BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 62, No. 3, 2014
DOI: 10.2478/bpasts-2014-0052

Towards development of a prototype high-temperature latent heat storage unit as an element of a RES-based energy system (part 1)

K. BOGUCKA-BYKUĆ[1]*, W. WŁOSIŃSKI[2], and S. BYKUĆ[1]

[1]The Szewalski Institute of Fluid-Flow Machinery Polish Academy of Sciences (IMP PAN), 14 Fiszera St., 80-231 Gdańsk, Poland

[2] Polish Academy of Sciences, 1 Defilad Sq., 00-901 Warszawa, Poland

Abstract. This paper presents briefly the state of the art literature review with respect to research in the field of latent heat storage systems as elements of heat only, power only or combined heat and power (CHP) plants utilizing renewable energy sources (RES) for residential applications. Next, a paper introduces initial research carried out in IMP PAN in Gdańsk, Poland, aimed at development of a prototype latent heat storage unit. Identification of the suggested application for the storage unit in a given system is presented. The first stage of development of a prototype heat storage unit, namely a process of PCM pre-selection is discussed.

Key words: latent heat storage (LHS), thermal energy storage system (TESS), phase change material (PCM), renewable energy sources (RES), microgeneration, solar energy.

1. Introduction

European Union (EU) underlines, in its umbrella energy document entitled "Energy Roadmap 2050", that "storage technologies remain critical" [1]. Buildings are responsible for 40% of total energy consumption in EU [2] and since nearly zero energy buildings, which shall even start to produce more energy than they actually use, are expected to become a standard in the upcoming years [1], the importance of the research in the field of energy storage appears indisputable. The concept of a latent heat storage has been one of the ideas under consideration since many years. Three main, however strongly overlapping, branches of research in this field can be identified as follows: i) investigation of phase changing materials, its characteristics and classification in terms of chemical and physical properties (see Subsec. 3.1 in this paper for short discussion), ii) investigation of methods for heat transfer enhancement e.g. dispersing particles with high thermal conductivity into PCMs, adding high thermal conductivity elements (plates, brushes, fins etc.), macro- and microencapsulation, preparation of PCM composites [3–10], analysis of different design configurations of storage units [11, 12] or means for improvement of storage performance, like exergy based optimization [13], iii) numerical and/or experimental investigation of thermal performance of latent heat storage units as elements of RES-based energy generating systems or modifications of conventional RES utilizing devices/plants (to be exemplified in Sec. 2).

2. Literature review of latent heat storage concepts in RES-based energy generating systems

Latent heat storage systems constitute a broad topic and as such has been widely investigated. The below presented selected examples are meant to give the general overview of a wide spectrum of different concepts of latent heat storage units and configurations of various energy systems they are parts of, which were developed and investigated so far. Additionally, an overview of applied PCMs is given, presenting its melting temperature, t_m[°C] and latent heat of melting, ΔH_m [J/g].

2.1. Latent heat storage units coupled with micro-CHP systems. Nuytten et al. [14] presented an experimental study carried out to evaluate performance of three different configurations of thermal heat storage tanks in a micro-CHP system. The performance of two concepts of latent heat storage, was investigated and compared with a performance of a conventional thermal energy storage (TES) tank filled with water as a reference scenario (300 l, same in all the configurations). Latent heat storage concepts differ with a type of PCM used and with an encapsulation method. First storage is based on an inorganic PCM packed in macroscopic tubes (diameter of 50 mm and 750 mm long), whereas second one uses a paraffin-based PCM packed in small (3–5 mm) capsules. Inorganic PCM is "a mixture of magnesium based hydrates [$Mg(NO_3)_2 \cdot 6H_2O$ and $MgCl_2 \cdot 6H_2O$], calcium hydroxide, thickening, nucleating and stabilizing agents" [14] with $t_m = 58$ [°C] and $\Delta H_m = 145$ [J/g], whereas paraffin-based PCM is characterised with $t_m = 52$ [°C] and $\Delta H_m = 150$ [J/g]. Gang et al. [15] investigated a performance of a low temperature solar CHP with regenerative Organic Rankine Cycle (ORC). In general, system consisted of solar collectors and the ORC subsystem. In contrast with a traditional solar Rankine system, the low temperature solar CHP system uses an organic fluid/heat storage unit with PCM and two-stage evaporators. According to [15], the appropriate PCM for the system could be erythritol ($t_m = 120$ [°C],

*e-mail: kbogucka@imp.gda.pl

$\Delta H_m = 339.8$ [J/g]) or magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$, $t_m = 117°C$, $\Delta H_m = 168.6$ [J/g]). However, although a latent heat storage constitutes a part of the system under consideration, its design/construction is not presented in the paper.

2.2. Latent heat storage as an element of energy system with various types of solar collectors. A prototype latent heat storage unit in a system of direct steam generation (DSG) in parabolic-trough solar collectors was investigated by Bayon et al. [16]. The tested prototype consists of 36 parallel tubes, arranged as six pipes placed in six passes. Those tubes are embedded in a PCM, which thermal conductivity is enhanced by addition of high-conductivity fins. The PCM is 54%-w KNO_3/46%-w $NaNO_3$ eutectic mixture ($t_m = 221$ [°C], ΔH_m = ca. 100 [J/g]), and "the conductive fins were 490 × 490 mm^2 1-mm-thick expanded graphite (EG) foil spaced 10-mm apart and perpendicular to the pipes" [16]. Zipf et al. [17] reported on a development of an innovative concept for a latent heat storage based on a modified screw heat exchanger in Concentrated Solarthermal Power (CSP). The high-temperature PCM used in the system is, similarly to [16], an eutectic mixture of $NaNO_3$ and KNO_3. A concept for the storage unit was proofed successfully (namely, it was shown that PCM inside the screw heat exchanger can crystallize continuously) and the prototype heat exchanger was constructed to undergo a series of further test, enabling its final use in a large scale solar thermal power plants. Performance of a latent heat storage unit, consisting of a series of identical tubes embedded in PCM, with water as heat transferring fluid, in a solar system, was investigated by Qarnia [18]. The following three PCMs were investigated in a series of numerical simulations: n-octadecane ($t_m = 27.5$ [°C], $\Delta H_m = 243.5$ [J/g]), paraffin wax ($t_m = 47$ [°C], $\Delta H_m = 226$ [J/g]) and stearic acid ($t_m = 58$ [°C], $\Delta H_m = 169$ [J/g]). A study of a performance of a latent heat storage as an element in the solar water-heating system of a laboratory building was presented by Kaygusuz [19]. The tested system consists of "the solar collector, energy storage tank, water-to-air heat exchanger, auxiliary electrical heater, water circulating pump and other measuring and control equipment" [19]. The storage tank under consideration consists of cylindrical tubes packed horizontally in a vessel. The PCM applied (calcium chloride hexahydrate, $CaCI_2 \cdot 6H_2O$, $t_m = 28$ [°C], $\Delta H_m = 188$ [J/g]) is packed inside the tubes (made of PVC plastic), while the heat transfer fluid (water) flows parallelly. Kaygusuz also pointed that application of a latent heat storage system appears especially interesting as a heat source for systems with heat pumps, which he further investigated [20–21].

2.3. Latent heat storage integrated with the modified construction of a conventional solar collector. Varol et al. [22] investigated experimentally a performance of a solar collector modified by addition of PCM into its construction and compared its efficiency with a non-PCM, conventional solar system. PCM (sodium carbonate decahydrate, $Na_2CO_3 \cdot 10H_2O$, $t_m = 32.85$ [°C], $\Delta H_m = 267$ [J/g]) was located at the bottom of the collector and additionally, heat transfer oil was added, in which copper pipes were immersed. Next, air gap and absorber were located, respectively, above oil and finally, the collector was covered with a transparent glass sheet on the top. Mettawee [23] presented an investigation of the performance of a compact PCM solar collector, where "the absorber plate – container unit" [23] performs a double function, i.e. works as an absorber and a latent heat storage simultaneously. Pipes with cold water were placed inside the paraffin wax (paraffin wax, $t_m = 53.5$ [°C], $\Delta H_m = 266$ [J/g]). Earlier, a PCM-modified solar collector, consisting of two neighbouring sections, i.e. one filled with water and the other one with PCM was investigated by Kürklü et al. [24]. Paraffin wax, with a melting and freezing range between 45–50°C, played a double role in the system i.e. as energy storage and as additional insulation (due to its low thermal conductivity).

2.4. Latent heat storage as a modification of a traditional hot water tank in a solar energy system. Al-Hinti et al. [25] presented an experimental investigation of the performance of paraffin wax contained in "38 thin walled, cylindrical, aluminum containers" [25], which are packed (in two levels) in a commercially available, cylindrical hot water storage tank in a conventional solar water heating system. A volume of each container is 1.3 l, and it corresponds to 1.0 kg of PCM (paraffin wax, $t_m = 52$ [°C], $\Delta H_m = 230$ [J/g]). The volume of the PCM containers is 49.4 l by total, and the remaining 58 l is filled with water in the storage tank. Canbazoglu et al. [26] investigated the experimental open-loop passive solar water-heating system, which consists of flat solar collectors, cold water tank, heat storage tank with PCM, and a set of computer aided electronic measurement system. A well-insulated, cylindrical heat storage tank is filled with PCM material (sodium thiosulfate pentahydrate, $t_m = 48.5$ [°C], $\Delta H_m = 208.80$ [J/g]), which is packed in polyethylene bottles of 0.44 l each. Bottles are placed in three rows and are filled with 180 kg of PCM (which corresponds to 107.8 l) Water occupies remaining volume of 82.2l. Mongibello et al. [27] presented results of comparison of a technical and cost analysis of two types of thermal energy storage (TES), i.e. conventional hot water and latent TES, designed for two different micro-CHP systems, for two types of buildings (i.e. a single family house and a block of flats). Both latent heat storages were built of a cylindrical tank filled with PCM (the salt hydrate sodium acetate trihydrate, $t_m = 58$ [°C], $\Delta H_m = 265$ [J/g]) and a coil heat exchanger and also an additional (when compared with hot water storages) heat exchanger to exchange heat from/to storage. The hot water storages consisted of a water-filled cylindrical tank and a coil heat exchanger. The performance of the hot water tanks, modernised by adding containers with PCMs, was also investigated by, among others [28–31]. Finally, a list of 23 sources on modelling and experimental investigation of PCM-hot water tanks reported in literature was given by Nkwetta et al. [32].

2.5. Latent heat storage and its application in photovoltaics. Since photovoltaic devices exhibit reduced efficiency under elevated operating temperatures, numerous concepts of their cooling has been considered so far. Application of PCMs in case of building integrated photovoltaics (BIPV) is especially tempting since they can be arranged to play a double role. First, PCM can absorb "excess" heat from "overheat" PV cells and thus stabilize its operating temperature at desired level, and second, store this heat, which could be used later, when and where needed (eg. for preparation of domestic hot water or space-heating at night). The above mentioned concept was investigated numerically and experimentally by Huang et al. [33], who developed a numerical model for a system applying PCM for a stabilization of the PV temperature rise, which was validated by comparison with experimental data. Three different configurations, namely single flat aluminium plate system and two PV/PCM systems were analysed (one with internal fin and the other without). PCMs applied were RT25 by Rubitherm ($t_m = 26.6$ [°C], $\Delta H_m = 232$ [J/g] and paraffin wax ($t_m = 32$ [°C], $\Delta H_m = 251$ [J/g]). Possibility of application of PCM in PV systems was also investigated by others [34–35].

3. Towards a prototype latent heat storage in IMP PAN in Gdansk, Poland

IMP PAN coordinates development of a micro-CHP ORC unit (2–3 kW_e) driven by the biomass-fired boiler [36]. Stemming from this idea, a new concept was initiated to develop a latent heat storage integrated with a micro-CHP ORC unit driven by the biomass-fired boiler and an additional solar collector. A target application of the LHS unit in such a system is to utilize solar energy absorbed in a solar collector as a heat source no. 1 to pre-heat a low boiling agent, after it leaves regenerator, and before it reaches a boiler and enters a micro-turbine. It is expected that such combination could (at least temporarily) allow to lower the amount of biomass fuel used in a boiler. The general scheme of the idea is presented in Fig. 1. The system consists of the following: (B) biomass-fired boiler, (μ-T) micro-turbine, (G) generator, (R) regenerator, (C) condenser, (LHS) latent heat storage unit, (SC) solar collector(s) and pumps.

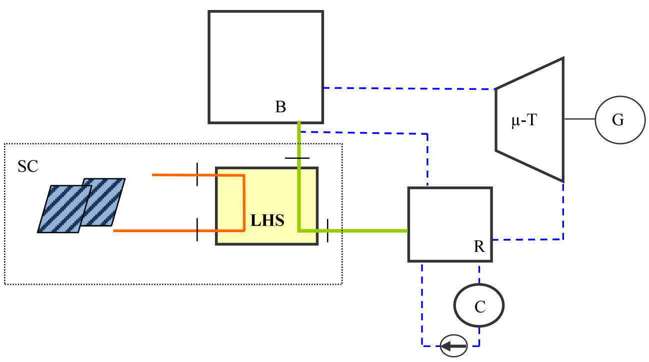

Fig. 1. Suggested location of the latent heat storage unit (LHS unit) as an element in a micro-CHP ORC system, driven by biomass-fired boiler (B) and solar collectors (SC)

3.1. Pre-selection of phase change material. Material investigation, leading to the identification and selection of PCMs meeting the set requirements for a given application is, next to the design of a heat exchanger, one of the two elementary steps while developing a latent heat storage unit. Since there exist no material that could meet not only all, but even most of the expectations, Dincer and Rosen [11] suggest to pre-select a number of PCMs that potentially could be used, and next, to compare their advantages and disadvantages, finally making a decision that most often requires a compromise. In reality, the choice is made basing firstly on the value of melting temperature [°C], which must correspond to the operating temperature of the system, and secondly on the value of the latent heat of melting [J/g], which should be as high as possible. Last but not least, cost of the material and expected savings need to be cross-analysed. There exist a number of publications dealing with phase changing materials and its properties, e.g. [37–44]. Nevertheless, majority of them concentrates mostly on PCMs with low melting temperatures, corresponding to temperatures of water in space heating systems, domestic hot water (DHW) or temperatures of thermal comfort in buildings. Publications listing PCMs with high values of melting temperature i.e. between 80–200 [°C], such as [15, 45–49], are less common. Nomura [47], who analysed publications on PCMs published yearly between 2001 and 2009, indicates that those dealing with melting temperature between 20–60°C were dominating through all this time. However, since 2006 amount of papers dedicated to high temperature PCMs (with t_m = above 100 [°C]) is increasing. Still, selection of a proper material for high temperature latent heat storage appears more challenging from one side, but on the other hand, scarcity of potential materials stimulates search for brand new solutions. Nevertheless, in both cases (high and low temperature PCMs), the availability of data about the materials in literature is scarce and/or differing from source to source, depending on differing conditions of measurements, which are rarely specified by authors. Summing up, selection of materials requires their further experimental investigation.

It is also worth noting that concept of application of proper coatings on selected materials, as is investigated in [50], constitutes an interesting idea in terms of development of new PCM structures for energy storage.

3.2. Methodology of PCM pre-selection. The following methodology for identification and pre-selection of PCMs for further theoretical and experimental investigation, involving three stages, was suggested and applied in IMP PAN. First stage involved a thorough literature review as well as investigation of commercially available PCMs with value of melting temperature [°C] within the desired interval (Table 1). At this stage, this value was the only criterion. As a result 33 materials were listed. During the second stage, more detailed literature data was sought and gathered, about the pre-selected materials, according to a list of "desired" parameters specified in the PCM Material Data Sheet (Table 1). As a result, it was possible to eliminate some materials at this stage, which were characterized with, at least one of the following three, disqualifying properties: occurrence of subcooling, low chemical stability and toxicity towards human beings and environment. Finally, eleven materials were left, though they did not necessarily met the requirements. Due to lack of data it was impossible to either eliminate or select them.

Table 1
PCM Material Data Sheet for a high-temperature latent heat storage unit under consideration

No.	Thermophysical properties	Desired value/characteristics
1.	**Melting temperature**	**between 110–150 [°C]**
2.	Melting enthalpy	As high as possible [J/g]
3.	Stability in many “melt/solidify” cycles	At least several thousands
4.	Thermal conductivity	As high as possible, or at least: > 0.15 [W/(m·K)] for organic materials > 0.40 [W/(m·K)] for inorganic materials
5.	Volumetric change during phase change	Max. 10-15%
6.	**Subcooling**	**Unacceptable**
7.	Density of both solid and liquid phases	High
	Chemical properties	**Desired characteristics**
8.	**Safe for human being and environment**	**Non-toxic, non-flammable, not explosive**
9.	**Chemical stability**	**Required chemical stability**
10.	Compatibility with materials used for storage unit construction	Compatible (*to be verified at later stage*)
11.	Corrosivity	Low or best with no impact on construction elements of the storage unit (*to be verified at later stage*)

Finally, during the third stage, it was decided to pre-select two PCMs (Table 2), representing different chemical groups, and choose them for further investigation and experiments. It is also planned to consider blends of polymer resin with metal alloy, which will be investigated in second place.

Table 2
Pre-selected materials and its basic parameters

No.	Pre-selected PCM	T_m [°C]	ΔH_m [J/g]
M1	Polyethylene Resin	110.0	64.0
M2	Sn50Bi50 alloy	140.7	55.0

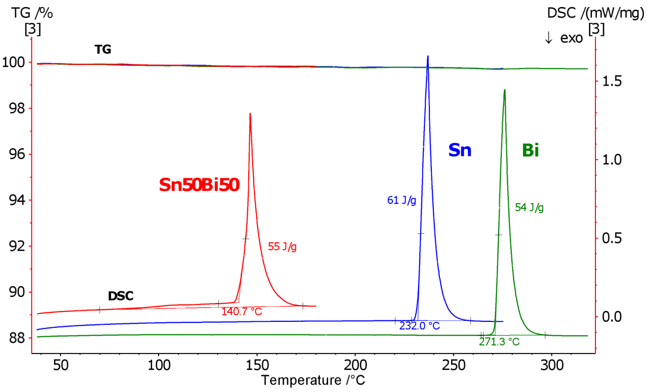

Fig. 2. Calorimetric heating curve of the Sn50Bi50 alloy as well as Sn and Bi separately and thermogravimetric (TG) curve

Elementary experimental measurements were performed to identify basic thermophysical parameters of selected materials. See below results of Differential Scanning Calorimetry (DSC) measurements for Sn50Bi50 alloy (Fig. 2).

4. Conclusions

Pre-selected materials (Table 2) meet the elementary criterion, which is the value of the melting temperature within the required interval. Metal alloy appears intriguing suggestion, especially due to the promising improvement in the conductivity when compared with majority of PCMs requiring different treatments to improve their heat transfer. Inorganic, metallic PCMs are less commonly described in literature when compared to organic phase changing materials. Some papers mention research in the field of potential application of metals and metal alloys as PCMs, but they concern its chemical and physical parameters rather than discuss experiments reporting attempts of application [41, 47, 51]. Blends of preselected materials, operating in two temperature ranges, may be beneficial in case of a heat source with variable temperature. Needless to add, addition of a metal alloy will improve heat transfer of polymer. Further investigation of materials is needed and it is to be performed parallel to development of the concept and design of a prototype high-temperature latent heat storage unit as an element of a RES-based energy system.

Acknowledgements. This project is enabled by a grant from National Centre for Research and Development in Poland.

REFERENCES

[1] “Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Energy Roadmap 2050”, *COM (2011) 885 final*, Brussels, (15.12.2011).

[2] “Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)”, *Official J. Eur. Union* (18.06.2010).

[3] J. Fukai, Y. Hamada, Y. Morozumi, and O. Miyatake, “Improvement of thermal characteristics of latent heat thermal energy storage units carbon-fiber brushes: experiments and modelling”, *Int. J. Heat and Mass Transfer* 46, 4513–4525 (2003).

[4] Z. Zhang, N. Zhang, J. Peng, X. Fang, X. Gao, and Y. Fang, “Preparation and thermal energy storage properties of paraffin/expanded graphite composite phase change material”, *Applied Energy* 91, 426-431 (2012).

[5] Y. Zhong, Q. Guo, S. Li, J. Shi, and L. Liu, “Heat transfer enhancement of paraffin wax using graphite foam for thermal energy storage”, *Solar Energy Materials and Solar Cell* 94, 1011–1014 (2010).

[6] D. Ai, L. Su, Z. Gao, C. Deng, and X. Dai, “Study of ZrO_2 nanopowders based stearic acid phase change materials”, *Particuology* 8, 394–397 (2010).

[7] Z. Zhang and X. Fang, “Study on paraffin/expanded graphite composite phase change thermal energy storage material”, *Energy Conversion and Management* 47, 303–310 (2006).

[8] A. Sari, “Form-stable paraffin/high density polyethylene composites as solid-liquid phase change material for thermal energy storage: preparation and thermal properties”, *Energy Conversion and Management* 45, 2033–2042 (2004).

[9] W. Wang, X. Yang, Y. fang, J. Ding, and J. Yan, "Preparation and thermal properties of polyethylene glycol/expanded graphite blends for energy storage", *Applied Energy* 86, 1479–1483 (2009).
[10] S. Qingwen, L. Yi, X. Jianwei, J.Y. Hu, and M. Yuen, "Thermal stability of composite phase change material microcapsules incorporated with silver nano-particles", *Polymer* 48, 3317–3323 (2007).
[11] I. Dincer and M. Rosen, *Thermal Energy Storage Systems and Applications*, John Wiley & Sons, London, 2011.
[12] F. Agyenim, N. Hewitt, P. Eames, and Mervyn Smyth, "A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS)", *Renewable and Sustainable Energy Reviews* 14, 615–628 (2010)
[13] S. Jegadheeswaran, S.D. Pohekar, and T. Kousksou, "Exergy based performance evaluation of latent heat thermal storage system: a review", *Renewable and Sustainable Energy Reviews* 14, 2580–2595 (2010).
[14] T. Nuytten, P. Moreno, D. Vanhoudt, L. Jespers, A. Solé, and L.F. Cabeza, "Comparative analysis of latent thermal energy storage tanks for micro-CHP systems", *Applied Thermal Engineering* 59, 542–549 (2013).
[15] P. Gang, L. Jing, and J. Jie, "Analysis of low temperature solar thermal electric generation using regenerative Organic Rankine Cycle", *Applied Thermal Engineering* 30, 998–1004 (2010).
[16] R. Bayon, E. Rojas, I. Valenzuela, E. Zarza, and J. Leon, "Analysis of the experimental behaviour of a 100 kW_{th} latent heat storage system for direct steam generation in solar thermal power plants", *Applied Thermal Engineering* 30, 2643–2651 (2010).
[17] V. Zipf, A. Neuhäuser, D. Willert, P. Nitz, S. Gschwander, and W. Platzer, "High temperature latent heat storage with a screw heat exchanger: Design of prototype", *Applied Energy* 109, 462–469 (2013).
[18] H. El Qarnia, "Numerical analysis of a coupled solar collector latent heat storage unit using various phase change materials for heating the water", *Energy Conversion and Management* 50, 247–254 (2009).
[19] K. Kaygusuz, "Experimental and theoretical investigation of latent heat storage for water based solar heating systems", *Energy Conversion and Management* 36 (5), 315–323 (1995).
[20] K. Kaygusuz and T. Ayhan, "Experimental and theoretical investigation of combined solar heat pump system for residential heating", *Energy Conversion and Management* 40, 1377–1396 (1999).
[21] K. Kaygusuz, "Experimental and theoretical investigation of a solar heating system with heat pump", *Renewable Energy* 21, 79–102 (2000).
[22] Y. Varol, A. Koca, H.F. Oztop, and E. Avci, "Forecasting of thermal energy storage performance of Phase Change Material in a solar collector using soft computing techniques", *Expert Systems with Applications* 37, 2724–2732 (2010).
[23] E-B.S. Mettawee and G.M.R. Assassa, "Experimental study of a compact PCM solar collector", *Energy* 31, 2958–2968 (2006).
[24] A. Kürklü, A. Özmerzi, and S. Bilgin, "Thermal performance of a water-phase change material solar collector", *Renewable Energy* 26, 391–399 (2002).
[25] I. Al-Hinti, A. Al-Ghandoor, A. Maaly, I. Abu Naqeera, Z. Al-Khateeb, and O. Al-Sheikh, "Experimental investigation on the use of water-phase change material storage in conventional solar water heating systems", *Energy Conversion and Management* 51, 1735–1740 (2010)
[26] S. Canbazoglu, A. Sahinaslana, A. Ekmekyaparb,Y G. Aksoya, and F. Akarsua, "Enhancement of solar thermal energy storage performance using sodium thiosulfate pentahydrate of a conventional solar water-heating system", *Energy and Buildings* 37, 235–242 (2005).
[27] L. Mongibello, M. Capezzuto, and G. Graditi, "Technical and cost analyses of two different heat storage systems for residential micro-CHP plants", *Applied Thermal Engineering,* available online 26 October 2013, (http://dx.doi.org/10.1016/j.applthermaleng.2013.10.026) (2013).
[28] T. Kousksou, P. Bruel, G. Chereau, V. Leoussoff, and T. El Rhafiki, "PCM storage for solar DHW: From an unfulfilled promise to a real benefit", *Solar Energy* 85 (9), 2033–2040 (2011).
[29] S. Wu and G. Fang, "Dynamic performances of solar heat storage system with packed bed using myristic acid as phase change material", *Energy Buildings*, doi:10.1016/j.enbuild.2010.08.029 (2010).
[30] M. Ibanez, L.F. Cabeza, C. Sole, J. Roca, and M. Nogues, "Modelization of a water tank including a PCM module", *Applied Thermal Engineering* 26, 1328–1333 (2006).
[31] Z. Pluta and R. Wnuk, "Influence of a presence of PCM in a traditional storage vessel on an operation of a solar system for preparation of domestic hot water (DHW)", *Bulletin of the Warsaw University of Technology* 80, 29–51 (1995), (in Polish).
[32] D.N. Nkwetta and F. Haghighat, "Thermal energy storage with phase change material – a state-of-the art review", *Sustainable Cities and Society* 10, 87–100 (2014).
[33] M.J. Huang, P.C. Eames, and B. Norton, "Thermal regulation of building-integrated photovoltaics using phase change materials", *Int. J. Heat and Mass Transfer* 47, 2715–2733 (2004).
[34] A. Hasan, S.J. McCormack, M.J. Huang, and B. Norton, "Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics", *Solar Energy* 84, 1601–1612 (2010).
[35] M. Cellura, G. Ciulla, V.L. Brano, A. Marvuglia, and A. Orioli, "Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics", *PLEA 2008 – 25th Conf. Passive and Low Energy Architecture* 1, CD-ROM (2008).
[36] J. Kiciński, "Do we have a chance for small-scale energy generation? The examples of technologies and devices for distributed energy systems in micro & small scale in Poland", *Bull. Pol. Ac.: Tech.* 61 (4), 749–756 (2013).
[37] H. Mehling and L.F. Cabeza, *Heat and Cold Storage with PCM – an Up to Date Introduction into Basics and Applications*, Springer, Berlin, 2008.
[38] M. Kenisarin and K. Mhkamov, "Solar energy storage using phase change materials", *Renewable and Sustainable Energy Reviews* 11, 1913–1965 (2007).
[39] B. Zalba, J.M. Mann, L.F. Cabeza, and H. Mehling, "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications", *Applied Thermal Engineering* 23, 251–283 (2003)
[40] S.M. Hasnain, "Review on sustainable thermal energy storage technologies, Part I: Heat storage materials and techniques", *Energy Conversion and Management* 39 (11), 1127–1138 (1998).
[41] A. Sharma, V.V. Tyagi, C.R. Chen, and D. Buddhi, "Review on thermal energy storage with phase change materials and

applications", *Renewable and Sustainable Energy Reviews* 13, 318–345 (2009).

[42] S.D. Sharma and K. Sagara, "Latent heat storage materials and systems: a review", *Int. J. Green Energy* 2, 1–56 (2005).

[43] R. Baetens, B.P. Jelle, and A. Gustavsend, "Phase change materials for building applications: a state-of-the-art review", *Energy and Buildings* 42, 1361–1368 (2010).

[44] Y. Zhang , G. Zhou, K. Lin, Q. Zhang, and H. Di, "Application of latent heat thermal energy storage in buildings: state-of-the-art and outlook", *Building and Environment* 42, 2197–2209 (2007).

[45] A. Gil, M. Medrano, I. Martorell, A. La'zaro, P. Dolado, B. Zalba, and L.F. Cabeza, "State of the art on high temperature thermal energy storage for power generation. Part 1 – Concepts, materials and modellization", *Renewable and Sustainable Energy Reviews* 14, 31–55 (2010).

[46] 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", *Applied Energy* 86 (10), 2047–2055 (2009).

[47] T. Nomura, N. Okinaka, and T. Akiyama, "Technology of latent heat storage for high temperature application: a review", *ISIJ Int.* 50 (9), 1229–1239 (2010).

[48] H. Hidaka, M. Yamazaki, M. Yabe, H. Kakiuchi, E. Ona, Y. Kojima, and H. Matsuda, "Adjustment of the melting point of Erythritol for heat storage at 80°C", *Futurestock 2003 – 9th Int. Conf. Thermal Energy Storage* 1, CD-ROM (2013).

[49] D. Haillot, T. Bauer, U. Kröner, and R. Tamme, "Thermal analysis of phase change materials in the temperature range 120–150°C", *Thermochimica Acta* 513, 49–59 (2011).

[50] J. Zimmerman, Z. Lindemann, D. Golański, T. Chmielewski, and W. Włosiński, "Modeling residual stresses generated in Ti coatings thermally sprayed on Al_2O_3 substrates", *Bull. Pol. Ac.: Tech.* 61 (2), 515–526 (2013).

[51] J.Q. Sun, R.Y. Zhang, Z.P. Liu, and G.H. Lu, "Thermal reliability test of AL-34%Mg-6%Zn alloy as latent heat storage material and corrosion of metal with respect to thermal cycling", *Energy Conversion and Management* 48, 619–624 (2007).