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Use of partial load operating conditions for latent thermal energy storage management

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HIGHLIGHTS

- Partial loads operating conditions were tested as a thermal management tool.
- A new key performance indicator has been developed.
- Partial loads substantially reduce the period of charge.
- Partial loads also reduce the energy accumulated and the heat transfer rates.

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ABSTRACT

A proper management of thermal energy storage (TES) charging and discharging processes allows the final users to optimize the performance of TES systems. In this paper, an experimental research is carried out to study how the percentage of charge in a latent heat TES system (partial load operating conditions) influences the discharge process. Several charging and discharging processes were performed at a constant heat transfer fluid (HTF) mass flow rate of 0.5 kg/s and temperature of 155 °C and 105 °C, respectively. High density polyethylene (HDPE) with a total mass of 99.5 kg was used as phase change material (PCM) in a 0.154 m^3 storage tank based on the shell-and-tube heat exchanger concept. Five different percentages of charge have been studied: 58 %, 73 %, 83 %, 92 %, and 97 % (baseline test). Results showed that by modifying the percentage of charge, the time required for the charging process was reduced between 97.2% and 68.8% in comparison to the baseline case. However, the energy accumulated was only reduced a maximum of 35.1% and a minimum of 5.2%, while the heat transfer rates during the first 60 min of discharge were reduced a maximum of 45.8% and a minimum of 6%. Therefore, partially charging the TES system not lower than 85% of its maximum energy capacity becomes a good option if the final application accepts a maximum decrease of discharging heat transfer rates of 10% if compared to the fully charged system.

1. Introduction

Storage technologies, such as thermal energy storage (TES) technologies, have become an indispensable component at any installation coupled to a renewable energy system since they help overcoming the dependence on the weather conditions and the mismatch between energy demands and supplies [1]. A TES cycling process consists of storing the energy when it is available or cheap, but not needed, to further release it when it is demanded and not available or more expensive, with the aim of increasing the efficiency of the thermal process. There are some energy supply sources which are known to be intermittent (i.e. solar energy and industrial waste heat recovery systems) which they might not give a continuous energy supply. Furthermore, if the energy source is able to provide a continuous heat supply, the periodicity of the charge can be adjusted depending on the final demand and the tank design, which is normally not optimized. All these conditions are known as partial load operating conditions and might lead to a TES material which is partially charged and, as a consequence, affect the TES discharging process, especially if the TES material is a phase change material (PCM).

Some of the research work done to study the effect of partial load operating conditions was focused on numerically studying and optimizing the size of sensible cold storage systems for cooling purposes by comparing full storage and partial storage strategies to conventional

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Nomenclature

C_p	specific heat, J/kg·°C
E	energy, J
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
R	function which depends on the measured parameters
t	time, s
T	temperature, °C
w	uncertainties which are associated to the independent parameters
W	estimated uncertainty in the final result, value-dependent
x	independent measured parameters

Greek symbols

$\Delta h(T)$	enthalpy variation (sensible and latent), kJ/kg
ΔT	temperature variation, °C

Subscripts

i	instant
in	inlet
max	maximum
n	control volume
out	outlet
pr	process

Abbreviations

DSC	differential scanning calorimeter
HDPE	high density polyethylene
HTF	heat transfer fluid
HTR	heat transfer rate
PCM	phase change material
RAE	ratio of accumulated energy
TES	thermal energy storage
TGA	thermogravimetry analysis

systems [2–7]. According to Dincer [8], the full storage strategy shifts the entire peak cooling load to off-peak hours, while the partial load strategy is used to either level the load or limit the demand, since the cooling load is partially met by the cooling source and partially met by the storage system. Sebzali et al. [2] studied the effects of using partial and full loads strategies on the TES and chiller size, the reduction of electrical peak demand and the reduction of the energy consumption of a chiller for a clinic building in Kuwait. They found that full storage operation allows larger electrical peak reduction and chiller and storage capacities, while it presents the higher energy consumption. Rahman et al. [3] analysed partial and full TES storage scenarios in a subtropical climate building. Results showed that in both cases more than 50% of the cooling electricity cost was saved when compared with the conventional system. Macphee and Dincer [4] studied the effect of partial and full storage strategies in the energy and exergy efficiencies of four different types of ice storage techniques for space cooling. They found that both efficiencies were always lower in partial storage systems. Hasnain et al. [5] showed that incorporating partial ice storage systems in Saudi Arabian office buildings reduced the peak electrical power demand and peak cooling load in the up to 20% and up to 40%, respectively. Similarly, Habeebullah [6] performed this analysis for a Saudi Arabian mosque. The author concluded that partial load operating strategies were not economically attractive if compared to full load or conventional systems. Boonnasa and Namprakai [7] performed an optimization of the payback period for a full load and three different partial load scenarios. They found that partial load scenarios show good economic results as well as manageability and flexibility.

On the other side, literature review showed that some research was also performed to study the influence of partial load operating conditions in latent heat TES systems [9–20]. It is known that when a PCM goes through consecutive melting and solidification processes, it might show specific effects such as hysteresis and/or subcooling. Hence, it might follow different enthalpy-temperature curves for each process (Fig. 1a). These effects bring new challenges when numerical models need to evaluate the transition between heating and cooling in TES systems working under partial load operating conditions, since the PCM might have not completely undergone phase change when the following process starts. Four methodologies were found in the literature defining how to address this transition. The first methodology, which was proposed by Bony and Citherlet [9], suggests switching from the heating to the cooling curves, or the other way around, with the same slope than the specific heat curve in the sensible region (points a-c-f in Fig. 1b). The second methodology, which was proposed by Rose et al. [10], has the same principle than the first methodology but the transition takes place with no equivalent slope (points a-c′-f in Fig. 1b). The third methodology, which was proposed by Chandrasekharan et al. [11], suggests staying at the same curve without considering the other curve (points a-d-f in Fig. 1b). Finally, the fourth methodology was obtained in an experimental PCM-equipped wall by Delcroix [12]. He observed that the curve was placed between the cooling and heating curves at a distance and with a slope which depended on the TES system operating conditions (points a-b-e-f in Fig. 1b). Palomba et al. [13] experimentally evaluated three short consecutive charging and discharging processes in a latent heat TES system for solar cooling purposes to study the

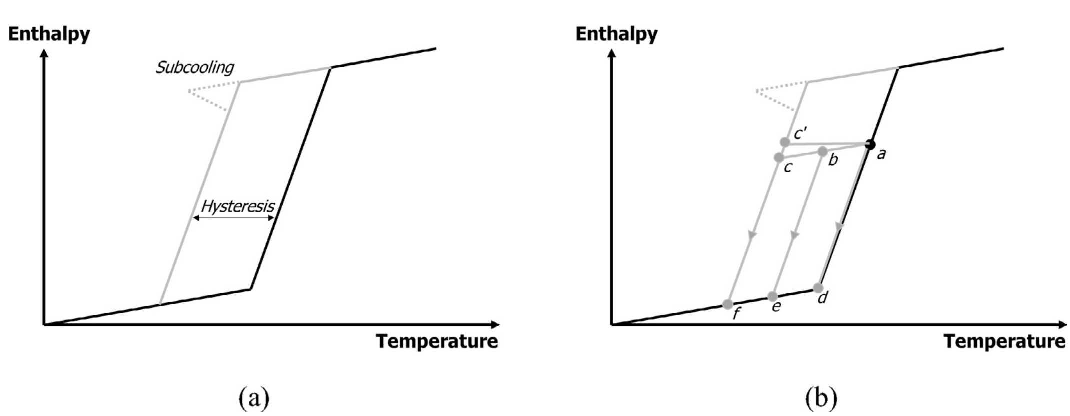

Fig. 1. (a) Hysteresis and subcooling in a PCM melting and solidification process. (b) Scenarios for modelling the transition between heating and cooling in a partially melted PCM. Based on [19].