EuroSun2026

EXPERIMENTAL CHARACTERIZATION OF A HEAT PUMP WATER HEATER USING PHASE CHANGE MATERIAL BY EN 16147 CONTINUOUS DRAW-OFF TESTS AND DAILY LOAD PROFILES

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Summary

This paper presents results from testing a prototype heat pump water heater in accordance with EN 16147, including continuous draw-off tests and standardized 24-hour load profiles (water tapping pattern). Unlike conventional systems, which use hot water as the storage medium, the investigated prototype uses phase change material (PCM). The prototype successfully passed the EN 16147 test for load profile L. However, the charging and discharging behavior of the PCM storage differs markedly from that of conventional water tanks. In particular, the useful storage energy defined in EN 16147 depends strongly on charging and discharging power, as well as on the frequency of water draw-offs and the duration of pauses between them. These findings indicate that, although standardized tests are useful for characterizing performance under realistic use-case scenarios, they are not fully suitable for direct comparison with conventional water-based storage systems.

Heat pump water heater, domestic hot water generation, propane heat pump, phase change materials

Field of application for the findings: Domestic hot water generation via heat pumps

Addressed audience: Theme 08. Thermal Energy Storage

1. Introduction

Heat pump water heaters (HPWHs) significantly outperform conventional thermal energy storage (TES) tank-type electric and gas-fired heaters in terms of energy efficiency (Rendall et al., 2023). Domestic Hot Water (DHW) preparation requires high power draws over short durations. For instance, for tempered draws, where hot and cold water are mixed to reach a comfortable end-use temperature of 40°C, heating water from a mains temperature of 10°C to 40°C requires 8.4 kW at 4 L/min and 25.1 kW at 12 L/min. These values align with typical design flow rates in European standards for showers (6–12 L/min), baths (8–12 L/min), and kitchen sinks (4–12 L/min) (Fuentes et al., 2018).

Since direct water heating is not feasible with current HP technologies, a storage tank is required, typically filled with water. Recent developments in integrating solid/liquid phase change materials (PCMs) in HPWHs, enhance storage capacity and enable better load shifting during peak demand (Rendall et al., 2023). The key metric for these solutions is the thermal power over time for heat exchange between the PCM and water, given the inherent heat transfer limitations of PCM.

Delgado-Diaz et al. (2020) compared various HEX designs to address heat transfer limitations in latent heat TES (LHTES) for high-power applications. Compact plate-fin and finned-tube HEX units demonstrated the highest performance in both compactness and heat transfer.

However, reports on the design and experimental evaluation of TES using PCM for DHW generation remain scarce, particularly those detailing achieved heating rates and/or the amounts of heated water produced under realistic draw-off or tapping conditions. Most studies focus on copper tube and aluminum fin heat exchanger (HEX) designs, with fewer considering aluminum compact plate-fin designs. These studies typically assess storage performance using European useful hot water or load-profile methods, based on EN 16147:2017 (2017) or EN 12977-3:2018 (2018) and EU Commission Regulation No. 814/2013 (2013). Or in the US, DOE first-hour rating procedure as defined in CFR pt. 430, U.S. Department of Energy (2024). Only Frazzica et al. (2016); Emhofer et al. (2022) explicitly considered intermittent tapping cycles or standardized load profiles, which better represent real DHW use compared to continuous draw-off tests. In addition, Dogkas et al. (2020); Sun et al. (2025) highlighted that incomplete solidification or incomplete charge/discharge may leave part of the latent storage capacity unused. Moreover, Frazzica et al. (2016) showed that tapping pauses of 45–60 min can enable thermal recovery and reheating, thereby extending hot-water delivery.

This contribution reports the systematic experimental assessment of a novel complete-system prototype HPWH utilizing solid/liquid PCM at technology readiness level (TRL) 6 using test methods as outlined in EN 16147:2017 (2017).

2. PCM-based HPWH design

The prototype, shown in Fig. 1, is designed as a standalone decentralized unit for installation in bathrooms or kitchens of individual apartments in multi-apartment buildings, replacing conventional electric DHW boilers. It is designed for a household of four to five people, primarily relying on showers with occasional bathtub use. Each apartment is assumed to be connected to a low-temperature underfloor heating network that serves as the heat source.

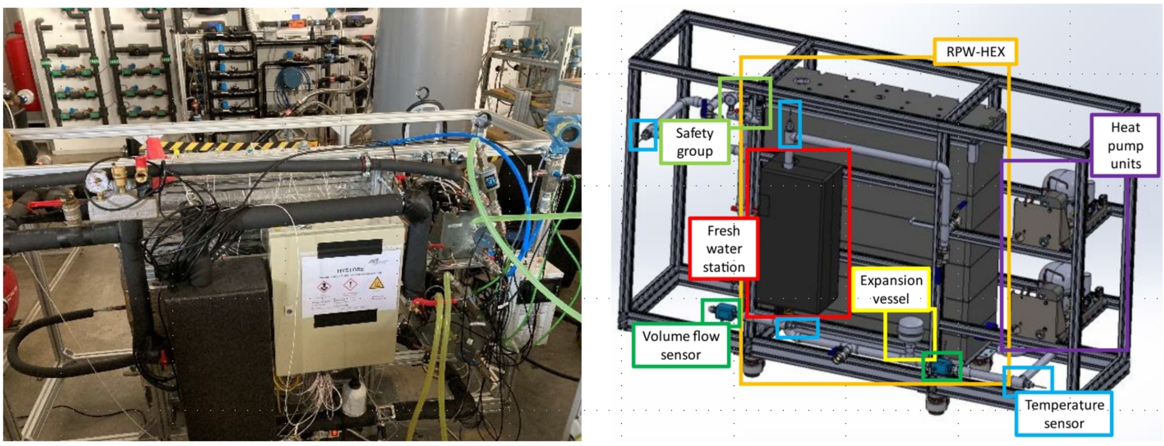

Fig. 1: Photo (left) and 3D drawing (right) of the prototype HPWH utilizing solid/liquid PCM.

The PCM storage is charged directly by two HP modules integrating the condenser HEXs in the storage. The HPs run at fixed compressor speed with a nominal heating capacity of 3 kW. R290 (propane) is used, owing to its low global warming potential (GWP=3), and favorable thermodynamic properties; however, its application is constrained by its A3 safety classification, which denotes high flammability. The need for a low refrigerant charge favors compact components, such as small compressors, valves, tubing, and HEXs. Micro-port extrusion (MPE) tubes, typically made from alloys, have low internal volume and are a cost-effective alternative to aluminum compact plate-fin condensers. In contrast, copper tube/aluminum fin designs are heavier, have higher internal volume, and are more expensive, but offer better thermal conductivity and compatibility with direct DHW contact.

The PCM storage is made of aluminum and weights 142.5 kg. Its external dimensions, excluding the handles and fittings, are 944 mm in length, 1004 mm in height, and 313 mm in width. It incorporates two aluminum refrigerant/PCM HEXs that function as condensers within the heat pump cycle and serve to charge the storage by melting the PCM. Both HEXs are arranged in a vertical stack and integrated into one single radiator-type

HEX unit. The storage also incorporates two (radiator-type) aluminum water/PCM HEXs for discharging, i.e., solidifying of the PCM. The three radiator-type heat exchangers are arranged side by side, resulting in a shallow storage depth and a flat container design. All HEXs utilize a brazed plate-fin design with aluminum MPE tubes. Refrigerant tubes, water tubes, and fins are joined by established vacuum-brazing technology. To ensure hygienic DHW preparation, the DHW circuit is separated from the thermal storage via a secondary loop, implemented through a commercial fresh water station.

The system was tested with two different commercial PCMs, RT60HC and SP58. Table 1 summarizes their material properties and storage-related data. Updated material property data were provided by Rubitherm Technologies GmbH (Germany) via personal communication with E.K., because the corresponding publicly available material data sheets were incomplete or outdated at the time of the study. According to Nienborg et al. (2018), SP58 contains sodium acetate trihydrate (SAT) as the PCM. However, since SP58 is supplied as a gel, its thermophysical properties may differ from those of pure SAT. In addition, 3.1 wt.% thickening agent was mixed into the supplied SP58 formulation at AIT to increase the material viscosity, mitigate phase separation inside the storage, and promote nucleation.

Tab. 1: Storage capacity for the two PCMs used in the HPWH.

PCM	**RT60HC**	**SP58**
material class	Ether	Salt-hydrate
latent heat of fusion	210 kJ/kg	220 kJ/kg
thermal conductivity	0.2 W/(m·K)	0.6 W/(m·K)
density (liquid)	0.75 kg/L	1.4 kg/L
mass/ volume	112 kg/ 150 L	225.5 kg/ 160 L
total capacity incl. container (theoretical 40–70°C)	9.32 kWh	18.45 kWh

The PCM was filled into the storage to a level such that, in its liquid state, it reached the top surface of the HEX core. The remaining space between the PCM and the top plate was intentionally left empty to accommodate volume changes during operation. Moreover, an expansion vessel additionally compensates for PCM-induced pressure build-up within the storage during melting, thereby protecting its structure from deformation or mechanical failure.

3. Performance Tests

3.1 Heat-up using RT60HC and SP58

During start-up, the HPs were switched off automatically and independently when the condensation temperature reached 78 °C. This threshold was assumed to indicate complete melting of the PCMs, which had nominal melting temperatures of 60 °C for RT60HC and 58 °C for SP58. In addition, to reduce thermal stress on the compressor, the HPs were switched off when the hot-gas temperature reached 100 °C. After switch-off, the HPs entered cycling mode, characterized by on/off switching.

With RT60HC as the PCM, complete charging of the storage was not achieved despite several adaptations to the HP settings. Consequently, not all of the PCM in the storage could be melted. It was found that for RT60HC, the hot-gas temperatures and condensation temperature, as well as some PCM temperatures increase markedly faster than for SP58. Consequently, both HPs soon started cycling (after approximately one hour), with on-times of about 10 min. PCM temperatures measured between the radiators and the container wall showed only a weak response to charging and remain within the phase-change temperature range of RT60HC. In contrast, some temperatures, for example close to the refrigerant inlet and near the radiator-type condensers, are strongly affected. This indicates poor and slow heat transfer, especially in the lateral direction, and results in frequent HP shut-offs due to overheating. Consequently, using RT60HC, the total energy transferred to the storage by the end of the experiment was relatively small, at 4.3 kWh.

For SP58, the HPs operated continuously for comparatively long periods. The improved performance is mainly attributed to the higher thermal conductivity of the PCM, which enables more efficient heat transfer within the storage, thereby reducing the occurrences of local overheating. HP 1, which uses the upper condenser in the centrally placed radiator, switched off earlier. In contrast, HP 2 operated continuously for approximately 5.5 h.

After 6 h of operation 15.7 kW h of energy had been charged. This value is close to the theoretical capacity of 17.8 kW h reported in 1. During the active periods the compressors of HP 1 and HP 2 consumed average electrical powers of 0.84 kW and 0.80 kW, respectively, and both units operated with an average COP of 2.2 and Carnot efficiencies of 30 %.

3.2 Useful energy for daily tapping considering load profile size L using SP58

Using SP58, results indicate that the unit successfully meets the requirements of load profile L. The test, conducted with water flow rates between 3 to 10 L/min, yields a final cumulative energy drawn of 12.5 kWh, which exceeds the minimum requirement of 11.655 kWh of useful energy (EN 16147:2017, 2017). The water drawn during the draw-off periods exceeds 40 °C, which defines the lower threshold for useful water (and energy). The maximum draw-off occurs at 08:05, with 3.605 kWh at 10 L/min, and is repeated at 21:00, both requiring power greater than 20 kW. The measured peak power exceeds 30 kW.

3.3 Maximum amount of mixed water at 40 °C *for a continuous draw-off (constant-flow) test using SP58*

Using SP58, in the constant draw-off test at 10 L/min a useful energy of 5.4 kWh is drawn, corresponding to V_{40} = 156 L of mixed water at 40 °C. This confirms that the system meets the minimum delivery requirements for the declared load profile L, which demands 130 L at 10 L/min, as defined in EU 814/2013.

Interestingly, V_{40} and the corresponding released energy showed significant negative correlations with the water flow rate during hot-water draw-off, see Fig. 2. At 10 L/min the storage provides 156.4 L of V_{40} (equivalent to 5.4 kWh). At 3 L/min the storage provides 308.6 L of V_{40} (equivalent to 10.7 kWh). It is evident that higher water draw-off flow rates require higher thermal power to generate V_{40}. The corresponding minimum discharge rates, for example 20.1 kW at 10 L/min compared with 6.2 kW at 3 L/min, are shown in the second subfigure of Fig. 2.

Moreover, the same phenomenon of thermal recovery and reheating is observed as reported by Frazzica et al. (2016). When the draw-off is stopped and the water temperature drops below 40 °C, pausing for 30 minutes (without recharging the storage) and then resuming the continuous draw-off allows an additional amount of useful mixed water to be drawn at temperatures above 40 °C. As a result, at 10 L/min the useful energy increases from 5.4 kWh to 7.3 kWh, corresponding to an increase in V_{40} from 156 L to 209 L. This phenomenon extends the hot water delivery by up to 34% over the investigated flow-rate range.

4. Discussion and conclusions

This contribution reports on the experimental testing of a HPWH prototype integrated with compact PCM storage, using either 112 kg of the organic PCM RT60HC or 225.5 kg of the salt-hydrate PCM SP58.

The results show that, when filled with SP58, the prototype meets the requirements of the standardised 24-hour tapping profile size L of EN 16147:2017 (2017), representing a medium household demand of three people. In particular, the required useful energy demand can be delivered. In contrast, performance is significantly reduced when RT60HC is used, resulting in poor utilisation of the storage capacity. This can be attributed to the higher storage density and thermal conductivity of SP58.

In addition, using SP58, continuous draw-off tests for determining the maximum amount of mixed water at 40 °C showed that, at high draw-off flow rates, significant portions of the storage capacity cannot be used because the storage cannot maintain the required heat transfer rate for extended periods. However, pause periods allow the temperature field in the storage to homogenise, with heat being transferred towards the water/PCM HEX surface. As a result, temperatures close to the water/PCM HEX surface recover after a pause, and the local temperature differences are again sufficient to provide the heating rates required for hot-water generation at 40 °C. For the draw-off at 10 L/min and using SP58 this phenomenon extends the hot water delivery by 34%.

The results provide a basis for discussing whether current standards developed for DHW preparation with conventional water-based storage systems are fully applicable to PCM-based HPWH systems.

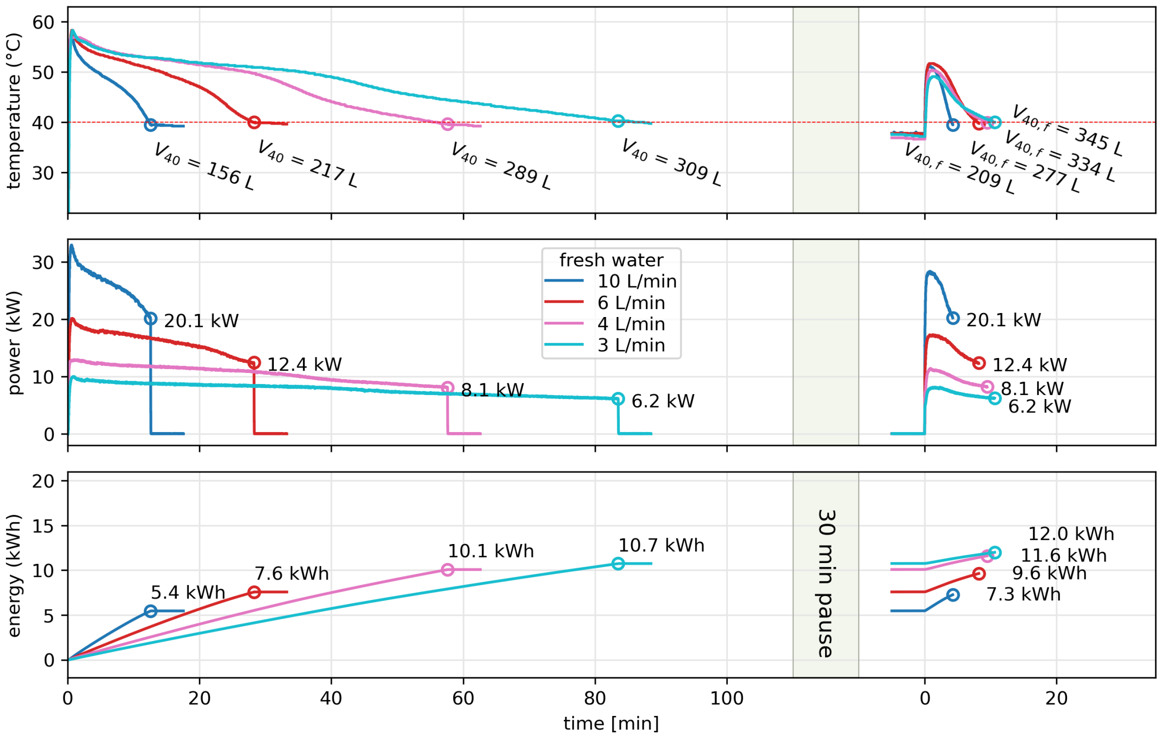

Fig. 2: Energy and mixed water at 40 °C for continuous draw-off (constant-flow) tests at 3, 4, 6, 10 L/min, EN 1647 EN 16147:2017 (2017). After initial charging, the HPs are not active.

5. Acknowledgements

This project is being carried out as part of the IEA research cooperation on behalf of the Austrian Federal Ministry for Climate Protection, Environment, Energy, Mobility, Innovation, and Technology. The authors acknowledge funding from the European Union Horizon Europe Programme under grant agreement No 101096789 (HYSTORE).

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