Analysis of a latent heat storage unit using a pillow plate heat exchanger during real operations in a zero-emission building

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Abstract

The zero-emission building (ZEB) Laboratory (Trondheim, Norway) has an innovative latent heat storage (LHS) unit. It consists of 24 parallel pillow plates and 3 tons of phase change material (PCM) CT37 (biowax – transition temperature 37 ˚C). There are two different operation modes to charge and two to discharge the LHS system depending on the heat demand, electricity costs, and forecast prediction, as it can be combined with photovoltaic panels installed on the building. After several months of utilization with a time-based control strategy, results on the temperature of the LHS unit versus the heat output and heat storage capacity over four consecutive weeks in winter 2021-2022 have been analysed. The results here presented shown a good reversibility in the partial charge/discharge processes (~120 kWh) during real operations of the building. We also report the contribution of the LHS unit to stabilise the room temperature of the building and to its heat demand. The long-term heat loss (1.29%) was also calculated, confirming the previously predicted value. The results obtained in this work are of high interest to improve the system design and the development of a predictive control strategy for the energy management of the whole building.

Keywords: Latent heat storage, phase change materials, PCM, building, peak shaving, pillow plate

1. Introduction

In 2021, the zero emission building (ZEB) Laboratory (www.zeblab.no; Time et al., 2019), owned by SINTEF and NTNU, was commissioned in Trondheim (Norway) as an office building and living laboratory (see Fig. 1). This building and all its systems (construction phase, regular operations, and materials) were and are being made towards having the corresponding CO_2-emissions fully offset within the 60 first years of operations of the building. One of the technologies that were implemented and demonstrated to reach this goal is a latent heat storage (LHS) unit (see Fig. 2) using a phase change material (PCM) for the central heating system of the building (Nocente et al., 2021; Sevault et al., 2022, 2020, 2019; Sevault and Næss, 2020).

Fig. 1: Zero-emission building (ZEB) Laboratory. Photo: Nicola Lolli / SINTEF

The LHS unit is integrated together with a heat pump providing hot water to preheat domestic hot water and feed radiators and heat ventilation air for space heating (Sevault et al., 2019; Sevault and Næss, 2020). The local district heating is also connected to the heating system. The LHS unit was built to store the excess heat during low-heat demand and release it during high demand. This experimental unit was custom-designed and demonstrated by the integration path offering the most flexibility in the heating system.

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Fig. 2: 200-kWh PCM heat storage unit installed at the ZEB Lab. Photo: Alexis Sevault / SINTEF

The main objective of this study is to analyze the thermal performance of the LHS unit during real operations of the central heating system of the ZEB laboratory for several days.

The design and integration of the LHS unit have been previously described by Sevault and Næss, 2020. The building heating system has two main hydronic heat sources: an air-to-water heat pump and the return loop of the local district heating network (see Fig. 3) providing heat at around 40-47 °C.

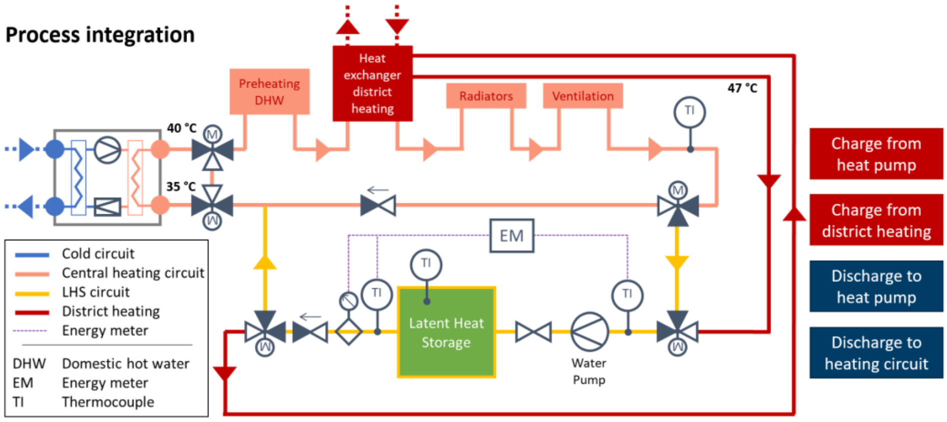

Fig. 3: Simplified process diagram of the central heating system focusing on the integration of the LHS unit, with four different operation modus. Only the instrumentation for control of the LHS unit is shown.

There are 4 different operation modes depending on the charge or discharge of the LHS unit: discharge to heat pump; charge from heat pump; discharge to the building heating system; or charge from the district heating. The system is currently following a time-based routine to establish a performance benchmark. However, a model predictive control strategy using combined economic and environmental objectives is in development and to be tested in the coming months.

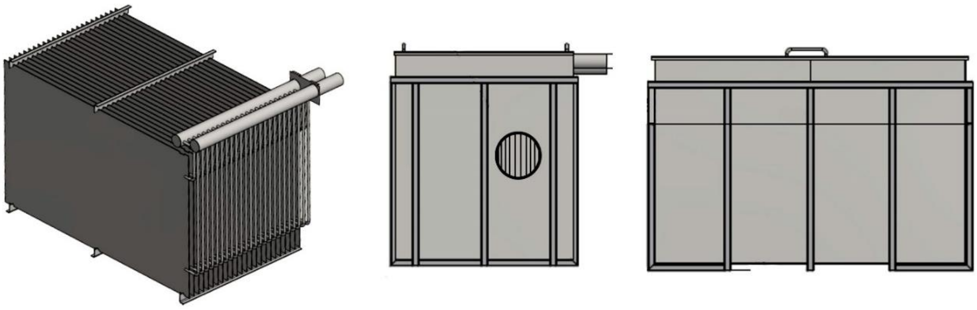

Fig. 4: Geometry of the LHS unit without container, left. The middle and right figures are lateral and front views, respectively.

The integrated LHS unit results from a design investigation (Sevault et al., 2019; Sevault and Næss, 2020) and is based on a pillow plate heat exchanger design (Mastani Joybari et al., 2022; Selvnes et al., 2019; Vocciante and Kenig, 2021) with 24 laser-welded stainless-steel pillow plates, mounted vertically in parallel. Water circulates in each of them following a 2-pass pattern. The LHS unit is filled with 3 tons of PCM CT37 (Crodatherm™ biowax – transition temperature 37 ˚C) to occupy the volume between the pillow plates. The specifications of the LHS unit and the PCM are described in Tab. 1. The geometry of the unit, with a pillow plate heat exchanger design, is shown in Fig. 4 (Sevault et al., 2022).

Tab. 1. Specifications of the LHS unit and the PCM CT37 (Sevault et al., 2022)

Dimensions of LHS unit (height * width * length) [m]	1.5 * 1.4 * 2.25
Measured PCM melting temperature range [°C]	35 – 39 (heat flow peak at 36.5)
Measured PCM solidification temperature range [°C]	32.5 – 35.5 (heat flow peak at 34.5)
Measured PCM latent heat of fusion [kJ/kg]	198.6
Measured PCM latent heat of crystallisation [kJ/kg]	196.4
PCM density [kg/m3]	957 (at 32 °C), 819 (at 75 °C)
PCM thermal conductivity [W/(m.K)]	0.24
PCM specific heat capacity [kJ/(kg.K)]	2.3 (solid), 1.4 (liquid)
PCM degradation temperature [°C]	90
Total theoretical thermal storage capacity [from 30 to 40 °C] [kWh]	194
The ratio of latent heat to total heat storage capacity	87 %

The performance of the LHS unit with a full charge and discharge was analyzed previously (Sevault et al., 2022). In that study, it was reported a maximum operating heat storage capacity of ca. 200 kWh. However, that study was run out of the time-based routine, so that the subsequent building conditions (very low or high temperature) could not affect the comfort of the users of the building. For a more realistic analysis of the performance of the LHS, it is necessary to carry out longer-term studies during the daily routine of the building, considering factors such as the energy demand of the building or the heat loss of the system, which were not included in the previous work. This complementary data, in addition to electricity cost and weather forecast (it is worth mentioning that the building has also photovoltaic panels) will help to develop the predictive control strategy for the energy system of the building (Drgoňa et al., 2020; Gholamibozanjani et al., 2018), so the LHS can operate with the most efficient modus depending on the conditions.

2. Monitoring system

For the analysis of the temperature distribution in the LHS system, 30 thermocouples were placed in different strategic locations. The thermocouples were distributed in 3 sets: PCM volume, along the pillow plates, and in the outer walls of the PCM-heat-exchanger tank. In addition to the thermocouples, energy meters were located outside the LHS unit to measure the process water mass flow rate and the inlet and outlet temperatures.

The analysis of the data collected in a full charge and discharge led to conclude different facts about the performance of the unit: there is a preferential water-course path inside the heat exchanger plates; and large free convection effects during charge were observed (Sevault et al., 2022). These phenomena did not significantly affect the performance of the LHS unit, but it must be noted that the mentioned analysis was run with a high temperature difference between the charge and the discharge. In the present work, we will focus on 4 weeks of performance of the unit during winter, pausing the activity during weekends. Also, the collected data will be compared to the calculated energy demand of the building and the external temperature.

3. Results and discussion

As the local thermal performance of the LHS system in its different parts was already studied, for this work we will show only the average temperature collected by the thermocouples along the heat exchanger plates over 4 weeks. Fig. 5 shows the calculated mean of the temperature from the sensors located in the pillow plates. We will consider this average as the temperature that the LHS can reach with the heating/cooling water that flows inside the pillow plates. The temperature range where the solidification and melting of the PCM take place is shaded in yellow and corresponds to 35-39 ˚C according to differential scanning calorimetry measurements from the previous work.

Observing Fig. 5, the temperature reached by the LHS unit is usually around the phase transition region. However, there are cycles where the maximum and minimum temperatures for charging and discharging (respectively) do not reach much above or below the limits of the phase transition. This could mean that the LHS-unit is not fully charged or discharged, so it is necessary to look at the data collected by the energy meters for further analysis.

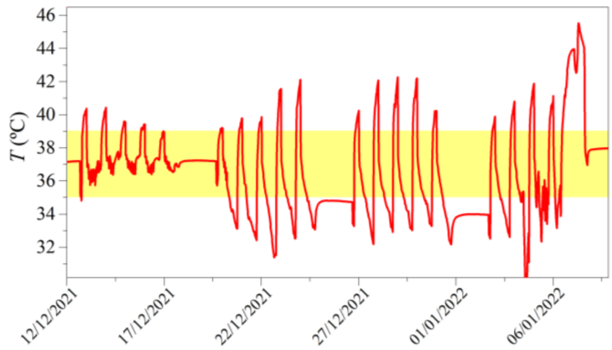

Fig. 5: Average temperature of the pillow plate thermocouples as a function of time. Yellow zone: phase change region (according to our own DSC measurements).

The process water mass flow rate, as well as its inlet and outlet temperatures, were measured using the energy meters located outside the LHS unit. Fig. 6 (left) shows the heat flow to the LHS unit. It can be observed that the heat flow is not constant during every charge and discharge. In the same way, the maximum charging and discharging temperatures are not constant either. This irregular heat flow is related to both varying inlet water temperature and the PCM along the pillow plates heating up or cooling down during discharge/charge processes and, thus, changing phase. The latter phenomenon significantly affects both the local thermal conductivity in the PCM and reduces the temperature difference between PCM along the pillow plate and water flow temperature, thus reducing the heat flow.

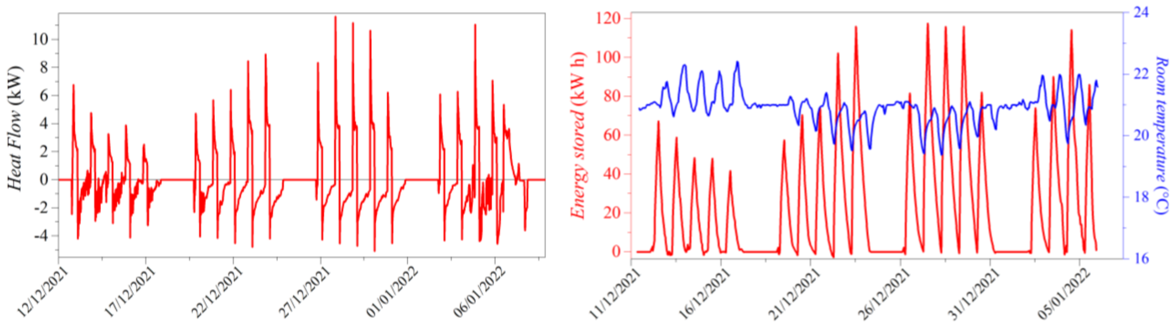

Fig. 6: (Left) Heat flow (power) measured by energy meters outside of the LHS unit, as a function of time for the LHS unit. Positive values indicate charging, while negative values indicate discharging. (Right) Red: Energy stored as a function of time calculated as the integral of the heat flow; The zero in the y-axis corresponds to the lowest recorded energy level in the LHS unit during the given period. Blue: average room temperature inside the building.

It can be observed that the maximum/minimum heat flow is reached when the temperature in the heat exchangers is considerably above or below the phase transition limits (35-39 ˚C). By integrating the energy flow as a function of time, the thermal energy storage capacity is obtained, and so is the energy level of the LHS unit (see Fig. 6, right). For the period studied in this work, the maximum energy stored was ca. 120 kWh. It takes around 6 hours to reach this level of charge in these operating conditions, but the charging time depends mostly on inlet water temperature, whose difference with the PCM average temperature was mostly under 5 K here. The discharging time for 120 kWh was around 18 hours in the given conditions. It must be noted that the LHS unit can be charged and discharged up to 200 kWh at maximum capacity, as was confirmed in our previous work.

By comparing the energy stored and released to the room temperature in the building, it can be observed that the processes of charge and discharge contribute to the regulation of the room temperature of the building (21±1 ˚C).

The total heat demand of the central heating system is the sum of heat produced by the heat pumps, heat extracted from district heating, heat discharged from LHS, minus the heat used charge the LHS. The calculated average daily heat demand is 22.2 kWh, while the peak heat demand was 104.8 kWh.

One important result from the partial charge and discharge tests shown here is that the energy level always comes down to zero between partial cycles. Since it was calculated form the energy meters outside the LHS unit, this means that it was possible to extract as much energy from the LHS unit as it was previously stored, despite the charge cycles not being completed. This shows reversibility in the partial charging/discharging processes, which ensures a close to 100 % round-trip thermal efficiency.

The average heat loss of the LHS unit has been calculated to be (107.8±0.2) W, which is an average heat loss of 1.29% over 24 hours. This has been calculated by linear regression of the heat flow into the unit over the period from January to June 2022. Due to the heat loss over time, more heat is supplied than what is discharged from the unit. This is in reasonable agreement with previous results (Sevault et al., 2022), which predicted the heat loss to be 1% over 24 hours based on the amount of insulation material on the unit. Note that the heat loss from the LHS-unit occurs inside the temperature-regulated building in this case, which is thus not a real energy loss for the building.

4. Conclusions

The zero-emission building (ZEB) Laboratory is an office building and living laboratory using an energy system with a latent heat storage (LHS) unit, which can be charged from heat pumps or district heating, and can be discharged to the central heating system. The performance of the LHS unit has been investigated in a period of four weeks during winter 2021-2022.

By analyzing the effect of the inlet and outlet temperatures to the LHS unit, it was observed that the unit is not always fully charged and often follow partial charge/discharge cycles. However, when the LHS-unit is partially charged, it releases almost the same energy in the discharge. The obtained heat loss over time is in agreement with the theoretically calculated in our previous work, which confirms the methodology for its prediction. Even though the maximum capacity of the LHS unit is 200 kWh from previous full charge tests, in this work we report a maximum storage capacity of 120 kWh (partial charge) under real operations in the building during 4 weeks. The maximum energy stored was linked to the actual heating demand of the building during the time period, when 200 kWh daily heat storage was not needed. Even though the LHS unit contributes to stabilise the room temperature of the building, the control system of the LHS unit is not optimal. The water inlet temperatures to the LHS unit should have a better prediction, so the system could decide under which modus it is operating in case a larger temperature difference for its charge or discharge is required. The heat demand of the building must also be included in the input data for the predictive control strategy to finely adjust the heat to be delivered by the LHS unit. Having now confirmed that the LHS unit operates efficiently in partial charges and discharges operations, the predictive system will confidently take into account partial charge/discharge as an extra degree of freedom of operations. These results will contribute to the design of the predictive control strategy to reach a higher efficiency of the whole heat management of the building.

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