Author Accepted Manuscript version of the paper by Olav Galteland et al.
in 2023 8th International Conference on Smart and Sustainable Technologies - SpliTech (2023)
http://dx.doi.org/10.23919/SpliTech58164.2023.10193589

Fourteen months operation of a 200 kWh latent heat storage pilot

Olav Galteland, Margaux Gouis, Jorge Salgado-Beceiro, and Alexis Sevault
Department of Thermal Energy
SINTEF Energy Research
Trondheim, Norway
olav.galteland@sintef.no

***Abstract*—A latent heat storage was in 2021 installed in an office building in Trondheim, Norway. The unit contains 3 tons of CrodaTherm 37, which is a bio-based wax phase-change material with a melting temperature of 37 degrees Celsius. The thermal energy storage can be charged from heat pumps or district heating and can be discharged to domestic hot water, radiators, ventilation, or heat pumps. This unit has been collecting data on operations for over 14 months. The total thermal energy capacity was measured to be 226 kWh, and the average discharge rate over 12.2 hours of 10.51 kW and average charge rate over 11 hours of 13.7 kW was measured. An average temperature reduction of 47.3 to 38 Celsius over 234 hours during storage was measured. The average heat loss was measured to be 64 W, or 0.68% of the total capacity per day.**

***Index Terms*—phase-change materials, thermal energy storage, latent heat storage, pillow plate heat exchanger, office building**

I. Introduction

Space heating and cooling, and water heating accounted for 21% of the EU's total energy consumption in 2020, in which 44% was fueled by fossil energy sources [1]. These heating and cooling processes can be electrified using heat pumps, which in turn will increase the total electricity consumption. To reach a zero-emission future this increase must be met with an increase in renewable energy sources, such as wind or solar power. Renewable energy sources are typically intermittent, meaning that energy storage is necessary to buffer supply and demand fluctuations. Latent heat storage (LHS) is an emerging compact and low-cost technology well suited for thermal energy storage (TES) for building heating and cooling demands.

Phase-change materials (PCM) are materials with high latent heat, making them suitable as a medium for compact thermal energy storage (TES). TES can reduce operational costs for heat processes in the industry, residential buildings, and office buildings by shifting the thermal load to low electricity cost periods (such as during the night time). In addition, it can reduce peak thermal load on heat pump and consequently reduce the heat pump capacity, and it can be used for heat supply security as it can operate during power shortages. LHS is especially well suited for building heating and cooling demands as it has a narrow operating temperature range (around the melting temperature). Energy storage enables flexibility in the energy market, giving stability to the grid networks.

Fig. 1. A photo of the latent heat storage unit in the zero-emission building.

The zero-emission building (ZEB) is a living laboratory office building in Trondheim, Norway, built in 2021 [2]. The building has four floors with a total floor area of $2000\,\mathrm{m}^2$ with offices, meeting rooms, lunch rooms, and technical rooms. It has a capacity of approximately 80 office workers. The building was designed to compensate for the emissions from the construction process, embodied material emissions, and energy use for operation and equipment by renewable energy production (With PV panels) on site after 60 years of operation [3]. The ZEB laboratory has PV panels with a peak capacity of $184\,\mathrm{kW}$, two $15\,\mathrm{kW}$ heat pumps, $200\,\mathrm{kWh}$ LHS, and is connected to district heating [4]. It is a living laboratory, where a total of 1171 data points are stored in a database server every 2 minutes, totaling an estimated 350 million data points over 14 months of operation.

In this paper, two quantities determined by experiment on

Author Accepted Manuscript version of the paper by Olav Galteland et al.
in 2023 8th International Conference on Smart and Sustainable Technologies - SpliTech (2023)
http://dx.doi.org/10.23919/SpliTech58164.2023.10193589

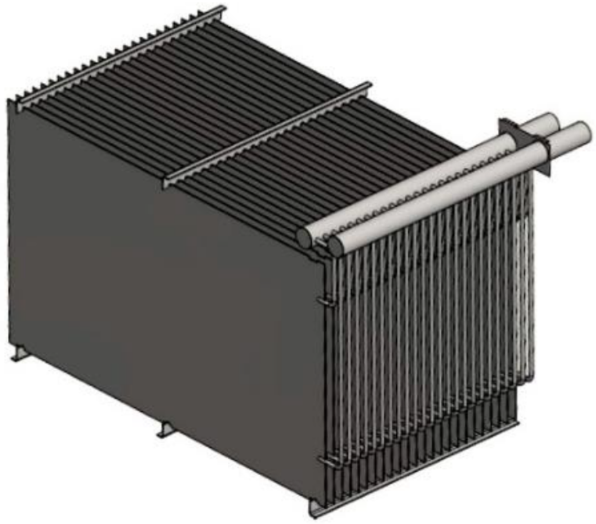

Fig. 2. Sketch of the pillow plate heat exchanges in the latent heat storage unit. There are 24 horizontal plates in the unit, with PCM filled between them.

the LHS unit will be evaluated:

- The total thermal energy capacity between an average PCM temperature of $22.8\,°\mathrm{C}$ and $41.8\,°\mathrm{C}$
- The heat loss over $234\,\mathrm{h}$

In addition, we will examine the operation of the unit over a 14-month period.

II. Latent heat storage unit

The LHS unit is placed on the first floor in a technical room centered in the middle of the building. A photo of the LHS unit is shown in figure 1. The outer dimensions of the unit are $1.5 \times 1.4 \times 2.25\ \mathrm{m}^3$ (height, width, length). The heat is transferred to and from the unit through 24 horizontal pillow plates using water as the heat transfer fluid. The pillow plates are shown in figure 2. There are a total of 30 thermocouples in various strategic locations in the unit; 11 are welded to the outside of the pillow plates, 15 are centered between the pillow plates in the PCM, and 4 are placed between the container and the insulation. The thermocouples welded to the pillow plates are considered to represent the temperature of the water flowing through the heat exchanger. The 15 thermocouples between the pillow plates are equally dived and spread into three positions, placed in the bottom, center, and top of the tank. In addition, the water flow inside the pillow plates is measured with a flow meter and thermocouples are placed at the water inlet and outlet. The heat flow to the LHS can be controlled with a water pump. We have previously analyzed the temperature distribution during charging and discharging in this unit [5], [6]. The unit is insulated with $150\,\mathrm{mm}$

The unit is filled with $3000\,\mathrm{kg}$ of CrodaTherm 37 (CT37), which is a bio-based wax forming a crystalline solid phase. Its melting temperature and latent heat of fusion have previously been measured with differential scanning calorimetry to be

TABLE I
Thermophysical properties of CrodaTherm 37 [7].

Property	Value
Melting temperature	$(37 \pm 1)\,°\mathrm{C}$
Liquid mass density	$819\,\mathrm{kg\,m^{-3}}$
Solid mass density	$957\,\mathrm{kg\,m^{-3}}$
Solid specific heat capacity	$2.3\,\mathrm{kJ\,K^{-1}\,kg^{-1}}$
Liquid specific heat capacity	$1.4\,\mathrm{kJ\,K^{-1}\,kg^{-1}}$
Thermal conductivity	$0.24\,\mathrm{W\,m^{-1}\,K^{-1}}$
Latent heat of fusion	$198.6\,\mathrm{kJ\,kg^{-1}}$

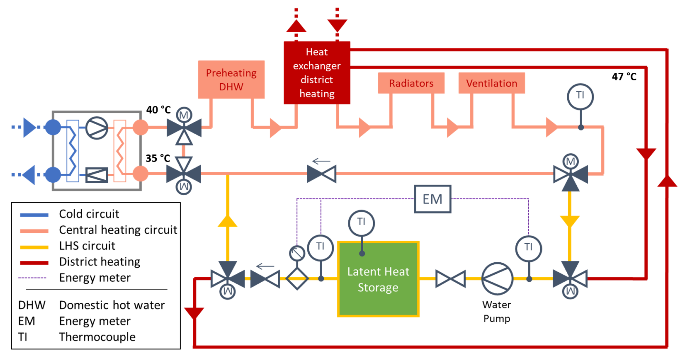

Fig. 3. The latent heat storage (LHS) unit is can be charged from heat pumps (HP) or district heating (DH), and it can be discharged to pre-heating domestic how water (DHW), radiators, and ventilation or it can be discharged to the heat pumps (HP).

$36.5\,°\mathrm{C}$ and $198.6\,\mathrm{kJ\,kg^{-1}}$, respectively [7]. More thermophysical properties are presented in table I.

A simplified process diagram is shown in figure 3. The LHS unit has five operational modes,

1) store (do nothing),
2) charge from heat pump (HP),
3) charge from district heating (DH),
4) discharge to building heating loop (HL),
5) discharge to heat pumps (HP).

The discharge to building heating loop goes to pre-heating of domestic hot water (DHW), radiators, and ventilation. The unit has for this period of 14 months been mainly controlled on a calendar schedule, except for periods when specific experiments have been run.

III. Results and discussion

The unit was fully charged to an average temperature $(41.8 \pm 0.5)\,°\mathrm{C}$, and then discharged to an average temperature $(22.8 \pm 0.4)\,°\mathrm{C}$ over $60\,\mathrm{h}$. The average temperatures of the PCM in the top, center, and bottom as well as the temperature of the pillow plates are shown in figure 4, and the heat flow and energy stored are shown in figure 5. The unit produced an average of $(10.51 \pm 0.08)\,\mathrm{kW}$ during the first $12.2\,\mathrm{h}$ for discharging (marked with dashed rectangle in figure 5). During this period the average temperature difference between the pillow plates and the PCM was $(2.95 \pm 0.06)\,°\mathrm{C}$. The unit discharged a total of $226\,\mathrm{kWh}$. After fully discharging, the unit was then charged up to an average temperature of $(40.5 \pm 0.7)\,°\mathrm{C}$ over $50\,\mathrm{h}$. The unit was able to be charged

Author Accepted Manuscript version of the paper by Olav Galteland et al.
in 2023 8th International Conference on Smart and Sustainable Technologies - SpliTech (2023)
http://dx.doi.org/10.23919/SpliTech58164.2023.10193589

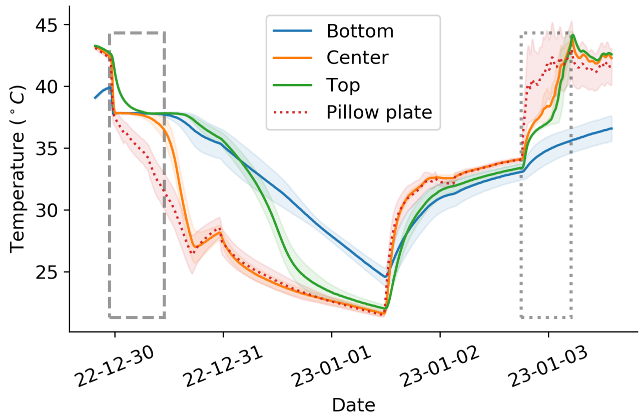

Fig. 4. Temperature in the phase-change material (PCM) and of the pillow plates during a full discharge-charge cycle. The light-shaded colored areas illustrate the standard deviation in each group of temperature measurements. The dashed rectangle to the left illustrates the peak discharge period, the average temperature difference between the pillow plates and the PCM was $(2.95 \pm 0.06)\,^\circ\mathrm{C}$. The dotted rectangle to the right illustrates the peak charge period, the average temperature difference was $(-3.76 \pm 0.08)\,^\circ\mathrm{C}$

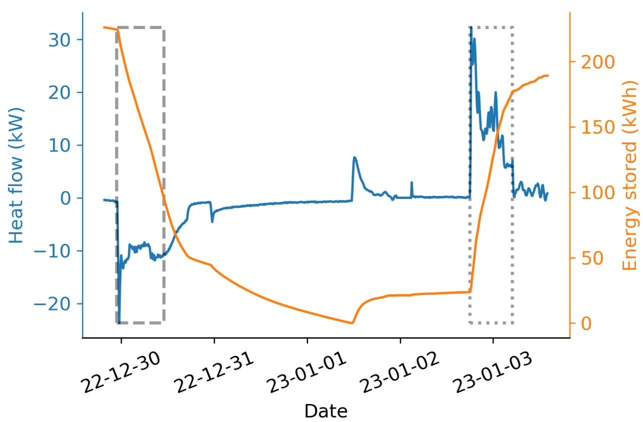

Fig. 5. Heat flow from the latent heat storage and total energy stored during a full discharge-charge cycle. The dashed rectangle to the left illustrates the peak discharge period, average $(10.51 \pm 0.08)\,\mathrm{kW}$ over $12.2\,\mathrm{h}$. The dotted rectangle to the right illustrates the peak charge period, average $(13.7 \pm 0.2)\,\mathrm{kW}$ over $11\,\mathrm{h}$.

at an average $(13.7 \pm 0.2)\,\mathrm{kW}$ over $11\,\mathrm{h}$ in the steepest part of the charging curve (marked with a dotted rectangle in figure 5). During this peak charging period, the average temperature difference was $(-3.76 \pm 0.08)\,^\circ\mathrm{C}$. The unit was charged with a total of $189\,\mathrm{kWh}$. The phase-change material has a theoretical storage capacity of $(164 \pm 2)\,\mathrm{kWh}$ in the discharging temperature range (latent and sensible heat). The additional $(62 \pm 2)\,\mathrm{kWh}$ storage capacity originates from the sensible heat of additional components, such as the pillow plate heat exchanger, pipes, and container.

The LHS unit was charged to an average PCM temperature of $(47 \pm 1)\,^\circ\mathrm{C}$ and left for $234\,\mathrm{h}$ to investigate the heat loss of the unit. In figure 6 the temperature of the PCM in three different locations (bottom, center, and top) is shown as a

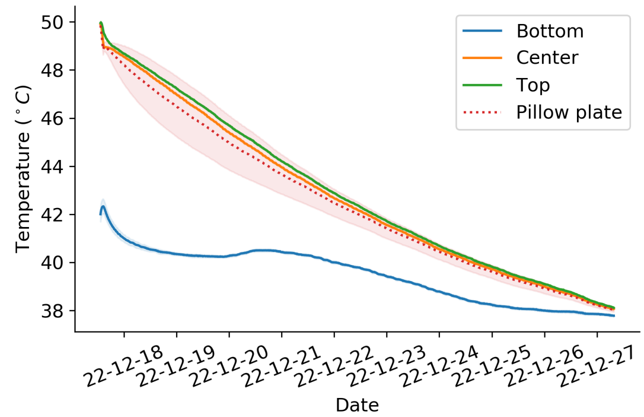

Fig. 6. Temperature in the phase-change material (PCM) and of the pillow plates during storage at full charge. The light-shaded colored areas illustrate the standard deviation in each group of temperature measurements.

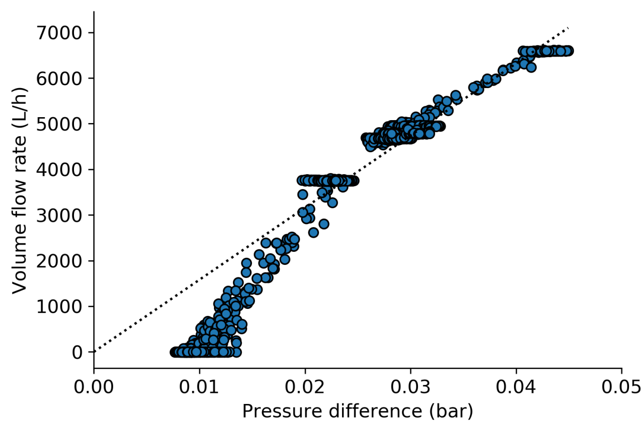

Fig. 7. Volume flow rate of water through the pillow plate heat exchanger as a function of negative pressure difference over 14 months of operation. Each dot is an average of 1 h. The black dashed line shows a least squares regression to Darcy's law. The permeability has been determined to be $\kappa = 2.5 \times 10^{-4}\,\mathrm{m}^2$.

function of time. The average temperature of the technical room was $28.4\,^\circ\mathrm{C}$ during this time. After $234\,\mathrm{h}$, the average temperature difference of the unit is $(37.99 \pm 0.04)\,^\circ\mathrm{C}$. The unit was then charged back up to the initial temperature, to investigate how much energy was lost during this time. The unit lost $15\,\mathrm{kWh}$ over $234\,\mathrm{h}$, meaning that the heat loss rate was $64\,\mathrm{W}$.

The volume flow rate of water through the pillow plate heat exchanger as a function of the negative pressure difference is shown in figure 7. The blue dots show data points from 14 months of operation, and the dotted black line shows a least squares regression of the data to Darcy's law. The deviation of the blue dots from Darcy's law is presumed to be because of dynamical effects, *i.e.* that the system has not reached a steady state. Darcy's law is given by

$$Q = -\frac{A\kappa}{\mu L}\Delta p. \quad (1)$$

Author Accepted Manuscript version of the paper by Olav Galteland et al.
in 2023 8th International Conference on Smart and Sustainable Technologies - SpliTech (2023)
http://dx.doi.org/10.23919/SpliTech58164.2023.10193589

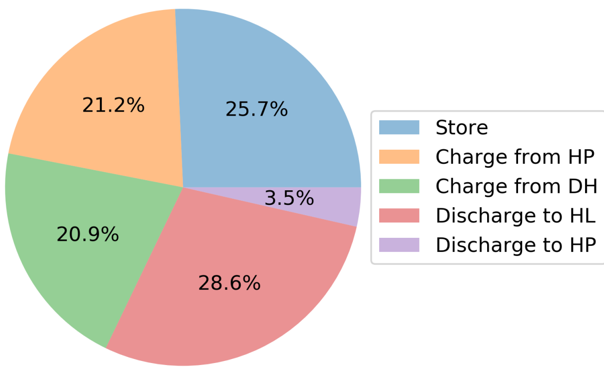

Fig. 8. Proportions of time in each operational mode from 14 months of operation. The abbreviations stand for HP: heat pump, DH: district heating, and HL: (building) heating loop.

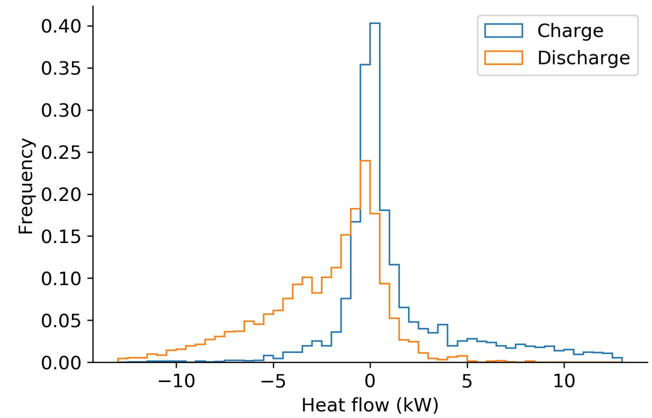

Fig. 9. Histogram of the heat flow through the latent heat storage unit from 14 months of operation in charging and discharging operational modes.

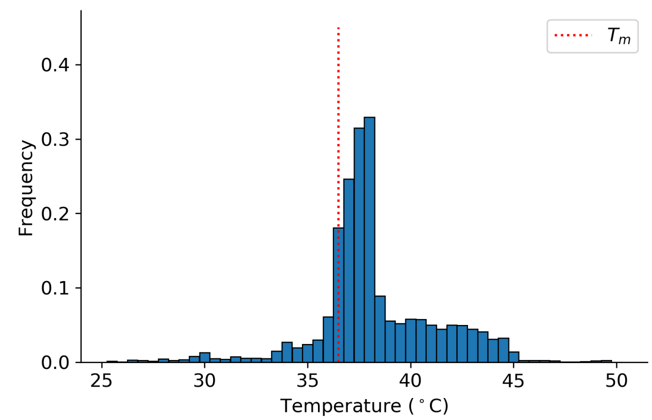

Fig. 10. Histogram of the average PCM temperature in the latent heat storage unit from 14 months of operation. The melting temperature of the phase-change material is shown as a dashed red line, $T_m = 36.5\,°\mathrm{C}$.

Where $A = \pi R^2$ is the cross-sectional area of the inlet pipe at the flow meter, with radius $R = 2.5\,\mathrm{cm}$, κ is the permeability, $\mu = 0.001\,\mathrm{Pa \cdot s}$ is the shear viscosity of water, L is the length of the system and Δp is the pressure difference. The length of the system $L = 2.25\,\mathrm{m}$ is defined as the length of the LHS unit. The tortuous path of the water is in other words not considered. Given this, the permeability of the pillow plate heat exchanger is determined to be $\kappa = 2.5 \times 10^{-4}\,\mathrm{m}^2$. When compared to Hagen-Poiseuille flow between two parallel plates ($\kappa = h^2/12$), this corresponds to a distance $h = 1.7\,\mathrm{cm}$ between the parallel plates.

The LHS unit has been in operation for 14 months. During this period, the unit has been mainly on a calendar schedule. The proportions of time in each operational mode are shown in figure 8. The unit has charged for $42.1\,\%$ of the time, discharged for $32.1\,\%$ of the time, and stored the thermal energy for $25.7\,\%$ of the time. The discrepancy between charging and discharging time has two reasons. First, the average discharge heat flow has been higher than the charge heat flow, $(2.61 \pm 0.05)\,\mathrm{kW}$ and $(1.81 \pm 0.07)\,\mathrm{kW}$, respectively. This is shown in figure 9. Secondly, the unit loses thermal energy. During 14 months of operation, the total integral of the heat flow curve gives a total heat loss of $684\,\mathrm{kW\,h}$, which gives a total heat loss rate of $63.6\,\mathrm{W}$. This is in close agreement with the heat loss presented in figure 6. The discrepancy can be explained by the high average temperature in figure 6 which increases the heat loss.

A histogram of the average PCM temperatures is shown in figure 10, with the melting temperature marked with a red dashed line. This shows that The temperature is higher than the melting point $85\,\%$ of the time, and lower $15\,\%$ of the time. The $85\,\%$ of the time the unit is operating in a temperature range between $34\,°\mathrm{C}$ to $42\,°\mathrm{C}$.

IV. Conclusion

The thermal energy storage capacity, peak charge, and discharge rate, as well as the heat loss of a latent heat energy storage, have been investigated over 14 months of operation. The unit is filled with $3000\,\mathrm{kg}$ biowax and is fitted with a pillow plate heat exchanger, built of 24 pillow plates.

The unit has a measured peak capacity of $234\,\mathrm{kW\,h}$, and it has reached an average discharge rate of $(10.51 \pm 0.08)\,\mathrm{kW}$ over $12.2\,\mathrm{h}$, and an average charge rate of $(13.7 \pm 0.2)\,\mathrm{kW}$ over $11\,\mathrm{h}$. The heat loss has been measured to be $64\,\mathrm{W}$, or $0.68\,\%$ of the total capacity per day.

The volume flow rate as a function of pressure difference has been investigated and used to calculate the permeability of the pillow plate heat exchanger. The permeability has been estimated, which will be important for modeling LHS units with pillow plate heat exchangers.

Statistics of the operational modes, heat flow, and operating temperatures over 14 months of operation have been presented. The unit has mainly been controlled on a calendar schedule, and we expect the unit control can be optimized with smart control algorithms. This data sets a baseline for future control optimizations. In the future, the LHS unit will be controlled with a model predictive controller, which use predicted thermal and electrical loads, PV production, and minimize the electricity cost.

The LHS pilot has shown to be an important component of optimized energy systems in the zero-emission building, allowing for the storage of energy when PV production is high or electricity price is low.

Acknowledgment

The LHS unit was co-financed through the ZEB Laboratory (www.zeblab.no) by SINTEF, NTNU, the Research Council of Norway, and ENOVA. This study was carried out with the support of the research projects KSP PCM-STORE and ZEN PRESAV. KSP PCM-STORE (308847), supported by the Research Council of Norway and industry partners, aims at building knowledge on novel PCM technologies for low/medium-temperature thermal energy storage. ZEN PRESAV is a project supported by the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN - 257660) and funded by the Research Council of Norway and its partners.

References

[1] "Eurostat database," https://ec.europa.eu/eurostat/data/database, accessed 22.02.23.
[2] "Project info - ZEB lab," https://zeblab.no/projectinfo, accessed 22.02.23.
[3] B. Time, A. Nocente, H. M. Mathisen, A. Førland-Larsen, A. R. Myhr, T. Jacobsen, and A. Gustavsen, "ZEB Laboratory - Research Possibilities," *SINTEF Academic Press*, 2019.
[4] M. Manni, A. Nocente, G. Kong, K. Skeie, H. Fan, and G. Lobaccaro, "Solar energy digitalization at high latitudes: A model chain combining solar irradiation models, a lidar scanner, and high-detail 3d building model," *Frontiers in Energy Research*, vol. 10, p. 1941, 2022.
[5] J. Salgado-Beceiro, O. Galteland, and A. Sevault, "Analysis of a latent heat storage unit using a pillow plate heat exchanger during real operations in a zero-emission building."
[6] A. Sevault, J. Salgado-Beceiro, and K. Pires Bjørgen, "200-kwh latent heat storage unit using a pillow-plate heat exchanger: demonstration in an office building," in *15th IIR-Gustav Lorentzen Conference on Natural Refrigerants*, 2022, pp. 190–232.
[7] A. Sevault and E. Næss, "Active latent heat storage using biowax in a central heating system of a zeb living lab," in *Proceedings of the 14th IIR-Gustav Lorentzen Conference on Natural Refrigerants*. IIR, 2020.