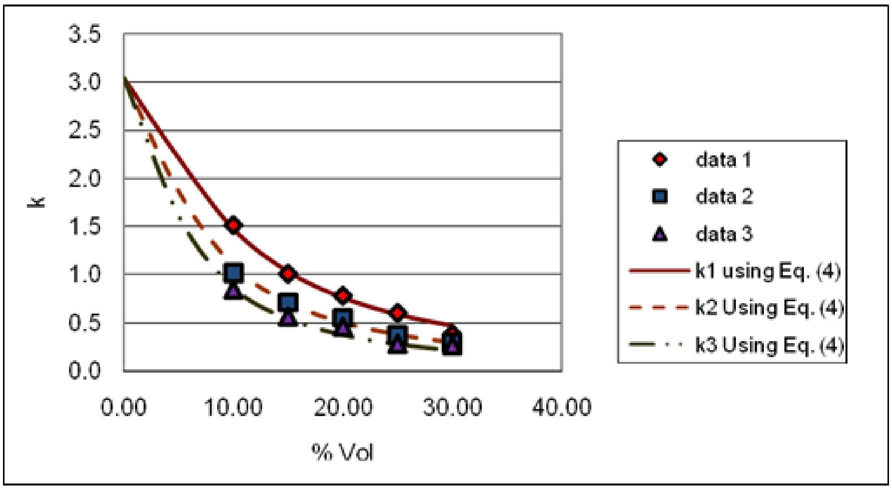

Fig. 6 The rate of constant (k_1, k_2, k_3) and Percent by volume of PCM for various mixing ratio P:V 1:1, 2:1 and 3:1 respectively

The plot of the Empirical **Equation (4)** in comparison to the experimental data is shown in **Fig. 6**, from this plot it is obvious that the first 15% addition of PCM is very effective in reducing the value of the rate constant k , the reduction to about 1/3 to 1/4 of the k_o is achievable.

3.5 Implication of the Model for solar dryer:

The model developed can be used as a guide to improve the solar dryer design especially in the case of solar dryer improvement by incorporated the PCM to the dryer. If the target temperature inside the solar dryer is about 50 to 60 ^oC 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 using equation (2) with (T_{est}) is set to target temperature for required charging period . The suitable P:V mixing ratio and the % Volume of PCM required can be solved using **Equation (4)**.

TABLE 3 AMOUNT OF PCM IN VOLUME RATIO REQUIRED TO PROVIDE TARGET TEMPERATURE WITHIN THE RANGE OF 50-60^{o}C AFTER 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

TABLE 3 below shows the results of this approach, the temperatures inside the dryer after 4 hours of charging in the case of no PCM used are shown in the first column, and if the target temperatures after 4 hours of charging is in the range of 50 to 60 ^{o}C then the amount of PCM (% by Volume) of three mixing ratio required to maintain the target temperature are shown in next three columns.

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 discharging period.

IV. CONCLUSION

Thermal properties of PCM can be design by selecting substances or compounds which have thermal properties close the requirement then combining or mixing the compounds to form the required PCM. By mixing Paraffin and Vaseline with various ratio the melting point of design PCM can be adjusted to be between the melting point of Paraffin and Vaseline. The ability of PCM to melt at target temperature is very important in the control of the temperature inside the dryer. However the percentage of melting PCM at the end of discharging period may not have great effect on the performance of the dryer. It was found that the PCM with maxing ratio of 3:1 has melting point at 51.23^{o}C and latent heat of 99.149 kJ/kg is practical. This research also shown that it is possible for the experiment with PCM in small scale solar dryer can generate the sufficient test data to verify the accuracy of the mathematical model in order to estimate the average temperature during the charging period **Equation (2)** and the retaining temperature during the discharging period **Equation (3)**. It has shown that the rate constant (k) reflects the general temperature behavior in the sense that the rapid respond of temperature inside the dryer indicated by the high value of k whereas the low value of k corresponding to more stable response as shown in **Equation (4)**. The Experimental data and mathematical model were used to construct **TABLE 3** to be used as a guide line for selecting the right amount of P:V of PCM required for a solar dryer in the practice with the inside temperature target in the range 50 to 60^{o}C.

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