Numerical Model of System with Heat Pump and Latent Thermal Energy Storage

Fran Torbarina, Kristian Lenić, Anica Trp and Mateo Kirinčić

University of Rijeka, Faculty of Engineering, Rijeka (Croatia)

Abstract

In the paper the numerical model of a system with heat pump and latent thermal energy storage has been developed. The system consists of water-water heat pump, latent thermal energy storage on the heat source side and two sensible thermal energy storages. The results obtained with numerical model of a presented system have been compared to experimental data, obtained using appropriate experimental setup. The comparison with experimental data is presented in terms of transient variations of temperatures for both water and paraffin, heat pump heating rate, heat pump cooling rate and compressor power as well as in terms of total delivered heat, consumed heat and consumed electrical energy by the heat pump.

Keywords: latent thermal energy storage, heat pump, system simulation

1. Introduction

The European Council has adopted strategies and targets for the next ten-year period, with the long-term goal of the EU becoming a net-zero greenhouse gas economy by 2050. According to the European Commission (European Commission, 2013.), 21% of the energy used for space heating comes from renewable sources, making the use of renewable energy sources for space heating a promising potential for achieving climate goals. One way to use renewable energy is heat pumps, because the energy produced by heat pumps is considered renewable if the annual performance factor of the heat pump is above 2.5 (European Parliament and of the Council on the Energy Performance of Buildings, 2013.). Most often, heat from outside air is used as the heat source for the heat pump evaporator, but the use of solar energy has the potential to further improve heat pump performance because heat pump efficiency is highly dependent on heat source and heat sink temperatures. Since both the availability of solar energy and the temperature of the outdoor air do not coincide in time with the highest heating demand on any given day, special care must be taken in the design of a heat storage tank to maximize heat pump efficiency, extend heat pump operating hours in the favorable mode, and reduce the number of ON / OFF cycles. Sensible thermal energy storages have traditionally been the most widely used due to their low investment cost. Recently, however, latent thermal energy storages are being increasingly used because they can store and release heat at a constant or near-constant temperature, which can be beneficial in heat pump systems. In addition, defrost cycles can be avoided, which are common with air-source heat pumps at low outdoor temperatures and degrade heat pump efficiency. Finally, the required cooling capacity of the heat pump can be reduced, which would lower the investment cost of the heat pump (Pardiñas, 2017.). However, due to the low thermal conductivity of the phase change materials (PCM) used in LTES and the transient nature of heat transfer in LTES, the exact benefits of implementing LTES in heat pump systems remain to be investigated (Streicher, 2008.).

There are two main options for combining LTES and a heat pump - LTES connected to the heat pump condenser and LTES connected to the heat pump evaporator. The former can be used to match the time of economically efficient operation with the time of highest heating demand, and the latter to provide a higher evaporating temperature throughout the day.

Several authors (Streicher, 2008., Leonhardt, 2009., Agyenim, 2010.) have studied such systems where LTES is connected to the heat pump condenser. The main results were that a lower number of heat pump ON / OFF cycles and lower energy losses can be achieved when LTES is used, compared to systems with sensible thermal energy storage. Leonhardt et al. (Leonhardt, 2009.) reported that further research is needed to improve heat transfer in LTES, which could significantly reduce the volume of LTES. Another reason for connecting the LTES to the condenser is to store the excess heat from the heat pump when the heating energy demand is lower and the outdoor air temperature is higher, and use it later in the afternoon and evening when the outdoor air temperature is lower. This could help to eliminate peaks in the heating load and improve the average COP (Maaraoui, 2012.).

doi:10.18086/swc.2021.36.02 Available at http://proceedings.ises.org

Systems in which LTES is connected to the evaporator of the heat pump are also found in the literature (Comakli, 1993., Kaygusuz, 2000.). Usually, solar collectors are used in such systems. In this way, the heat pump can operate as an air source heat pump during the day, while the solar thermal energy can be stored in LTES to serve as a heat source for the evaporator later when the outdoor air temperature is lower and the heating demand is higher. Such systems could allow the heat pump to operate at a higher evaporating temperature and achieve higher efficiency (Comakli, 1993., Kaygusuz, 2000.).

Heat pump systems using latent thermal energy storage (LTES) have the potential to reduce the required installed power, shift working hours to a lower cost electricity tariff, reduce energy consumption and improve efficiency (Leonhardt, 2009., Agyenim, 2010., Kelly, 2014., Maaraoui, 2012., Comakli, 1993., Kaygusuz, 2000). With the aim of further investigating the advantages of these systems and establishing guidelines for sizing, a numerical model of a system with a heat pump and LTES was created in TRNSYS after which the numerical results were compared to experimental data.

2. System description

The schematic diagram of the experimental system is shown in Fig. 1. The system consists of a water-to-water heat pump, an LTES, two sensible thermal energy storages (STES), a heat load, solar collectors, a dry cooler, circulating pumps, an automatic control system, and measurement equipment with data acquisition system to track the temperatures and flow rates of the heat transfer fluid and the temperatures of the PCM within the LTES. During the LTES discharge process, the heat pump operates in heating mode and uses the heat from the LTES as a heat source for the evaporator. The heat needed to charge the LTES can be provided by a solar collector system or by the same heat pump operating during periods when ambient air heat can be used as a heat source. The use of the LTES as a heat source can lead to a shift in operating hours and help to overcome possible peak loads.

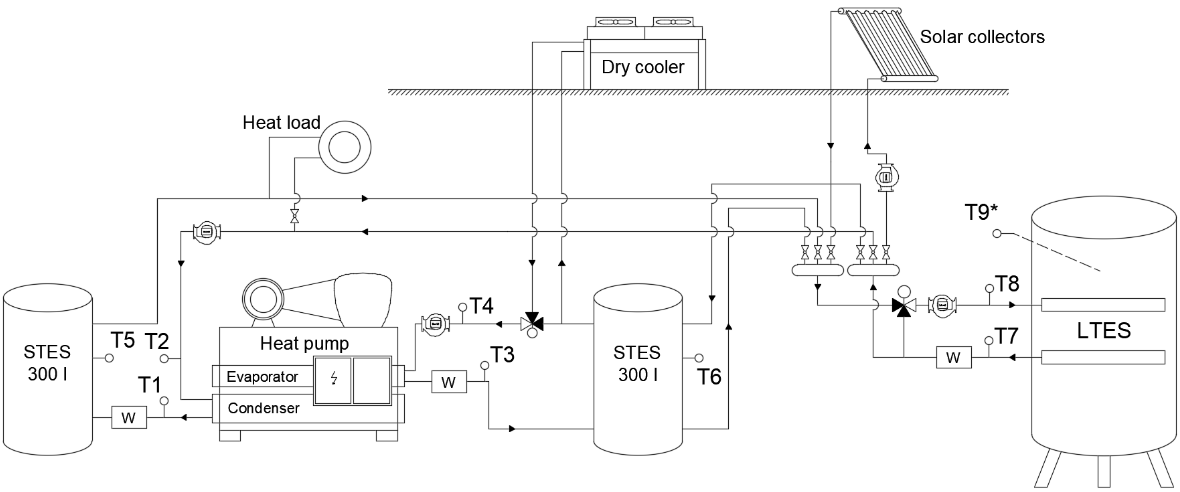

Fig. 1: Schematic diagram of the system with heat pump and LTES

For measuring temperatures of heat transfer fluid eight PT100 temperature sensors were used. Temperatures were measured at the outlet and inlet of the heat pump condenser and evaporator (T1-T4), in the sensible thermal energy storage tanks (T5, T6), and at the outlet and inlet of the LTES (T7, T8). The temperature of the paraffin inside the LTES was measured with thermocouples at different locations inside the LTES (T9). Three ultrasonic flow meters have been installed to measure the volumetric flow rates of the heat transfer fluid through the heat pump condenser and evaporator and through the LTES.

An application has been created in Labview software and used to read and store the measured values of temperatures and volume flows, as shown in Fig. 2.

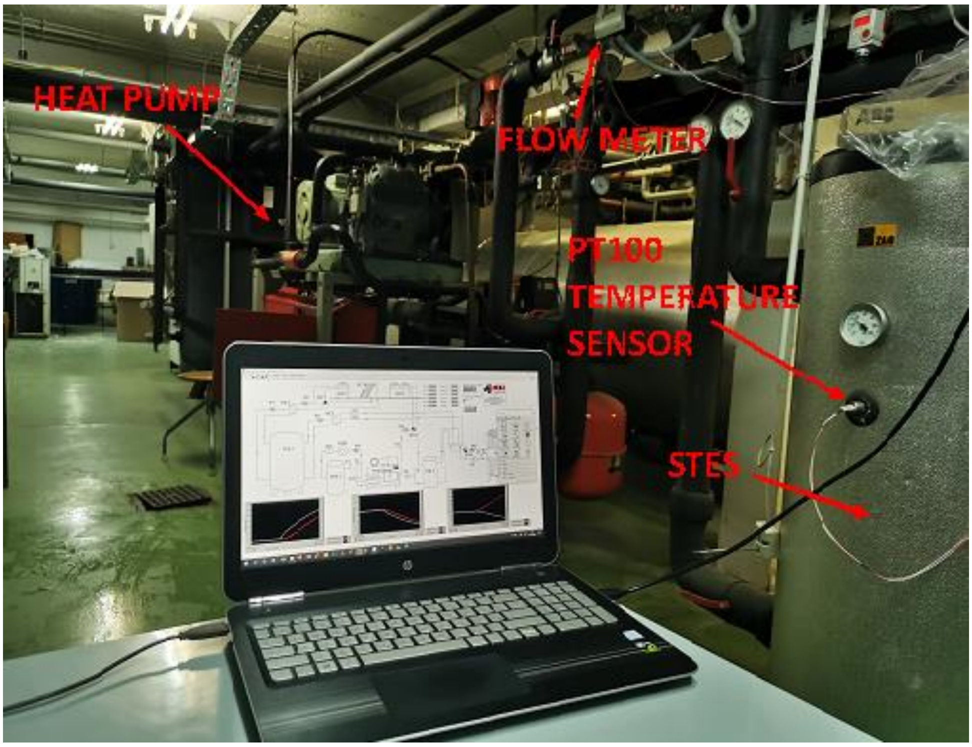

Fig. 2: Data acquisition during the experiments

The Labview application has been run on a personal computer during the experiments and allowed real-time monitoring of the measured values. The heat pump and sensible heat storage tank connected to the heat pump condenser are also shown in Fig. 2.

The LTES and the flow and temperature control system are shown in Fig. 3.

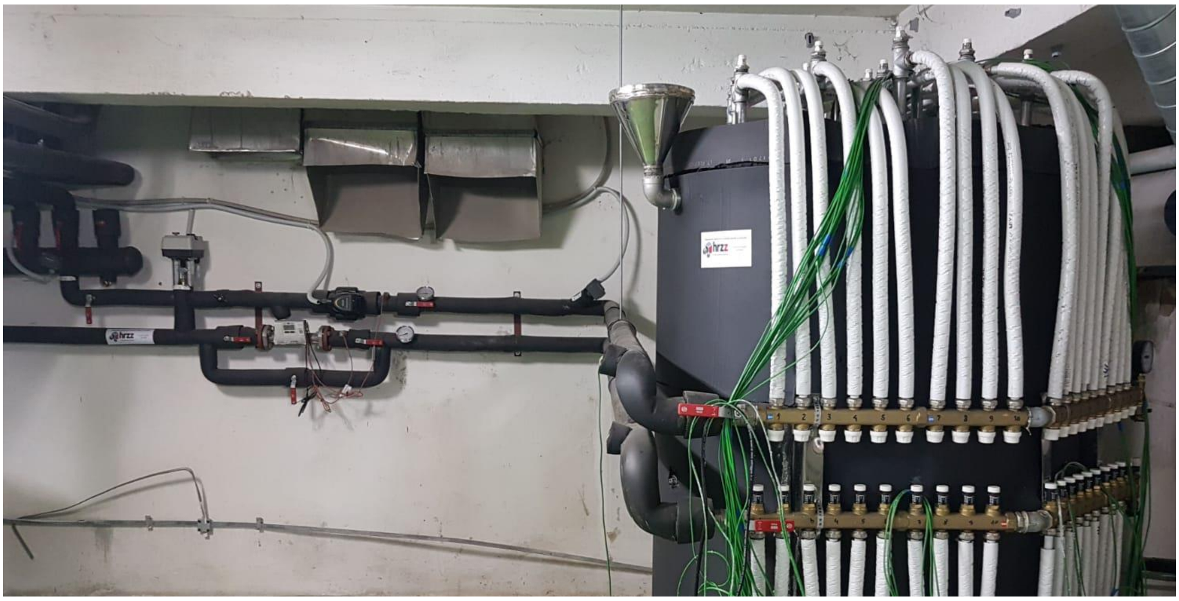

Fig. 3: LTES and flow and temperature control system

The PCM inside the LTES was Rubitherm's RT25 paraffin (Rubitherm GmbH, 2018.). The heat transfer fluid flows through the tubes while the paraffin fills the shell side of the LTES. The thermal and physical properties of paraffin RT 25 are given in Table 1.

Tab. 1: Thermal and physical properties of RT 25 (Rubitherm GmbH, 2018)

Melting/solidification temperature range	22-26 °C
Latent heat	170 000 J/kg
Thermal conductivity	0.2 W/mK
Specific heat capacity	2000 J/kgK
Density solid/liquid	880/760 kg/m^3
Kinematic viscosity (liquid)	4.7 mm^2/s

A constant temperature of the heat transfer fluid at the inlet of the LTES was ensured by a three-way control valve that was continuously adjusted by the control system.

Experiments were completed when all thermocouples indicated temperatures above the melting point in the charging analyses and temperatures below the melting point in the discharging analyses.

Another measurement has been performed on the heat pump to obtain data on the normalized capacity and power consumption of the heat pump as a function of the entering source fluid temperature and the entering load fluid temperature. Using the measured volumetric flow rates and the temperature difference of the heat transfer fluid at the condenser and evaporator inlets and outlets of the heat pump, the heating and cooling capacities were calculated, while the compressor capacity was measured with electricity power analyzer. These data were used to model the performance of the installed heat pump.

3. System modelling

The transient numerical model of the system was developed in Trnsys (TRaNsient SYstems Simulation Program). It consists of more than 20 components called types, which are mathematical models of the actual components such as heat pump, energy storage, circulating pump, etc. (see Fig. 4).

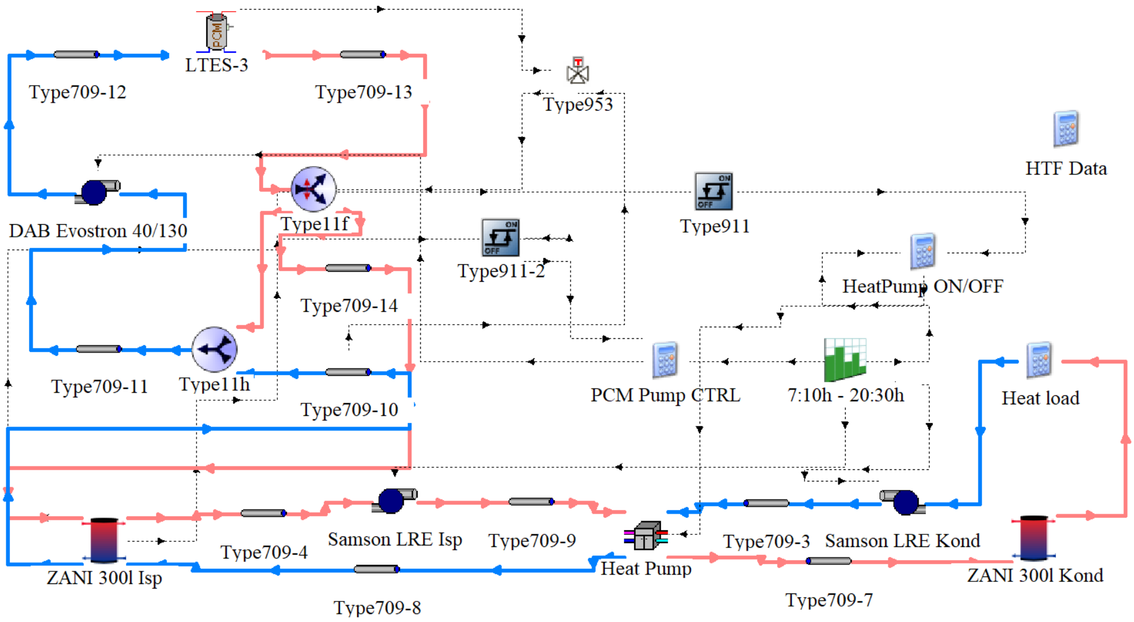

Fig. 4: System model in TRNSYS

For modelling of sensible thermal energy storages Type 534 was used (TESSLibs, 2017.). The sensible thermal energy storage is uniformly divided into isothermal nodes, each of which thermally interacts with neighboring nodes through the following mechanisms: Thermal conduction between nodes and by fluid motion caused by natural destratification - mixing due to temperature inversions in the tank. For modelling of the latent thermal energy storage

Type 840 was used (Schranzhofer, 2006.), which is based on the enthalpy approach, where enthalpy is a continuous and invertible function of temperature. A water-to-water heat pump was modelled using type 927 (TESSLibs, 2017.). This type models a single-stage heat pump that requires the user to provide data for the normalized capacity and power consumption of the heat pump as functions of entering source fluid temperature and entering load fluid temperature, based on which the evaporator and condenser outlet temperatures are calculated. Other types used to model the system were Type 654, which models a single speed circulating pump; Type 709, which models a circular pipe filled with liquid; Type 647, Type 649, and Type 953, which model liquid mixing valves; Type 911, which models a differential controller with lockouts; and a general forcing function model - Type 14. The time step size was one minute.

4. Results and discussion

The solidification and melting processes of the PCM have been analyzed both experimentally and numerically, and the comparison is presented for the solidification process. The numerically and experimentally determined temperatures at positions T1, T3, T7 and T9 are shown in Fig. 5. The operating conditions were as follows: heat transfer fluid temperature at LTES inlet was T8 = 7 °C and mass flow in LTES loop was m_{LTES} = 830 kg/h, heat transfer fluid mass flow in heat pump condenser loop was m_{COND} =4700 kg/h and in heat pump evaporator loop was m_{EVAP} = 9620 kg/h. The initial temperature of the PCM was 30°C.

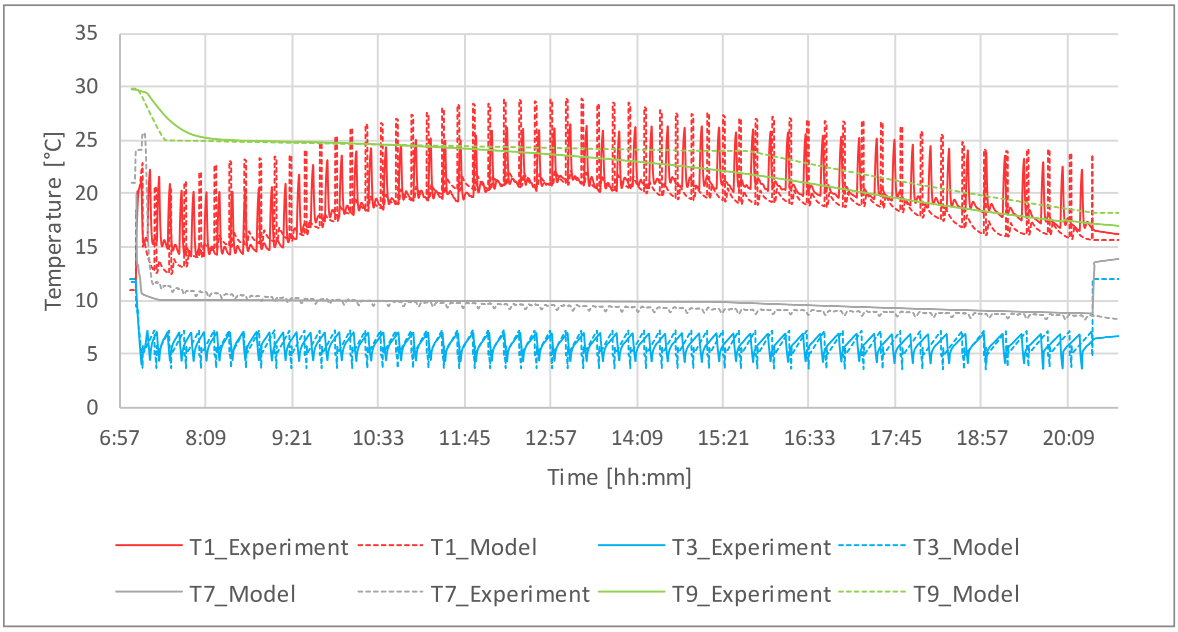

Fig. 5: Comparison of numerically and experimentally obtained temperatures at heat pump condenser outlet (T_1), evaporator outlet (T_3), LTES outlet (T_7) and average PCM temperature (T_9) for heat transfer fluid temperature at LTES inlet T_8 = 7 °C and mass flow m_{LTES} =830 kg/h, heat transfer fluid mass flow in heat pump condenser loop m_{COND} =4700 kg/h in heat pump evaporator loop m_{EVAP} = 9620 kg/h

The transient variations in the temperatures of the heat transfer fluid at the outlet of the condenser, evaporator, and LTES, as well as the temperatures at PCM, are shown in Fig. 5. Sudden jumps in condenser and evaporator outlet temperatures indicate the beginning of the heat pump cycle ON and sudden drops indicate the end of the heat pump cycle. Good agreement in ON-OFF cycle dynamics between the installed heat pump and the model can be seen in the form of nearly simultaneous jumps and drops in condenser and evaporator outlet temperatures throughout the time period shown. The differences in condenser outlet temperatures are due to the limitations of the Type 927, which does not account for the transient nature of the heating rate at the beginning of the ON cycle. Nevertheless, good agreement can be seen in the transient temperature variations between the temperatures obtained with the numerical model and the measured temperatures.

The comparison of numerically obtained heating rate (Q), cooling rate (Q_0) and compressor power (P) with experimental data during the first ON-OFF cycle of the heat pump is shown on Fig.6.

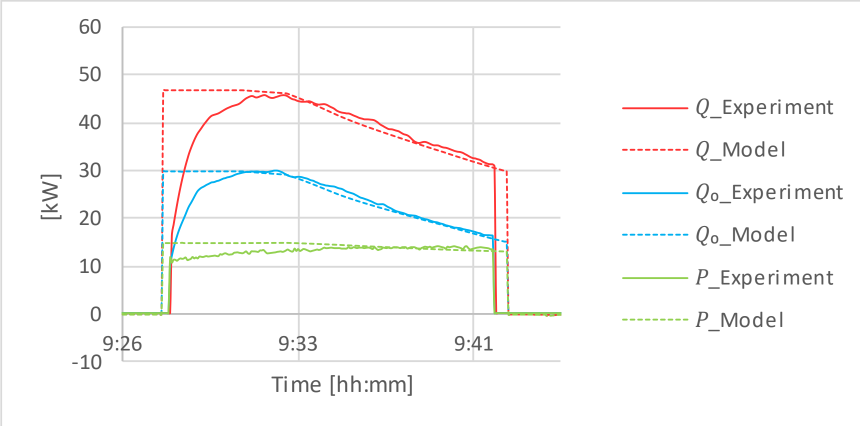

Fig. 6: Comparison of numerically obtained heat pump heating rate (*Q*), cooling rate (Q_0) and compressor power (*P*) with the experimental data

The first ON-OFF cycle is considered to be the first ON cycle in a day when the sensible thermal energy storages (STES1 and STES2) connected to the heat pump condenser and evaporator are at the same temperature. The heat pump is turned ON and remains in operation until the temperature of the heat transfer fluid at the outlet of the condenser reaches 50 °C. At this time, the heat pump is switched to OFF. Since the heat transfer fluid at the outlet of the condenser reached 50 °C after about 15 min, the total operating time of the presented cycle was approximately 15 minutes. Due to the aforementioned limitations of the TRNSYS Type 927 heat pump model, which does not account for the transient nature of the heating rate, cooling rate, and compressor capacity at the beginning of the ON cycle, some discrepancy is observed between the installed heat pump performance and the model performance. In order to quantify this discrepancy and justify the application of the model, the heat supplied by the heat pump (Q), the heat consumed (Q0) and the electricity consumption (P) calculated with the numerical model and the experimental data were compared and presented in Table 2.

Table 2: Comparison of heat pump delivered heat (*Q*), heat pump consumed heat (Q_0) and compressor electricity consumption (*P*) obtained numerically with experimental data

	Model	Experiment	Discrepancy
Q [MJ]	81.07	73.48	10.3 %
Q_0 [MJ]	48.86	44.91	8.8 %
P [MJ]	28.67	25.00	14.6 %

The highest observed discrepancy was 14.6% for electricity consumption, while heat supplied and consumed were 10.3 and 8.8%, respectively.

5. Conclusion

The heat energy stored in the LTES can potentially be used as a heat source for the heat pump during the late afternoon and evening hours, allowing for a higher heat source temperature and more efficient operation of the heat pump compared to operation with outside air as the heat source. A numerical model of the system with heat pump and latent thermal energy storage was created and compared to experimental measurements. The comparison of numerically obtained and measured temperatures has been presented for the whole system during a solidification process. Additionally, the calculated and measured heat pump delivered heat, consumed heat and electricity consumption have been compared and presented. The presented numerical model can be used for further analysis of similar systems to further investigate the advantages of combining LTES with a heat pump.

6. Acknowledgement

This work has been supported in part by Croatian Science Foundation under the project HEXENER (IP-2016-06-4095) and in part by the University of Rijeka under the project number „uniri-tehnic-18-69“.

7. References

Agyenim, F., Hewitt, N., 2010. The development of a finned phase change material (PCM) storage system to take advantage of off-peak electricity tariff for improvement in cost of heat pump operation, Energy and Buildings, 42 (9) p. 1552-1560.

Comakli, O., Kaygusuz, K., Ayhan, T., 1993. Solar-assisted heat pump and energy storage for residential heating, Solar Energy, 51 (5) p. 357-366.

European Commission, Energy consumption by end-use, 2013. Retrieved from ec.europa.eu/energy/content /energy-consumption-end-use_en

European Parliament and of the Council on the Energy Performance of Buildings, Commision Decision No. 2013/114/EU, 2013. O.J. L 62/27

Kaygusuz, K., 2000. Experimental and theoretical investigation of a solar heating system with heat pump, Renewable Energy, 21 (1) p. 79-102.

Kelly, N.J., Tuohy, P.G., Hawkes, A.D., 2014. Performance assessment of tariff-based air source heat pump load shifting in a UK detached dwelling featuring phase change-enhanced buffering, Applied Thermal Engineering, 71 (2) p. 809-820.

Leonhardt, C., Müller, D., 2009. Modelling of Residential Heating Systems using a Phase Change Material Storage System, Proceedings 7th Modelica Conference, Como, Italy.

Maaraoui, S., Clodic, D., Dalicieux, P., 2012. Heat pump with a condenser including solid-liquid phase change material, International Refrigeration and Air Conditioning Conference, Purdue, USA.

Paraffin RT 25 data sheet, Rubitherm GmbH, 2018.

Pardiñas, A.A., Justo Alonso M., Diz, R., Husevåg Kvalsvik, K., Fernández-Seara, J. 2017. State-of-the-art for the use of phase-change materials in tanks coupled with heat pumps, Energy and Buildings, 140 (1): p. 28-41.

Schranzhofer H, Heinz A and et al., 2006. Validation of TRNSYS simulation model for PCM energy storages and PCM wall construction elements in: Ecostock Conference 31st May– 2nd June 2006, Pomona, USA

W. Streicher, J. Schultz, C. Solé, L. Cabeza, J. Bony, S. Citherlet, 2008. Final report of subtask C “phase change materials”, Report C7 – IEA SHC Task 32, International Energy Association

TESSLibs 18 Component Libraries for the TRNSYS Simulation Environment Volume 11 - Storage Tank Library Mathematical Reference, 2017.

TESSLibs 18 Component Libraries for the TRNSYS Simulation Environment Volume 11 - HVAC Library Mathematical Reference, 2017.

TRaNsient SYstems Simulation Program, http://sel.me.wisc.edu/trnsys/ (last access: Sep, 21. 2021.)