www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 66, No. 6, 2018
DOI: 10.24425/bpas.2018.125942

A system for monitoring and controlling a thermal energy store and an energy capture system

P. PIETKIEWICZ, K. NALEPA*, W. MIĄSKOWSKI, and M. WILAMOWSKA-KORSAK

Department of Technical Sciences, University of Warmia and Mazury in Olsztyn, 11 Oczapowskiego St., 10-719 Olsztyn, Poland

Abstract. The structure and operating principles of a system for monitoring and controlling the operation of a thermal energy store have been presented in this study. As a novel feature of the presented solution, the device can be operated as a thermal energy store that relies on specific heat of fluids or phase transition heat when packages of phase change materials (PCM) are placed inside the device. Grates were used to arrange PCM packages in a manner that guarantees the flow of the heat transfer medium. The grates were equipped with temperature sensors to control thermal decomposition throughout the entire tank. The use of aerogel for thermal insulation was also a novel solution. Only a thin layer of aerogel was required to reduce heat loss across the tank wall. The structure and functionality of the modelled thermal energy store correspond to real-life conditions. The model can be used to test monitoring and control systems and to analyse the phenomena observed during the operation of similar devices. The operation of the thermal energy store can be regularly monitored and controlled on-line from any location in the world. The developed model supports the automatic import of operating parameters into a database for further analysis.

Key words: energy storage, phase change materials, SCADA MHI, energy monitoring.

1. Introduction

For several years, the authors have been researching various methods for generating and storing energy from renewable sources. Energy storage is particularly important for distributed energy generation systems working with renewable energy sources [1]. Selected sources of renewable energy are characterized by non-constant availability [2, 3], and all systems that use renewable energy have to be provided with monitoring and control tools which partially or fully automate device operation and create access to operating parameters in the automatic mode [4–7].

Thermal energy stores rely on specific heat, latent heat, thermochemical changes and heat of sorption [3]. Various materials with heat storing properties are used in the construction of thermal energy stores. The physical properties of substances and materials for heat storage have been broadly discussed and compared by Alva et al. [8].

Research into thermal energy storage requires laboratory-scale test stands. Devices similar to that presented in this article have been widely discussed in the literature. Khana et al. [9] analysed changes in phase transition heat when packages of phase change materials (PCM) were placed inside an energy storage system. The cited authors emphasized the importance of tank structure and pointed to the problem of heat retention in the tank at an unfavourable ratio of PCM volume to heat exchange area. This problem requires new solutions to increase the tank's heat exchange area relative to the volume of the heat absorbing substance. A solution to the above problem was proposed by Cascetta et al. [10] where air was the heat transporting medium and thermal energy was stored in alumina beads.

A test stand for analysing the storage of heat from solar collectors based on the phase transition effect has been developed by Nullasamy et al. [11]. In the cited study, water was the heat transporting medium, and thermal energy was stored in spherical capsules filled with PCM. A similar solution was proposed by Pandiyarajan et al. [12] who installed cylindrical capsules in a storage tank. A special framework was built to distribute capsules on several levels.

Pan and Zhao [13] designed a thermal energy storage tank featuring cylindrical pipes filled with an aluminium-based thermochemical solution. The pipes were arranged in a vertical position. In a similar solution developed by Zhang et al. [14], vertically arranged cylindrical pipes were filled with PCM and placed in two horizontal sections.

A similar study was presented by Karwacki et al. [15]. In this research, the authors focused on obtaining the accurate information about the transfer of heat between the heat transfer fluid (HTF) and the phase change material (PCM) during energy accumulation process using shell-and-tube thermal energy storage units.

Fopah-Lele et al. [16] designed a test stand with a heat exchanger made of porous material. The proposed solution increased the contact surface between the heat transporting medium and heat storage material. An interesting concept was also proposed by Dinker et al. [17], who analysed and compared various arrangements of heat exchangers in a tank filled with PCM.

The thermal energy store presented in this study has been designed for operation with any source of heat. Packages containing various PCMs were placed inside the tank, and the col-

*e-mail: nalepka@uwm.edu.pl

Manuscript submitted 2017-10-06, revised 2017-12-31, initially accepted for publication 2018-01-22, published in December 2018.

lection, utilization and distribution of heat were controlled. A database management system (DBMS) was also designed and built to monitor and acquire measurement data. The system supports the collection and analysis of data acquired at any frequency. The charging and discharging of the thermal energy store can be controlled on-line with the use of the applied software.

The data control and acquisition system is a key element of the test stand for evaluating thermal energy stores. It relies on computerized control and measurement systems based on programmable logic controllers (PLC). A PLC has been analysed extensively by Milik et al. [18] who described the programming operations performed by PLCs, time dependencies and responses to real-time events. Data control and acquisition systems operate autonomously in a supervisory control and data acquisition system (SCADA). Upadhyay and Srivastava [19] used a SCADA system to manage a solar power farm with a thermal energy store. The system can be used to visualise operating parameters, control the power station and its communication with an energy store.

2. Structure of a thermal energy store

The thermal energy store presented in Fig. 1 has been designed and built by the authors. Three coil pipes inside the main storage tank act as heat exchangers which receive energy from the tank. The received energy is transferred to dissipation devices which can be replaced by a residential heating system or any heat store in a real-life application.

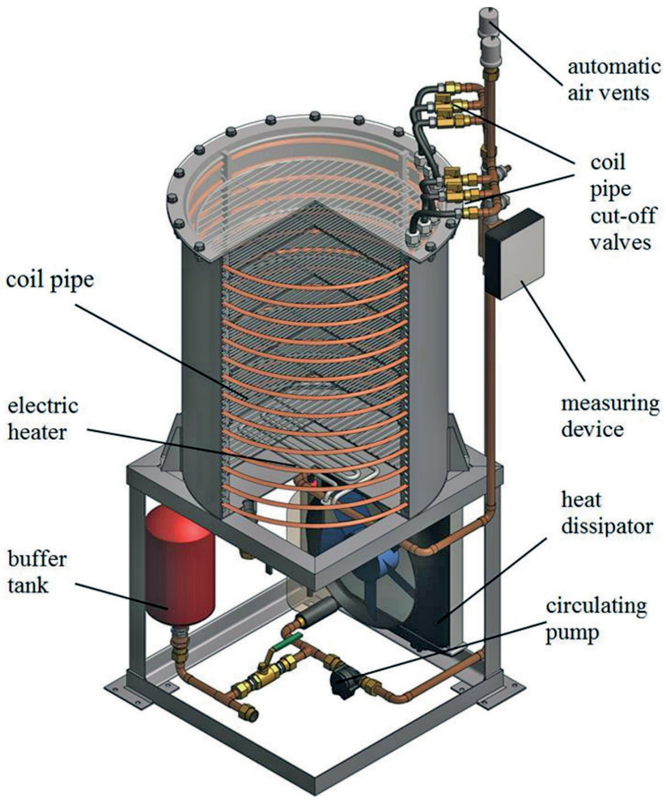

Fig. 1. Diagram of a thermal energy store with an energy capture system

The tank is the main element of the thermal energy store, and it is filled with substances which undergo phase change within the range of operating temperatures of the analysed unit. Paraffin immersed in water was used for modelling purposes. Thermal energy is freely transmitted from the heater to phase change material via a liquid medium. The medium is moved by convection, and it transfers heat to paraffin blocks in the storage tank. Twelve temperature sensors were installed in the tank at four levels, with three sensors on each level (one along the tank's axis, one at half the tank's radius and one near the coil pipe – the heat exchanger). Thermal energy was generated by an electric heater which can be supplied from any power source (power grid, wind power generator, microturbine, etc.).

Stored energy is captured from the system by an internal heat exchanger comprising three parallel coils connected to the main system circuit. A circulator pump sets the working medium (glycol/water solution) into motion inside the system. Heat captured from the store is dissipated by a cooler equipped with an electric fan. The device was built on a laboratory scale, but it can be used in real-life applications.

The modelled thermal energy store has been designed for operation with a small wind turbine. The store is "charged" by an electric heater powered by a wind turbine generator. Thermal energy produced by the device supplies heat for a residential building via a heating system [20–23].

The system's operating parameters have to be controlled. While the process of heating the working medium in the thermal energy store is controlled by an electric heater (which will be powered by a wind turbine generator in a real-life application), the process of receiving heat is limited by several factors:

- differences in temperature between the heating medium and the surroundings of the medium cooler,
- surface of the heat exchanger in the storage tank,
- flow rate of the working medium in the cooling system,
- cooler efficiency controlled by an electric fan.

The system has been designed to provide the widest possible range of control options for the cooling process in the thermal store. The rate at which heat is received from the store will be determined mainly by the temperature of the heating medium. Paraffin undergoes phase change [24–27] at the temperature of around 55–60°C. Since heat exchange is most effective during phase change, the planned experiment will take place at the temperature of approximately 60°C.

A control and measurement system is needed for the device to operate effectively. More than ten parameters have to be monitored and controlled during the operation of the thermal energy store and the heat capture system:

- Temperature inside the storage tank, measured at 12 points distributed throughout the tank (T1_1, T1_2, …, T4_3);
- Temperature of the medium in the heat capture system at the outlet from heat receiving coils (Tg) and at the point of return to the tank (Tz);
- Ambient temperature;
- Air temperature before the fan which cools the heating medium;

- Air temperature behind the fan which cools the heating medium;
- Pressure inside the heat capture system (p);
- Flow rate of the heating medium;
- Energy generated by the electric heater which "charges" the thermal energy store.

The following parameters have to be controlled during the storage and capture of thermal energy from the store:

- Output of the pump which circulates the heating medium (% rated power),
- Output of the fan which cools the heating medium (% rated power of the fan motor),
- Output of the heater which supplies heat to the heat store (heater output will be controlled naturally in systems operating with a wind turbine generator. During modelling, heater output is set by the operator).

The system for monitoring and controlling the operation of the thermal energy store, including its hardware and software components, has been designed and built by the authors.

3. Control and measurement system – hardware

The main element of the control and measurement system is the PLC Siemens S7–1200 controller with analogue input modules for operation with PT100 resistance temperature detectors (RTD) and an analogue output module for operation with the heater output controller. The PLC controller system generates control signals, collects and transmits measurement data.

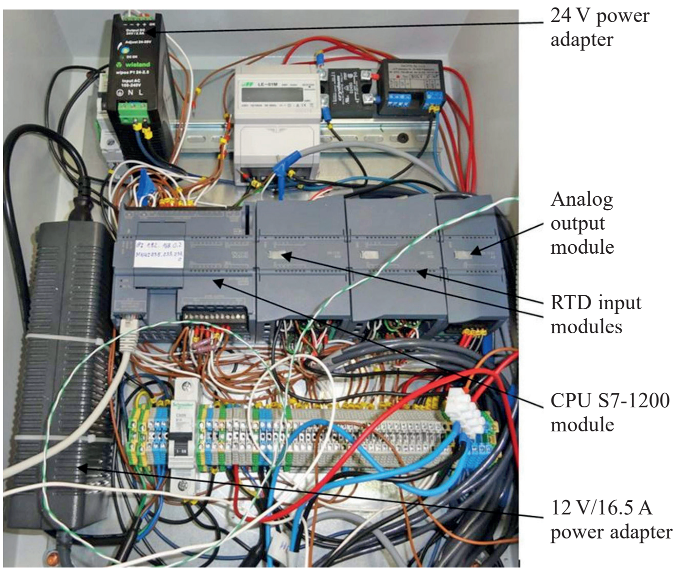

Fig. 2. Basic elements of the control and measurement system

Electric parameters are set by a voltage signal generated by the analogue output module. The actuating element is the connection between the group controller and an SSR switching device. Electric parameters are measured by the LE-01M digital meter.

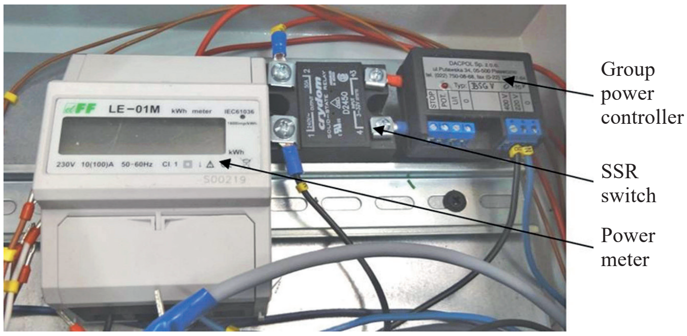

Fig. 3. Elements of the system which controls heater output and registers the parameters of energy supplied to the store

A simple dual channel DC PWM controller was designed for controlling the operating parameters of the circulator pump motor and the fan motor. IGBT transistors are actuators which control high power DC receivers via low power signals available directly from the PLC controller.

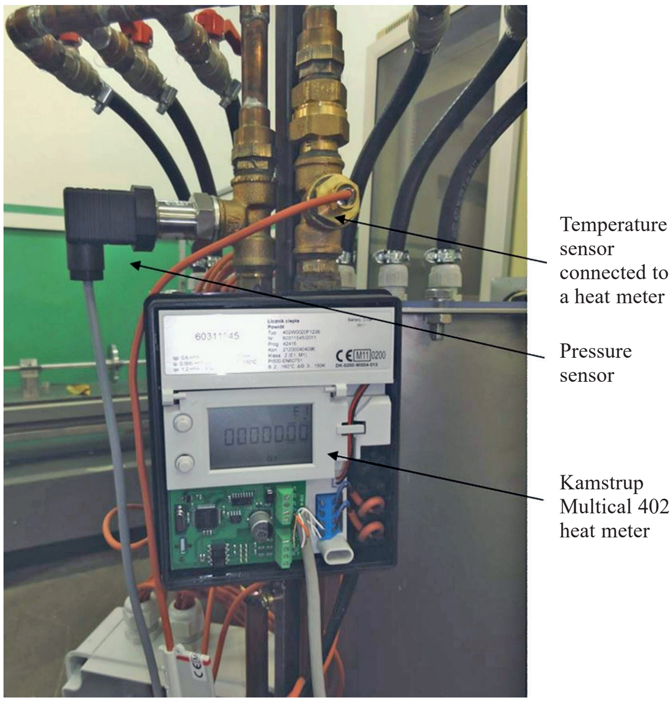

Fig. 4. Kamstrup Multical 402 heat meter

Heat parameters, including feed temperature, return temperature, flow rate and quantity of heat, are measured by the Kamstrup Multical 402 heat meter.

4. Control and measurement system – software

Measurement data from heat and power meters and data acquired by the PLC controller is transmitted to the SCADA HMI system for the visualization and registration of measurement

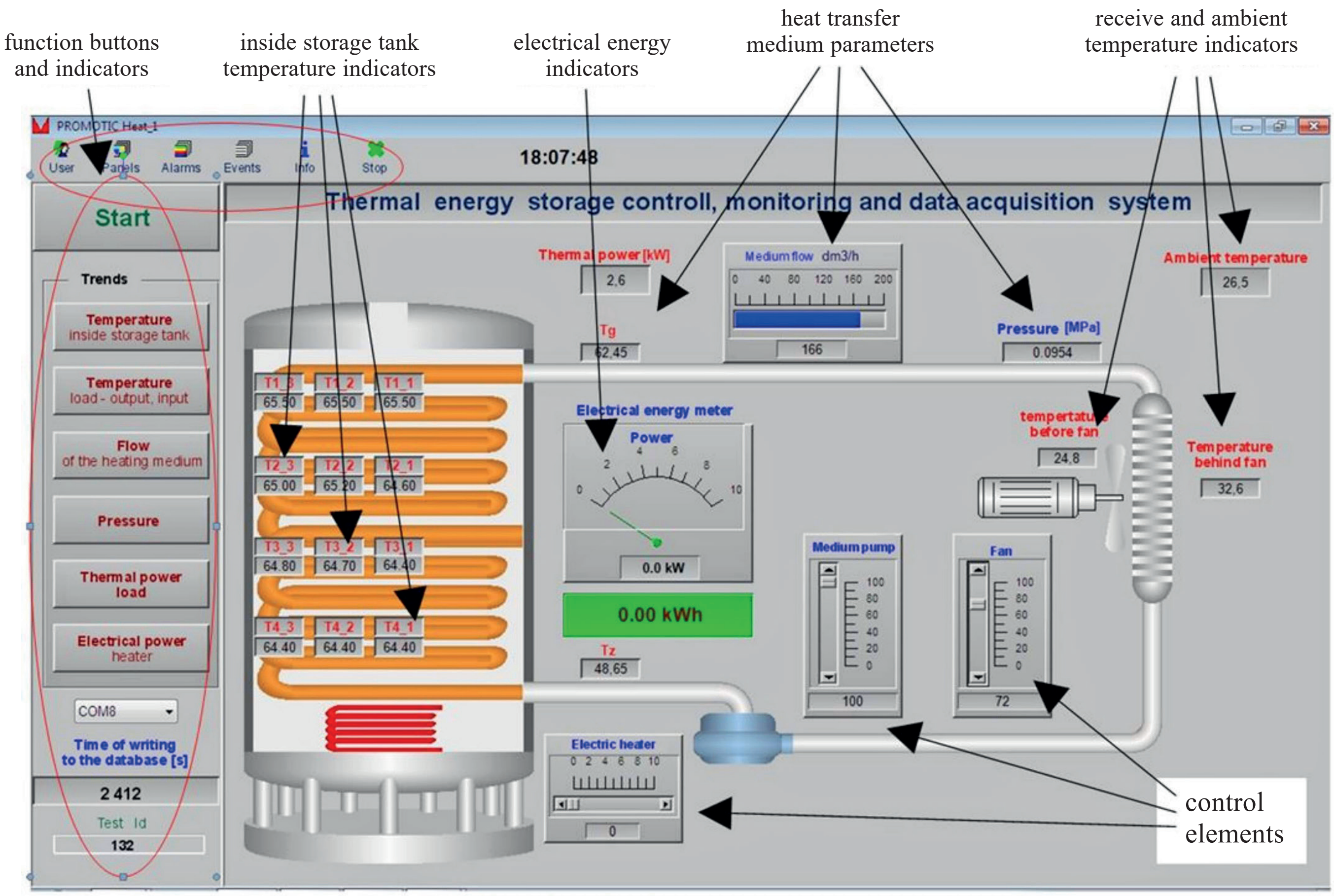

Fig. 5. The main console for controlling the system and monitoring operating parameters

and control data. The SCADA HMI system was developed in the PROMOTIC environment [15], and it also generates control signals which are transmitted to the system by the PLC controller.

Signal converters had to be used due to various types of communication interfaces in different parts of the system: RS485-USB for communication with the power meter, M-BUS – Ethernet for communication with the heat meter. Devices communicate with the PLC controller via the Ethernet interface.

The system is controlled by a computer application developed in the PROMOTIC SCADA environment. The application supports communication with all devices that "charge" the thermal energy store and receive stored heat. The control pulpit is presented in Fig. 5.

The values of operating parameters in the thermal energy store and the heat capture system are displayed in windows in the centre of the screen. The parameters indicated in section 3 are read and set with the use of a graphic interface.

Additional tools are displayed on the left side of the pulpit. Before launching the application and the system, the operator can set the parameters of the communication port which is used by the application to communicate with control and measuring devices. Time intervals (in seconds) can be set between recording sessions of data packets in the database. The recorded results can be allocated to specific experiments registered in the database. The application also features graphic tools for visualizing changes in the values of selected parameters:

- Temperatures inside the tank (T1_1, T1_2, …, T4_3),
- Temperature of the heating medium at tank outlet and upon return to the tank (Tg, Tz),
- Flow rate of the heating medium,
- Pressure of the heating medium,
- Heat power at heat reception point,
- Output of the heater supplying the thermal energy store.

5. Data archiving and analysis

The application described in section 4 can be used to control the system remotely in real time from any location in the world. To analyse changes in parameter values over longer periods of time, a database for storing values from system sensors has been designed and launched.

Recording intervals are set in the control application. The application has automatic on-line access to the database created in the MySQL environment, which is located on a professional server.

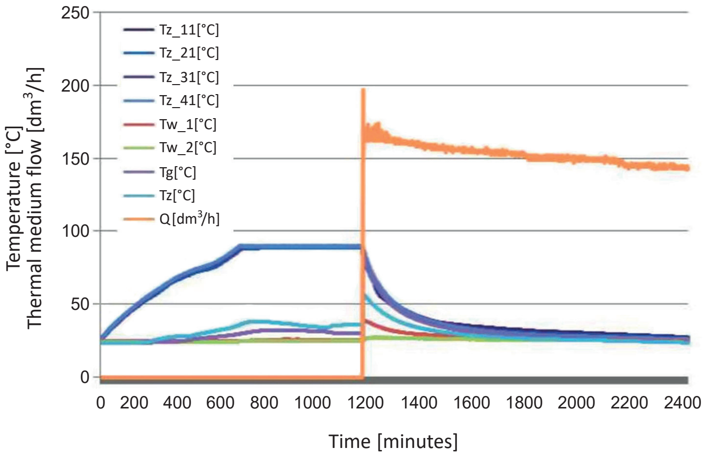

Fig. 6. Diagram of changes in selected system parameters over time

Registered data is used in various analyses. A diagram of changes in selected parameters over time is presented in Fig. 6. In the illustrated experiment, the medium was heated in the store, and stored energy was received by the energy capture system.

The diagram in Fig. 6 illustrates changes in the following parameters: temperature inside the storage tank (Tz_11, Tz_12, Tz_13, Tz_14), temperature before and behind the heat dissipation fan (Tw_2, Tw_1), temperature of the heating medium at the outlet of the storage tank (Tg), temperature of the heating medium returning to the heat exchanger (Tz), flow rate of the heating medium (Q).

This data can be divided into two parts which correspond to different experimental processes:

Part 1 – heating the working medium of the thermal energy store (charging the store). Temperature increases inside the storage tank, and temperature variations are influenced by paraffin. The fluctuations in temperature measured by other sensors are caused by convection heating of the medium which evacuates heat from the store. The flow rate of the heating medium equals 0.

Part 2 – cooling of the working medium of the thermal energy store (discharging the store). Temperature measured by sensors Tg, Tz, Tw_1 and Tw_2 changes rapidly when the energy capture system is activated. The above also leads to changes in flow rate Q.

The values on the horizontal axis correspond to successive intervals between sessions when the monitoring system records data in the database. In the discussed experiment, the interval was set at 30 s.

6. Research opportunities

The developed system for control and monitoring the work of the heat storage allows for a number of experimental tests aimed at improving the efficiency of this installation type. Thanks to full control over the devices supplying energy to the storage tank and receivers, it is possible to model the operation of the heat storage with different strategies of charging and discharging energy storage system:

– energy supply at various power values;
– supplying energy to the storage while receiving heat with different intensity;
– modeling of storage work in variable time conditions;

Due to the design of the heat storage and its control system, it is also possible to conduct research in other directions:

– research on the efficiency of the heat storage process using packages containing various substances, both as heat storage and as a heat carrier between the packages and devices receiving them from the heat storage tank;
– research on the impact of the size and shape of heat accumulating packages on the process of loading and unloading the heat storage system;
– modeling the impact of selected failures of the installation elements on its operating parameters (determination of the symptom-defect relationship) and elaboration of the so-called reverse device models.

The construction of the measurement and control part of the stand and the design of the application for monitoring the system's operation has been developed with the focus on the possibility of using it on a technical scale. The use of a heat meter with a suitable measuring range for the technical scale equipment of heating system and minor changes in the application for monitoring and control are the only modifications required to adapt the presented system to work in a technical scale.

7. Conclusions

The hardware and software solutions discussed in this experiment were designed on a laboratory scale, but they can be applied directly to monitor energy storage and distribution systems in practical applications. The above applies to the designed equipment, which comprises standard sensors, energy meters, measuring transducers and controllers, as well as the software application developed based on the SCADA PROMOTIC system. The proposed solution supports on-line system management in real time, the registration and analysis of measurement data and alarm signals.

The laboratory thermal energy store presented in this paper can be used to:

– acquire information about the distribution of temperature and heat in the process of charging and discharging an energy store,
– examine different combinations of heat transporting media and heat storage materials,
– store thermal energy from different sources of electricity or heat and simulate the operation of various heat receivers,
– design the optimal charging and discharging cycles by controlling a thermal energy store's parameters on-line.

The proposed thermal energy store and database systems can be used to develop strategies for charging and discharging energy stores in industrial applications. The developed control and monitoring system can be directly implemented in an industrial setting.

Acknowledgements. The test stand described in this study was developed as part of National Project No. POIG.01.01.02–00–016/08, entitled "Model agroenergy complexes as an example of distributed cogeneration based on local renewable energy sources", under the Innovative Economy Operational Program 2007–2013 co-financed by the European Regional Development Fund.

References

[1] 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, Bulletin of the Polish Academy of Sciences: Technical Sciences. Volume 61, Issue 4, Pages 749–756, ISSN (Print) 0239–7528, DOI: 10.2478/bpasts-2013–0080, January 2014,

[2] A. Oniszk-Popławska, M. Rogulska, G. Wiśniewski, Renewable-energy developments in Poland to 2020, Applied Energy, Volume 76, Issues 1–3, September–November 2003, Pages 101–110,

[3] Y. Tian, C.Y. Zhao, A review of solar collectors and thermal energy storage in solar thermal applications, Applied Energy, Volume 104, April 2013, Pages 538–553,

[4] C.-D. Dumitru, A. Gligor, SCADA Based Software for Renewable Energy Management System, Procedia Economics and Finance, Volume 3, 2012, Pages 262–267,

[5] A. Salihbegovic, V. Marinković, Z. Cico, E. Karavdić, N. Delic, Web based multilayered distributed SCADA/HMI system in refinery application, Computer Standards & Interfaces, Volume 31, Issue 3, March 2009, Pages 599–612,

[6] J. Wiles, Chapter 2 – Supervisory Control and Data Acquisition, Techno Security's Guide to Securing SCADA, Syngress, Burlington, 2008, Pages 61–94,

[7] J.-M. Gallardo-Calles, A. Colmenar-Santos, J. Ontañon-Ruiz, M. Castro-Gil, Wind control centres: State of the art, Renewable Energy, Volume 51, March 2013, Pages 93–100,

[8] Alva G., Liu L., Huang X., Fang G., Thermal energy storage materials and systems for solar energy applications, Renewable and Sustainable Energy Reviews, Volume 68, 2017, Pages 693–706,

[9] Khana M. MA., Saidura R., Al-Sulaiman F.A., A review for phase change materials (PCMs) in solar absorption refrigeration systems, Renewable and Substainable Energy Reviews, 2017,

[10] M. Cascetta, G. Cau, P. Puddu, F. Serra, A study of a packed-bed thermal energy storage device: test rig, experimental and numerical results, Energy Procedia 81 (2015) 987 – 994,

[11] N.Nallusamy, S. Sampath, R. Velraj, Experimental investigation on a combined sensible and latent heat storage system integrated with constant/varying (solar) heat sources. Renewable Energy, Volume 32, Issue 7, June 2007, Pages 1206–1227,

[12] Pandiyarajan V. , Chinna Pandian M., Malan E. , Velraj R., Seeniraj R.V., Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system, Applied Energy, Volume 88, April 2011, Pages 77–87,

[13] Pan Z.H., Zhao C.Y., Gasesolid thermochemical heat storage reactors for high-temperature applications, Energy, Volume 130, 2017, pages 155–173,

[14] Zhang P., Ma F., Xiao X., Thermal energy storage and retrieval characteristics of a molten-salt latent heat thermal energy storage system, Applied Energy, Volume 173, April 2016, Pages 255–271,

[15] Karwacki, J., Bogucka-Bykuć, K., Włosiński, W., Bykuć, S. Towards development of a prototype high-temperature latent heat storage unit as an element of a RES-based energy system (part 2) Bulletin of the Polish Academy of Sciences Technical Sciences, Volume 64, Issue 2, 2016. Pages 401–408,

[16] Fopah-Lele A. i inni, Lab-scale experiment of a closed thermochemical heat storage system including honeycomb heat exchanger, Energy, Volume 114, 2016, pages 225–138,

[17] Dinker A., Agarwal M., Agarwal G.D., Heat storage materials, geometry and applications: A review, Journal of the Energy Institute, Volume 90, 2017, Pages 1–11,

[18] Milik, A., Chmiel, M. & Hrynkiewicz, E. (2016). On the systematic method of conditional control program execution by a PLC. *Bulletin of the Polish Academy of Sciences Technical Sciences*, 64(1), pp. 161–170. Retrieved 5 Oct. 2017, from doi:10.1515/bpasts-2016–0018,

[19] Upadhyay S., Srivastava J., Load Frequency and Excitation Control of Solar Thermal Power Plant through SCADA, International Journal of Engineering Science and Computing, May 2016, s. 4771–4773, DOI 10.4010/2016.1184a

[20] G. Xydis, Wind energy to thermal and cold storage—A systems approach, Energy and Buildings, Volume 56, January 2013, Pages 41–47, ISSN 0378–7788,

[21] X. Weiqiang, Y. Xiugan, Heat Absorbing and Releasing Experiments with Improved Phase-change Thermal Storage Canisters, Chinese Journal of Aeronautics 23(2010),Pages 306–311,

[22] E. S. Barbieri, F. Melino, M. Morini, Influence of the thermal energy storage on the profitability of micro-CHP systems for residential building applications, Applied Energy, Volume 97, September 2012, Pages 714–722, ISSN 0306–2619, 10.1016/j.apenergy.2012.01.001,

[23] J. C. Kurnia, A. P. Sasmito, S. V. Jangam, A. S. Mujumdar, Improved design for heat transfer performance of a novel phase change material (PCM) thermal energy storage (TES), Applied Thermal Engineering, Volume 50, Issue 1, 10 January 2013, Pages 896–907,

[24] M.J. Huang, P.C. Eames, S. McCormack, P. Griffiths, N.J. Hewitt, Microencapsulated phase change slurries for thermal energy storage in a residential solar energy system, Renewable Energy, Volume 36, Issue 11, November 2011, Pages 2932–2939,

[25] A. Trp, K. Lenic, B. Frankovic, Analysis of the influence of operating conditions and geometric parameters on heat transfer in water-paraffin shell-and-tube latent thermal energy storage unit, Applied Thermal Engineering, Volume 26, Issue 16, November 2006, Pages 1830–1839,

[26] A. Mawire, M. McPherson, Experimental characterisation of a thermal energy storage system using temperature and power controlled charging, Renewable Energy, Volume 33, Issue 4, April 2008, Pages 682–693,

[27] Y. Dutil, D. R. Rousse, N. Ben Salah, S. Lassue, L. Zalewski, A review on phase-change materials: Mathematical modeling and simulations, Renewable and Sustainable Energy Reviews, Volume 15, Issue 1, January 2011, Pages 112–130,