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Dynamic performance tests of a heat pump cycle integrated latent heat thermal energy storage for optimized DHW generation

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Abstract

Latent heat thermal energy storage (LHTES) bears the advantage of high energy storage density and balancing demand and supply. A promising application for residential buildings is the use of a compression heat pump (HP) in combination with a LHTES to generate domestic hot water (DHW) with the aid of the hot refrigerant compressor discharge. In this case the LHTES enables load shifting, heat pump operation harmonization and results in energy efficiency improvement. The setup investigated here is built of a compact combination of an air/water compression HP with R32 as refrigerant and a novel 3-media – Refrigerant, Phase Change Material (PCM) and Water – Heat EXchanger (RPW-HEX) which is directly integrated into the HP cycle between compressor and condenser. A key challenge of this combination is the dynamic system operation and control which is experimentally examined in this work. RPW-HEX charging and discharging as well as continuous operation is analyzed based on several weeks of operation. In this work it is proven that the proposed combination is capable to operate stable over a wide operating range and to generate DHW effectively.

Keywords: Heat Pump; COP increase; Experimental Analysis; System Performance Tests; Phase Change Material; Domestic Hot Water Generation

1. Introduction

The demand for heating and cooling has seen a tremendous upswing in the past. Solely the cooling demand is reported to have five-folded between 1990 and 2014. For this reason, a great share (approx. 40%) of today's world's final energy consumption is used for heating and cooling applications in buildings as well as industries. In these applications about 65% is attributable to fossil fuels [1,2]. A cut in the fossil fuel consumption and switch to renewable energy sources is inevitable to reach the 20/20/20 target set by the European Union [3,4] and to limit the effects of climate change [5].

The trend towards energy sustainability is a key challenge and at the same time an opportunity for enabling technologies. Among others, the compression heat pump (HP) technology is traded as an enabling technology for a future carbon-emission free world. The technology enables efficient, carbon emission-free heat and cold when embedded into a renewable electricity grid. For this and other reasons the technology has seen a tremendous rise with continuously growing sales - three years in a row double-digit growth rates (2015-2017) have been reported - passing the 1-million-unit sales figure in the EU-21 end 2017 [6].

Compression HPs are particularly interesting in building applications where they serve to deliver cooling in summer, heating in winter and domestic hot water (DHW) all year long. Radiant heating and cooling by means of underfloor heating in office and residential buildings offer superior internal comfort compared to legacy air condition system for heating. The low temperature level for heating can be provided at excellent efficiency by HPs' [7]. On the other hand, DHW must be provided at elevated temperatures to tackle the risk of legionella [8]. These elevated temperatures go hand in hand with lower COPs and therefore with a significant higher electric energy consumption of the HP compared to the operation in heating mode. Hence, concepts, that can lower the electric energy consumption for DHW generation are more than welcome. This transient and high-temperature operation and the resulting inefficiencies for HPs' give rise to novel concepts which include thermal energy storage (TES). By means of load shifting and harmonization of the HP operation they can provide energy savings and result in a cost advantage [9]. TES systems can include sensible energy storage, e.g. water tanks, or latent heat thermal energy storage (LHTES) using phase change material (PCM). LHTES offer high thermal energy storage densities but the selection of the best-suited PCM material is a key issue to take advantage of the technology [10].

A promising application for residential buildings is the use of a compression heat pump (HP) in combination with a LHTES in residential buildings to generate domestic hot water (DHW) with the aid of the hot gas of the refrigerant at compressor discharge. The setup investigated here is built of a compact combination of an air/water compression HP using R32 as the refrigerant and a novel 3-media – Refrigerant, Phase Change Material (PCM) and Water – Heat EXchanger (RPW-HEX) which is directly integrated into the HP cycle after the compressor. High-temperature heat is transferred from the hot compressor discharge gas to the RPW-HEX to charge the PCM during heating or cooling operation. In DHW generation operation, low-temperature heat continues to be delivered from the condenser of the HP and only the remaining energy needed to reach the desired DHW temperature is covered by discharging the PCM inside the RPW-HEX to the water circuit.

The concept was originally presented by Emhofer et al. [11] who proved the considerable annual energy performance advantages compared to legacy systems. More than 120 potential suitable PCM materials for this concept were screened by Zsembinszki et al. [12] and, based on key performance indicators, the most suitable material was selected.

While a detailed techno-economic analysis of the systems is presented at this conference as well [13]. This contribution focuses on the experimental validation of the HP/RPW-HEX system including:

- RPW-HEX charging operation,
- RPW-HEX discharging operation,
- Continuous charging/discharging operation, and
- Continuous charging/discharging operation for DHW generation.

2. Technology

2.1. Heat pump technology

The heat pump is a water/air type heat pump with R32 as the refrigerant and comprises an inside unit, an outside unit, and the RPW-HEX. The schematic process flow diagram of the setup is depicted in Fig. 1.

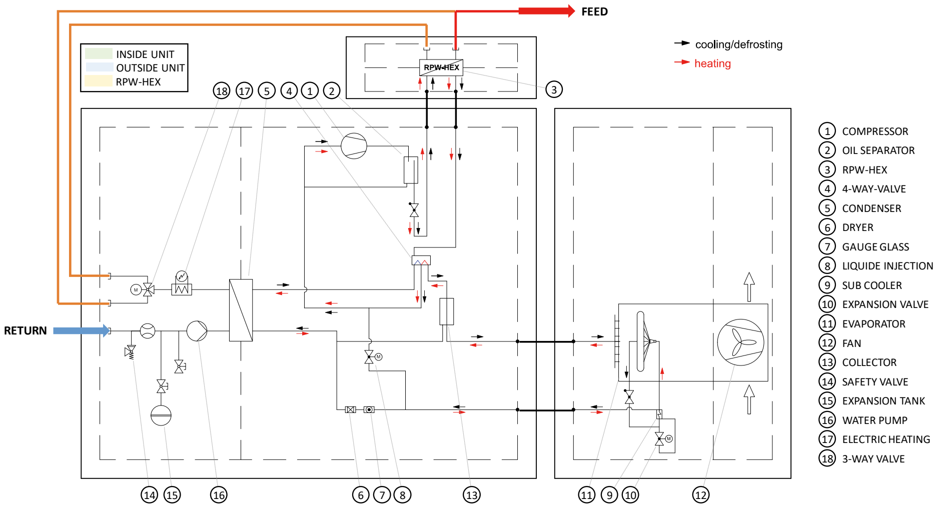


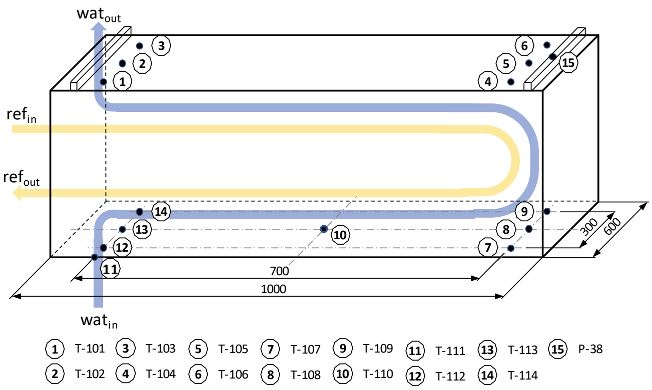
Fig. 1 Process flow diagram of the compression heat pump setup with the inside unit (light green), the outside unit (light blue) and the RPW-HEX (light orange).

In the inside unit, the compressor ① is placed which is driven by a variable speed drive. The frequency converter of the variable speed drive has a DC bus that is routed to the outside and therefore can handle AC and DC-supply as well. This allows for the direct use of DC energy from PV. After passing the oil separator ② the hot compressor exhaust flows to the RPW-HEX ③. Inside the RPW-HEX high-temperature sensible heat is effectively recovered from the refrigerant and stored mainly in the PCM. The 4-way valve ④ allows to reverse the flow of the refrigerant and facilitates either cooling or defrosting operation. In heating mode operation, the hot refrigerant is directed to the condenser ⑤ to heat the process water flowing to the heat sink. After passing a filter dryer ⑥ and a gauge glass ⑦ the refrigerant is subcooled in the sub-cooler ⑨, expanded in the expansion valve ⑩ before entering the evaporator ⑪. The outside unit is equipped with a variable speed fan ⑫ controlled depending on the operating conditions. A small refrigerant collector ⑬ (pipe in pipe-type) is used to allow operation over a wide operating range while keeping the refrigerant volume low. The 4-way-valve closes the refrigerant cycle and directs the refrigerant to the compressor suction side. To limit the temperature at the compressor exit – a peculiarity of the R32 refrigerant cycle – liquid refrigerant is injected into the compressor suction side using the liquid injection valve ⑧. In cooling or defrosting operation, the 4-way-valve directs the hot refrigerant to the evaporator, where it condenses releasing heat. The cold refrigerant then passes the condenser where it evaporates absorbing low-temperature heat for cooling. In the water circuit a safety valve ⑭ is placed to avoid overpressure in the water circuit of the heat pump. To compensate for the density fluctuation, the expansion tank ⑮ is placed. The water pump ⑯ compensates for the pressure drop of the condenser. After passing the condenser an electric heater ⑰ would allow covering the demand whenever the heat pump delivers insufficient thermal power. However, this additional electric heating was never used in the experiments. To control the feed-water temperature the 3-way valve ⑱ is used allowing to mix the water from the condenser and the RPW-HEX.

2.2. RPW-HEX

The RPW-HEX is a novel 3-passage heat exchanger made of aluminum (110 kg empty mass) and includes a refrigerant passage, a phase change material (PCM) passage and a water passage (a cross-section is illustrated in Fig. 2 right).

The high-temperature heat is extracted from the compressor discharge and, depending on the operating condition, stored inside the PCM and/or transferred to the water directly. To enhance the heat transfer, aluminum fins are placed inside the PCM, the refrigerant passages, and the water passages. The RPW-HEX is filled in total with 40 kg of PCM. The PCM is manufactured by Rubitherm Technologies type RT64HC [14] which melts at 63-65 °C and has a total latent heat storage capacity of about 2.8 kWh. For the experimental evaluation, the RPW-HEX is equipped with in total 14 thin-film PT-100 temperature sensors class A (manufacturer RS-components type 70643577), which are directly applied to the surface of the RPW-HEX. A pressure transmitter is attached to the PCM section to capture the pressure caused by the volume displacement of the melting PCM. A schematic of the RPW-HEX including the position of the temperature sensors is shown in Fig. 2 left.



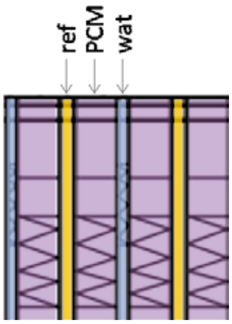


Fig. 2 Left: Schematic of the RPW-HEX showing the refrigerant pass (ref_{in} and ref_{out}) the water pass (wat_{in} and wat_{out}) as well as sensor positions (① to ⑮). Temperature sensors are attached to the surface of the RPW-HEX and include position ① to ⑭. A pressure sensor is attached to the PCM section indicated at position ⑮. Right: Cross-section of the RPW-HEX showing the refrigerant passage (ref), the PCM passage (PCM) and water passage (wat).

2.3. Energy balance calculations

Thermal energies were determined based on temperature, pressure, and flow rate measurements. Measurements were taken in the refrigerant cycle and the water circuit. The following thermal energies were determined:

- E_{Cond}: energy from the condenser either during charging $E_{\text{Cond charge}}$ or discharging $E_{\text{Cond discharge}}$ based on measurements in the water circuit directly at the inlet and outlet of the condenser.
- E_{RPWW}: energy from the RPW-HEX based on measurements in the water circuit directly at the inlet and outlet of the RPW-HEX.
- E_{RPWR}: energy from the RPW-HEX based on measurements in the refrigerant cycle directly at the inlet and outlet of the RPW-HEX.
- E_{RPW}: energy from the RPW-HEX itself (PCM and aluminium) derived from

$$E_{RPW} = E_{RPW_W} - E_{RPW_R} \tag{1}$$

- E_{tot}: energy transferred from the HP/RPW-HEX system to the water circuit based on measurements in the water circuit at the inlet and outlet of the entire system.

3. Experiments

3.1. Experimental setup

To assess the performance of the RPW-HEX integrated in the HP cycle, the system was placed in a controlled laboratory environment at the AIT Austrian Institute of Technology. The laboratory infrastructure allows for high precision control of the temperature and flow rate of water to the system. The outside unit of the heat pump was placed in a climate chamber enabling air temperature and humidity control over a wide range (down to -20 °C). Calibrated water temperature, pressure/pressure drop and flow sensors, air humidity and temperature sensors, as well as electric consumption meters, were used. A mass flow meter (Coriolis type), positioned after the gauge glass ⑦ (see Fig. 1), allows measuring the refrigerant mass flow rate. Note, the refrigerant mass flow rate was not always accessible because of 2-phase flow in the sensor at certain operating conditions. In addition to these sensors, heat pump internal sensors (mainly temperatures, pressures, and flows) were integrated into the laboratory control and data acquisition system via Modbus interface to allow for control and real-time monitoring of the system operation.

For testing, the system was filled with 3.9 kg of R32 and water was used in the hydraulic circuit. The arrangement of the HP and RPW-HEX including hoses and measurements is shown in Fig. 3.

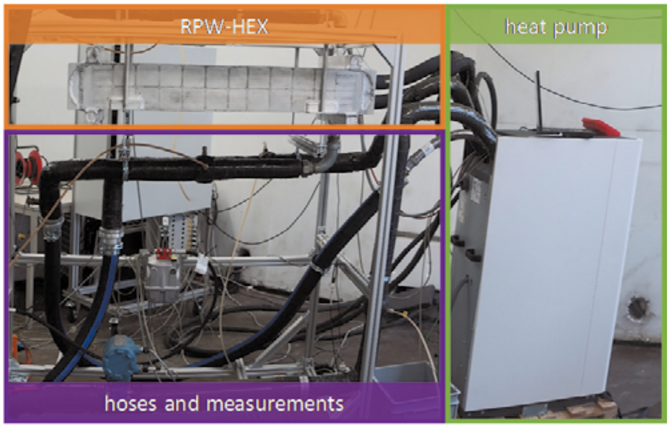


Fig. 3 Experimental setup showing the heat pump inside unit (green), the RPW-HEX (orange) and hoses and sensors for the flow rate measurements (violet).

3.2. Experimental campaign

To gain an understanding of the operation of the HP with an integrated RPW-HEX a series of experiments have been conducted. For these experiments the climate chamber, where the outside unit of the heat pump was located, was operated at -7 °C dry/-8 °C wet bulb temperature, which reflects the requirements prescribed by the EN 14511 for HP testing. The water inlet temperature of the heat pump ("RETURN" in Fig. 1) was held constant to 33 °C while the water mass flow was changed depending on RPW-HEX charging or discharging operation. In the first measurement series solely charging or discharging was investigated, while in the second series the system was operated cyclical (continuous charging/discharging operation). Furthermore, the water mass flow through the RPW-HEX controlled by the three-way valve (⑱ in Fig. 1) was once switched between on/off only (*discharging I* operation) and the other time varied to guarantee a stable outlet temperature to the heat sink (*discharging II* operation). The water flow rates have been selected to meet the requirements in typical operation of such a system. An overview of the experiments is shown in Table 1.

Table 1. Overview of experiments

Series	Description	Compressor speed in %	Water mass flow in kg/s		Flow rate through the RPW-HEX
			charging	discharging	during discharging
1	charging	90	0.245	-	none
1	discharging I	0	-	0.14	constant
1	discharging II	90	-	0.14	constant
2	cyclic operation I	90	0.245	0.14	constant
2	cyclic operation II	90	0.245	0.14	variable

4. Results

4.1. Experiments Series 1

Series 1 focused on the complete charging and discharging behavior of the system considering long term charging and discharging to assess the operating limits of the RPW-HEX.

For the first charging experiment (cf. *charging* in Table 1) the system was operated for more than 20 hours where the measured RPW-HEX temperatures, as well as RPW-HEX refrigerant outlet temperature, is shown in Fig. 4. The RPW-HEX was pre-heated to 33 °C at the beginning with the aid of the external water cycle. The refrigerant inlet temperature to the RPW-HEX was almost constant at approx. 110 °C. After approx. 4, 10.5, and 17 hours of operation, the HP switched to defrosting operation (refrigerant cycle operated in reverse mode) due to icing of the outside unit. The defrosting operation caused a sharp decrease of RPW-HEX temperatures T-101 to T-103 as well as RPW-HEX refrigerant outlet temperature (T-06) attributable to the drop of compressor outlet temperature in this operating mode. After about 6.5 hours of operation all RPW-HEX temperatures passed the melting temperature of 64 °C of the PCM. The steep increase of T-107 to T-109 (blue lines) as well as T-06 after this event can interpreted as the end of melting of the PCM inside the RPW-HEX.

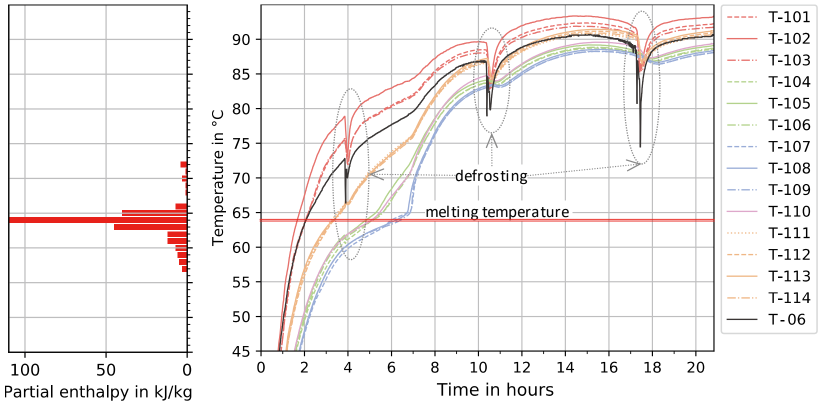


Fig. 4 Experimental results for the *charging* test in Series 1. Left: Partial enthalpy diagram PCM melting [14]. Right: Measured temperature profiles of RPW-HEX surface temperature measurements (T-101 to T-114, cf. Fig. 1) as well as RPW-HEX refrigerant outlet temperature (T-06).

To obtain the thermal energy stored in the RPW-HEX for the first discharging experiment (cf. *discharging I* in Table 1), the heat pump was switched off and the entire water was directed to the RPW-HEX using the 3-way valve (cf. ⑱ in Fig. 1) in the water circuit. Discharging was stopped once the RPW-HEX temperatures reached the level of the water inlet temperature (33 °C) – after about 1 hour. The PCM has two solidification peaks: at 64 °C and 61 °C (cf. Fig. 5 left). The 64 °C solidification peak was very well observed from the RPW-HEX temperature measurements while the second solidification peak at 61 °C appeared later in the experiments at about 57°C (cf. Fig. 5 middle). This may be an indication of delayed solidification which has been observed by others as well [15-17]. The same melting/solidification behaviour was found for a different LHTES application and phenomenological modelling was presented in [18]. However, the experiments revealed that the water temperature at the RPW-HEX outlet can reach up to 85 °C (cf. Fig. 5 right) if the three-way valve is fully open. This must be considered for the implementation in residential buildings where often plastic-compound pipes with a maximum operating temperature of 75 °C are used today. After the 85 °C peak the water reaches a plateau at about 57 °C, which can be attributed to the second solidification peak of the PCM. At the end of the discharging experiment, in total 6.3 kWh thermal energy was extracted from the RPW-HEX if it is cooled from initial approx. 90 °C to 33 °C.

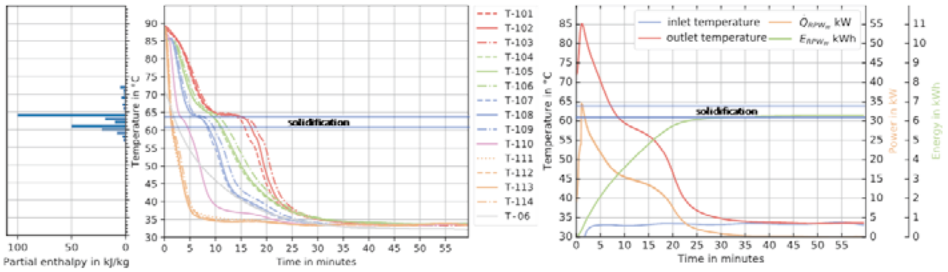


Fig. 5 Experimental results for the *discharging I* test in Series 1. Left: Partial enthalpy diagram PCM melting [14]. Middle: Measured temperature profiles of RPW-HEX surface temperature measurements (T-101 to T-114, cf. Fig. 1) as well as RPW-HEX refrigerant outlet temperature (T-06). Right: Water temperatures at the inlet and outlet of the RPW-HEX as well as thermal power and energy from the RPW-HEX.

The discharging experiment with running compressor (cf. *discharging II* in Table 1) is shown in Fig. 6. Similar solidification plateaus were observed compared to the *discharging I* test. However, for this test the solidification plateau appeared even more pronounced because the water, in this case, was pre-heated by the condenser to about 45 °C and therefore, less energy was drawn from the RPW-HEX compared to *discharging I* at the beginning (cf. orange lines in Fig. 5 and Fig. 6 right). The experiments showed that with running compressor the RPW-HEX is not only discharged but also allows to direct exchange heat between the refrigerant and the water side, transferring approx. 2.5 kW (see $\dot{Q}_{RPW_w}$ in Fig. 6 right after about 50 minutes).

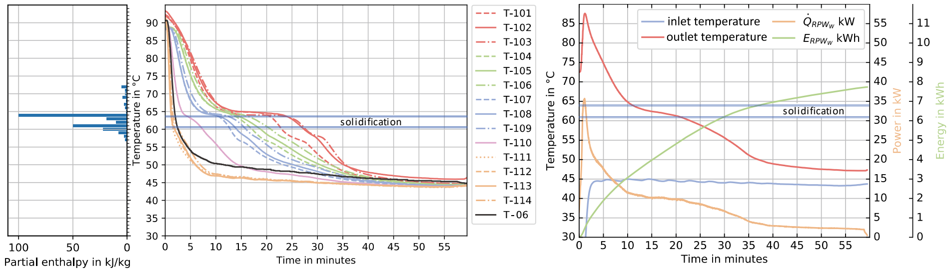


Fig. 6 Experimental results for the *discharging II* test in Series 1. Left: Partial enthalpy diagram PCM melting [14]. Middle: Measured temperature profiles of RPW-HEX surface temperature measurements (T-101 to T-114, cf. Fig. 1) as well as RPW-HEX refrigerant outlet temperature (T-06). Right: Water temperatures at the inlet and outlet of the RPW-HEX as well as thermal power and energy transferred from the RPW-HEX to the water circuit.

4.2. Experiments Series 2

To test the continuous operation of the system, it was operated in subsequent charging/discharging cycles. Based on the results from complete charging/discharging tests both the optimal conditions for switching between both operating modes was identified. Charging of the RPW-HEX should preferably end if all the PCM is molten. As an indicator for this event, the point in time when the average value of T-107, T-108 and T-109 exceeds 70 °C was identified (cf. Fig. 2). Discharging was stopped once the water temperature at the RPW-HEX outlet dropped below 55 °C. This limit was selected since a lower temperature is considered useless for DHW generation and most of the latent energy should already be released from the RPW-HEX at this point (cf. outlet temperature in Fig. 6 right), too.

For the first cyclic operation test run (cf. *cyclic operation I* in Table 1), the 3-way valve (cf. ⑱ in Fig. 1) in the water circuit was not controlled, but rather fully opened or closed. To meet the requirements in a real application, the water flow to the system was reduced for RPW-HEX discharging operation.

For *cyclic operation I* the system was operated for more than 50 hours covering 7 RPW-HEX charging and discharging cycles (see Fig. 7). While the charging cycle took between 6-7 hours, depending on how many defrosting cycles were needed, the discharging cycle always took approx. 30 minutes.

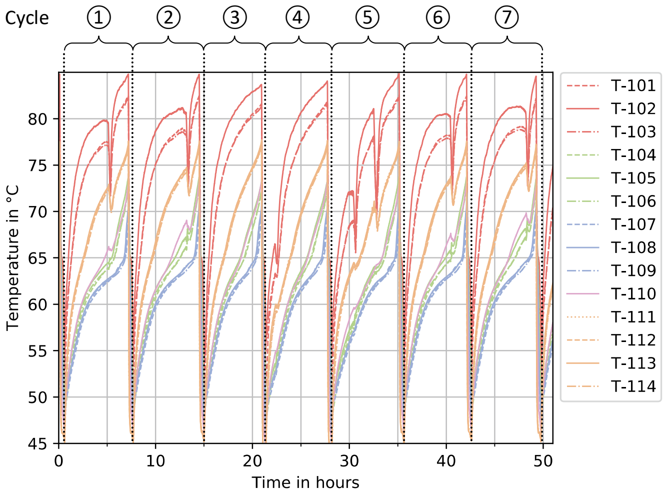


Fig. 7 Experimental results for the cyclic charging I test in Series 2. Shown are the RPW-HEX surface temperatures.

The energy balance for one typical charging/discharging cycle in test run *cyclic operation I* is depicted in Fig. 8 left. While charging the RPW-HEX, about $E_{\mathrm{Cond\ charge}}$=49.2 kWh is delivered from the condenser, which can be used for heating purposes. During discharging of the RPW-HEX about 60% of the energy is attributable to the RPW-HEX (E_{RPWw}=5.36 kWh). Only about $E_{\mathrm{Cond\ discharge}}$=3.5 kWh is covered by the condenser which, however, is crucial for efficient DHW generation. During the complete charging/discharging cycle, about E_{tot}=56.7 kWh is delivered to the water circuit, which is 1.37 kWh less than what is recovered from the condenser and the RPW-HEX. This discrepancy is caused by thermal losses in the piping system.

A detailed analysis of the energy balance during discharging is given in Fig. 8 right (shown as stacked plot). Based on the measurements, it is obvious that a share of about 11% is attributable to direct heat transfer from the refrigerant – the hot gas from the compressor – to the water. The analysis also reveals that about 0.86 kWh appears as thermal loss, which is relatively high compared to the total cycle (1.37 kWh). This is because the thermal energy loss is attributable to stagnant water in the piping system to the RPW-HEX, which becomes effective during discharging operation only.

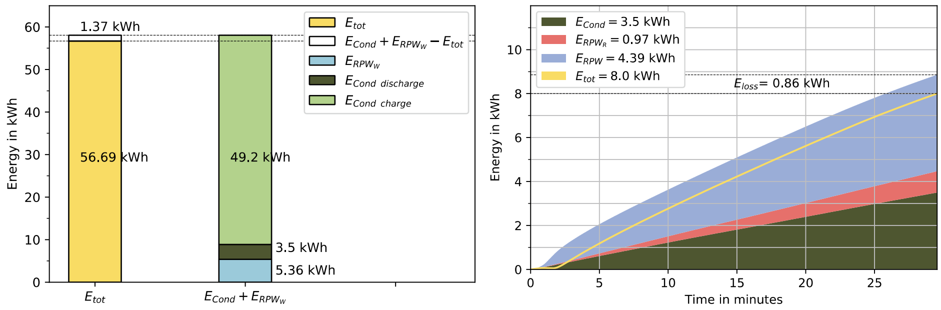


Fig. 8 Energy balance considerations for one typical charging/discharging cycle for test run *cyclic operation I* in Series 2. Left: Energy transferred to the water cycle for one complete charging/discharging cycle. Right: Energy transfer during discharging illustrated as stacked plot.

For the efficient use of the thermal energy stored in the RPW-HEX, the temperature at the outlet of the system must be controlled. This is obtained by controlling the 3-way valve (cf. ⑱ in Fig. 1) and mixing warm water from the condenser outlet with hot water from the RPW-HEX outlet. Therefore, a control loop was implemented (cf. *cyclic operation II* in Table 1) to reach a target temperature of 55 °C at the system outlet for the use as DHW.

Measured water temperatures for one representative discharging cycle for test run *cyclic operation II* are shown in Fig. 9 left. The discharging time is longer, compared to the test run *cyclic operation I* since only a part of the water passes the RPW-HEX. Due to the reduced water flow for discharging, the condenser outlet temperature immediately increased from 41 °C to 45 °C and then drops to 43 °C later due to increased heat transfer inside the RPW-HEX caused by decreasing PCM temperature during discharging. Similarly, the discharging experiments presented before the RPW-HEX water outlet temperature increases quickly and reaches about 82 °C after about 2 minutes. The water temperature at the system outlet at the beginning decreases quickly reaching a mere at 38 °C due to the stagnant water in the piping system of the RPW-HEX – as mentioned before here as thermal energy loss. However, after about 5 minutes the setpoint (55 °C) at the system outlet is reached and DHW is obtained for about 42 minutes.

The detailed analysis of the energy balance is given in Fig. 9 right. Compared to the test run *cyclic operation I* (cf. Fig. 8 right) the total energy available for DHW increases by 22%, while the contribution from the RPW-HEX (E_{RPW}) is almost equal. This is caused by the increased contribution from the condenser ($E_{Cond\ discharge}$) and the direct heat transfer from the hot gas (E_{RPW_R}).

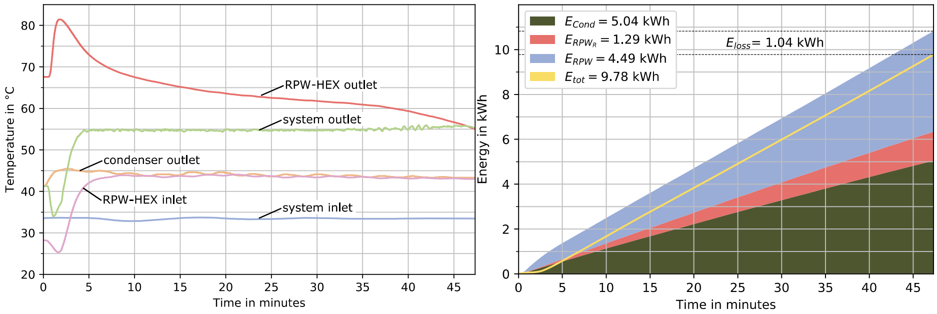


Fig. 9 Left: Temperature profiles in the water circuit for a typical discharging cycle for test run *cyclic operation II* in Series 2. Right: Energy transfer during discharging illustrated as stacked plot.

5. Conclusions and Outlook

In this work, it was experimentally verified that the proposed setup, a LHTES – in the form of an RPW-HEX – integrated in the hot gas section of the refrigerant cycle of a compression HP, allows for effective, parallel generation of heat and DHW for residential buildings at a beneficial *COP*. Startup, normal operation, reverse cycle operation, i.e. outside unit defrosting, shutdown and restart operation were successfully tested without major difficulties. However, it was found that care must be taken to avoid condensation of refrigerant inside the RPW-HEX – a safety measure to avoid refrigerant, and potentially also oil accumulation inside the refrigerant section of the RPW-HEX. This requirement demands adapted startup and operation procedures which shall be implemented on the level of the HP controller.

The RPW-HEX surface temperature measurements turned out to be effective to trigger discharging in an automated system. Certain temperatures can give an idea for the melting and solidification peaks of the PCM inside the RPW-HEX.

The continuous charging/discharging operation of the system revealed that for the selected operating conditions the current design of the RPW-HEX can deliver approx. 8 kWh of DHW per discharging cycle and 3 discharging cycles can be obtained per day. Compared to what is needed according to EN16147 (2017), this is 1.36 times the daily DHW consumption of an average apartment (5.845 kWh) per discharging cycle. Therefore, the RPW-HEX with decentral sensible DHW storages (cf. [11,13]) may serve DHW to in total 4 apartments if a constant return water temperature of 33 °C is assumed. Note, that the return water temperature from the sensible DHW storages in a real-life application strongly affects this temperature value. Switching between heating and DHW generation was smooth and HP operation itself was uninterrupted neither had to be adjusted. This clearly underlines the ability of the system for effectively shifting thermal loads, harmonizing the operation to run the HP at high efficiency although generating high-temperature heat.

Based on the knowledge gained from the experimentation the design of the RPW-HEX, the defrosting operation procedure, and the startup-procedure were adapted. A new optimized design of the RPW-HEX is currently being manufactured to be tested in near future.

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References

[1] IEA. Energy Technology Perspective 2017. IEA Publications, International Energy Agency; 2017. ISBN: 978-92-64-27597-3
[2] Mengxue, L., Joseph, L. Review on carbon emissions of commercial buildings. Renewable and Sustainable Energy Reviews 119 (2020). DOI: 10.1016/j.rser.2019.109545.
[3] European Council. *2020 climate & energy package*. European Comission.
[4] COP24. *United Nations Framework Convention on Climate Change.* Presented at the 21st Conference of the Parties 2018, Katowice, Poland.
[5] IPCC. Global Warming of 1.5 °C. The Intergovernmental Panel on Climate Change; Special Report; October 2018.
[6] Nowak, T., Westring, P. European Heat Pump Market and Statistics: Report 2018. The European Heat Pump Association AISBL (EHPA); 2018.
[7] Olesen, B. W. Radiant Floor Heating In Theory and Practice. ASHRAE Journal, July 2002.
[8] World Health Organization. *Guidelines for drinking-water quality*. World Health Organization, 2017; 4th edition. ISBN: 978-92-4-154995-0.
[9] Moreno, P., Solé, C., Castell, A., Cabeza, L.F. *The use of phase change materials in domestic heat pump and air-conditioning systems for short term storage: A review.* Renewable and Sustainable Energy Reviews 39 (2014) 1–13. DOI: 10.1016/j.rser.2014.07.062.
[10] Xu, H., Sze, J. Y., Romagnoli, A., Py, X. *Selection of Phase Change Material for Thermal Energy Storage in Solar Air Conditioning Systems*. Energy Procedia 105 (2017) 4281 – 4288. DOI: 10.1016/j.egypro.2017.03.898
[11] Emhofer, J., Barz, T., Marx, K., Hochwallner, F., Cabeza, L. F., Zsembinski, G., Strehlow, A., Nitsch, B., Weiss, M.. *Integration of a compact two fluid PCM heat exchanger into the hot superheated section of an air source heat pump cycle for optimized DHW generation*. 25th IIR International Congress of Refrigeration, Montreal, Canada, August 24−30, 2019. DOI: 10.18462/iir.icr.2019.645.
[12] Zsembinszki, G., Gasia, J., Oró, E., Cabeza, L.F. Phase change material selection for two innovative compact energy storage systems in residential buildings. XI Congreso Nacional y II Internacional de Ingeniería Termodinámica; 2019.
[13] Emhofer, J., Marx, K., Hochwallner, F., Barz, T., Cabeza, L.F., Zsembinszki, G., Strehlowc, A., Nitsch, B., Wiesflecker, M., Pink, W. *Techno-economic analysis of a heat pump cycle including a three-media refrigerant/phase change material/water heat exchanger in the hot superheated section for efficient domestic hot water generation.* 13th International Energy Agency Heat Pump Conference; May 11-14; Korea.
[14] Rubitherm. *Data sheet RT64HC*. Rubitherm Technologies; retrieved on July 22, 2019 from https://www.rubitherm.eu/media/products/datasheets/Techdata_-RT64HC_EN_06082018.PDF
[15] Cabeza, L.F. *Advances in thermal energy storage systems: meth-ods and applications*. Woodhead Publishing, Oxford, 2014
[16] Rathgeber, C., Schmit, H., Miró, L., Cabeza, L. F., Gutiérrez, A., Ushak, S. N., Hiebler, S. *Enthalpy-temperature plots to compare calorimetric measure-ments of phase change materials at different sample scales*. Journal of Energy Storage 15 (2018), p. 32–38. DOI: 10.1016/j.est.2017.11.002.
[17] Mehling, H., Barreneche, C., Solé, A., Cabeza, L. F. *The connection betweenthe heat storage capability of PCM as a material property and their performance in real scale applications*. Journal of Energy Storage 13 (2017), p. 35–39. DOI: 10.1016/j.est.2017.06.007.
[18] Barz, T., Emhofer, J., Marx, K., Zsembinszki, G., Cabeza, L.F. *Phenomenological modelling of phase transitions with hysteresis in solid/liquid PCM.* Journal of Build Performance Simulation. DOI: 10.1080/19401493.2019.1657953.