Adaptive Stratifier Lance: A Novel Method and Control Strategy for Stratified Thermal Energy Storages to Improve System Efficiency

Summary

This experimental study investigates an innovative approach for thermal storage management in advanced energy systems. A vertically actuated stratifier lance is developed and controlled by a newly implemented algorithm that allows targeted heat extraction at specific temperature levels. The concept is experimentally tested in a laboratory environment where stored hot water drives an adsorption chiller to produce cooling. Three operating strategies are compared: mixed storage, stratified storage, and stratified storage with adaptive lance control. The experiments explore whether controlled extraction at varying temperature levels increases the usable heat from storage while maintaining efficient cooling performance. Results indicate that active storage management extends the operating time of the adsorption chiller and improve overall utilization of stored heat. The work represents a proof-of-concept of an actuated stratifier lance control strategy to improve the overall thermal energy storage performance.

Keywords: thermal storage management, experimental study, CCHP system, exergy efficiency, stratification, storage management, heat storage

Field of application for the findings:

Addressed audience: Researchers

1. Introduction

Managing the thermal energy storage (TES) is a key factor in improving the performance of advanced energy systems integrating technologies such as heat pumps, solar thermal collectors or adsorption chillers. TES buffers temporal mismatches between variable renewable generation and heat or cooling demand (Abdur Rehman et al. 2021). The preservation of thermal stratification in TES represents a major advantage, as it has proven to improve the overall efficiency of thermally driven systems (Sifnaios et al. 2019) and must therefore be actively maintained to avoid efficiency losses caused by mixing.

To exploit this potential, a TES management concept with a vertically actuated stratifier lance was designed, allowing targeted discharge of heat at a freely definable temperature level within the stratified storage. This concept was implemented in a combined cooling, heating and power (CCHP) laboratory system with heat pump and cogeneration unit to drive an adsorption chiller. The underlying idea is to enable flexible adjustment of the desorption temperature (Wittstadt 2018). By operating at a lower desorption temperature during the initial phase of the cycle, a reduced energy efficient ration (EER) of the chiller is accepted in favor of improved overall system efficiency and increased utilization of the stored thermal energy. The implementation of this principle constitutes a proof-of-concept and helps to determine an optimal trade-off between reduced EER and enhanced overall system efficiency.

This raises the central research question of how such adaptive TES management influences system performance under different operating strategies and whether this principle can be transferred to other thermally driven energy systems.

2. Methodology

In a laboratory setup of a CCHP system (see Fig. 1), a series of experiments was conducted to investigate the use of hot water from a 1.5 m^3 hot thermal energy storage (HTES) to drive a silica gel 4.8 kW adsorption chiller for cooling a 1.45 m^3 cold thermal energy storage (CTES).

In conventional operation, the hot water is extracted exclusively from the top of the HTES. To enable flexible extraction, an actuated stratifier lance was integrated in the HTES. A control program was developed that receives a target temperature as input and dynamically adjusts the vertical position of the movable discharge lance according to the phase of the adsorption chiller.

Three different operating modes were experimentally investigated for identical initial conditions of the HTES:

- A mixed HTES, continuously mixed with a recirculation pump
- A stratified HTES, with fixed discharge at the top
- A stratified HTES, with targeted control of the discharge lance

For the experiments involving lance control, the target discharge temperature was additionally varied in order to evaluate its influence on system performance.

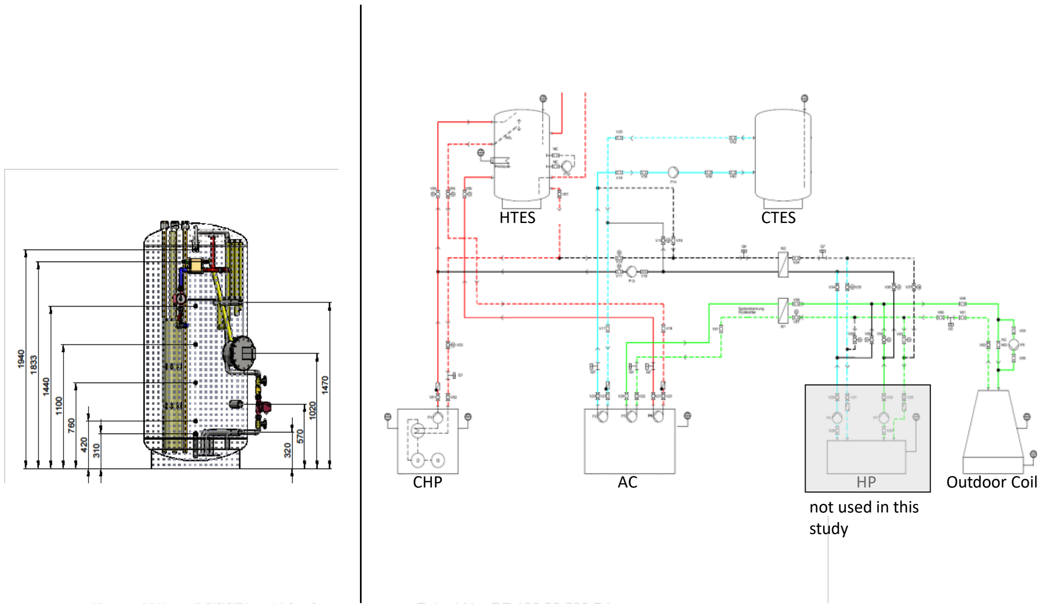

Fig. 1: Left: Detailed view of the Hot Thermal Energy Storage (HTES) with the actuated stratifier lance. Right: Combined Cooling, Heat and Power System in a laboratory setup HTES with the actuated stratifier lance, Combined Heat and Power (CHP), Adsorption Chiller (ADC), reversible Heat Pump (HP), and Cold Thermal Energy Storage (CTES).

2.1. Experimental setup

To ensure comparability between the investigated operating modes, identical boundary conditions in the HTES and the CTES were applied in all experiments. For the mixed HTES operating mode the recirculation pump was switched on after charging the HTES and the adsorption chiller was switched on only once the HTES was fully mixed. The ADC was operated with a constant cooling setpoint temperature of 11 °C.

The targeted discharge using the movable lance is controlled by a newly developed control program. Based on a predefined setpoint temperature, the control algorithm positions the lance at the beginning of each adsorption cycle at the vertical location within the HTES that provides the desired temperature level (within a reasonable tolerance). During operation, the lance is gradually moved upward to follow the evolving temperature stratification while minimizing mixing effects. Exactly at the end of the adsorption cycle, the lance reaches the top of the storage, after which the process is repeated for the next cycle.

Each experiment was terminated once the feed temperature from the HTES to the ADC dropped below 55 °C, which is the minimum feed temperature of the ADC.

2.2. Evaluation

For the experimental evaluation, the recorded datasets are subset to ensure comparability. Each dataset begins at the time the adsorption chiller starts operation and ends when the feed temperature from the HTES drops to 55 °C. The experiments are evaluated based on key performance indicators, including the exergy efficiency, the coefficient of performance (COP) of the adsorption chiller, total runtime, utilization of the initially stored thermal energy in the HTES and useful cooling energy delivered to the CTES.

3. Results

The following result section shows first experiments that compare the TES discharge behavior. The full paper will also include dynamic experiments with a combined automated charging and discharging of the TES mimicking realistic system dynamics.

3.1. Thermal Energy Storage Performance

Figure 2 illustrates the extractable heat from the TES across three different operation modes, starting from identical initial conditions. Although the boundary conditions remain constant, the amount of heat that can be utilized until the cutoff temperature of 55 °C is reached varies significantly.

The comparison demonstrates that the stratified TES increases the utilizable heat by 10%, while the adaptive lance control achieves an increase of 22% compared to a fully mixed TES. The superior performance of the adaptive lance is due to its ability to continuously discharge fluid at the precise temperature level required by the process. By dynamically adjusting its vertical position, the lance prevents turbulent mixing and maintains a sharp thermocline. This maximizes the utilization of the storage capacity and significantly enhances the exergetic efficiency of the system. As a consequence 24 % more cooling energy can be generated with the stratified storage and 35 % with the adaptive lance.

These results highlight the potential of an actuated stratifier lance for the high-efficiency thermal management of both HTES and CTES. A similar approach for adaptive charging lances could be implemented accordingly to further optimize system performance.

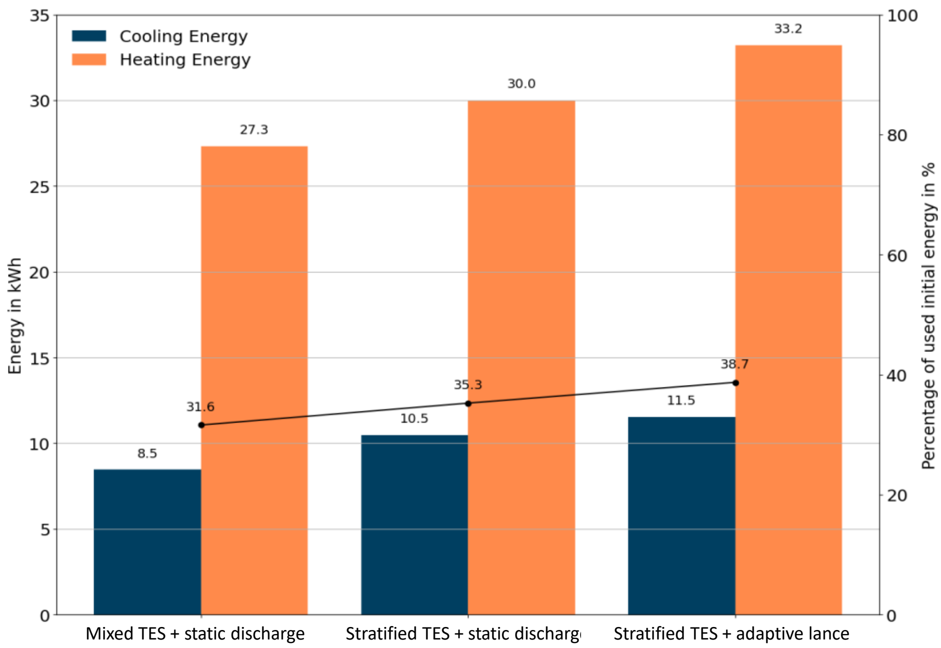

Fig. 2: Energy balance comparison of the three operation modes regarding heating energy consumed and cooling energy produced

3.2. System performance of adsorption chiller and TES with adaptive lance

The evaluation of the performance indicators summarized in Table 1 reveals significant differences in adsorption chiller operation. Compared to the mixed TES, a stratified TES increases the runtime of the adsorption chiller by 16 %, while the implementation of lance control extends the runtime by 32 %. Although the mixed TES results in a lower EER, the stratified TES exhibits comparable EER values both with and without active lance control.

Tab. 1: Comparison of adsorption chiller performance metrics

Metric	**Unit**	**Mixed TES**	**Stratified TES**	**Stratified TES with lance control**
Operation time of one discharge cycle	Minutes	105	122	139
EER of ADC	-	0.3	0.35	0.34
Produced cooling energy in CTES	kWh	8.5	10.5	11.5
Consumed heating energy in HTES	kWh	27.3	30.0	33.2
Mean temperature of HTES for one discharge cycle	°C	62.7	59.3	59.0

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