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State and state of charge estimation for a latent heat storage

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ABSTRACT

A nonlinear state observer is designed for a thermal energy storage with solid/liquid phase change material (PCM). Using a physical 2D dynamic model, the observer reconstructs transient spatial temperature fields inside the storage and estimates the stored energy and the state of charge. The observer has been successfully tested with a lab-scale latent heat storage with a single pass tube bundle and the phase change material located in a shell around each tube. It turns out that the observer robustly tracks the real process data with as few as four internal PCM temperature sensors.

1. Introduction

Thermal energy storages (TES) have a great potential in energy conservation in the building and industrial sector (Gracia & Cabeza, 2015). Their integration in thermal and electric/ thermal systems can optimize the use of renewable or industrial waste energy by peak shaving and shifting strategies leading to a more rational use of energy and reduction of CO_2 emissions (Nomura, Okinaka, & Akiyama, 2010).

TES using phase change materials (PCM) have been extensively studied recently. Such latent heat TES (LHTES) combine a high energy density with the advantage of the isothermal nature of the storage process. Applications of LHTES in buildings primarily aim at improving the performance of space heating and/or cooling and domestic hot water generation. Typically LHTES are integrated in sorption systems and seasonal storages, solar collectors, water tanks, packed beds, and duct networks (Arteconi, Hewitt, & Polonara, 2012; Gracia & Cabeza, 2015; Sharif et al., 2015). However, PCM might also be directly integrated into evaporators or condensers, e.g. in domestic refrigerators (Mastani Joybari, Haghighat, Moffat, & Sra, 2015). Industrial applications integrate LHTES in concentrated solar thermal power plants, and air-conditioning, cold production, and refrigeration units (Cárdenas & León, 2013; Nomura et al., 2010; Youssef et al., 2013). Another industrial use case is the exploitation of industrial (intermittent) waste heat by transportation using mobile latent heat accumulators (Nomura et al., 2010).

Under the different methods for storing the thermal latent heat, the change from solid to liquid has been most widely studied and used (Cárdenas & León, 2013; Gracia & Cabeza, 2015). Typical solid/liquid PCM suitable for low temperatures are e.g. paraffins, fatty acids and salt hydrates (Gracia & Cabeza, 2015). For high temperature (> 100 °C) applications usage of inorganic salts, salt eutectic compounds, metal alloys and metallic eutectics is reported (Cárdenas & León, 2013). Each PCM presents its own advantages (e.g. high specific latent heat and thermal stability, low volumetric expansion during phase change, low costs) and limitations (such as subcooling and hysteresis effects during phase change), so its selection has to be done based on the requirements of the respective application (Cárdenas & León, 2013; Gracia & Cabeza, 2015; Liu, Saman, & Bruno, 2012). However, the most serious drawback of solid/liquid PCM certainly is the poor thermal conductivity. Various techniques for improving the heat transfer (e.g. encapsulation of PCM or fins and extended surfaces) have been proposed (Cárdenas & León, 2013; Liu et al., 2012).

Control of thermal systems with storages: Because systems that use energy storages and the storage itself are inherently transient, effective operating strategies for dynamic heat integration are needed, such as optimal thermal regulation functions under transient operating conditions (Cole, Powell, & Edgar, 2012; Powell, Cole, Ekarika, & Edgar, 2013). Model based techniques and advanced control (such as model predictive control) of TES can significantly improve the management of dynamic power demands and intensify intermittent energy services, e.g. in solar

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thermal systems, district energy systems and building applications (Cole et al., 2012; Edgar & Powell, 2015). There is also a growing interest in using TES systems for demand-side management in the building sector (Arteconi et al., 2012). The idea is to couple TES with electrically driven heating and cooling systems and to optimally manage electrical loads by means of control, adaptation and/or enhancement of the comparatively large heating, cooling and hot water demands (Arteconi et al., 2012).

Limitations of current models: Dynamical models of TES and related equipment that can be packaged into commercial or open source software, as well as accurate models for model-based observers and control can be considered a key technology for plant and network design, demand side management and advanced system control (Cole et al., 2012). During the last decade, much effort was made to integrate PCM models into commercial software packages for domestic and building applications (Castell & Solé, 2014). It seems that corresponding LHTES models are developed mainly in view of an optimal storage design and integration. They are frequently based on elaborate computational fluid dynamics and multi-physics tools, which leads to extremely time-consuming simulations (Castell & Solé, 2014). Still, developments for model-based observers and controllers seem rather scarce.

State of charge (SOC) of latent thermal storages: Undoubtedly, monitoring of SOC of a LHTES is a key issue for optimal management of TES and TES systems. For LHTES with solid/liquid PCM, it seems most reasonable to define the SOC as the mean liquid phase fraction (or mean melting fraction) of the storage. The SOC then quantifies the extent to which a latent storage is charged relative to storable latent heat. This information is crucial for estimating how long the storage can continue to supply or store latent energy at a given heat flow and/or temperature level. Moreover, estimation of storage-internal temperature fields might allow more accurate and tailored charging and discharging operation strategies, e.g. for realizing complex cyclic and partial loading/unloading scenarios.

A thorough literature review on the use of the term 'SOC' of a latent storage revealed that this term is rarely used and not unambiguously defined. However, the terms 'solidified mass fraction' or 'liquid mass fraction' are frequently used, describing essentially the same as SOC. Oró, Gracia, Castell, Farid, and Cabeza (2012) use solidified mass fraction besides other parameters (such as time for complete solidification and number of transfer units) to characterize the state of an TES system and numerically investigate the effects of storage-internal design, material and operational parameters. Similarly, Tiari, Qiu, and Mahdavi (2016) use 'liquid fractions' in a recent numerical study for a finned heat pipe-assisted TES system. Strumpf, Avanessian, and Ghafourian (1994) use SOC to denote the melted fraction of PCM for discussing characteristics of a solar receiver which incorporates a thermal storage with PCM, to be used for electrical power production for Space Station. SOC is furthermore used in characterizing the thin layer of PCM for the overheating protection of facade integrated solar thermal collectors (Hengstberger, Zauner, Resch, Holper, & Grobbauer, 2016) and for characterization of shell and tube (S&T) latent storage (Barz et al., 2016). Vaca Jiménez (2013) uses two different definitions for the SOC of a refrigerator for charge and for discharge (both considering also sensible heat). They are defined as the ratios of available to maximal energies calculated from actual and reference temperatures, respectively. Cuneo, Ferrari, Pascenti, and Traverso (2014) use the term 'SOC' to denote the calculated sensible enthalpy content in a (sensible) stratified water thermal storage tank, obtained from discrete temperature measurements. For solar heat receivers employing encapsulated PCM, Hall, Glakpe, Cannon, and Kerslake (1998) define the 'thermal SOC' as ratio of instantaneously available power to minimum required power. Henze, Kalz, Liu, and Felsmann (2005) denote by SOC the ice level in the tank of a chilled-water or ice storage in a cooling system and use this quantity in supervisory model predictive control for optimal storage charging and discharging.

Measurement based approaches for estimating SOC: Reports on measurement based approaches for monitoring the phase transition or the phase fractions in a closed storage during operation are scarce. A possible approach is tracing the temporal solid/liquid interface through direct visual measurements, see e.g. (Naghavi, Ong, Mehrali, Badruddin, & Metselaar, 2015) and references therein. Henze et al. (2005) use direct measurement of the ice level in a storage tank. Steinmaurer, Krupa, and Kefer (2014) discuss approaches for determining the SOC and enthalpy of a PCM in closed storage systems. They propose to apply pressure sensors to measure volumetric changes during phase transition, which can be feasible for materials with high density differences between liquid and solid phase (e.g. paraffin). The authors also propose local techniques which use mechanically induced acoustic waves that propagate through the PCM and measure the change in propagation speed and the dampening of the signal (Steinmaurer et al., 2014). Similarly, Bauer, Laing, and Steinmann (2012) propose local electric resistance measurement techniques. Steinmaurer et al. (2014) argue that local temperature measurements are generally not feasible to gather the SOC as this implies high uncertainties and requires a large number of sensors to get a spatial resolution. Lastly, measurement of heat flux through the storage heat exchanger is also discussed (Steinmaurer et al., 2014). This approach requires integration of charging and discharging energies while considering thermal losses. It shows severe disadvantages, since errors in the estimated thermal losses accumulate with increased application time (Steinmaurer et al., 2014).

State observer applied to thermal storages: Up to the best of the authors knowledge, state and/or parameter observers have not been applied to LHTES until now. This is possibly due to the complexity of corresponding LHTES models, being distributed parameter models with (storage-internal) temperature and phase fractions fields. Kreuzinger, Bitzer, and Marquardt (2008) present the design of two different state observers for a (sensible) stratified water tank for domestic hot water storage. The observer is used for reconstruction of storage internal time-varying vertical temperature profiles from a few measurements. The tank is described by an energy balance equation model which consists of a 1D quasi-linear partial differential equation (PDE). Kreuzinger et al. (2008) adopt a so called late lumping and an early lumping observer design approach. In the former a spatially weighted correction function is injected in the energy balance equation and the correction gain is designed based on a physical interpretation. The corrected model is then numerically solved. In the latter the energy balance equation is first transformed into an ordinary differential equation (ODE) system by spatial discretization and an Unscented Kalman filter is used as observer. It is found that both observer give comparable results in terms of convergence and accuracy. Considering an optimal placement of storage internal temperature sensors, it is found that at least three temperature sensors are necessary to attain satisfying estimation results during all operational modes.

This contribution: This paper proposes a definition of the SOC of LHTES with solid/liquid PCM. A reduced model and a state observer are developed for the dynamic reconstruction of 2D temperature fields and estimation of SOC of a lab-scale S&T LHTES. Theoretical and experimental results from testing the observer are presented.

The paper is organized as follows: Section 2 briefly presents the storage container design and instrumentation. The energy balance equations for modeling the LHTES are formulated according to previous works. This mathematical model consists of three coupled PDEs and is referred to as detailed model (dMod). dMod serves in this work as a reference and is used for in silico studies. In addition, a (physical) simplification of dMod is presented, which yields a reduced model (rMod) consisting of 12 state variables originating from the discretization of two coupled PDEs. It is developed with the aim to design a nonlinear state observer, following the early lumping approach as described by Kreuzinger et al. (2008). In addition, the definition for the SOC of LHTES with solid/liquid PCM is given and its computation is discussed. Section 3 discusses transformation of rMod into a low order nonlinear ODE by efficient (coarse) spatial discretization. A collocation scheme is derived