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STATE OF CHARGE DETERMINATION OF AN ICE STORAGE FOR BUILDING APPLICATIONS

Summary

This work presents the successful upscaling of a domestic **ice storage** system designed for implementing improved **state of charge (SOC)** determination. The setup integrates a stainless-steel spiral heat exchanger equipped with both temperature sensors and a **capacitive** sensor for ice-layer detection. The capacitive method utilizes the permittivity difference between water and ice, enabling sensitive detection of ice and corresponding layer thickness. The measurements confirm that the combination of temperature and permittivity measurements provide reliable SOC estimation sufficient for storage **operation control**. By introducing different operation strategies an efficient icing behavior was achieved across the heat exchanger units. The results were validated against earlier small-scale experiments, confirming scalability of the SOC method.

Keywords: ice storage, state of the charge (SOC), capacitive, operation control

Field of application for the findings: Thermal energy storage

Addressed audience: researchers and academics, industrial stakeholders

1. Introduction

Ice storage systems represent a promising approach for enhancing energy efficiency and increasing the share of renewables. Their versatility allows them to support both heating and cooling demands, making them attractive components in modern residential energy systems [3]. Combined with technologies such as heat pumps or solar thermal collectors, ice storage units can significantly boost overall system performance by shifting loads and providing a reliable thermal buffer across a wide range of conditions. Beyond the fact that water–ice is an abundant and non-toxic storage medium, such systems can often be integrated as relatively simple and cost-effective upgrades to existing installations, requiring minimal structural modifications. Despite these advantages, several technical challenges continue to limit broader adoption. Designing efficient and durable heat exchangers (HEX) remains a key engineering hurdle. An equally important challenge lies in the accurate determination of the state of charge (SOC) of the storage. Due to the presence of latent heat during phase transitions, temperature measurements alone cannot reliably indicate the amount of stored energy. Developing robust SOC estimation methods is crucial for an effective system control, optimization, and long-term reliability.

In this work, we present a comprehensive set of measurements taken from an upscaled domestic ice storage system, specifically designed to evaluate and compare a variety of SOC determination techniques under realistic operating conditions for a spiral HEX design. This investigation aims to contribute to the development of more accurate, practical, and cost-efficient methods for monitoring and controlling ice storage in residential applications.

2. Materials and methods

The ice storage consists of a stainless-steel tank equipped with six spirally formed stainless-steel heat-exchanger (HEX) units, here also coils, each containing four parallel channels for the heat-transfer fluid (HTF). The tank holds approximately 1200 l of water, while the coils have an internal volume of 63 l and provide a total HEX surface area of 14 m^2. The spacing between the coils is about 110 mm. A 3D schematic of the storage unit, including a view of the HEX configuration, is presented in Figure 1.

The capacitive measurement principle relies on the distinct dielectric properties of water and ice. Their dielectric spectra, expressed as $\epsilon'(\omega)$ and $\epsilon''(\omega)$, exhibit similarly shaped step- and peak-like features, but shifted by roughly six decades on the logarithmic frequency axis ($\approx 10^{-4}$ s for ice and $\approx 10^{-10}$ s for water at 0 °C [1]). Consequently, both phases show comparable permittivity at low frequencies, while at frequencies above $\approx$ 100 kHz the permittivity of ice drops sharply [2]. The latter distinct difference in permittivity enables capacitive sensing of phase change and can be utilized for ice layer thickness measurements [4]. In this study, a commercial capacitive sensor was mounted alongside the heat exchanger (red dashed line in Figure 2, designed to detect uniform ice-layer growth on straight pipes up to 50 mm. In addition to the commercial sensor, a self-built capacitive sensor will be tested and validated for the first time.

Table 1 provides a detailed overview of the sensors used to assess the charging state of the ice-storage system. It summarizes the sensor types, their notations, installation positions, and their specific roles in characterizing the SOC within the storage unit. To resolve the vertical temperature profile, the temperature sensors were positioned vertically, one per coil. Furthermore, coil C3 was selected as the installation point for the 1 m-long capacitive sensors; one commercial unit and one self-built prototype. To characterize the horizontal temperature distribution along this coil, four additional temperature sensors were installed, providing a detailed spatial resolution across the coil's length.

Tab. 1: List of main sensors utilized for the determination of state of the charge of the storage.

Sensor Type	Position	Name	Aim
Temperature	C2 - C6	T1 - T4, T10	vertical (depth)
Temperature	C3	T4 - T9	horizontal (radial)
Temperature	-	T11 & T12	HTF temepratur in/output
Capacitive	C3	Cap	ice layer thickness (commercial)
Capacitive	C3	Cap	ice layer thickness (self-built)
Flowmeter	-	F	flow rate of HTF

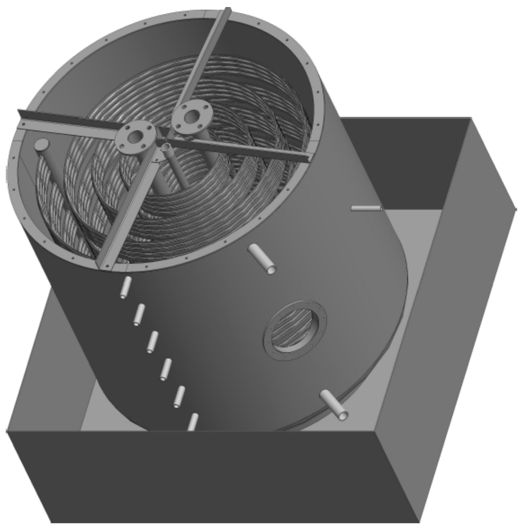

Fig. 1: A 3-dimensional drawing of the ice storage with a top view of the spiral steel heat exchanger coils. In and output heat exchanger fluid pipes are also shown in the middle of the storage. ©ECOTHERM Austria GmbH, Christof Lehner.

The hydraulic circuit, where the ice storage was integrated, consists of a circulation pump, and a process thermostat serving as the cooling unit (see Figure 2). The process thermostat provides a cooling capacity of $9 - 16$ kW and enables precise thermal conditioning of the circulating fluid between $-20 - 0$ °C. The hydraulic loop can be operated bidirectionally, allowing both charging (ice formation) and discharging (ice melting) modes to be controlled within the same circuit, thereby ensuring flexible and stable operation of the experimental setup.

3. Results

The preliminary measurements conducted on the pilot-scale ice storage setup enabled detailed monitoring of ice growth using a combination of temperature sensors and a capacitive sensor. Initial tests conducted

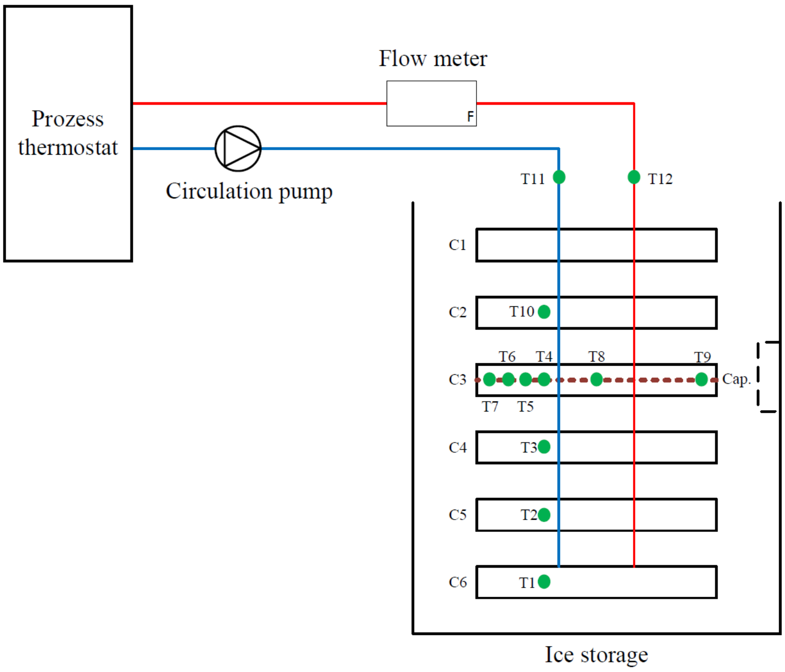

Fig. 2: A schematic representation of the ice storage system setup containing a process thermostat, a circulation pump and the sensors listed in Table 1 (temperature, capacitive and flowmeter).

with unidirectional flow confirmed that the heat transfer rate is high during the early stages of ice formation but decreases as the ice layer thickens in inlet sections. To address this non-uniform growth, a bidirectional flow strategy was implemented, resulting in more predictable and homogeneous icing patterns across the heat exchanger. This operational mode substantially improved capacitive SOC estimation, demonstrating that bidirectional icing and capacitive sensing offer a more robust approach to monitoring and controlling the thermal storage process.

4. Conclusion and further work

The experimental setup was successfully upscaled from the earlier lab-scale configuration, expanding the applicability of earlier laboratory findings and demonstrating that the methodological approach and instrumentation can be reliably transferred to larger system scales. The combined use of temperature sensors and capacitive sensing proved effective for determining the state of charge, enabling a robust foundation for advanced operational control strategies. Future work should focus on integrating appropriate safety measures for long-term steel-tank operation and incorporating the already available solar collectors into the hydraulic circuit to further test and expand system functionality and energy-management capabilities.

References

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