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MATHEMATICAL MODELLING AND EXPERIMNTATION OF SOY WAX PCM SOLAR TANK USING RESPONSE SURFACE METHOD

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ABSTRACT

Worldwide, governments tend to reduce the CO_2 emissions, and the storage of the solar energy system is still considered the most challenging problem to solve under the current state. Mainly, in relatively cold countries, as domestic hot water or for heat process services, where the loss in the tank is huge. Any improvement in the design can achieve a higher solar yield. Since water is the usual medium for heat storage, the integration with phase change material (PCM) can store energy when there is abundant energy and release it when it is needed. In this study, we conducted a capsulated PCM soy wax 52°C in an insulated water tank filled with 5 litres of water. To estimate the appropriate number of samples and the quantity of the PCM at two temperature levels using the response surface method with non-linear correlation for the charging phase. The results show 3.16, 0.95, 0.38 first degree magnitude effect for temperature, sample numbers, and wax quantity respectively and 0.29, -0.38 second-degree magnitude effect for quantity and temperature. In addition, an illustration of each two-factors interaction contour plots.

Keywords: solar tank, PCM, energy storage, process heat

1. INTRODUCTION

The human civilisation's fast development and technology revolution in the last few decades brought with it an essential consequence of environment and natural resources over-exploitation. These all drove the researchers to find a better sustainable solution and to optimise the current ones. While fossil fuel is currently the primary source of energy causing a massive amount of carbon dioxide emissions, the environment-friendly solutions, like renewable energy systems, started to appear with long life spans, and high reliability and efficiency [1]. Those systems became an alternative solution to the old ones. The utilisation of the renewable energies is not just because of the conventional fuel CO_2 and being environment friendly, but also because of the continually increasing energy demand and oil price fluctuation. Nowadays, renewable technologies are suitable to supply stable, independent energy for isolated areas. For instance, in Hungary, the desire of supporting the new projects with renewable energy increased because it showed an excellent economic investment with a payback period of less than ten years [2]. Where it became clear that, by using renewable energies, it is the best way to complying with the Kyoto protocol. Even under difficult economic situations, solar heating and cooling proved its place as a driver according to the data published by ESTIF (European solar thermal industry federation) [3]. With more than 37 Mm^2 of a solar power equalling 26.3 GW_{th}.

Agri-Food sector is famous for many problems: high carbon emissions, packaging waste, and food waste[4], with massive consumption of water, land, and considerable environment-friendly growth of the human population worldwide, sustainability is needed urgently in this sector. This means that any small improvement in machines, storage, and energy consumption can lead to a massive saving [5].

Another way of integrating the PCM is the latent heat storage material. Where the chemical bonds of the material break when it changes its phase, they are more commonly used in the solar system as a cooling technology for the PV panels which increases its efficiency. Or it can be used as a storing material [6] to increase the solar system energy capacity in case of thermal collectors. A significant advantage of the integrated PCMs in the solar systems that is easy to mount and has no components' complexity [2]. Adding

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to high storage density at a small temperature change [7]. Therefore, any research in this direction can lead to an increase in the efficiency of the tank and decrease the size [8], which leads to higher solar system efficiency. Other researchers tried successfully to integrate the PCMs in the solar domestic hot water (SDHW) loop using mono and multi genetic algorithms [9], [10], which is a stochastic optimisation method particularly efficient with discontinuous parameters.
Energy is usually stored and retrieved as sensible heat, latent heat, or thermo-chemical reaction, all through a change in the internal power of the medium. The sensible heat storage (SHS) stores by raising the medium's temperature. While latent heat storage (LHS) utilise the absorbed/released heat when the storage medium changes its phase from solid to liquid, liquid to gas, or vice-versa. The PCM is a latent storage material that absorbs a large amount of heat at an almost constant temperature. This process remains until the whole PCM transferred into the liquid phase. While the surrounding temperature falls, the PCM starts to solidify, which releases the stored latent heat. The usual range of the melting temperature is wide (from -5°C up to 190°C). Within the human comfort zone (20-30°C), some PCMs are very useful, allowing the storage of 5 to 14 times more heat density compared to conventional storage mediums like water or rocks [7], [11].
The numerical model of the whole system is used to choose the adequate operating parameters, and to optimise the stored energy by using a response surface method RSM. The storage system is a critical component and aspect of the solar system. Moreover, to maximise the solar yield, storage density (amount of energy per the volume or mass), the efficiency of the appliances (solar collector, tank, and so forth), and the demand consumption [12], are essential factors to determine the potential of using PCM in the storage tank [13],[14]. This can be useful to satisfy the energy demand because of solar energy's sporadic nature [15]. Where different simulation efforts have been executed to determine the performance of the water storage tanks with PCM [16], but there are no references to model the optimisation of the working variables [8], since it causes 2^k experiments operated differently, where k is the number of the factors.

2. MATERIALS AND METHODS

The system consists of a well-insulated water tank covered by 5 cm of expanded polystyrene (EPS), an insulation material extracted from oil, that works as a perfect insulator in foam form. This foam is an environmentally friendly material that’s properties do not change with time. The thermal conductivity is ≈0.033 W/m.K. Tank dimensions are 42x13x16 cm and can store up to 8.7 litres of water as shown in Figure 1a, but during the measurement it was filled with 5 litres and the rest volume was for the specimen tray. The tray has 7x3 specimens, each one can store 50 ml of the assigned material as shown in Figure 2a. After fixing the specimen tray inside the tank and filling it with the assigned material, the heater as in Figure 1b, turns on to a specific desired temperature ranged between (-20 – 100) °C. During the heating process, the by-pass line mixes the water better, which leads to a temperature homogeneity in the tank. In the meanwhile, the data-logger (Almemo 2890-9) with nine input channels as shown in Figure 2b, stores the data coming from the sensors. The sensors are two temperature sensors NiCr-Ni type k (-40 →1000°C) at the right and left side of the tank, and one ambient temperature sensor used as the reference temperature, to identify when the container cools down to near ambient temperature, and another sensor inside the PCM capsule, as well as two heat flux sensors in the internal and external part of the insulation. In the end, the objective is to estimate the time needed for each experiment where the water cools down to a near ambient temperature after heating, that is represented by the following equation:

$$T_{avg\_tank} - T_{amb} \leq +1\ {}^{0}C \quad (1)$$

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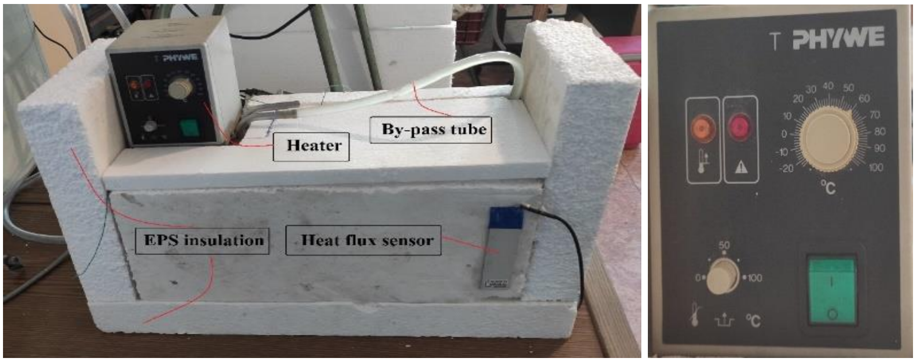

(a) *(b)*

Figure 1.(a) Experiment tank (b) Heater

(a) *(b)*

Figure 2. (a) Capsules tray (b) Data logger

3. RESULTS AND DISCUSSION

The modelling process was created using R-program, with coded values varying between [-1, +1] for each variable and the variables being "S" representing **S**ample numbers where the code -1 is used for four samples and +1 for eight samples. **Q**uantity of the PCM in each sample represented by "Q" where -1 code is 5g and +1 is 10g. Finally, the **T**emperature represented by "T", where code -1 is $30^{\circ}C$ and +1 is $40^{\circ}C$. Together this creates a cube pattern, where each corner represents a set of these three variables creating one experiment, as shown in Figure 3. The number of experiments calculated by the form 2^k where k is the number of variables, so 2^3 equals eight measurements, as shown in Table 1. Adding to the fact that the correlation known before starting the measurement is non-linear, another two measurements were conducted out of the cube borders at (S=0, Q=0g, T=$30^{\circ}C$) and (S=8, Q=10g, T=$60^{\circ}C$) to identify the second-degree non-linear coefficients.

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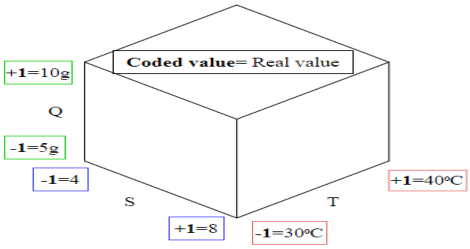

Figure 2. Expirement data set cube

To transfer between coded values and real values the following equations represents the relationship:

$$Coded\ value = \frac{Real\ value - Center\ point}{\frac{1}{2}(range)} \quad (2)$$

Table 1. Experiment parameters and results

	1	2	3	4	5	6	7	8	9_extra _pre	10_extra _post
Samples	-1	+1	-1	+1	-1	+1	-1	+1	-3=0	+1=8
Quantity	-1	-1	+1	+1	-1	-1	+1	+1	-3=0g	+1=10g
Temperature	-1	-1	-1	-1	+1	+1	+1	+1	-1=30^0 C	+5=60^0 C
y [hour]	**4.86**	**6.33**	**5.87**	**7.28**	**10.88**	**13.4**	**11.58**	**13.75**	**4.68**	**17.62**

The applied method is the least-squares method, which attributes to Carl Friedrich Gauss in 1795, that provides the overall rationale for the best fit placement of the line among the studied data points. In our experiment, the non-linear model is solved using iterations. The following coded equation represents the generated model:

$$\begin{aligned} y = 9.33 + 0.95\boldsymbol{S} + 0.38\boldsymbol{Q} + 3.16\boldsymbol{T} - 0.38\boldsymbol{T}^2 + 0.29\boldsymbol{Q}^2 \\ -0.05\boldsymbol{S} * \boldsymbol{Q} + 0.23\boldsymbol{S} * \boldsymbol{T} - 0.11\boldsymbol{Q} * \boldsymbol{T} - 0.04\boldsymbol{S} * \boldsymbol{Q} * \boldsymbol{T} \end{aligned} \quad (3)$$

To understand the relationship between the factors and the objective, Pareto plot is conducted as in the Figure 4.

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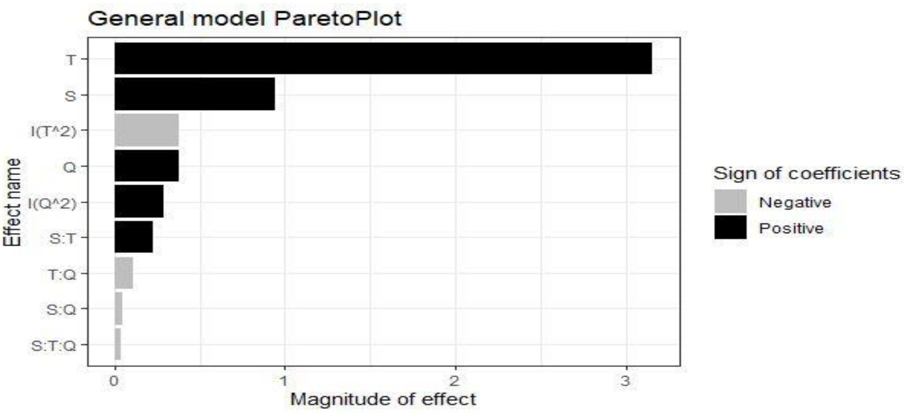

Figure 3. General model Pareto plot

The magnitude of each parameter is easily observed using Pareto plot, while temperature has the biggest positive magnitude, followed by sample numbers. At the third place, contrariwise the second-degree temperature coefficient has a negative magnitude due to the non-linear behaviour. In the end, the quantity first and second degree has a low positive magnitude on the overall result. Adding to the fact that the 3-factor interaction S*Q*T or any three-factor interactions are not existing in nature, but as it is shown in the Pareto plot, it has almost zero magnitude. This is similar to S*Q and Q*T that has a low influence. On the other hand, the contour plot of each two-factor interaction shows the curves where the overall result can be better as seen in Figure 5,6 and 7. Paying attention to some coded values that may have no meaning on the chart, for instance, Q = -3 or S = -3 matches 0g and 0 samples, so below -3 value in the chart has no meaning in real-world values. As we can see in the chart, to increase the time we should increase the samples and the PCM quantity as in the referring arrow. On the other hand, the coefficient of S, Q and T in the equation (3) shows the direction of the plot. In other words, a coded value of ΔT → [+1] will add 3.16 hours to the overall result. Similarly, ΔQ → [+1] will add 0.38 hours and ΔS → [+1] adds 0.95 hours.

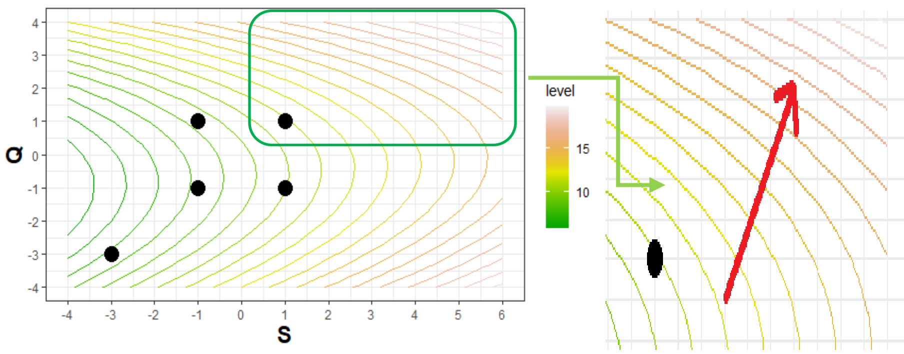

Figure 4. Quantity samples correlation

On the other hand, the T*Q interaction shows better results (as shown in the Figure 6), using more PCM materials and no more than 3.5 coded value temperature equaling 52.5˚C which is close to the melting temperature of the PCM. This result is another proof that the melting point of the PCM is around 52.5˚C compared to 52˚C as mentioned in the material description. The black dots in the graph represents the 4 corners of the cube from 2D Q*T prospective, adding to two pre and post experiments that were needed to

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identify the second order coefficients. The interpretations of those factors corresponding with the coefficients are 0.38Q, 3.16T, $-0.38T^2$, and $0.29Q^2$.

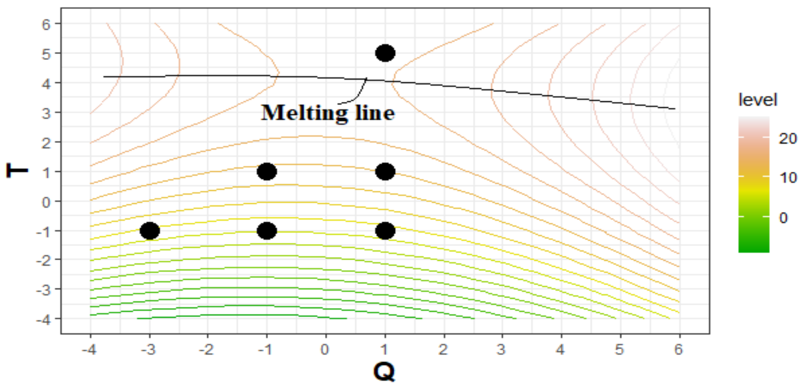

Figure 5. Temperature Quantity correlation

Like T*Q contour, T*S contour has similar results (as in igure 7). They show that at a near-code value of 4, corresponding to 55°C temperature, with extra samples we should obtain better results. The black dots show the cube corners adding to two pre- and post-measurement values from 2D projection.

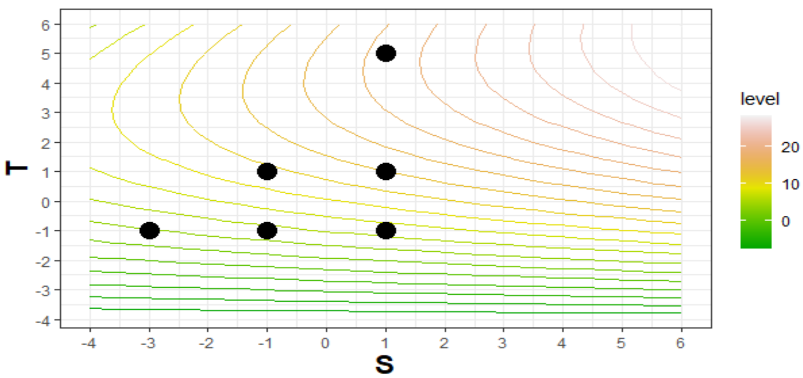

Figure 6. Temperature Samples correlation

4. CONCLUSIONS

This paper presents mathematical modelling of an encapsulated PCM material in a thermal tank, clearly showing that it plays a substantial role in SDHW and heat process systems. We can see significant heat loss in the tank, that takes place in cold countries to a higher extent. The integration with PCMs in the thermal tank used as capsules or insulating layer, will give a better performance and as a result reduce the CO_2 emissions. With this being the biggest concern nowadays and by using PCMs, we can conserve more energy and create better utilisation. In our work, we investigated a matrix set or three variables: Temperature, Quantity, and Sample number of Soy wax 52°C by conducting eight experiments to optimise the performance in a specific thermal tank.

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Based on the results using R script we generated the mathematical second-degree, non-linear, 3-factors interaction equation. Moreover, to generate the second-order coefficients, two other experiments were needed before and after the set variables. Furthermore, to have a better visualization, Pareto plot illustrates the most influential factors of the non-linear equation, where Temperature has the most significant positive magnitude followed by sample and quantity of PCM. In contrary, the temperature has the most potent negative magnitude, which is proof of the non-linearity.
On the other hand, the contour plot of each 2-factor interaction generated to illustrate the contour lines and the direction of the equation optimization. Easier observation of the curved temperature contour line illustrates the melting temperature of the PCM's. Despite new efforts to generate the modelling and experiments, more research is needed to obtain new models of other cheap and available PCMs like Soy wax 68°C, white beeswax, and Paraffin wax 58°C.

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REFERENCES

[1] A. J. Gallego et al., "Mathematical modeling of a PCM storage tank in a solar cooling plant," Sol. Energy, vol. 93, pp. 1–10, 2013, doi: 10.1016/j.solener.2013.03.026.
[2] M. Al-ktranee, "overview of the hybrid solar system," vol. 14, no. 1, pp. 100–108, 2020, doi: 10.14232/analecta.2020.1.100-108.
[3] M. Noro, R. M. Lazzarin, and F. Busato, "Solar cooling and heating plants: An energy and economic analysis of liquid sensible vs phase change material (PCM) heat storage," Int. J. Refrig., vol. 39, no. 0, pp. 104–116, 2014, doi: 10.1016/j.ijrefrig.2013.07.022.
[4] R. Ghabour and P. Korzenszky, "Optimal design of solar-assisted industrial processes considering solar energy hybridized with pasteurizer," in Researched Risk Factors of Food Chain, G. Géczi and P. Korzenszky, Eds. Gödöllő, Hungary: Szent István Egyetemi Kiadó, 2018, pp. 93–96.
[5] A. Tolnay, A. Nath, and A. Koris, "CHALLENGES OF SUSTAINABLE FOOD TECHNOLOGY - A REVIEW," vol. 14, no. 1, pp. 118–129, 2020, doi: 10.14232/analecta.2020.1.118-129.
[6] L. F. Cabeza, M. Ibáñez, C. Solé, J. Roca, and M. Nogués, "Experimentation with a water tank including a PCM module," Sol. Energy Mater. Sol. Cells, vol. 90, no. 9, pp. 1273–1282, 2006, doi: 10.1016/j.solmat.2005.08.002.
[7] B. Zalba, J. Marin, L. F. Cabeza, and H. Mehling, Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, vol. 704. 2003.
[8] M. Ibáñez, L. F. Cabeza, C. Solé, J. Roca, and M. Nogués, "Modelization of a water tank including a PCM module," Appl. Therm. Eng., vol. 26, no. 11–12, pp. 1328–1333, 2006, doi: 10.1016/j.applthermaleng.2005.10.022.
[9] D. Haillot, E. Franquet, S. Gibout, and J. P. Bédécarrats, "Optimization of solar DHW system including PCM media," Appl. Energy, vol. 109, pp. 470–475, 2013, doi: 10.1016/j.apenergy.2012.09.062.
[10] R. Padovan and M. Manzan, "Genetic optimization of a PCM enhanced storage tank for Solar Domestic Hot Water Systems," Sol. Energy, vol. 103, pp. 563–573, 2014, doi: 10.1016/j.solener.2013.12.034.
[11] B. Kanimozhi and B. R. R. Bapu, "Experimental study of thermal energy storage in solar system using PCM," Adv. Mater. Res., vol. 433–440, pp. 1027–1032, 2012, doi: 10.4028/www.scientific.net/AMR.433-440.1027.

DOI: https://doi.org/10.14232/analecta.2020.2.35-42

[12] M. Medrano, M. O. Yilmaz, M. Nogués, I. Martorell, J. Roca, and L. F. Cabeza, "Experimental evaluation of commercial heat exchangers for use as PCM thermal storage systems," Appl. Energy, vol. 86, no. 10, pp. 2047–2055, 2009, doi: 10.1016/j.apenergy.2009.01.014.
[13] J. Deng, S. Furbo, W. Kong, and J. Fan, "Thermal performance assessment and improvement of a solar domestic hot water tank with PCM in the mantle," Energy Build., vol. 172, pp. 10–21, 2018, doi: 10.1016/j.enbuild.2018.04.058.
[14] Víg. P, Seres. I. Application of PCM in food storage, In: Géczi, Gábor; Korzenszky, Péter (szerk.) Researched Risk Factors of Food Chain, Gödöllő, Magyarország : Szent István Egyetemi Kiadó, (2018) pp. 165-168. , 4 p.
[15] L. Moens, D. M. Blake, D. L. Rudnicki, and M. J. Hale, "Advanced thermal storage fluids for solar parabolic trough systems," J. Sol. Energy Eng. Trans. ASME, vol. 125, no. 1, pp. 112–116, 2003, doi: 10.1115/1.1531644.
[16] Bődi. Sz. , Víg. P, Farkas. I. Comparison of water and paraffin for heat storage, MECHANICAL ENGINEERING LETTERS: R AND D: RESEARCH AND DEVELOPMENT 17 pp. 7-13. , 7 p. (2018)