International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 0573

Modular two-phase heat storage for Carnot Batteries

Christoph Regensburger[1]*, Daniel Steger[1], Eberhard Schlücker[1]

1 Institute of Process Machinery and Systems Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Cauerstraße 4, 91058 Erlangen, Germany

*Corresponding Author: Christoph.Regensburger@fau.de

ABSTRACT

Carnot Batteries are a promising approach to store electrical energy in a thermal way. Besides the loading and unloading thermodynamic processes, the heat storage is a field of mayor interest in research. This paper presents an innovative modular storage setup that is easily scalable and contains an immiscible liquid phase to separate the hot and cold side of a sensible water storage. The separation of hot and cold side thus reduces the heat losses and improves the efficiency of the whole storage concept. A pilot plant to study the idea experimentally is in construction.

Keywords: sensible heat storage, Carnot Battery, modular energy storage, two-phase, thermal stratification

NONMENCLATURE

Abbreviations	
HP	Heat Pump
ORC	Organic Rankine Cycle
Symbols	
z	height
t	temperature

1. INTRODUCTION

To counteract the global climate change, a massive energy transition is necessary. Solar and wind power generate regenerative electricity but are much more volatile than conventional energy sources. With an increasing amount of those renewables, energy storage becomes more and more important. Concepts summarized under the term Carnot Battery transform electrical energy into heat in case of surplus, store the thermal energy and convert it back into electrical energy when needed [1]. The loading process can be realized with an electrical heater (in the easiest setup) or by using external low temperature heat with heat pumps (HP) to increase the efficiency. The unloading process uses a heat engine, which is for lower temperature levels often an organic Rankine cycle (ORC). Figure 1 shows the energy flows of the loading (1) and unloading process (2).

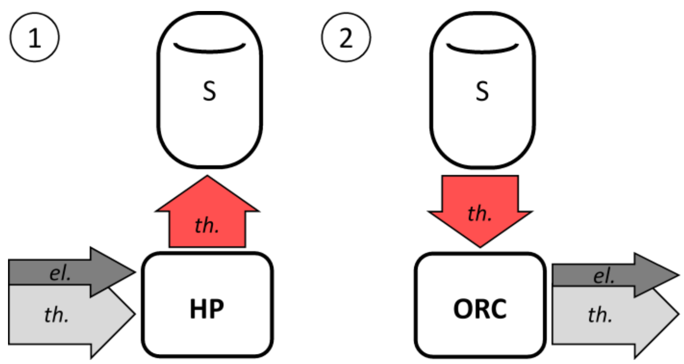

Figure 1: Energy flow diagram of the concept Carnot Battery during loading (1) and unloading (2); (el.: electrical energy, th.: thermal energy, S: Storage)

Small- and medium-scaled concepts often use pressurized water as a sensible storage medium. Until an upper storage temperature up to 180 °C, pressurized water is favorable compared to other approaches (latent storage, sensible solid storages, etc.). Still there are some challenges with the storage concept: The HP and ORC need a constant heat source/sink to work with high efficiency, therefore a constant temperature provided from the storage system is very important to run the process with high efficiency and small temperature differences in the heat exchangers [2].

2. HEAT STORAGE OF CARNOT BATTERIES

2.1 Motivation and discussion of sensible heat storage

Sensible heat is the most common form to store heat for short time periods. This is due to several reasons. Media used for sensible heat storage are often inexpensive, like water. A second advantage sensible heat provides is, that usually the same medium can be used to store and transfer the heat, minimizing temperature gradients and therefore maximizing the process efficiency, while keeping the process simple.

2.2 Heat loss mechanics in sensible heat storage

The loss mechanisms in heat storage are the energy loss towards the environment (1) and the exergy loss due to internal mixing of the hot and cold storage medium (2) symbolized in Figure 2.

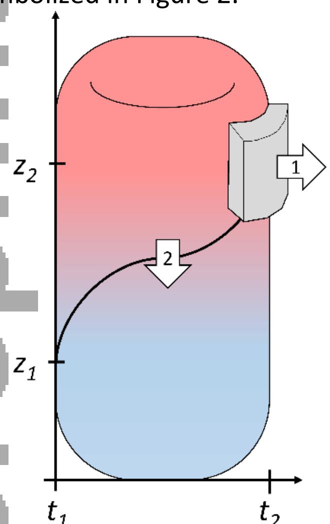

Figure 2: Loss mechanisms and thermocline in sensible heat storage

Since the energy, loss to the environment can be counteracted by insulation, the main challenge in sensible heat storage is usually the thermocline in the heat storage. The thermocline describes the temperature gradient in the storage tank, that expresses itself by mixing of hot and cold storage medium. The mixing is driven by natural convection and thermal conduction. A second mechanic to induce mixing is the inflow during the charging and discharging process, resulting in a forced convection on the boundary layer of hot and cold storage medium. The result is the stratification of the medium, that should be minimized as presented by *H. O. Njoku et. al*. [3].

2.3 Basic storage concepts for sensible heat

The most prominent versions of sensible heat storage are the one-tank and the two-tank storage system. For the one-tank storage, the same vessel is used to store the cold and hot fluid. The advantage of this system is its low investment and simplicity, while its major disadvantage is the potentially significant thermocline due to mixing effects during the charging and discharging process or at partially charged state. The two-storage system strives to avoid this by separating the hot and cold fluid in separate vessels. This leads to a two storage system in which two mediums interact. In theoretical concepts, the second phase, not used for storage, is often ignored. Nevertheless, this phase bears significant challenges. In case of a gaseous second phase the effect of a thermocline or a significant heat loss towards the second phase fluid can be avoided. If the solubility of the gas phase in the fluid is significant, the effect on the system pressure and the heat transfer in the heat exchanger can be compromised. Especially the change of solubility of the gas phase in the storage medium can influence the performance of the heat exchanger, as observed by *Steinke & Kandlikar* [4]. In case of an unfortunate geometrical orientation of the heat exchanger, this gas accumulates and partially insulates the heat transfer surface.

3. INTRODUCTION OF THE 2-PHASE CONCEPT

While there are several interesting concepts to optimize sensible heat storages, in the following only the concept of the 2-phase fluid sensible heat storage is presented as a new concept. The main idea is to approach the theoretical performance of a two-storage system while avoiding the disadvantages of a gas phase and minimizing the added costs though modularization.

The idea originates from the desire to provide a concept that is easily scalable while providing an optimized storage output temperature and minimizing exergy losses. The concept is shown for five storage tanks, but this number is scalable.

3.1 Essential fluid properties enabling the concept

The concept is based on the inherent differences of the storage medium water and the adversary fluid, in this case oil. The first major difference is the higher density of water. Up to a temperature of around 150°C, the density of water is higher than common biological oils at 20°C [5]. The density of natural oil can vary due to its composition.

The second major difference of water and oil is the polarity. While water is a polar fluid due to its molar structure, common oil is non-polar. Therefore, the fluids do not usually mix in significant quantity. These two main properties provide the foundation of the 2-phase fluid storage concept.

3.2 Analyzing the storage process

Figure 3 shows the scheme of the 2-phase storage process. For each step of the charging process five storage tanks are displayed. The color represents the temperature of the storage medium. The state of the taps is displayed by the dot in the middle. A filled dot shows a closed tap an unfilled dot symbolized an open tap.

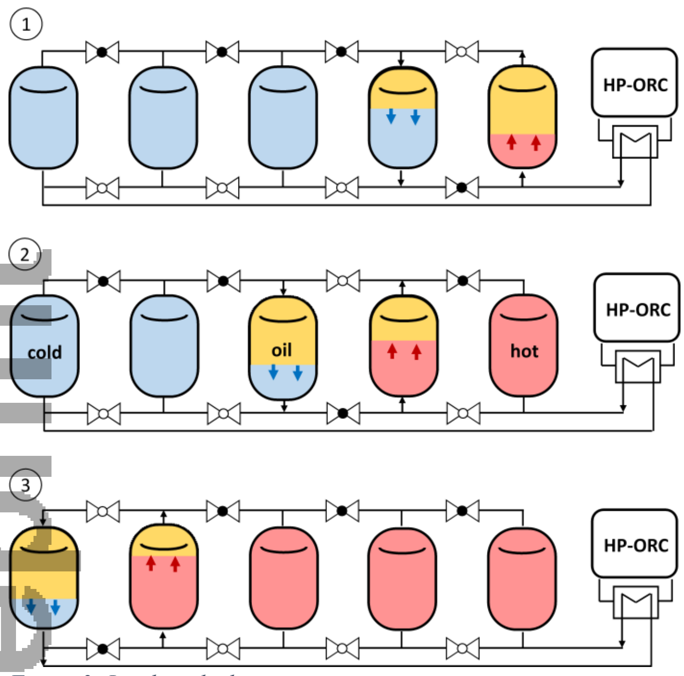

Figure 3: Loading the heat storage

This process presents the charging of the system. In the beginning, oil fills the second most right storage, while the other storage units are filled with cold water. During the loading process, the cold water of one storage is pulled towards the heat exchanger heating the water. The hot water flows back into the oil filled storage unit. The oil phase is pushed into the cold water storage tank. The hot and cold water flows through the bottom tank connection, while the oil flows through the upper storage connections.

As the loading process commences the oil phase moves from one tank to the next. This mechanism prevents the direct contact of hot and cold water avoiding the expression of a mixing zone, respectively a thermocline. This provides an optimized output of cold, temperature constant, fluid towards the HP-ORC.

At the end of the charging process all storage units are filled with hot water and the oil phase resides in the last tank. Due to sudden changes in the electrical grid the storage process can easily be stopped mid charging. Of course, it is desired to achieve a clear separation by completely filling one storage unit, thereby avoiding exergy losses due to heat conduction. This already relates to the oil temperature discussed at a later stage of this paper.

The discharge process is not presented separately, since it simply reverses the flow direction of the fluid, subsequently cooling one storage unit after the other until the whole system has reached the lower storage temperature.

The only pump in the system should be located on the cold side of the heat exchange on low ground, to avoid cavitation and has only contact with water. Basic expansion tanks should be installed to stabilize the system pressure. These units are available for municipal heating. The same pump can be used for the charging and discharging process by intelligent valve placement. These are not shown in the scheme to keep it clearly arranged.

4. DISCUSSION OF THE CONCEPT

To illustrate the benefits of the concept, the advantages and disadvantages of the system are outlined below.

4.1 Discussion of the oil phase

As commonly known, small drops of mineral oil can poison water and environment [6]. Therefore, biological alternatives should be used to avoid the production of huge amounts of poisonous waste water. Moreover, experimental data, by *J.-F. Hoffmann et. al.* [7], shows that biological oils are viable for long-term use as heat storage media.

It makes sense to heat the oil phase to minimize the heat losses while charging a storage tank. While this concept looks promising regarding the minimization of heat conduction it also has a problem with keeping the temperature of the oil constant. The oil can be heated the same way as the water simply by transferring heat from the HP-ORC to the oil and using the oil part of the system as storage, but a second heat exchanger in a different dimension is necessary to provide the same amount of heat to HP-ORC process during charging and discharging.

The economic version of the oil phase heating might be a small electrical heating keeping the oil phase at the upper storage temperature. This heating compensates the losses to the environment and the conduction losses to cold water at the boundary layer.

The simple solution is to not heat the oil phase at all. This comes with the drawback of inducing turbulence in the two-phases since the cold oil phase is located above the hot water. That results in the loss of exergy.

As an additional benefit, the heating of the oil phase enables higher storage temperatures by reducing the density.

4.2 Discussion of heat exchange between the two-phases

As postulated above it seems necessary to heat the oil phase to the upper storage temperature to avoid the cooling of the hot water phase. This results in a temperature difference on the boundary to the cold water in the corresponding storage tank. This is the preferred configuration considering the density stratification correlates with the thermal stratification. Since the two phases do not mix only thermal conduction is expected. This results in an increase of the temperature at the top part of the cold water phase and a decrease in temperature at the bottom of the oil phase. Since the thermal conductivity of oil is about 4,5-times smaller than that of water the effect should significantly decrease compared to a hot water to cold water boundary [5]. The turbulence should be minimized at the boundary layer to avoid heat transfer improvements [8].

4.3 Discussion of the modularity of the system

As already discussed the modularity of the storage volume, discretely stored in several tanks, provides a huge advantage, if the system is only partially loaded. The exergy losses, due to tank internal mixing effects, that can occur in huge one-tank storage systems, only separates by stratification, are avoided.

Furthermore, there is no down time during scheduled inspections. The storage capacity can be scaled according to the local conditions and easily expanded if necessary.

In a practical application an interesting idea is to use standardized storage modules for transport. These modules have a second live application in this storage system. They all have a standard size, the one thing that cannot be changed after the first storage tanks are erected, due to the fixed oil volume. These storage units in 20 ft size have a volume of 26 m³ and are produced in large quantities.

4.4 Compensation of the heat expansion

Once the system is in stable conditions nothing has to be changed, the heat expansion should be compensated on the water side of the system. For the oil, no compensation is necessary.

4.5 Outlook

Currently a storage system consisting of two 4 m³ storage tanks and a HP-ORC process capable of converting 100 kW of heat is getting installed in the facilities of the Energy Campus in Nuremberg.

To integrate the concept of the two-phase storage system in the HP-ORC and heat storage system currently in construction in the labs of the EnCN, is desired. This will generate comparable results to determine the exergetic improvement of the system in comparison to a one-tank system.

The storage concept is viable for other fluid combinations, which share a similar counter set of properties.

ACKNOWLEDGEMENT

The authors would like to offer their special thanks to the Bayerische Staatsregierung for financing the project within the Energie Campus Nürnberg (EnCN).

REFERENCE

[1] Olivier Dumont, Guido Francesco Frate, Aditya Pillai, Steven Lecompte, Michel De paepe, Vincent Lemort, Carnot battery technology: A state-of-the-art review, Journal of Energy Storage, Volume 32, 2020, 101756, ISSN 2352-152X, https://doi.org/10.1016/j.est.2020.101756.

[2] Steger, D., Regensburger, C., Eppinger, B., Will, S., Karl, J., & Schlücker, E. (2020). Design aspects of a reversible heat pump - Organic rankine cycle pilot plant for energy storage. Energy, 208. https://doi.org/10.1016/j.energy.2020.118216

[3] Njoku, H. O., Ekechukwu, O. V., & Onyegegbu, S. O. (2014). Analysis of stratified thermal storage systems: An overview. Heat and Mass Transfer/Waerme- Und Stoffuebertragung. Springer Verlag. https://doi.org/10.1007/s00231-014-1302-8

[4] Steinke, M. E., & Kandlikar, S. G. (2004). Control and effect of dissolved air in water during flow boiling in microchannels. International Journal of Heat and Mass Transfer, 47(8–9), 1925–1935. https://doi.org/10.1016/j.ijheatmasstransfer.2003.09.031

[5] Lemmon, E.W., Bell, I.H., Huber, M.L., McLinden, M.O. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2018.

[6] www.bmu.de/WS649; acessed 31/10/2020 Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit; Umgang mit wassergefährdenden Stoffen
[7] Hoffmann, J. F., Vaitilingom, G., Henry, J. F., Chirtoc, M., Olives, R., Goetz, V., & Py, X. (2018). Temperature dependence of thermophysical and rheological properties of seven vegetable oils in view of their use as heat transfer fluids in concentrated solar plants. Solar Energy Materials and Solar Cells, 178, 129–138. https://doi.org/10.1016/j.solmat.2017.12.03
[8] Karimi, H., & Boostani, M. (2016). Heat transfer measurements for oil-water flow of different flow patterns in a horizontal pipe. Experimental Thermal and Fluid Science, 75, 35–42. https://doi.org/10.1016/j.expthermflusci.2016.01.007