Analysis of Thermal Energy Storage Based *on Phase Change of* Sugar Alcohol Type Material for *Solar Water Heater System*

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ABSTRACT

Meningkatnya pemanfaatan sumber energi terbarukan sebagai pengganti energi fosil tentu berfokus akan pentingnya aspek penyimpanan energi, khususnya Latent Heat Thermal Energy Storage. Diantara sejumlah Phase Change Material yang dapat dipergunakan dalam sistem tersebut maka Sugar Alcohol dengan kandungan latent heat yang tinggi dan jangkauan temperatur rendah hingga menengah, yaitu dibawah temperatur 140°C, sesuai untuk diterapkan pada teknologi Thermal Energy Storage khususnya Solar Water Heater. Penelitian ini menguji performa termal Sugar Alcohol bertipe Xylitol dan Erythritol, baik secara murni maupun dicampur dengan material komposit. Penggunaan High-Density Polyethilene sebanyak 10% dan 15% berat dipergunakan sebagai material penstabil pada saat transisi perubahan fasa liquid-solid. Metode pengujian yang dilakukan dalam penelitian ini menggunakan Hybrid Energy-Temperature Method, dimana sampel dipanaskan mulai dari temperatur lingkungan hingga mencapai temperatur 150°C kemudian didinginkan hingga mencapai temperatur lingkungan kembali, pada proses siklus charging/discharging, untuk menganalisis State of Charge dan Depth of Discharging dari sampel yang diuji. Penelitian ini juga menggunakan metode Differential Scanning Calorimetry dan Heat Capacity-isostep method untuk mengetahui perilaku perubahan fasa dari sampel dan menghitung jumlah kandungan energi total yang dimiliki oleh sampel yang terpilih.

Kata kunci: ***Latent Heat Thermal Energy Storage, Phase Change Material, Sugar Alcohol, State of Charge, State of Charge***

ABSTRACT

The increasing use of renewable energy sources as a substitute for fossil fuels certainly highlights the importance of energy storage aspects, especially Latent Heat Thermal Energy Storage. Among the various Phase Change Materials that can be used in the system, Sugar Alcohol, with a high latent heat content and a low to medium temperature range below 140°C, is suitable for application in Thermal Energy Storage technology, especially in Solar Water Heaters. This study examined the thermal performance of sugar alcohols, specifically xylitol and Erythritol, in both pure and mixed forms with composite materials. High-density polyethene, used as a stabilizing material, accounts for as much as 10% and 15% of the weight during the transition from liquid to solid phase. The test method carried out in this study uses the Hybrid Energy-Temperature Method, where the sample is heated from the ambient temperature until it reaches a temperature of 150°C and then cooled until it reaches the ambient temperature again, in the process of charging/discharging cycle, to analyze the State of Charge and Depth of Discharging from the tested sample. This study also utilizes Differential Scanning Calorimetry and the Heat Capacity-isostep method to determine the phase change behaviour of the sample and calculate the total energy content of the selected sample.

Keywords: Latent Heat Thermal Energy Storage, Phase Change Material, Sugar Alcohol, State of Charge, State of Charge

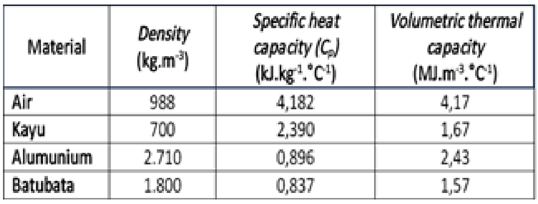
INTRODUCTION

A report from the International Energy Agency (IEA) states that the world's energy needs grew by 2.3% in 2019, with approximately 70% of these needs met by fossil energy sources [1]. Solar Water Heater (SWH) systems are one of the best examples of solar heat collectors in renewable energy technology, due to their advantages, including relatively low costs, minimal impact on global warming, and a relatively long service life. SWH is equipment used to supply water for various temperature needs in its applications to residential, commercial, and utility buildings. In Australia, domestic hot water use accounts for between 15% and 27% of a building installation's total energy consumption [2]. SWH technology is currently available in a variety of technology configurations tailored to market needs.

The efficiency challenge of the TES system remains open to innovation and improvement, enabling it to meet consumer demands. The use of SWH to supply hot water to household buildings is very cost-effective in many regions of the world, where the strategy used is to reduce the need for electricity at peak electricity consumption [3]. Various studies have been conducted for SWH applications, using various materials to absorb the sun's thermal energy to heat water.

Based on its working principle, heat energy storage is categorised into three parts, namely sensible heat storage, latent heat storage, and thermochemical heat storage. The working principle of the sensitive heat storage method, also known as Sensible Thermal Energy Storage (STES), involves utilising the sensitive heat properties of the material for the heat storage process. Commonly used STES materials have been used for a long time, as shown in Table 1. It has properties that vary from the elements of density, specific heat capacity and volumetric thermal capacity [4]

Table 1. Properties of Multiple Materials Sensible Thermal Energy Storage



Material	*Density* (kg.m^{-3})	*Specific heat capacity (C_p)* (kJ.kg^{-1}.°C^{-1})	*Volumetric thermal capacity* (MJ.m^{-3}.°C^{-1})
Air	988	4,182	4,17
Kayu	700	2,390	1,67
Alumunium	2.710	0,896	2,43
Batubata	1.800	0,837	1,57

The amount of energy depends on the magnitude of the difference between the initial and final temperatures of the material in question, where the value of the specific heat capacity plays a crucial role, as the total energy storage capacity depends on the specific heat capacity value of the material. STES materials generally utilize solid and liquid phases, including water, heat transfer oil, molten salt, and ceramics, such that the amount of sensitive heat is a function of material density (kg/m^3), volume (m^3), as well as specific heat capacity values and temperature differences. Volumetric thermal capacity is used as a comparison indicator for large-scale systems. For example, water has a volumetric thermal capacity value less than half that of aluminium, which is due to the greater density of aluminium compared to water. STES stores and excretes energy by absorbing and excreting directly.

STES materials for SWH have entered an era of technological saturation because they have been mass-produced using the simplest technology. The disadvantage of using SWH with STES is its relatively large physical size, which necessitates thermal insulation to maintain higher temperatures or extended storage times, as well as the potential requirement for energy input to maintain the specified temperature target [5].

The limitations contained in STES can be overcome by the use of Latent Heat Thermal Energy Storage (LTES) materials, considering that LTES has a higher energy storage density and the LTES system working fluid, which is in the form of Phase Change Material (PCM), shows relatively stable changes in chemical and thermal properties after experiencing thousands of thermal cycles [6][7].

Latent heat is heat energy used to change the phase of a material without any increase in temperature. LTES stores and releases energy through PCM. LTES has been widely applied to SWH technology [8][9], and also to other applications including in the electric energy sector, building energy saving [10], thermal management of electronics products [11], thermal insulation fabric and air conditioning system [12], industrial waste heat recovery [13], and so on. LTES materials have undergone many developments in the current era. Many studies have been conducted by researchers over the past decade on LTES materials and the design of heat exchanger equipment powered by LTES.

The classification of PCM LTES materials is divided into 3 (three) categories, namely organic, inorganic, and eutectic (mixed) materials or composite PCM [14]. Organic materials include paraffin, fatty acids, sugar alcohols, esters and ethylene glycol. Inorganic materials include salts, salt hydrates, hydroxides, and alloys (metals). Organic-based LTES materials offer several advantages, including a relatively low cost and the ability to operate over a wide temperature range, from 0°C to 200°C, with stable chemical properties and minimal phase separation. Organic-based LTES materials, in addition to having several advantages, also have various disadvantages, including relatively low thermal conductivity, significant volume changes and high flammability [15].

Another problem with PCM sugar alcohol that must be controlled is the low crystallization rate. Crystallization consists of 2 (two) different categories of processes, namely nucleation, in the form of the formation of new crystals in the sample, and crystal growth. The nucleation process is also divided into two types: primary nucleation, which involves the formation of a crystal from the melt, and secondary nucleation, which involves the formation of a nucleus from an existing crystal.

The secondary nucleation process quickly becomes the primary force for crystal formation in the crystallisation process after the primary nucleation process has formed enough nuclei. Secondary nuclei, on the other hand, can be formed through contact between crystals, contact with surfaces or through fluid friction. The friction that occurs also encourages crystallisation in a highly saturated solution until the maximum crystallisation rate is reached.

Some techniques to encourage the acceleration of the crystallisation rate in sugar alcohol-based xylitol, among others, include mechanical cutting (mechanical shearing) [16][17], the addition of additives [17], Bubble (bubbling) [18], or the use of ultrasound [19]. However, the crystallisation process does not occur instantaneously, regardless of the technique used [20].

Researchers have made various efforts in order to anticipate the adverse effects of the supercooling and crystallization phenomenon of the use of PCM sugar alcohol, by trying to add carbon-based materials or nanoparticles with higher thermal conductivity properties such as using carbon nanotubes, graphene, and also polyethylene, both in the form of high-density polyethylene (HDPE) and low-density polyethylene (LDPE). Polyethene is a corrosion-resistant plastic material, which is widely used for the manufacture of household goods, packaging, insulation, rope mesh, piping, and conduit [21].

From the explanation above, the researcher can improve the performance of the PCM sugar alcohol family of Xylitol and Erythritol types without and with the effect of adding HDPE phase stabilizer and how much energy content and heat capacity of the selected PCM sugar alcohol PCM, with the DSC and Heat Capacity method, without and with the addition of HDPE phase stabilizer.

The purpose of the researcher is to analyze the performance of the PCM sugar alcohol family of Xylitol and Erythritol types without and with the effect of adding HDPE phase stabilizer and also to determine the amount of energy content and total heat capacity of the selected PCM sugar alcohol, by the DSC and Heat Capacity method, without and with the addition of a phase stabilizer HDPE.

RESEARCH METHODS

This research aims to increase the operational capacity of thermal energy materials through energy filling function tests (charging) and energy discharge function tests (discharging). The materials used in this study are in the form of Phase Change Material (PCM) based on sugar alcohols, specifically Xylitol and Erythritol, mixed with phase-stabilising materials in the form of High-Density Polyethene (HDPE).

HDPE mixing is specified as 10% and 15% by weight. The results of the research of Budi Suyitno et al [42] prove that the addition of HDPE polymers at the appropriate ratios, i.e. 10% and 15% by weight, is proven to maintain the long-term thermal performance of Paraffin organic PCM. The average fusion enthalpy performance decreased only slightly by about 0.5 J/g in the Paraffin mixture: HDPE = 85:15% by weight. HDPE composites generally have better thermal reliability than pure Paraffin, protecting them from significant thermal degradation due to repetitive cycling processes. The mixture of HDPE polymers at a ratio of 10% and 15% by weight in Paraffin contributes positively to maintaining the heating and cooling rate at the desired level, protects pure Paraffin from thermal stress and makes a positive contribution to the long-term maintenance of PCM operations in LTES systems. The heavy 5% HDPE composite mixture in Paraffin has the disadvantage of encouraging higher cooling rates and fast compaction after thermal treatment.

The flow diagram of the PCM sugar alcohol sample testing carried out in this study is shown in Figure 1.

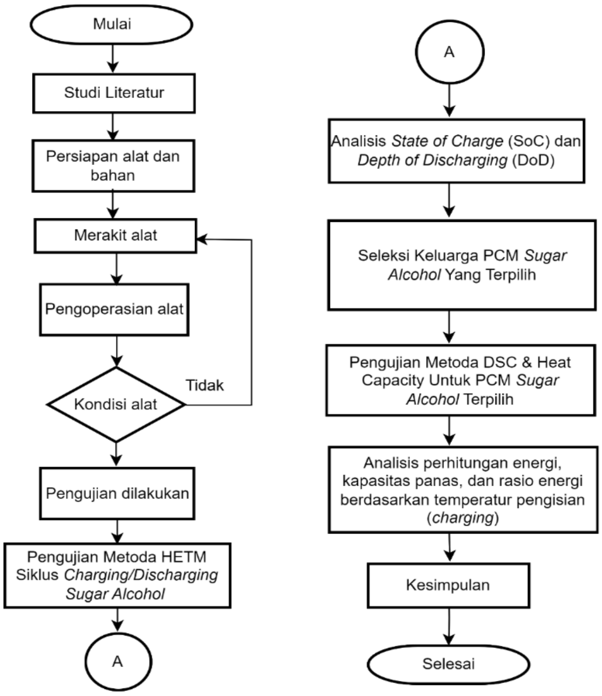


Figure 1. Sugar Alcohol Testing Flow Diagram

Data Collection Techniques

a. Prepare all components of the test equipment and instrumentation that will be used in the experiment, and then assemble them.
b. Prepare samples of Xylitol, Erythritol, and HDPE composite PCM materials, then determine the material limits and capacities, as well as the PCM-HDPE composite ratio.
c. Conduct tests on the test equipment with the HETM method to ensure the equipment is functioning correctly.
d. Perform all stages of testing within the specified problem limits.
e. The data from the charging/discharging cycle test stored in the Data Logger is retrieved and entered into the computer for further analysis in the form of State of Charge (SoC) and Depth of Discharge (DoD) profile data.
f. The results of the SoC and DoD performance analysis are then used to select the Sugar Alcohol PCM family that offers the best SoC and DoD performance.
g. Laboratory testing of Differential Scanning Calorimetry (DSC) and Heat Capacity (isostep) methods on selected PCM Sugar Alcohol samples to obtain data on melting point, melting heat, and specific heat capacity. These data are used to calculate the content of solid sensitive energy, latent energy, and liquid sensitive energy. Ultimately, the total energy content of the sample, along with heat capacity data, can be determined based on the amount of mass used.

RESULTS AND DISCUSSION

State Of Charge *Profile*

The State of Charge (SoC) profile, also called the fill level of 6 (six) samples, has been tested in a test sequence from sample A in a row to sample F according to Table 2. The sample is heated from an ambient temperature of 30°C to a temperature of 150°C.

Table 2. PCM and Composite Usage Ratio

Sampel	PCM	Rasio	Komposit	Rasio
A	Erythritol	100%	-	-
B	Erythritol	90%	HDPE	10%
C	Erythritol	85%	HDPE	15%
D	Xylitol	100%	-	-
E	Xylitol	90%	HDPE	10%
F	Xylitol	85%	HDPE	15%

Determination of *the Best* State of Charge *and* Depth of Discharging Profile

The results of the performance test for all samples, from sample A to sample F, are based on the graph profile analysis of all samples, as described above, and summarised in both SoC performance during the static charging cycle and DoD performance during the discharging cycle, as shown in Table 3.

Table 3. SoC and DoD From All Samples

Sampel	Laju SoC (%/min)	Laju DoD (%/°C)
A	1,48	1,636
B	2,00	1,625
C	2,64	1,651
D	1,82	1,599
E	2,47	1,622
F	2,88	1,616

Samples D, E, and F from the Xylitol type PCM sugar alcohol family were seen to have better performance than samples A, B, and C from the Erythritol type PCM sugar alcohol family. The SoC rate values of samples D, E, and F are greater than the SoC rate values of samples A, B, and C, and the DoD rate values of samples D, E, and F are slower than the DoD rate values of samples A, B, and C.

DSC and Heat Capacity *Laboratory Test Results Data*

DSC laboratory testing on 3 (three) selected samples, namely samples D, E, and F, obtained the results of melting point data from the sample as shown in Figure 4.13. Sample D (pure Xylitol) had a lower melting point than sample E (Xylitol: HDPE mixing = 90:10) and sample F (Xylitol: HDPE mixing = 85:15). The melting point of sample E is lower than that of sample F.

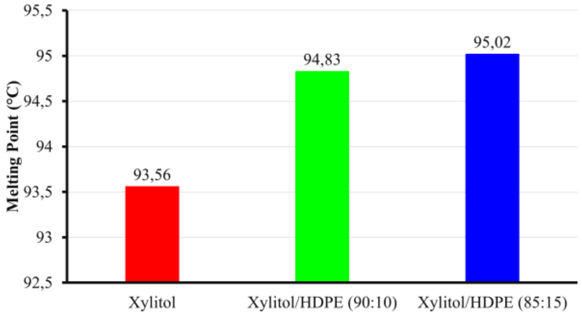


Figure 2. Melting Point of 3 (Three) Samples

The results of subsequent tests on samples D, E, and F yielded enthalpy melting data, also known as melting heat, as shown in Figure 4.14. The melting heat of sample D has the highest value compared to the melting heat value of samples E and F. The melting heat of sample E is slightly higher than the melting heat of sample F.

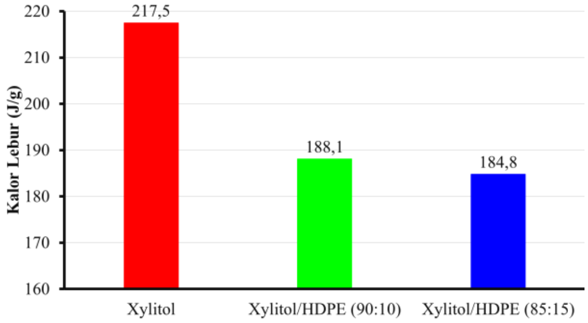


Figure 3. Melting Heat

The results of the following test, conducted on the three samples D, E, and F, yielded data on Heat Capacity or energy capacity, as shown in Figure 4.15.

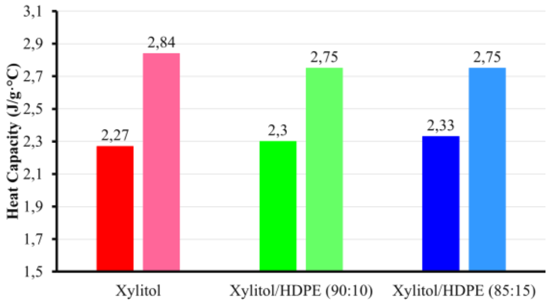


Figure 4. *Heat Capacity* of 3 (Three) Samples

Total Energy and Heat Capacity Calculation

The results of the calculation of the amount of energy per zone from the 3 three selected samples are then accumulated to determine the total amount of energy (units of Joules and kilo Joules) of the samples D, E, and F as shown in Table 4.5. The heat capacity results are also included, with reference to the sample mass data (D, E, and F) of 309 grams each at the time of testing.

Table 4. Total Energy And Heat Capacity Sample D, E, F

Sampel	Energi Total (J)	Energi Total (kJ)	Kapasitas Panas (J/g)	Kapasitas Panas (kJ/kg)
D	161.319,90	161,32	522,07	522,07
E	151.078,30	151,08	488,93	488,93
F	150.634,90	150,63	487,49	487,49

Energy Ratio Based on Charging Temperature

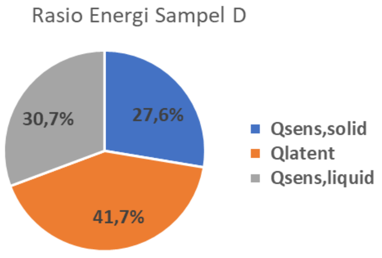


Figure 5. Sample Energy Ratio D

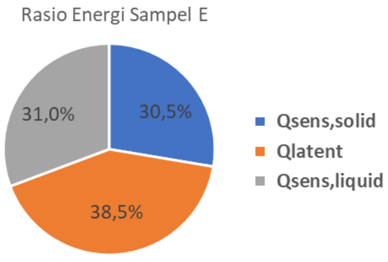


Figure 6. Sample Energy Ratio E

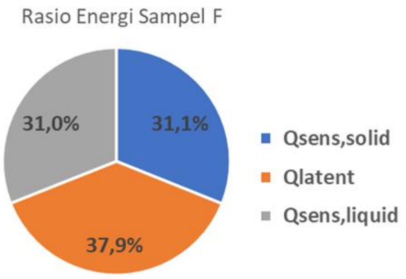


Figure 7. Sample Energy Ratio F

CONCLUSION

Based on the results of the discussion that has been described in this study, it can be concluded that:

1. The SoC rate performance result of pure Xylitol is 19% greater than that of pure Erythritol. The performance of the Xylitol-HDPE 90:10 mixture is 34% greater than that of the Erythritol-HDPE 90:10 mixture. The performance of the Xylitol-HDPE 85:15 mixture is 9% greater than that of the 85:15 Erythritol-HDPE mixture. The performance rate of DoD obtained within the tolerance was 2.3% smaller than that of pure Eryritol. The Xylitol-HDPE 90:10 mixture exhibits a DoD performance 0.2% lower than that of the 90:10 Erythritol-HDPE mixture. The DoD performance of the Xylitol-HDPE 85:15 mixture was 2.2% smaller than the performance of the Erythritol-HDPE 85:15 mixture. In conclusion, the thermal performance of the PCM sugar alcohol family type Xylitol is better than the thermal performance of the PCM sugar alcohol family type Erythritol.

2. The total energy content of pure Xylitol of 161.3 kJ is greater than the total energy content of the Xylitol-HDPE mixture of 90:10, which is 151.1 kJ, and of the Xylitol-HDPE mixture of 85:15, which is 150.6 kJ. The heat capacity of pure Xylitol of 522.07 kJ/kg is also greater than the heat capacity of the Xylitol-HDPE mixture of 90:10, which is 488.93 kJ/kg, and of the Xylitol-HDPE mixture of 85:15, which is 487.49 kJ/kg.

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