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Thermal Enhancement for Paraffinic Thermal Energy Storage by Adding Volcanic Ash

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ABSTRACT

Thermal energy storage has a good opportunity to be applied in engineering field, especially for low temperature application like automotive thermal management system. Paraffinic is a better option and considered as a good phase change material with main advantages like economically feasible, non-corrosive and safe. The main drawbacks of paraffinic system are low thermal conductivity and supercooling effect. The effort to improve the performance for paraffinic system is by g sensible material. Considering the spread of volcano in Indonesia, it can be used as sensible material for paraffinic system. The aim of the research is to examine the volcanic ash characteristic and the effect of sand addition on the paraffinic system. a standardized approach for sand examination is done and the effect of the hybrid PCM (90% paraffin and 10% volcanic ash mass ratio) are studied. The overall performance of hybrid PCM is better than pure paraffin where the vapor point of hybrid PCM is increased and there is no supercooling phenomenon observed.

Keywords: Automotive thermal management system, Paraffin, PCM, Thermal energy storage, Volcanic ash

INTRODUCTION

The thermal energy storage system is an essential key in utilizing heat energy sources, such as Concentrated Solar Power (CSP) systems [1][2][3]. Thermal energy storage systems can also be developed for solar water heating systems [4][5][6][7], seawater desalination systems [8][9][10], and also the utilization of thermal waste in vehicles through vehicle thermal management systems [11][12][13]. Heat storage systems can also be utilized for domestic warm water supply systems for sub-tropical countries [14].

Focused at the application of the Concentrated Solar Power (CSP), the thermal energy storage plays the critical role to improve the overall performance and reducing energy cost because with proper thermal energy storage the system can work at a longer period (during the night time or cloudy day) [15][16][17]. The application of thermal storage in a CSP system can be addressed according to the working temperature of the CSP system [18][19][20]. There are three types of thermal energy storage material based on the characteristic of the material; there are sensible, latent and thermochemical heat [21]. Thermochemical heat has the highest theoretically capacity but has not widely used for real application and still under research and development phase [22]. Sensible heat has mature technology and widely used in various application, especially for water heater storage, but it has a drawback that it depends on the volume and mass of the storage material. Thus it has lower energy density which increased the cost per unit energy [23][24]. An alternative option that can be further developed is the phase change material (PCM) latent heat storage system [25].

The recommended PCM material is generally paraffin-based. Paraffin is a material that is very commonly used as a PCM material with consideration of safer, stable, non-corrosive and low prices and a reasonably wide temperature range (5-80ºC) [26][27][28]. One of the main challenges of applying paraffin as PCM is low thermal conductivity and low enthalpy of phase change. An alternative solution to improve the nature of paraffin as a TES is through integration with sensible heat materials, such as water, sand and rocks. The application of sand is recommended because it has good thermal conductivity, abundant availability and considered cheap [29].

There were some researched to improve the performance of PCM based paraffin for thermal storage application. The effort mostly by g sensible material or additive and also enhancement the packaging model of the material. [30] developed PCM material based on high-density polyethene (HDPE) composites with expanded graphite (EG) and ammonium polyphosphate (APP) found that the additional help to increase the temperature of the maximum weight loss of the PCM composites at 650^{o}C. S. [31] simulated the dynamic charging characteristics with spherical capsules using paraffin as a heat storage material for solar heat storage system the influence of porosity of packed bed on time for complete solidification is not so significant. [32] analyzed the addition of aluminum foil from waste material to increase the thermal conductivity of the paraffin storage material using paraffin wax with 8% w/w of aluminum foils and found the thermal conductivity increased up to 0.63 W/mK. [24] a suitable proportion of expanded graphite (EG) into the paraffin can enhance the heat transfer rate, thus improve the thermal efficiency of the whole heat storage system.

[33] proved that the addition of TiO2-Ag nanocomposite particles able to improved thermal properties of PCM storage. [34] studied the effect of nanoencapsulation of paraffin wax with a polyurethane-based shell and found the energy storage efficiency and the energy storage capacity of adequate nanocapsules are 80.2% and 97.5%, respectively. [35] investigated the combination of paraffin and carbon-coated nanoscroll to improve the thermal conductivities and found that the thermal conductivities of the paraffin and carbon-coated nanoscroll were increased by 1.98, 1.92, 2.7 and 2.01 times compared to pure paraffin.

The addition of additive material can be considered as an easy and cheap method to improve paraffin performance as thermal energy storage. For lower temperature application, the addition of sensible heat material like water, rock and sand considered as the easiest and cheapest way to enhancing the paraffin performance [36][37][32]. The recommended working area for sensible-PCM as thermal storage in the solid-liquid transition is known better than the liquid-vapor phase and the solid-solid phase [38][39][40][41]. [42] conducted an experimental test for hybrid sensible/latent storage for hot water applications by utilizing commercial paraffin grade and hydrate salt mixture and found that the heat storage capacity increased for the system. For combined system (*hybrid material*). [43] states that combined sensible-latent material can be used to tackle the drawback of PCM material. However, in most cases, it leads to another problem, such as higher cost and material compatibilities issues. Therefore, the addition of sensible material must take account of these barriers.

The addition of sensible material should be done carefully because it will decrease the total amount of the paraffin incorporated in the PCM and thus, the overall thermal efficiency and capacity will be reduced. From the data references and previous researches, the maximum of the additive in the PCM should be equal or lower than 50% [44]. Sand is well known sensible thermal storage material. The application of sand is recommended because it has good thermal conductivity, abundant availability and low cost [45][46][47][43]. It is crucial to examine the detail properties and its effect of the PCM performance to obtain a better understanding to specify the proper application of the thermal storage and also the fabrication of the bed storage [48].

The data from previous research is limited and do not specify the type of sand, sand properties, both chemical elements and grain size and the proportion between sand and the paraffin. To study the effect of the sand for the PCM, it needs to be further investigated the chemical and physical properties from the sand. In this study, the sand comes from volcanic ash. The primary motivation to choose volcanic sand as the sensible material is due to the higher metal content of this sand. The next consideration is that the bulk size of the sand is generally finer than other sand so that it is expected to get an average size that is larger than the bulk size without having to be further processed to reduce the size of the sand grains. Besides, the potential of volcanic ash in Indonesia is quite vast due to volcanoes, so it is easily obtained. The study aims to examine the chemical and physical properties of the sand. Once the data from the sand has obtained, experimental testing is done by mixing paraffin with sand in different portions and grain size. From the experimental result the detailed phase-change transition of the paraffin, the temperature of the phase transition and the duration for charging and discharging the sample can be investigated; thus, a detailed conclusion of the material performance can be made, and it can be used as reliable references for the further application of the material as thermal storage.

RESEARCH METHOD

The sand from volcanic ash for this research does not have MSDS so the first step that needs to be studied is to evaluate the chemical content of the sand and its intensive properties. The preparation is started by ensure the particle size uniformity of the sand through the sieve test. The sieve test was carried out to determine the average size of the sand particles with the target particle size used is 44 μm. The sieve test procedure follows the NIST 906-1 standard [48].

Furthermore, chemical content in the uniformed sand was observed using an atomic absorption spectrometer under ASTM D 4691-17 standard [49]. After observation using AAS, intensive properties were observed using a density test and probe test according to ASTM D-1298 [50] and ASTM D 5091-95 standards [51]. The use of standardized procedure is to ensure a better measurement for a valid research result.

Two different samples were prepared; pure paraffin (commercial grade 155/160, MSDS [52] and hybrid PCM consisting of 90% paraffin and 10% volcanic ash based on mass ratio. The addition of 10% volcanic ash was carried out with the aim to avoid decreased overall thermal capacity for the PCM as it was associated with a reduction in the capacity of paraffin as a PCM material. The test is carried out by using the High-Pressure High-Temperature apparatus (Fann HPHT) based on the ASTM D87-04. This test is carried out to determine important temperature changes in time units for the initial melting point

(T_{melt}), fully melting point (T_{Fmelt}) and vapor point (T_{vap}) during the charging process and solidification point (T_{solid}) and fully solidification point (T_{Fsolid}) during the discharging process.

RESULT AND DISCUSSION

Sand Characterizations

Sand characterization starts from uniform sand size without going through a mechanical process [53]. The goal is to know the average particle size of the sand in general. Table 1 shows the size of the sand after finishing the sieve test.

Table 1. Screening particle size of the sand

Test Sequence	Bulk Mass (grams)	Percentage of 44 μm (%)
1	40.64	38.83
2	38.59	46.18
3	39.82	44.30
4	37.51	45.19
5	41.05	37.59
6	41.84	38.93
7	38.28	43.78
8	42.24	42.45
9	38.67	37.65
10	37.85	42.91

Based on the data in table 1, the average size of the sand 44 μm is 41.72%. It is very beneficial because without going through the mechanical particle downsizing process, there is more than 40% of the 44 μm size. The smaller size allows for better sand dispersion on PCM. In addition, the smaller size makes it easier for mechanical particle downsizing if needed for further process.

Uniform size facilitates the characterization process to determine chemical contain in the sand [54]. Table 2 represent the result for Atomic Absorption Spectrometer.

Table 2. Chemical contents from the sand

Elements	Percentage (%)
Fe	51.23
Fe2O3	23.24
SiO2	11
Others	14.53

The chemical content of sand is dominated by iron and iron oxide, both of which are known as excellent thermal conductivity elements. Excellent thermal conductivity will facilitate the heat transfer process on PCM and can increase the power rate of thermal energy storage. Intensive testing properties of the sand is shown in Table 3.

Table 3. Intensive properties of the sand

Elements	**Value**	**Unit**
Average density	2.76	Gram/cm^3
Conductiviy	291	μS/cm
pH	8.77	-

Data table 3 supports the results of screening elements from table 2 where the dominance of metal elements causes a good sand conductivity value, the presence of iron oxide and silica oxide makes the pH value smaller, closer to neutral, and help to minimize the corrosivity rate in PCM.

Charging and Discharging Performance

Tests were carried out on two samples: pure paraffin and hybrid PCM with a mass ratio of 90% paraffin and 10% volcanic ash. The test shows an important temperature indicator in each sample and help to understand the characteristics of the temperature change per time. Figure 1 shows the pure paraffin charging test.

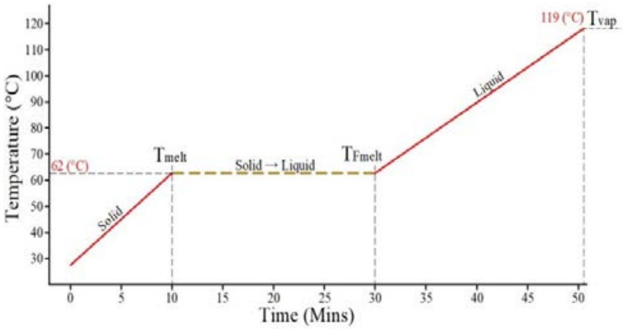

Figure 1. Charging for pure paraffin

Figure 1 the initial melting point (T_{melt}) for the paraffin is reached within 10 mins at 62^{o}C. The phase change (shown in brown dashed line) from initial melting point (T_{melt}) to fully melt (T_{Fmelt}) has done within 20 mins. As the heating process continued, the paraffin reachs the highest temperature point denoted as vapor point (T_{vap}) at 119^{o}C within 22 mins after the fully melting point (T_{Fmelt}). The total charging time (from $T_{ambient}$ to T_{vapor}) is 52 mins, with temperature range from 27^{o}C to 119^{o}C.

To make a comparison, Figure 2 represents the characteristic of the paraffin during discharging process where the temperature drops from T_{vapor} to $T_{ambient}$.

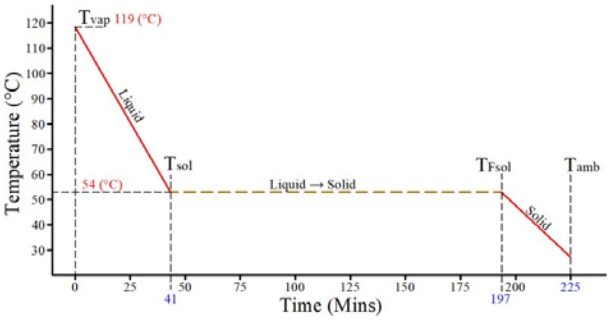

Figure 2. Discharging for pure paraffin

A significant difference is seen in the heat release process where it takes a longer time during discharging. the total time required for the paraffin to release the heat from T_{vapor} to $T_{ambient}$ (119^{o}C to 27^{o}C) is 225 mins. In addition, phase changes also occur over a longer duration and it is related with the nature of the phase change material where it tends to release heat at longer period during phase change change. The most important information is the significant difference between the starting point of the melting process at charging process and the starting point of freezing during discharging. The difference between these two points is 8^{o}C (T_{melt} is 62^{o}C and T_{sol} is 54^{o}C). The difference is known as supercooling phenomenon. A higher value of supercooling degree is a disadvantage because it makes the freezing process occur lower than the targeted temperature, leading to the possibility of decreasing the cycle of paraffin as thermal energy storage.

The addition of 10% sand to paraffin as a form of hybrid PCM material has a positive effect related to the increase in temperature absorption performance. Figure 3 shows the temperature and time function for hybrid PCM during charging process.

The positive effect from g volcanic ash into PCM can be seen from Figure 3 where the vapor point of the hybrid PCM is higher than the pure paraffin. The vapor point of hybrid PCM is 125 ^{o}C, higher 6 ^{o}C than pure paraffin. The increase in vapor point allows the hybrid PCM to work at relatively higher temperatures so the stored energy during sensible heat may be higher.

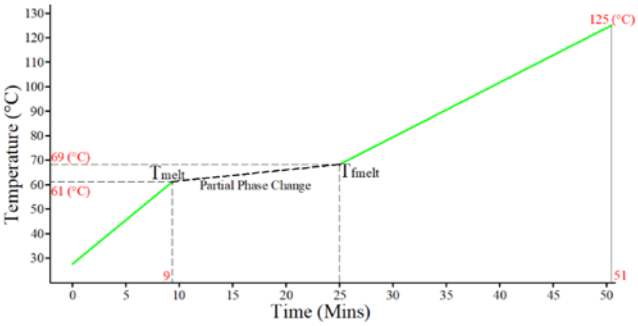

Figure 3. Charging for hybrid PCM (90% paraffin and 10% volcanic ash)

The next most important characteristic is that there is not fully phase change phenomenon as it observed from pure paraffin. It happens on hybrid PCM because it contains sensible material (volcanic ash) and led to a phenomenon called partial phase change or mushy region. The partial phase change promotes the increase in temperature can occur faster and allows an increase in the vapor point as seen in Figure 3. The phenomenon also gives the advantage that the charging process is faster where it takes 51 minutes to reach a higher vapor point.

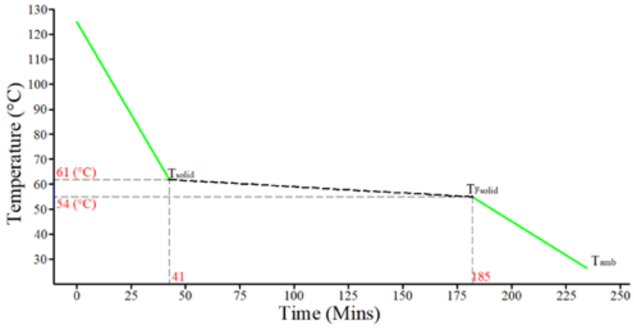

Figure 4. Discharging for hybrid PCM (90% paraffin and 10% volcanic ash)

For the final test of hybrid PCM, figure 4 shows the discharging process in the hybrid PCM. The total duration required for the hybrid PCM to drop to ambient temperature from the vapor point is 235 mins, which is longer than pure paraffin which takes only 225 minutes. This condition is specifically caused by the influence of the supercooling degree. The melting point (during charging) and solidification (during discharging) in hybrid PCM is the same at 61 ^{o}C, which means that the supercooling degree is 0. It is an important finding because the addition of volcanic ash can prevent supercooling. g volcanic ash can provide a more even heat distribution effect on the PCM and able to prevent supercooling.

CONCLUTIONS

The effort to improve the phase change material based on paraffin was done by g 10% volcanic ash with a particle size of 44 µm. The addition of volcanic ash material to PCM provides the following advantages:

a. Increase the vapor point from 119 ^{o}C to 125 ^{o}C, which means more energy can be absorbed by the hybrid PCM;
b. Accelerates the charging process from 52 minutes to 51 minutes at higher temperatures (125 ^{o}C);
c. Slows down the discharging process which means minimum heat losses.
d. And the most important thing is in the hybrid PCM there is no supercooling phenomenon.

Taking this into account, the addition of volcanic ash sand with these properties and characteristics can provide good benefits for hybrid PCM as a thermal energy storage. This can be used as a basis information for further development of hybrid PCM thermal energy storage materials for low temperature applications or automotive thermal management systems to minimize heat loss from the engine. Further development can be focused on the model and design of a generator type heat exchanger for hybrid PCM in thermal management system applications or low temperature applications.

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