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Research paper

Adsorption thermal energy storage for cogeneration in industrial batch processes: Experiment, dynamic modeling and system analysis

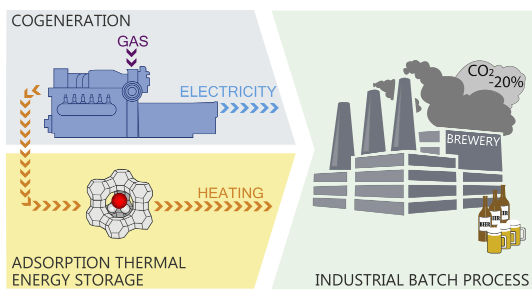
Heike Schreiber, Stefan Graf, Franz Lanzerath, André Bardow*

Chair of Technical Thermodynamics, RWTH Aachen University, Schinkelstraße 8, 52062 Aachen, Germany

HIGHLIGHTS

- A highly efficient energy supply for industrial batch processes is presented.
- Adsorption thermal energy storage (TES) is analyzed in experiment and simulation.
- Adsorption TES can outperform both peak boilers and latent TES.
- Performance of adsorption TES strongly depends on low grade heat temperature.

GRAPHICAL ABSTRACT



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ABSTRACT

Adsorption thermal energy storage is investigated for heat supply with cogeneration in industrial batch processes. The feasibility of adsorption thermal energy storage is demonstrated with a lab-scale prototype. Based on these experiments, a dynamic model is developed and successfully calibrated to measurement data. Thereby, a reliable description of the dynamic behavior of the adsorption thermal energy storage unit is achieved. The model is used to study and benchmark the performance of adsorption thermal energy storage combined with cogeneration for batch process energy supply. As benchmark, we consider both a peak boiler and latent thermal energy storage based on a phase change material. Beer brewing is considered as an example of an industrial batch process. The study shows that adsorption thermal energy storage has the potential to increase energy efficiency significantly; primary energy consumption can be reduced by up to 25%. However, successful integration of adsorption thermal storage requires appropriate integration of low grade heat: Preferentially, low grade heat is available at times of discharging and in demand when charging the storage unit. Thus, adsorption thermal energy storage is most beneficial if applied to a batch process with heat demands on several temperature levels.

1. Introduction

Considerable effort is invested to reduce energy expense and CO_2 emissions in industrial processes. Major energy savings in industrial processes can be obtained by establishing efficient energy supply systems [1]. Efficient energy supply can be realized by cogeneration providing combined heat and power [2]. However, combined supply of heat and power is only energy efficient if time profiles match for the different energy demands and supplies. A perfect match is rarely found in real processes. In this case, the heat demand normally dictates the operation of the cogeneration unit. But heat demand is often discontinuous, especially for batch processes, resulting in low full load hours of the cogeneration unit. To satisfy the discontinuous demand and to distribute heat, thermal

* Corresponding author. Tel.: +49 241 8095380; fax: +49 241 8092255.
E-mail address: andre.bardow@ltt.rwth-aachen.de (A. Bardow).

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energy storage can be applied [3]. Thermal energy storage then allows for smaller cogeneration units running at increased full load hours [4].

In order to realize an efficient cogeneration system with thermal energy storage, the storage technology must be chosen according to the specific process settings: First of all, the temperature level of heat supply from the thermal energy storage unit must fit the heat demand [5]. In this paper, we consider a temperature range of $T = 100 - 200$ °C, which covers many industrial applications [6]. Moreover, storage density should be preferably high to reduce space and cost requirements. Potentially high storage densities can be provided by adsorption [7]. Adsorption thermal energy storage has a large range of working temperatures between 60 and 300 °C [8]. In addition, adsorption thermal energy storage allows exploiting the heat pump effect whereby low grade heat can be integrated into the process heat supply to enhance energy efficiency [9]. Consequently, integrating adsorption thermal energy storage into energy supply systems with cogeneration has the potential to reduce energy costs and CO_2 emissions. Practical feasibility of adsorption thermal energy storage has already been demonstrated for heating applications by Bales et al. [10]. Thermal storage at higher temperatures, e.g. for industrial processes, has been also tested with closed adsorption systems [11].

In this paper, we analyze the impact of adsorption thermal energy storage on primary energy consumption for an industrial batch process. As representative example for an industrial batch process, we consider breweries. In particular, small and medium sized breweries have large potential to improve their energy efficiency [12]. Sturm et al. [13] show that cogeneration can be profitably applied to meet the brewing process energy demand. Still, high investment costs can be an obstacle to apply cogeneration in practice. To make best use of the investment, the cogeneration unit should run at full load all the time. Full-load operation also allows to run the cogeneration unit with its highest efficiency [14]. Constant full-load operation is, however, not possible in batch processes with a time-varying heat demand. In this case, the cogeneration units have to be sized according to the peak demand leading to large investments costs while running at inefficient part-load conditions most of the time. Thus, reduced unit size with full load operation would be preferable, for instance with the help of thermal storage. Muster-Slawitsch et al. [15] conclude that identifying the most efficient energy supply for a brewery requires comparison of different technologies. Typically, innovative thermal energy storage concepts are compared to solutions without any storage [16], or to water storage [17].

Quantifying the potential for energy savings requires a holistic analysis, since thermal energy storage is not a stand-alone technology, but operates in response to the system. Thus, analysis of the storage technology must consider the entire energy system. In particular, the temperatures of the heat flows have a strong influence on storage performance. However, the effect of temperature levels is still largely unexplored as pointed out by Yu et al. [7] in their recent review on adsorption thermal energy storage systems. Dicaire and Tezel [18] evaluated the heat recovery ratio of adsorption thermal energy storage for different temperature levels of desorption. They showed that the heat recovery ratio decreases with increasing regeneration temperatures due to higher heat losses. In addition, the influence of temperature levels of the low grade heat should be investigated. Low grade heat is the key to the heat pump effect which is known to have a crucial impact on adsorption thermal energy storage performance [7].

Beyond temperature, storage performance strongly depends on the amount of stored thermal energy, as well as on the achievable heat flows. To account for these dependencies in our analysis, we need a reliable description of adsorption thermal energy storage. As adsorption is an intrinsically dynamic process, dynamic storage models are required [19]. Duquesne et al. [20] propose a dynamic model for a closed adsorption storage system and compare it to the model by Sun et al. [21]. Bales et al. [22] published several dynamic models of chemical and sorption thermal energy storage units. These models have partly been compared to experimental data [10] showing qualitatively good agreement. However, reliable dynamic models can only be achieved by calibration to experimental data [23].

This work consequently provides a comprehensive analysis of adsorption thermal energy storage integration into an industrial batch process with cogeneration energy supply. A brewing process is considered as a representative batch process. The heat demand is given at a temperature of above 120 °C. Our approach is to model an adsorption thermal energy storage unit based on an experimental prototype developed in our laboratory. By calibrating the model to measurement data, we achieve a reliable basis for our analysis (Section 2). The model is used to evaluate the integration of cogeneration and adsorption thermal energy storage into the brewery batch process (Section 3). In particular, we examine the effect of low grade heat temperature levels on the storage performance. In order to assess the true potential of adsorption thermal energy storage for batch process energy supply, we benchmark different cogeneration integration concepts regarding their efficiency (Section 4). For this purpose, we compare adsorption thermal energy storage to cogeneration integration concepts using either a conventional non-storage solution with a peak boiler or using innovative latent thermal energy storage. Section 5 summarizes the results.

2. Storage modeling and calibration

In this section, we present the working principle and the experimental investigation of our adsorption thermal storage prototype, as well as the calibration procedure of our dynamic model. The adsorption thermal energy storage unit is based on zeolite 13X and water, an adsorption pair with high storage density and well known properties [7]. The storage unit is designed as a closed adsorption system. The working principle of adsorption thermal energy storage is shown in Fig. 1: During storage charging, the heat input Q_{des} leads to an increase of the temperature in the storage unit and to desorption. Water vapor is released from the zeolite and condensed at a lower temperature. The heat obtained from condensation Q_{cond} can be used in the process or be

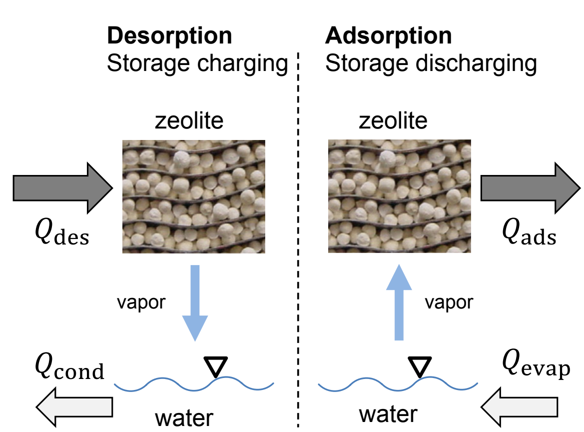

Fig. 1. Working principle of adsorption thermal energy storage.