PAPER • **OPEN ACCESS**

Feasibility study of $MgSO_4$ + zeolite based composite thermochemical energy stores integrated with vacuum flat plate solar thermal collectors for seasonal thermal energy storage

To cite this article: D Mahon *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **556** 012012

View the article online for updates and enhancements.



IOP ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

This content was downloaded from IP address 27.195.216.57 on 18/09/2019 at 23:03

IOP Conf. Series: Materials Science and Engineering **556** (2019) 012012 doi:10.1088/1757-899X/556/1/012012

Feasibility study of $MgSO_4$ + zeolite based composite thermochemical energy stores integrated with vacuum flat plate solar thermal collectors for seasonal thermal energy storage

D Mahon[1], P Henshall[2], G Claudio[1] and P Eames[1]
[1]Loughborough University, Loughborough, UK
[2]Oxford Brookes University, Oxford, UK
E-mail: d.mahon@lboro.ac.uk

Abstract. A primary drawback of solar thermal technologies, especially in a domestic setting, is that collection of thermal energy occurs when solar irradiance is abundant and there is generally little requirement for heating. Thermochemical Energy Storage (TCES) offers a means of storing thermal energy interseasonally with very little heat loss. A combination of Solar Thermal Collectors (STC) and TCES systems will allow a variety of different heating applications, such as domestic space and hot water heating as well as low temperature industrial process heat applications to be met in a low carbon way. This paper describes and assesses the feasibility of two novel technologies currently under development at Loughborough University; i) an evacuated flat plate STC and ii) composite TCES materials, coupled together into a system designed to store and supply thermal energy on demand throughout the year. The predicted performance of an evacuated flat plate STC is described. The objective of this paper is to evaluate the economic, energy and carbon saving potential of conceptual STC + TCES systems suitable for domestic use. This research uses experimental results from Differential Scanning Calorimeter tests to evaluate the total enthalpy, dehydration enthalpy and sensible component enthalpy of composite TCES materials. The experimental results along with predicted performance of STC are used within a developed model to assess key metrics of conceptual STC + TCES systems feasibility, including; charging time, payback time, cost/ kWh, energy savings and CO_2 savings. Preliminary results suggest the combination of these two technologies has significant potential for domestic applications.

Keywords: solar; energy; storage; thermochemical; solar-collector; feasibility

1. Introduction

Nearly half of the UK's total energy consumption is used for heating purposes [1], with 26% of the UK's total energy consumption used specifically for Domestic Space Heating (DSH) and Domestic Hot Water (DHW)[1]. 88% of the energy for DSH and DHW comes directly from gas and oil with only 2% of the energy required for heating generated from renewable energy sources [1]. Thermochemical Energy Storage (TCES) stores thermal energy in reversible chemical reactions and can be used to help decarbonise the UK's DSH and DHW by storing summer generated thermal energy for use in the winter time to meet demand. $MgSO_4$ is an abundant, non-toxic, relatively cheap salt hydrate, with a high theoretical energy density (2.8GJ/m^3 / 778kWh/m^3) that can be used as a thermochemical energy storage material [2]. $MgSO_4$ is interesting for domestic interseasonal TCES as it will dehydrate (charge) when exposed to a temperature of 150˚C [2]. There has been some recent research into the potential of $MgSO_4$ [2,3] however, studies have shown problematic characteristics of such material. Zeolite is an absorbent material which has the potential to be used as a standalone

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

TCES material [4]. Due to the porous structure and typically large surface area zeolites tend to be very adsorbent [5]. Zeolites have been specifically used to enhance the characteristics of $MgSO_4$ [6].
STC are commonly used to heat water to be used for DSH and DHW supply. They usually come in two conventional non-concentrating varieties. One type, known as Flat Plate Collector (FPC) STC employs a thin metal sheet with a selective surface as a solar absorber, which fills a large proportion (>90%) of the gross collector area [7]. A FPC loses energy directly from the absorber via conduction, convection and radiation heat loss mechanisms. The other type of STC is an Evacuated Tube Collector (ETC) STC which has an absorber that is divided so that each section of the absorber can fit inside a glass tube. The glass tube is evacuated surrounding the absorber by a high vacuum. This results in the suppression of both convection and gas conduction heat loss mechanisms. ETC's are capable of achieving higher operational temperatures and higher efficiencies in terms of absorber area compared to FPC's [8]. However, ETC's have less absorber area per gross collector area in comparison to FPC's. A recent innovation in STC technology has been the development of Vacuum Flat Plate Collectors (VFPC) STC [9] which combine the benefits of FPC's and ETC's via the use of a flat and robust enclosure that surrounds a Flat Plate solar absorber. The FPC efficiency is improved thanks to the thermal insulation properties of the surrounding vacuum layer; similar to an ETC.
Composite materials of zeolite-Y containing various wt% of $MgSO_4$ have been created and experimentally characterized using a Differential Scanning Calorimeter (DSC). The generated DSC data was used to calculate the feasibility of a combined TCES and STC system for domestic inter-seasonal thermal energy storage and annual heat delivery. This study presents the potential of a TCES and VFPC thermal energy storage system for providing DSH and DHW energy. The proposed system has the advantage of offering a secure supply of heat and can potentially be used off-grid.

2. Materials and methods

To assess the energy density of the TCES materials a TA Instruments Discovery DSC was utilised. For the DSC tests the sample mass used was 6-10mg. The DSC is not configured to provide a humid air flow; therefore hydration of the samples took place in a custom built microcontroller regulated hydration chamber. The hydration conditions, were ~56% (+/- 3%) Relative Humidity (RH) at 20˚C (pH_2O =~1.3kPa) for a minimum of 18 hours. The DSC samples were dehydrated to 150°C using a double DSC dehydration approach, (explained in more detail in a paper by Mahon et al. [10]), to establish i) the effective specific heat capacity, ii) the sensible enthalpy component and iii) the dehydration enthalpy of the TCES samples.

3. Solar collector information

The useful energy gain (Q) from a STC is given generally by equation (1) [11]:

$$Q = A[S - U_L(T_C - T_a)] \tag{1}$$

where A is the area of the absorber, S is the absorbed solar energy per unit area, U_L is the thermal loss coefficient of the collector, T_C is the collector temperature and T_a is the ambient temperature. The efficiency of a STC in terms of aperture area (η_a) can be evaluated by equation (2):

$$\eta_a = \frac{Q}{A_a G} \tag{2}$$

where G is the local solar irradiance and A_a is the area of the aperture. The efficiency in terms of gross collector area (η_c) can be evaluated by equation (3):

$$\eta_c = \frac{Q}{A_c G} \tag{3}$$

where A_c is the gross collector area. From equations (1-3), for a given solar irradiance, the efficiency of a STC decreases as the temperature of the collector increases or if A_c is used to calculate efficiency rather than A_a (as $A_c > A_a$). In order to model and compare the three types of domestic STC (FPC, ETC, VFPC) previously discussed, the characteristics of two commercial STC's were identified: a FPC [7] and a ETC [12]. The characteristics of a VFPC in this study was derived from the characteristics of both these commercial collectors in that the VFPC has a similar U_L to the ETC whilst having a similar A_a/A_c ratio as the FPC. The area available for the STC was limited to ~8m^2 with the

values of A_a and A_c scaled appropriately. Efficiency curves for commercial collectors are characterized by equation (4):

$$\eta = \eta_0 - k_1 \frac{(T_c - T_a)}{G} - k_2 \frac{(T_c - T_a)^2}{G} \quad (4)$$

where the values of constants η_0, k_1 and k_2 are given by manufacturers in terms of aperture area. The characteristics of the STC's used in the model can be found in table 1.

Table 1. STC properties in terms of aperture area.

Collector	A (m^2)	A_a (m^2)	A_c (m^2)	η_0	k_1 (W/m^{2}K)	k_2 (W/m^{2}K^2)
FPC [7]	2.01	1.97	2.15	0.775	3.73	0.0152
ETC [12]	2.01	2.16	2.77	0.75	1.18	0.0095
VFPC	2.01	1.97	2.15	0.75	1.18	0.0095

4. Feasibility analysis and assumptions

The TCES material in the system was assumed to be charged over the 3 months of summer by the STC and to be discharged throughout the winter using pumped humid ambient air. The maximum amount of TCES material which could be charged was calculated from the summer gains produced by the STC. The remaining 9 month gains produced by the STC were assumed to be utilised when generated to provide DSH or DHW. The calculated average domestic energy consumption for space heating was 14,373 kWh [1]. To calculate the Winter Space Heating Demand (WSHD) average degree days for the UK were used and the WSHD was calculated to be 5,737 kWh. The value used for the average CO_2 production (kg/kWh) from current DSH energy sources was 0.23kg/kWh, calculated from taking averages of the CO_2 production from each DSH energy source and then calculating a weighted average depending on the % each energy source was used for DSH. To calculate the yearly useful gain from the STC when they were not charging the TCES (i.e. the remaining 9 months of the year) it was assumed that the STC's were outputting an increase in temperature of 50°C. First the efficiency of each STC was calculated using equation 4 assuming $T_c - T_a$ equals 50°C, the value used for G was an average hourly irradiance value for Loughborough, UK [13]. Once the efficiency was calculated the useful kWh gains from the STC were calculated. The effective specific heat capacity used for the TCES materials changed every 5°C with each value an average value within the 5°C band calculated from the DSC data. It was defined as the "effective" specific heat capacity as it was a combination of the specific heat capacity of the material and also the dehydration enthalpy of the material. The STC's efficiency for the summer months were calculated using equation (4) taking into account the irradiance for each specific hour for that month. The delta T when charging the store (i.e. $T_c - T_a$) was equal to (temperature of the store + 5°C) – T_a. This means that the TCES material store was always being charged with a temperature 5°C above the temperature of the store. The ambient temperature used was a 24 hour monthly average for each month [13]. The heat into the store was given by equation (5):

$$Q_{in} = 8E_e\eta \quad (5)$$

where E_e is the irradiance for that hour of the day and η is the efficiency of the collector calculated for the required delta T, using equation (4). The temperature of the store at a given time was described by equation (6):

$$T_i = T_{i-1} + \frac{3600(Q_{in} - Q_{loss})}{mC_{p(T)}} \quad (6)$$

where $C_{p(T)}$ is the effective specific heat capacity at a given temperature for the TCES material and Q_{loss} is the heat loss to the surroundings due to conduction and convection. The store temperature was calculated hourly over the summer period. The model calculated the maximum WSHD% which could be stored within the TCES material. The calculated average cost for space heating used was 5.01p/kWh. The likely increase in the average space heating energy cost (£/kWh) over the next 30 years was calculated as 7%/annum, considering the average change in fuel costs over the past 20

years, the inflation value used was 3.6%. The system life time was assumed to be 30 years. With the assumption that the system was paid in full, the system was fitted alongside the current heating system and only the savings in energy costs were used to assess the financial feasibility of the system. To assess the cost of each system configuration the cost for each component was based on bulk prices which were found from several sources and then averaged.

5. Results and discussion

To alleviate some of the $MgSO_4$ issues composite materials of $MgSO_4$ + zeolite-Y were synthesized in the laboratory and tested. Figure 1 shows the average dehydration enthalpy for each composite material measured from the DSC dehydration experiments from 20-150˚C. The values on Figure 1 were found by conducting a sigmoidal integration of the DSC enthalpy plots. The dehydration enthalpy for each material was derived from the total enthalpy minus the sensible component. With increasing $MgSO_4$ wt% the dehydration enthalpy of the composite samples increased. As the sample will be dehydrated (charged) in the summer months when, typically, heat is not required all of the sensible heat which is stored within the TCES material has been assumed to be lost and not used. The sensible component for the 35wt% and 15wt% composite materials was approximately 17% and 20% of the total enthalpy, respectively.

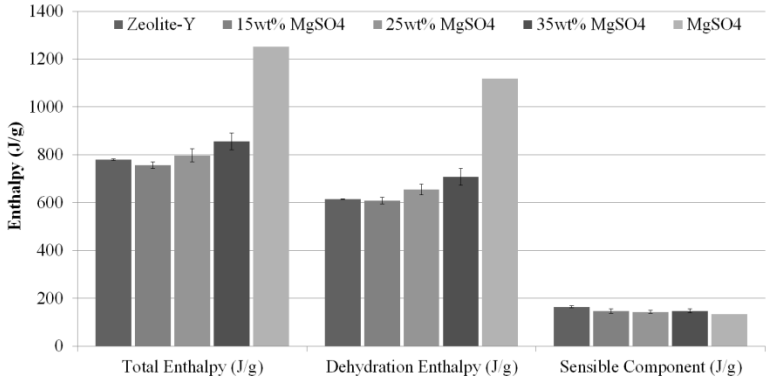

Figure 1. DSC measured average composite: total enthalpy, dehydration enthalpy and sensible component.

Table 2 shows the properties of each of the TCES materials used for the model.

Table 2. The properties of each of the TCES materials used for the model.

Material	$MgSO_4$-80˚C	$MgSO_4$-150˚C	35wt%-80˚C	35wt%-150˚C	Zeolite-150˚C
Dehydration enthalpy (J/g)	484	1118	302	708	615
Density (kg/m^3)	2666	2666	1453	1453	800

Figure 2 shows the initial summer charging time of each of the TCES + STC configurations modelled. The key on figure 2 shows the volume and the WSHD% stored, within only the TCES material after the initial summer charge, for each system. The system which stored the highest WSHD% (23.4%) is the $MgSO_4$ system charged to 150˚C using a VFPC ($MgSO_4$-150°C-VFPC). The store volume for this system was 1.62m^3. In comparison the 35wt%-80°C-VFPC system was able to store 19.3%, the second highest WSHD% with a required store size of 9.1m^3 making this system less likely to be used in a domestic environment. The FPC systems are not able to dehydrate any material to 150˚C due to the low efficiency of the STC at high temperatures.

The most financially attractive system configuration was the $MgSO_4$-150˚C-VFPC system, which also stores the most energy. The payback time for this system was 22 years. Over the lifetime of this system it should save the user over £4,300. Only five of the system configurations were financially viable. The financially viable systems were each of the VFPC systems, minus the 35wt%-80˚C-VFPC

system, and the $MgSO_4$-150˚C-ETC system. The 35wt%-150˚C-VFPC system had a payback time of 26 years, meaning this system would also result in financial savings to the user.
The initial cost per kWh (£/kWh) is the amount of energy stored from each system over its 30 year lifetime divided by the cost of the system. In all cases the ETC had a lower £/kWh cost than the FPC systems. The VFPC systems had an energy cost of (0.05-0.09£/kWh) and the ETC and FPC systems an energy cost of (0.08-0.16£/kWh). The more competitive VFPC systems had an energy cost (£/kWh) which is competitive with the current average energy cost (0.05£/kWh) for current space heating energy sources in UK.

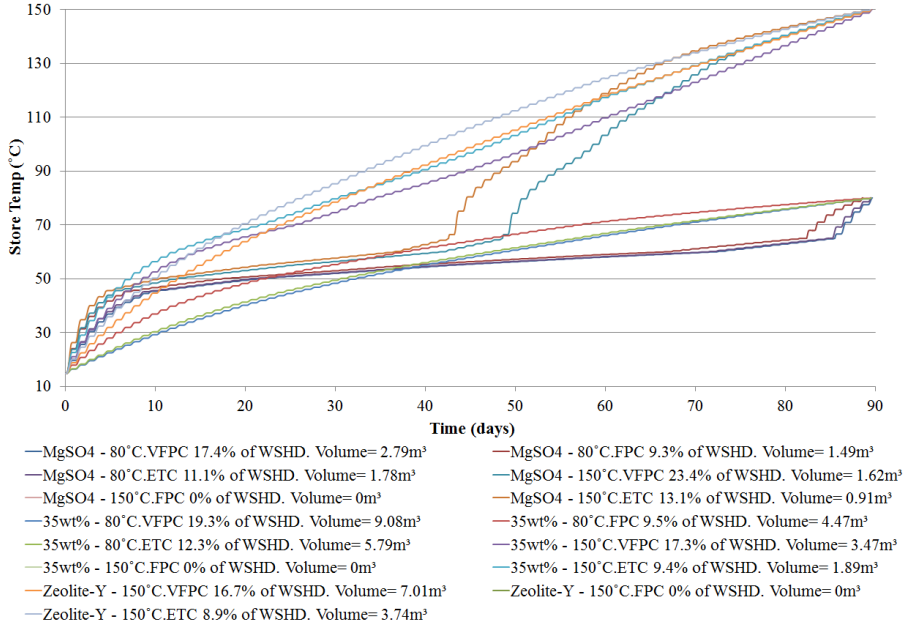

Figure 2. The store temperature with time for each of the proposed systems during initial charging.

For this investigation each of the systems were compared assuming it was beneficial to store the highest amount of WSHD% demand possible in the TCES material over the 3 summer months of charging. The WSHD% increased with the CO_2 saving however, the £/kWh did not necessarily decrease due to the material costs. For the 35wt%-150˚C-VFPC system the initial £/kWh of the system increased with increasing WSHD%. The 35wt%-150˚C-VFPC system was able to store a maximum of 17.3% WSHD%. The initial £/kWh of this system was 6.4p/kWh. If the WSHD% stored was decreased to 5% the initial £/kWh reduced to 6.0p/kWh. The initial payback time for this system was 26 years and with a store of 5% WSHD could potentially reduce to 25 years. Apart from the CO_2 savings of the system, storing the maximum WSHD% for this material does not represent a clear financial gain.
The average energy output of each system over its 30 year lifetime was calculated. The VFPC + TCES systems were able to meet around 30% of the total yearly Space Heating Demand (SHD) (4,312kWh/year) whilst each system using a FPC + TCES or an ETC + TCES were only able to meet less than 20% of the yearly SHD (2,875kWh/year). The choice of TCES material used in the VFPC systems did not have a significant impact on the amount of energy output from the systems, the best VFPC system ($MgSO_4$-150˚C-VFPC) and the worst VFPC system (Zeolite-Y-150˚C-VFPC) had an 8% annual difference in energy output. The selection of the TCES material should be a function of the available domestic storage volume and TCES material characteristics which in turn could favour the implementation of composite materials designed to reduce the agglomeration of the $MgSO_4$ while maintaining a high energy density.
The cumulative CO_2 savings were calculated for each system configuration assuming that a system was installed in 10% of all UK households. As the CO_2 savings were directly linked to the amount of energy output from each system the VFPC systems saved the most CO_2 over their lifetime (82.8-89.3MtCO_2e). The UK's CO_2 production from the residential sector for 2013 and 2014 was

74.4MtCO_2e and 62.3MtCO_2e , respectively [14]. This means a possible reduction of ~4.8% to the total residential CO_2 output if a TCES + VFPC system was installed in 10% of all UK households. The system with the most CO_2 savings was the VFPC-150˚C-$MgSO_4$ system which saved 89.3MtCO_2e over the operational life. The CO_2 savings from the ETC and the FPC systems was between 49.8-53.8MtCO_2e and 27.9-39.7MtCO_2e, respectively.

6. Conclusion

This study has shown that systems combining TCES and VFPC systems for domestic interseasonal heat storage can be financially viable and result in significant CO_2 savings. From a financial standpoint each one of the system configurations using a VFPC produced a saving to the user over its lifetime with the exception of the 35wt%-80˚C-VFPC system. Furthermore, the only system using either an ETC or a FPC which was financially viable was the $MgSO_4$-150˚C-ETC system. The best system choice was one which incorporated a VFPC due to its financial savings, energy output and CO_2 savings. The system which was the most financially feasible was the $MgSO_4$-150˚C-VFPC system which has the lowest system costs (£6,924), store volume (1.62m^3) and outputs the highest average amount of energy per year (4,622 kWh). The 35wt%-150˚C-VFPC system was a financially viable choice and saved the user around £2,250 with a payback time of around 26 years. Future work will be conducted to identify the characteristics of these TCES materials on a large scale and investigate the characteristics of potential large scale TCES reactor designs for domestic implementation.

7. References

[1] UK.GOVERNMENT. Estimates of heat use in the United Kingdom in 2012, 2013, p. 73–80.
[2] Van Essen VM, Zondag HA, Gores JC, Bleijendaal LPJ, Bakker M, Schuitema R, et al. Characterization of MgSO4 Hydrate for Thermochemical Seasonal Heat Storage. J Sol Energy Eng 2009;131. doi:10.1115/1.4000275.
[3] Van Essen M., Zondag HA, Schuitema R, van Helden WGJ, Rindt CCM. Materials for thermochemical storage : characterization of magnesium sulfate. 2009.
[4] De Boer R, Smeding SF, Zondag HA, Krol G. Development of a prototype system for seasonal solar heat storage using an open sorption process. Eurotherm Semin. #99, 2014, p. 1–9.
[5] Janchen J, Brosicke W, Ackermann D, Stach H. Studies of the water adsorption on Zeolites and modified mesoporous materials for seasonal storage of solar heat. Sol Energy 2004;76:339–44. doi:10.1016/j.solener.2003.07.036.
[6] Hongois S, Kuznik F, Stevens P, Roux JJ. Development and characterisation of a new MgSO4-zeolite composite for long-term thermal energy storage. Sol Energy Mater Sol Cells 2011;95:1831–7. doi:10.1016/j.solmat.2011.01.050.
[7] Kingspan. Kingspan Thermomax Flat Plate Collectors n.d.
[8] Henshall P, Moss R, Arya F, Eames P, Shire S, Hyde T. An evacuated enclosure design for solar thermal energy applications. Gd. Renew. Energy 2014, 2014.
[9] Shire FGS, Moss WR, Henshall P, Arya F, Eames CP, Hyde T. Renewable Energy in the Service of Mankind Vol II: Selected Topics from the World Renewable Energy Congress WREC 2014. In: Sayigh A, editor., Cham: Springer International Publishing; 2016, p. 859–66. doi:10.1007/978-3-319-18215-5_78.
[10] Mahon D, Claudio G, Eames PC. An experimental investigation to assess the potential of using MgSO4 impregnation and Mg2+ ion exchange to enhance the performance of 13X molecular sieves for interseasonal domestic thermochemical energy storage. Energy Convers Manag 2017. doi:http://dx.doi.org/10.1016/j.enconman.2017.03.080.
[11] Duffie JA, Beckman WA. Solar engineering of thermal processes. 3rd ed. New York etc.: Wiley; 1980.
[12] Kingspan_Solar. THERMOMAX HP400 EVACUATED TUBES n.d.
[13] Commission E. Photovoltaic Geographical Information System 2016. http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php.
[14] DECC. 2014 UK Greenhouse Gas Emissions, Provisional Figures 2015:1–33.