Agronomy Research **13**(2), 477–484, 2015

Conceptual design of experimental solar heat accumulation system with phase change materials

M. Dzikevics*, A. Blumberga and D. Blumberga

Riga Technical University, Faculty of Power and Electrical Engineering, Institute of Energy Systems and Environment, Azenes 12/1, LV1048 Riga, Latvia;
*Correspondence: mikelis.dzikevics@rtu.lv

Abstract. The research on solar heating systems often is faced with choice of carrying out experiments in real systems with changing parameters or to use modelling software with constant parameters but many undefined parameters or assumptions. The design of experimental system for simulating solar heat accumulation is proposed in this paper. The proposed design allows testing of phase change materials which provide higher thermal density compared to water. Results from computational fluid dynamic simulations carried out by other studies have been analysed for implementation into designing of the tank. All of these factors have been taken into account to create a system that resembles real case and can simulate for a long periods of time.

Key words: thermal, energy, renewable, hot water, PCM.

INTRODUCTION

In latest years the market of the solar thermal systems in Europe has been in slow stagnation from 3.36 GW_{th} in 2008 to 2.14 GW_{th} in 2013 of annually installed power. Nevertheless the role of solar thermal heating is important since it saved 3.8 million tons of CO_2 in Europe in 2013 and 24.5 million tons of oil in 2012 globally, which is equivalent to 80 million tons of CO_2 (Mauthner & Weiss, 2014). The use of renewable energy is a necessity since in Europe 46% of the energy in residential sector is used for heating and cooling (H&C). The EU target for year 2020 is that 1.26% of energy required for H&C is supplied by solar thermal systems (ESTIF 2014).

For scientific community, in the field of solar thermal energy, to help to improve the growth of new technologies and improvements of existing ones, it is necessary to provide access to facilities where these ideas can be tested. The research on solar heating systems often is faced with choice of carrying out experiments in real systems or to use modelling software. In the first case the parameters of the system are never constant, it is impossible to recreate the conditions twice, access may be limited if the system is not solely used for experimental purposes and possibilities may be limited if the system is used as a primary supply for heating or preparation of hot water. The modelling softwares cannot be disregarded, since they provide a fast, economically liable and easily adjustable solution. However any computation is based on set amount of formulas and number of assumptions. Belessiotis et al. (2013) calculated the discrepancy between the measured energy outputs calculated using the experimental values and measured energy output. The discrepancy value in most cases is in range of 5%, but in some cases for specific conditions it can reach 19%, therefore a real life system is integral part of a process of delivering a reliable new technology to the consumer. It becomes even more complicated when non-traditional elements are introduced in the system, for example phase change materials in heat accumulation tank.

All of the solar heating systems are faced with variable energy supply. Since all of the energy must be stored during the daytime, accumulation tank is crucial part of the system. Latent heat of fusion of phase change materials (PCMs) are used to increase heat accumulation capacity of solar system by increasing thermal density of accumulation tank. Latent heat of fusion, compared to traditional systems with sensible heat storage, is isothermal during the melting or solidification of PCM. PCM can be divided into paraffin's, fatty-acids, inorganic and organic salt hydrates and organic and inorganic eutectic compounds (Sharma & Chen, 2009).

The use PCMs in solar thermal systems have been studied mainly by use of modelling. Pielichowska & Pielichowski (2014) presented a thorough review of PCMs for thermal energy storage applications. Many of the studies have been dealing with calculating the phase change phenomena with different types of containers, types of PCM and scenarios (Karthikeyan & Velraj, 2012; Oró et al., 2013; Yaïci et al., 2013). A common outcome of the studies were that the use of PCM increased the storage capacity. However only few have gone as far as simulating annual gains from using PCM in accumulation tanks. Two studies, one followed by the other were carried out by Talmatsky & Kribus (2008) and Kousksou et al. (2011) and the conclusions were that there can be cases were use of PCM increases heat losses to the environment during night and can cancel gains made during day. Interestingly in earlier study Kousksou et al. (2007) neglected the heat losses in the mathematical model. Similarly Yang et al. (2014) have assumed that the heat losses from bottom and sides of the storage tank can be neglected. These and other studies prove that modelling always has to be backed up with experimental systems.

Similar system to the one described in this paper has been used in study of López-Navarro et al. (2014). It consists of single heating circuit from building condensation ring and a cooling circuit with evaporation chiller and was used for analysing cooling with PCMs. Most of the studies employ traditional system with addition of more sophisticated measurement apparatus or small scale set-ups (Sharma et al., 2009). In this paper the design of experimental system for simulating solar heat accumulation is proposed. It allows scientists to imitate heating load of certain real building in a laboratory environment. It allows researchers to provide solutions for an individual cases and study them in further detail without the need of setting up a solar collector system at the building under investigation.

DESIGN OF SYSTEM

The experimental solar thermal system design proposed in this paper consists of two sets of solar collectors, heat exchanger loops, two accumulation tanks, gas boiler and systems for imitating domestic hot water consumption and energy used for heating.

System have two sets of solar collectors that allow to carry out side-by-side tests for collectors, accumulation tanks and other optimization of such parameters as angle of collectors, flow speed, pipe size, heat exchanger size, insulation thickness, inlet and outlet positions for tank and other small adjustments.

Temperature can be measured before and after solar collector, before and after each side of heat exchanger, at the inlets and outlet of the storage tank. Temperature is converted into signal and sent to controller, which subsequently sends signal to pumps and or mechanical valves. Employment of sophisticated control system allows optimization of control algorithms or to create different conditions for each of the storage tanks.

Solar collector loops (SCL) for both tanks are similar and if needed can be made identical. SCL (Fig. 1) consists of elements such as solar collectors (SC), balancing valves (BV), expansion tank (EV), hydraulic blocks (HB), heat meters (HM), temperature sensors (T), solar controller connections (S,A) and electric heater (ES).

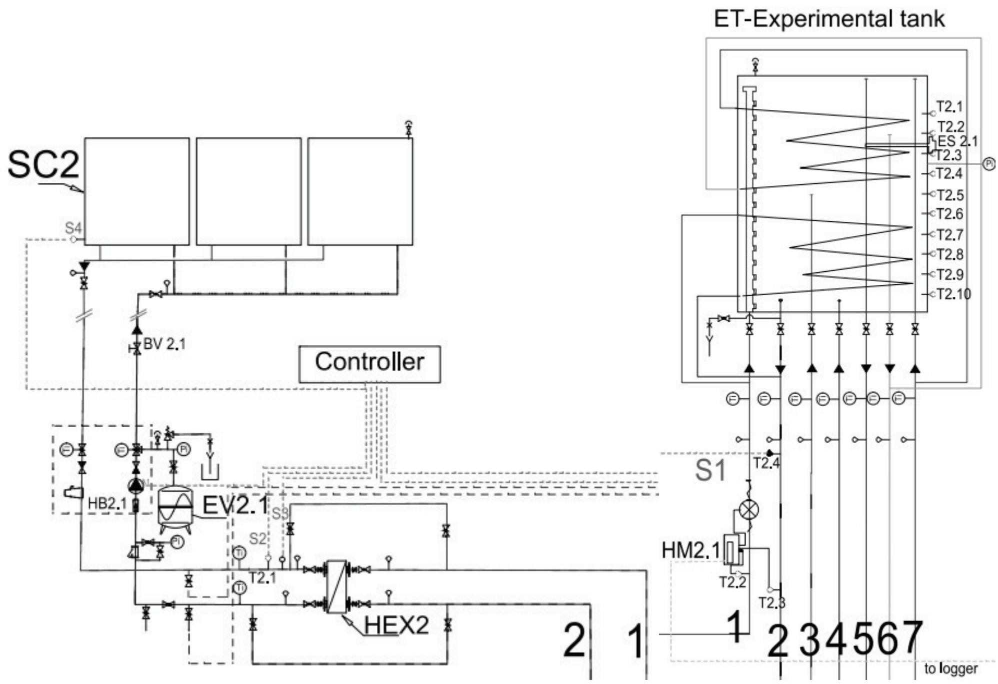

Figure 1. Solar collector loop on left; inlets and outlets in experimental tank (1 – hot water from HEX2; 2 – return to solar HEX2; 3 – return from heating; 4 – return from DHW; 5 –supply to DHW; 6 – return to gas boiler; 7 – hot water from gas boiler).

SCL with heat exchanger dividing SCL (HEX2) gives an option to use two types of working fluids – glycol and water mixture for collector side and mixture or pure water in tank side. Use of glycol is common in northern countries, however it is possible to remove HEX2 and to simulate solar collector systems that use water as only working fluid. In similar fashion immersed HEX can be used either at SCL side or at the side of load or removed if it is an open system.

There are two parameters controlling the pump – the change in the pressure or temperature difference between solar collector and inlet of HEX2 at collector side. The secondary pump is controlled by the changes in temperature between tank and temperature before the HEX2 at collector side or it can automatically turn of if the temperature in collectors are too low.

The role of heating load imitation (HLI) in Fig. 2 is to cool the fluid flowing into heat exchanger (HEX3) similarly as radiators or other heating equipment is cooled due to heat losses from building. Like in buildings, the heating power can vary depending on the outside temperature and the individual comfort levels of occupants. HLI consists of on-roof cooler (condenser) with variable cooling power (in this case 8 kW), that measures the temperature outside and before heat exchanger (HEX3) separating cooler from other parts of the system.

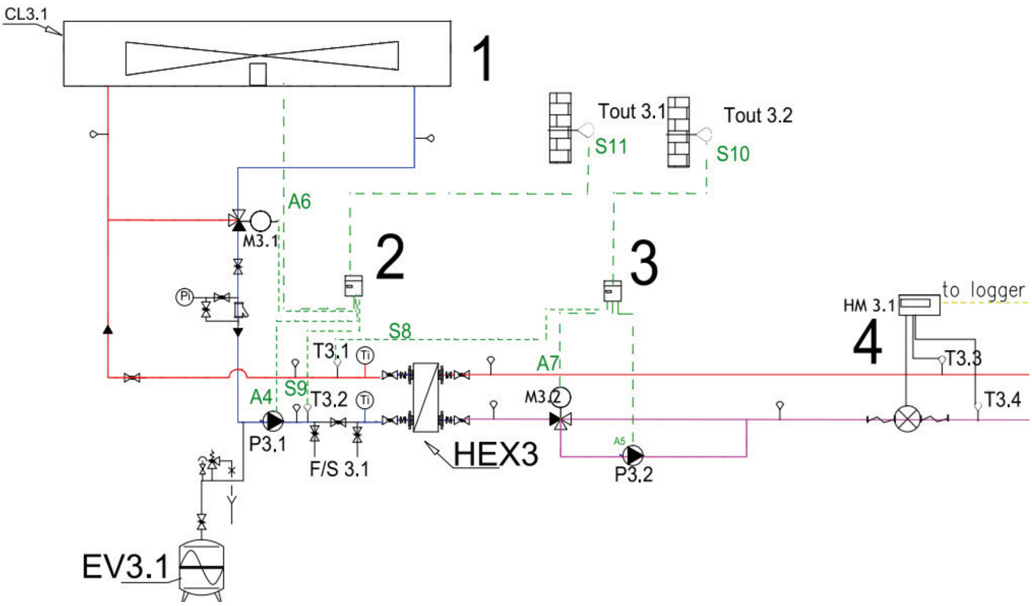

Figure 2. Heating load imitation diagram (1 – on-roof cooler; 2 – controller for imitating temperature at cooler loop; 3 – controller for valve and pump; 4 – flow rate and power meter).

For the control of HLI two controllers are used to turn on pumps depending on the temperature, regulate cooler depending on the outside temperature or heating curve and regulate motorized three-way valve depending.

The domestic hot water imitation (DHWI) is achieved by using motorized valve and a controller allowing to create consumption patterns for different types of consumers (Fig.3). Additionally backpressure regulator (PS) is required, since the water is sent to drainage at atmospheric pressure. Use of PS ensures that the HEX4 is pressurized equally in both sides. On the left side of HEX4 no pump is required, since central cold water (CW) is under pressure.

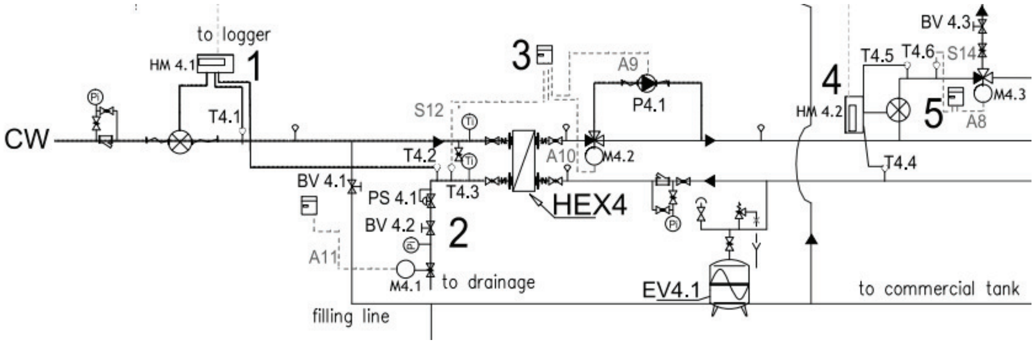

Figure 3. Domestic hot water load imitation diagram (1 – flow rate and power meter for cold side; 2 – pressure valve; 3 – controller for imitating DHW load; 4 – flow and power meter for test tank; 5 – controller for test tank return option).

The main element of the system is the experimental tank (Fig. 4). The base of design is existing commercial tanks – cylindrical, with attachments for immersed heat exchangers, filling and emptying. For the tank to work as stratification tank there are 3 options – to add immersed stratification pipes from the top or bottom, or use multiple side inlets to direct the water with higher temperatures at the higher inlets. Additionally the top of the tank can be removed, allowing to customize the elements within the tank.

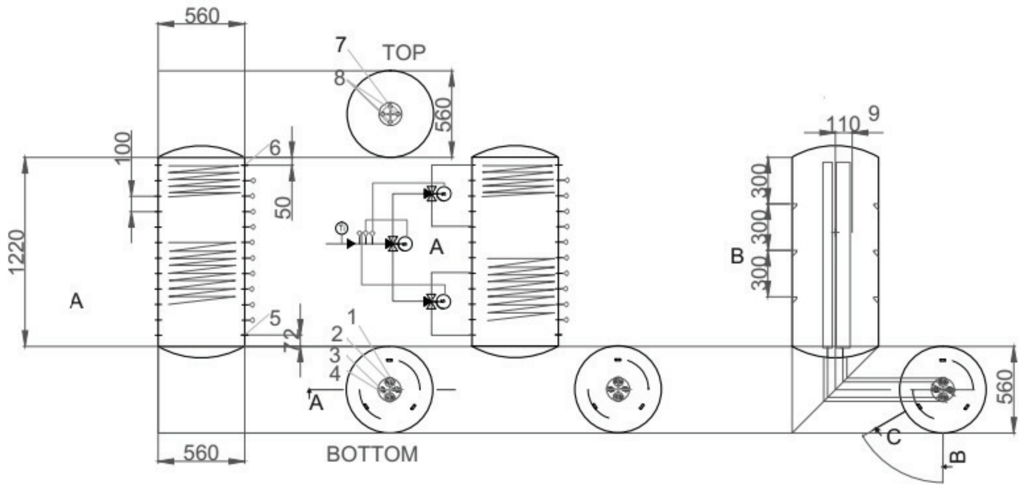

Figure 4. Experimental tank's inlet/outlet elements (1 – hot water from solar collector; 2 –supply to DHW; 3 – return to solar collector loop; 4 – return from heating load; 5 – cold water supply; 6 – supply to heating load and DHW; 7 – bleeding valve; 8 – spare fittings; 9 – stratification pipe).

In the making of the tank, stratification was looked at as an important parameter that can increase the efficiency of the solar system. Suitable height and diameter (H/D) ratio for achieving stratification has been analysed by Furbo and Shah (2005) and Yaïci et al. (2013). Former concluded that the higher the H/D ratio, the better is stratification. Lateral used computational fluid dynamics (CFD) and found that by changing the ratio from 2 to 3.5 showed that stratification remained the same. It was found that the tanks with higher H/D ratio have advantage in cases where hot water layer becomes so thick, that the thermocline becomes too narrow to separate hot and cold water. Based on these results, the dimensions of the experimental tank was chosen to have an H/D ratio above 2. However, the experimental tank was kept at low H/D ratio (2.17) to improve the accessibility to the elements at the bottom and sides of interior of the tank.

Location of the inlet of the hot water was found to have high influence on the stratification. In the study by Yaïci et al. in Fig 5. it can be seen that after 1,000 s, the temperature distribution vary due to different jet momentum (horizontal flow) and bouyancy effect (vertical flow). Further away the inlet is from the top, lower is the jet momentum and higher bouyancy effect causing mixing of the warm water.

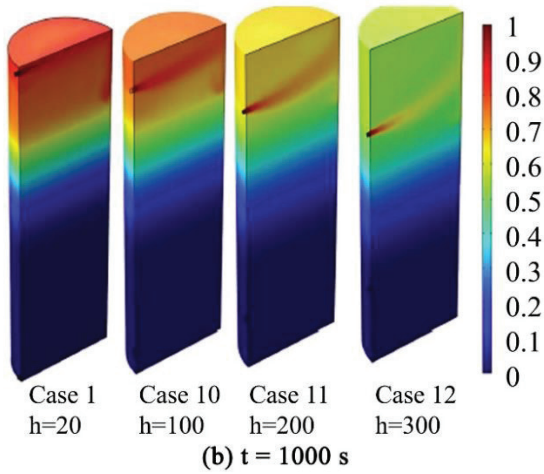

Figure 5. Effect of inlet locations on thermal stratification. X axis has a dimensionless temperature $(T-T_{ini})/(T_{in}-T_{ini})$ (Yaïci et al. 2013).

CFD can be used to analyse location of inlet, the effects of changes in mass flow rate, inlet hot water temperature and initial temperature conditions. In the mentioned study, the validation was calculated using experimental data from study of Zachar et al. (2003). However the experimental data were gathered on a tank with a different H/D ratio, different inlet position and a baffle plate at the bottom. As a result, the uncertainty is estimated to be ≤ 15%. It is planned that the use of experimental tank proposed in this paper will reduce uncertainty since different options can be tested experimentally.

The experimental tank can also be used to analyse performance of accumulation tank filled with multiple types of PCM with different melting temperatures. If the PCM is capsulated in the shape of spheres with a diameter around 50 mm, the solution is to employ the packed bed principle where the PCM spheres are freely placed inside tank. However to achieve separation of different types of PCM, round plates can be used. Similar system has been numerically analysed by Yang et al. (2014). Other experimental system have employed steel mesh (Reddy et al., 2012), however perforation of the plates allow many design options since different distribution and sizes of holes will have different impact on the flow of the water between the two layers divided by the plates.

The studies analysing use of baffle (buffer) plates have been review by Altuntop et al. (2005). Often small obstacle are placed in front of the inlet to reduce the jet momentum, however in some cases larger plates are used to improve stratification. The study also concluded that the use of plates provide better thermal stratification compared to the no obstacle case and that the gap in the middle performed better than having a gap closer to the tank wall. However to the knowledge of the author, no studies have been carried out to analyse different plates in combination with PCM.

CONCLUSIONS

There are many challenges in programming any system to imitate real life situations. In this system there are 12 controllable elements where some of them can be used to complement other, meaning that they have to improve each other rather than compete. For example – a pump, a motorized valve and a variable cooler. All of the elements affect the cooling power, so there is a question of prioritizing them.

As mentioned in this paper, experimental systems can favour from the use of numerical analysis, therefore creating the same design within the environment of software such as TRNSYS will increase the number of applications for the system.

The adaptability of the experimental tank allows it to be used for gathering required validation data and to reduce the uncertainty of the numerical analysis that use experimental data from the systems that differ from the one modelled.

The use of PCM in experimental systems has often been restricted to a small scale systems. By the knowledge of the authors, no experimental studies with real life consumption has been carried out where PCM was employed in solar thermal system accumulation tanks for long periods. The proposed system will provide the necessary experimental data required for quicker and safer implementation of PCM into consumer systems.

ACKNOWLEDGEMENTS. The work has been supported by the National Research Program 'Energy efficient and low-carbon solutions for a secure, sustainable and climate variability reducing energy supply (LATENERGI)'.

REFERENCES

Altuntop, N., Arslan, M., Ozceyhan, V. & Kanoglu, M. 2005. Effect of obstacles on thermal stratification in hot water storage tanks. *Appl. Therm. Eng.* **25**, 2285–2298.

Belessiotis, V., Mathioulakis, E. & Papanicolaou, E. 2013. Experimental validation of the input–output modeling approach for large solar thermal systems − Accuracy of the test procedure. *Renew. Energy* **51**, 197–205.

ESTIF 2014. *Trends and Market Statistics 2013*.

Furbo, S. & Shah, L.J. 2005. How mixing during hot water draw-offs influence the thermal performance of small solar domestic hot water systems. In *Proceedings of the 2005 Solar world Congress*. Orlando, pp. 6.

Karthikeyan, S. & Velraj, R. 2012. Numerical investigation of packed bed storage unit filled with PCM encapsulated spherical containers – A comparison between various mathematical models. *Int. J. Therm. Sci.* **60**, 153–160.

Kousksou, T., Bruel, P., Cherreau, G., Leoussoff, V. & El Rhafiki, T. 2011. PCM storage for solar DHW: From an unfulfilled promise to a real benefit. *Sol. Energy* **85**, 2033–2040.

Kousksou, T., Strub, F., Castainglasvignottes, J., Jamil, A & Bedecarrats, J. 2007. Second law analysis of latent thermal storage for solar system. *Sol. Energy Mater. Sol. Cells* **91**, 1275–1281.

López-Navarro, A., Biosca-Taronger, J., Corberán, J.M., Peñalosa, C., Lázaro, A., Dolado, P. & Payá, J. 2014. Performance characterization of a PCM storage tank. *Appl. Energy* **119**, 151–162.

Mauthner, F. & Weiss, W. 2014. *Solar Heat Worldwide. Markets and Contribution to the Energy Supply 2012*, Gleisdorf, Austria.

Oró, E., Chiu, J., Martin, V. & Cabeza, L.F. 2013. Comparative study of different numerical models of packed bed thermal energy storage systems. *Appl. Therm. Eng.* **50**, 384–392.

Pielichowska, K. & Pielichowski, K. 2014. Phase change materials for thermal energy storage. *Prog. Mater. Sci.* **65**, 67–123.

Reddy, R.M., Nallusamy, N. & Reddy, K.H. 2012. Experimental Studies on Phase Change Material-Based Thermal Energy Storage System for Solar Water Heating Applications. *J. Fundam. Renew. Energy Appl.* **2**, 1–6.

Sharma, A. & Chen, C.R. 2009. Solar Water Heating System with Phase Change Materials **1**, 297–307.

Sharma, A., Tyagi, V.V., Chen, C.R. & Buddhi, D. 2009. Review on thermal energy storage with phase change materials and applications. *Renew. Sustain. Energy Rev.* **13**, 318–345.

Talmatsky, E. & Kribus, A. 2008. PCM storage for solar DHW: An unfulfilled promise? *Sol. Energy* **82**, 861–869.

Yaïci, W., Ghorab, M., Entchev, E. & Hayden, S. 2013. Three-dimensional unsteady CFD simulations of a thermal storage tank performance for optimum design. *Appl. Therm. Eng.* **60**, 152–163.

Yang, L., Zhang, X. & Xu, G. 2014. Thermal performance of a solar storage packed bed using spherical capsules filled with PCM having different melting points. *Energy Build.* **68**, 639–646.

Zachar, A., Farkas, I. & Szlivka, F. 2003. Numerical analyses of the impact of plates for thermal stratification inside a storage tank with upper and lower inlet flows. *Sol. Energy* **74**, 287–302.