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High School Exploration of a Phase Change Material as a Thermal Energy Storage

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ABSTRACT. The present study describes a hands-on experiment to help students understand the concept of phase change or phase transition and its application in a phase change material (PCM). PCMs are substances that have the capability of storing and releasing large amounts of thermal energy. They act as energy storage materials that provide an effective way to save energy by reducing the electricity required for heating and cooling. Lauric acid (LA) was selected as an example of the PCM. Students investigated the temperature change of LA and the temperature (of air) inside the test tube. The differences in the temperatures of the systems helped students understand how PCMs work. A one-group pretest and posttest design was implemented with 34 grade-11 students in science and mathematics. Students' understanding was assessed using a multiple-choice test and a questionnaire. The findings revealed that the designed activity helped students understand the concept of phase change and its application to materials for thermal energy storage.

Key words: Phases change, Phase transition, Hands-on activity, High school laboratory, Introductory chemistry

INTRODUCTION

A phase change material (PCM) is a substance that absorbs or releases large amounts of thermal energy during the physical transition state of melting and freezing, i.e. from solid to liquid and vice versa. The energy absorbed or released at a certain temperature during the phase transition is called latent heat.[1–3] The stored energy is continually released to the environment during the change of the state from liquid to solid when the temperature of the environment drops to the freezing point. PCMs function like a thermal buffer, which can be used to control the temperature of a system.[1,4] Different materials have different latent heats of fusion and different melting points.[5] The choice in the usage of PCMs is made based on the requirements of the application.

The interest in PCMs has grown significantly over the last decade as an alternative solution for thermal energy conversion storage and temperature control for buildings,[6–10] thermal energy storage and management systems for electronic components,[11] photovoltaic modules,[12] thermoregulation of textiles,[13–14] refrigerators,[15] cold storage packages,[16–18] and so on. Currently, several commercial products have arrived on the market with various areas of applications.[19–22] For this reason, introducing PCMs and their applications to students in a meaningful context for learning the concept of *phase change* is presented in this work. Some reports related to the concept of phase change are published in this journal.[23–25]

The objectives of the present study are 1) to help students understand the concept of phase change; and 2) to help students understand the working principle of PCMs as thermal energy storage. The learning activity was designed as a hands-on experiment. Students observe and record temperature changes in systems with and without a PCM. The differences in the temperatures of the systems help students understand how PCMs work.

EXPERIMENTAL

Materials and Experimental Setup

Lauric acid (LA, content 99%) from ACROS Organics was purchased from Italmar (Thailand) Co., Ltd, and used as is without further purification. Thermocouples with a data logger were used for measuring the temperature. A water bath was used as a heat source.

The students first set up the apparatus as in *Fig.* 1. LA was used as the PCM. It has the melting point of about 43 °C. The students observed and recorded the temperature changes during the experiment. Five grams of LA was used. A water bath filled with glycerol was used as the heating source. Three thermocouples were used to measure the temperature changes of the experiment: the 1st

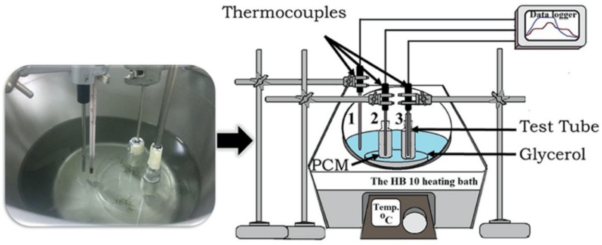


***Figure* 1.** Diagram of the apparatus used to study phase changes and how PCMs work.

thermocouple measured the temperature of the glycerol in the water bath (as the environment temperature); the 2nd thermocouple measured the temperature of the LA inside the vial; and the 3rd thermocouple measured the temperature of the air inside the test tube inserted in the vial containing the LA. The temperature changes in the glycerol, the LA, and the air inside the test tube were recorded using a data logger. The data logger started to record the temperature changes before the water bath was turned on and the recording continued until the temperature of the whole system cooled down to room temperature or the three thermocouples gave the same reading. The water bath would be turned on until the LA completely melted.

Description of Implementation

Before the experiment, the students engaged in an experiment to understand the effect of temperature or heat on the kinetic energy of substance based on the addition of a food-coloring pigment in hot water and cold water without stirring. The students observed and compared the movement of the food coloring in hot water and cold water. The difference in the diffusion of the pigments throughout the beakers was used to explain how increasing temperature will increase kinetic energy. This activity aimed to guide the students to think more on the molecular level, which would help explain what happened to the material during the phase change. Thirty–four high school students participated in this study. They were divided randomly into a group of 4–5 students. They were asked to explain the result with the use of evidence to support their claims. The questionnaire (three situations) related to the basic concepts of PCMs and a multiple–choice test containing 21 questions were used to assess the students' understanding before and after the activities.

RESULTS AND DISCUSSION

Effects of Temperature on the Kinetic Energy

As seen from *Fig.* 2, the food coloring in hot water diffused throughout the water, while that in cold water did so in a much lesser extent. This laboratory demonstration helped the students understand the effect of temperature (or energy) on the molecules in the material. This demonstration helped them to understand that increasing the energy made the molecules move faster (increased kinetic energy) and to intuitively visualize the microscopic level during the phase transition of PCMs.

Heating and Cooling Curves of the PCM

Fig. 3 shows an example of the students' results obtained for the heating and cooling curves of LA. The heating and cooling curves clearly show that the temperature of LA and the temperature inside the test tube with LA were stable at about 43 °C, which is the melting point of LA. The temperature of the glycerol (environment) was maintained at ~46 °C. If the temperature of glycerol was significantly higher than 46 °C, we would not clearly see the effect of PCM to maintain a constant temperature of the air inside the test tube during the phase transition (of the heating

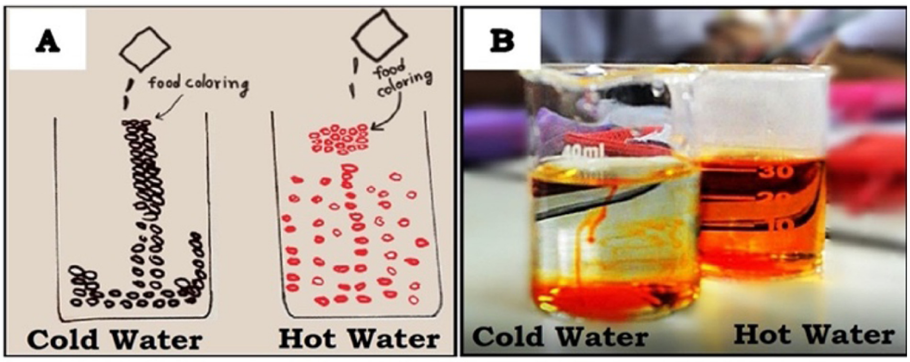


***Figure* 2.** (A) Student's illustration of the movement of food coloring in hot water and cold water; and (B) the picture of the food coloring in hot water and cold water after ~ 5 minutes.

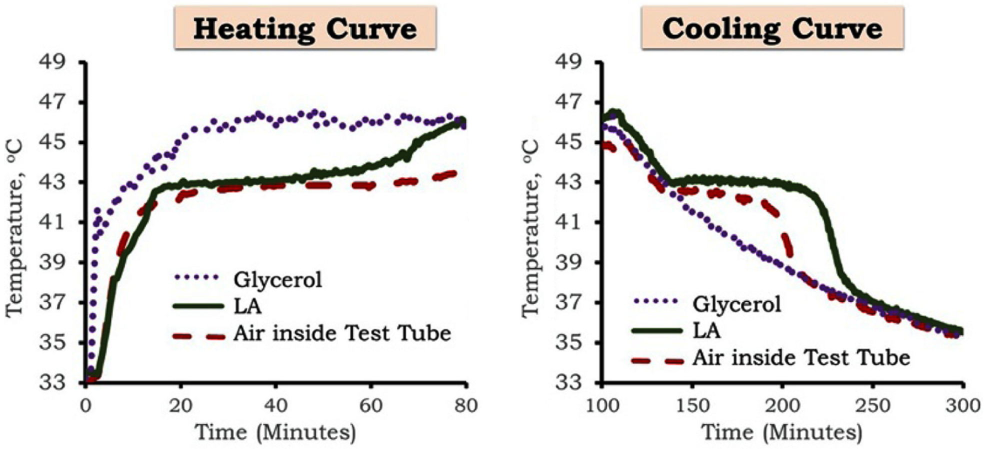


***Figure* 3.** Students' results of the heating and cooling curves.

curve). The LA started to melt after being heated for about 15 min. The heating and cooling curves of the air inside the test tube were quite similar to the heating and cooling curves of LA. This was because the heat energy inside the test tube (surrounded by the LA) was absorbed and released by the LA, which helped maintain the temperature inside the test tube at about the melting point of LA. In addition, the temperature of the air inside the test tube increased at a slower rate compared to the increase in temperature of the environment (glycerol). This slower-late of increasing temperature during the daytime can help shift peak load to off-peak hours, reducing electricity bills.[26] The capability to store and release large amounts of thermal energy of PCMs can provide an effective way to save energy by reducing the electricity required for heating and cooling. The students could observe the phase transition of LA directly during the experiment, which helped them understand how the PCMs work.

***Table* 1.** Students' scores for the pre– and posttests

Concepts	Mean Scores (SD)		t	p
	Pre	Post		
Phase change (12 items)	3.03 (1.49)	9.35 (1.56)	19.06	0.00*
Applications of PCMs (9 items)	3.03 (1.57)	5.68 (1.34)	9.69	0.00*

*Significant difference at 0.05

Students' Learning Outcomes

Multiple choice test. The students' scores from the pretest and posttest were analyzed using a paired-samples *t*–test to identify the mean differences between the pre- and post-scores at the significance level of 0.05, as shown in *Table* 1. Before conducting the paired–samples *t*–test analysis, the pre– and post-scores of the students were normally distributed as confirmed by the Shapiro–Wilk test ($p > 0.05$).

Questionnaire. The questionnaire was used to assess the students' ability to explain situations concerning the concepts of phase change and applications of PCMs. The questions were adapted from the questionnaire for measuring chemical literacy.[27–28] Each situation was followed by 5–7 sentences related to the topic. Three situations were used. The students were asked to determine whether the sentence was true or false, and if the sentence was incorrect, they had to write down the correct answer. The Wilcoxon signed rank test was used to determine whether there was a significant difference between pre– and posttest scores, as shown in *Table* 2. The percentages of the students' answers to items 1–3 are shown in *Tables* 3–5. The Wilcoxon signed ranks test's results show that the students' pre- and post-scores were significantly different for all situations (Situation 1, Z = 5.13, $p = 0.00$; Situation 2, Z = 4.75, $p = 0.00$; Situation 3, Z = 4.66, $p = 0.00$; overall scores, Z = 5.09, $p = 0.00$). The overall mean scores of the pretest and posttest were 5.21 and 13.12, respectively. These results indicated that the students improved their conceptual understanding after participating in the activity.

Table 3 shows that most of the students understand the melting of coconut oil and water. The percentages of students' correct answers range from 61.8 to 97.1, while the percentages of students' incorrect answers range from 2.9 to 38.2. Some students were still confused about the temperature change during the phase change.[19] However, the results of items 3 and 6 show a large improvement in the percentages of students' correct answers from 0% of the pretest to 61.8% and 70.6% of the posttest, respectively. In

***Table* 2.** Wilcoxon signed ranks test of conceptual literacy from the pre- and posttest

Situation	Mean (SD)	Z	p	Mean rank (*n*)		Ties (*n*)
				Negative	Positive	
Situation 1: (7 points)						
Pre	2.53 (0.93)	5.13	0.00*	0.00 (0)	17.50 (34)	0
Post	5.94 (1.04)					
Situation 2: (5 points)						
Pre	1.68 (0.98)	4.75	0.00*	0.00 (0)	15.00 (29)	5
Post	3.56 (0.71)					
Situation 3: (5 points)						
Pre	1.00 (0.85)	4.66	0.00*	0.00 (0)	15.00 (29)	5
Post	3.62 (1.23)					
Overall scores: (17 points)						
Pre	5.21 (2.06)	5.09	0.00*	0.00 (0)	17.50 (34)	0
Post	13.12 (2.34)					

*Significant difference at 0.05

***Table* 3.** Percentages of students' answers to pre- and post-questionnaire, situation 1 (n=34)

The melting points of coconut oil and water are 25 °C and 0 °C, respectively. Bring the coconut oil and water that have the temperature of about 30 °C into a refrigerator at –15 °C at the same time. Please indicate whether the statements below are true or false.

Items	Statements	% of students' answer			
		Correct		Incorrect	
		Pre	Post	Pre	Post
1	The water will freeze before the coconut oil. (Answer: False)	17.6	91.2	82.4	8.8
2	The coconut oil's temperature will stable at ~25 °C for some time while freezing. After that, the temperature will decrease. (Answer: True)	52.9	91.2	47.1	8.8
3	During freezing, the kinetic energy of water and coconut oil will increase. (Answer: False)	0	61.8	100	38.2
4	During freezing, the average kinetic energy of water and coconut oil remains constant. (Answer: True)	44.1	88.2	55.9	11.8
5	The melting of coconut oil and water occurs at their freezing temperature. (Answer: True)	58.8	94.1	41.2	5.9
6	If we take the frozen coconut oil and water from the refrigerator to a room temperature 30 °C, the coconut oil will melt first. (Answer: False)	0	70.6	100	29.4
7	The latent heat is the energy required for freezing or melting. (Answer: True)	79.4	97.1	20.6	2.9
Average		36.1	84.9	63.9	15.1

addition, 84.9% of students understood the phase change of coconut oil after they participated in the activity.

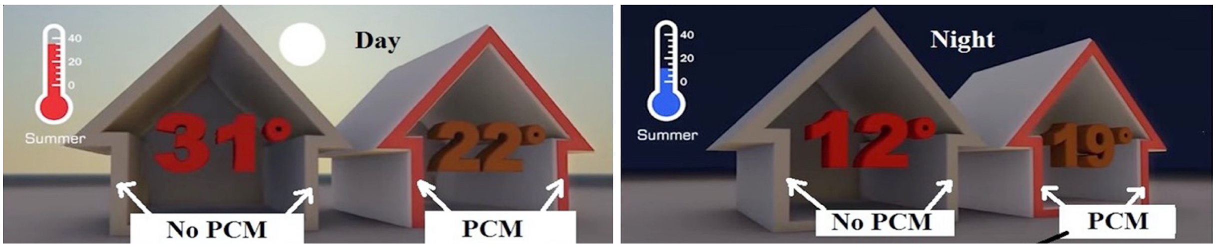
Table 4 shows that the percentages of the students' correct answers range from 8.8 to 97.1, while the percentages of the students' incorrect answers range from 2.9 to 91.2. The results of items 2 and 3 show that more than 50% of students improved their understanding. These results show that students could connect their understanding of the hands-on activity to explain the application of PCMs. However, some students still have misunderstandings. Examples of students' misunderstanding are; "*(Item 3) PCMs are insulator.*", *and* "*(Item 5) The temperature inside the buildings lower than the melting point and freezing point of PCMs during the daytime and night.*"

The highest percentage of students answered item 5 incorrectly in the posttest (91.2%). This might be because some students still misunderstood that the PCM was an insulator which helped maintain the building's temperature. On the other hand, some students might not carefully read the question, which asked them to consider the case when the temperature was below the melting point of the PCM. Therefore, they thought that the statement was correct.

Table 5 shows that the percentages of the students' correct answers range between 38.2 and 94.1, while the percentages of the students' incorrect answers range between 8.8 and 61.8. The highest percentage of students answer item 5 incorrectly in the posttest (61.8%). This item was used to check student's understanding at the microscopic level, which is abstract. They might think only about the solid particles inside the ice structure. Therefore, they can only collide with other particles around them. These results

***Table* 4.** Percentages of students' answers to pre– and post–questionnaire, situation 2 (*n*=34)

From the picture, please indicate whether the statements below are true or false.



Items	Statements	% of students' answer			
		Correct		Incorrect	
		Pre	Post	Pre	Post
1	During the daytime and nighttime, PCMs can store and release heat energy, which helps control the temperature in the building. (Answer: True)	67.6	97.1	32.4	2.9
2	In the daytime, after the ambient temperature reaches the melting point of the PCMs. The PCMs will melt. During melting, the PCMs will absorb the heat energy in the building, which helps slow down the building's temperature. (Answer: True)	41.2	97.1	58.8	2.9
3	PCMs can help control the temperature inside the buildings because PCMs are good insulators. (Answer: False)	0	55.9	100	44.1
4	In the nighttime, after the ambient temperature lower than the freezing point of the PCMs, the PCMs will solidify and release the heat energy. This helps keep the building warm. (Answer: True)	58.8	97.1	41.2	2.9
5	The PCMs in buildings can help maintain the temperature inside the buildings below the melting point or freezing point of the PCMs. (Answer: False)	0	8.8	100	91.2
	Average	33.5	71.2	66.5	28.8

***Table* 5.** Percent of students' answers to pre– and post–questionnaire, situation 3 (*n*=34)

The statements below are related to the process of ice-melting. Please indicate whether the statements below are true or false.

Items	Statements	% of students' answer			
		Correct		Incorrect	
		Pre	Post	Pre	Post
1	During the phase transition, the temperature remains constant because the molecules or particles move freely at the same speed. So, the average kinetic energy is constant. (Answer: False)	5.9	67.6	94.1	32.4
2	There are two states coexisting, solid and liquid, during a phase transition from solid to liquid. Some particles move fast, and some particles move slow. (Answer: True)	52.9	91.2	47.1	8.8
3	During the melting process, the potential energy and kinetic energy of molecules remain constant. (Answer: False)	0	70.6	100	29.4
4	Substances can change state when they are heated or cooled. For example, when a solid material is heated, the heat energy can be transfer to molecules, and the molecules will move faster. If the supplied heat is enough to break down the lattice structure, they can change the state from solid to liquid. (Answer: True)	38.2	94.1	61.8	5.9
5	During the phase transition, there are both solid and liquid states of water. The molecules in the liquid state will collide with each other and also with those in the solid state. However, the solid particles collide with only the solid particles. (Answer: false)	2.9	38.2	97.1	61.8
	Average	20.0	72.3	80.0	27.7

show that the students still had difficulty imagining about the molecular movement during the phase change. However, the intervention of this study helped students understand better about the concepts of potential energy and kinetic energy of molecules, as shown by the result of item 3 where 0% of students on the pretest correctly answered, but on the post test, 70.6% were correct. The overall results show that most of the students were able to make the connection among the molecular movement, the kinetic energy, and the phase change at the end of learning.

CONCLUSION

This study provided a simple experiment to help high school students understand the concept of phase change and its application in a phase change material. PCMs are solutions to contemporary energy storage engineering that provide an effective way to save energy by reducing the electricity required for heating and cooling. The LA was selected as an example of a PCM because of its melting point and because it is nonhazardous. Students investigated the temperature change in the system. The change of temperature inside the test tube, which differs from the environment's temperature (glycerol), indicated how the PCM work. This experiment illustrates the phenomena as a practical means of the real application of the PCMs. The findings from students' multiple–choice test and students' questionnaire revealed that the designed activity helped students understand the concept of phase change and its application to materials for thermal energy storage. However, some students still had difficulty in understanding the concept of phase change due to the abstract and unobservable nature of the microscopic level.[29–30] The use of simulation or animation to help students see what happens during phase change would help students understand better. The laboratory experiment was designed to keep everything not too difficult for a high school student level. However, this basic, but important, thermodynamics concept of the heat of fusion from the aspect of phase change materials can easily be expanded and adapted for higher education, such as by including the concept of crystal formation, entropy, and the volume changes of crystallization and melting. Also, designing more difficult and complex questions to serve the level of skills and knowledge of higher education would also be appropriate.

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