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Feasibility of small-scale cold energy storage (CES) through carbon dioxide based Rankine cycle

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ABSTRACT

The CES technology stores cheap electricity in off-peak time as cold energy and utilises the cold exergy for electricity re-generation in peak time, showing its significant value in peak-shifting. This study is in the aim of validating the feasibility of a small-scale (lab-scale) CES system as a fundamental step in the development of the CES technology. A small-scale CES system with a power capacity of ~5 kW and total electricity storage capacity of approximately 10 kWh was developed. The experimental results of the CES system showed the feasibilities of the electricity-to-cold storage in the deep refrigerator, the cold energy exchange process for CO_2 cooling in the Rankine cycle, and the cold-to-electricity conversion by the piston based engine system. The Practical tests of the large engine achieved a maximum net electricity output of −160 W in the case study of using compressed air of 10 bar to expand in the engine with a motor speed of 60 rpm, resulting in a practical CES efficiency of 24–44%. However, due to the technical issues such as the gas leakage and blocking in the engine system, effective approaches for improving the engine performance need to be further investigated.

1. Introduction

Three of the main energy challenges are sustaining supply of electrical energy, demand side management (DSM) and effective utilisation of renewable energy [1,2]. Energy storage can play significant role in all these aspects and has therefore attracted more and more attention in recent years. The importance of energy storage lies in its ability to deal with fluctuation of electricity demand (demand side) [3,4] and intermittency of renewable resources (supply side) [5–7] on top of many other advantages.

There are many established energy storage technologies. Examples include pumped-hydroelectric energy storage (PHES), compressed air energy storage (CAES), heat/cold thermal energy storage (TES), battery energy storage (BES), flywheel energy storage (FES), super capacitor energy storage (SCES), super conducting magnetic energy storage (SMES), and hydrogen energy storage (HES). From the point of view of technical maturity, PHES is a mature energy storage technology that accounts for more than 99% of bulk storage capacity worldwide. Developed technologies include CAES, heat TES, BES, FES, SCES, SMES, HES. Commercialized systems for these technologies are available; but the competitiveness of large-scale system for actual applications still need to be proved. Compared with mature or developed energy storage technologies, CES (cold energy storage) technology is a developing technology that has being investigated by various research organizations. Currently, CES is a low-efficient technology since less than 50% of the stored cold energy can be converted into electricity. However, CES technology result in a relatively high cold energy storage density, which induces compact systems and reduced capital cost for system construction [8,9]. Besides, CES system has a long life time and little environmental concern. These advantages enable the development of CES technology for both lab scale (small scale) and large scale applications.

Technically, the referred CES technology stores cold energy in PCM solutions by consuming low-cost electricity in off-peak time, while regenerates electricity in peak hours by converting the cold energy to dynamic power based on the Rankine cycle. In the cold charging process, cold is stored in the forms of sensible and latent heat, leading to large energy storage density and small temperature fluctuation of the CES system [9–13]. These merits enable the CES system to be used in electrical peak-shifting, thermal protection of food, medical applications and industrial cooling systems, etc. [14].

However, due to the poor thermal conductivity of the PCM solution, the cold discharge rate of the storage media is strongly suppressed. Fan and Khodadadi [15] reviewed the studies in

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improving the thermal conductivity of PCMs in the past a few decades. It was reported that the effective solution was the use of PCM composite by inserting highly conductive structures or materials. Examples include the insertion of metal foams (i.e. Chen et al. [16]), graphite (i.e. Zhou and Zhao [17],) and nano-particles with high conductivity (i.e. Fan et al. [18]).

The common methods for cold exergy utilisation include direct expansion and using thermodynamic cycles (i.e. Rankine cycle). The drawback of the direct expansion is the small heat efficiency and net power generation due to the low fluid temperature before expansion. Therefore, numerous studies have focused on cold utilisation based on thermal dynamic cycles [19–27]. Although the heat addition and heat rejection processes in Rankine cycle are isobaric, these processes happen with relatively small temperature variation due to the phase change of the working fluid. As a result, the heat efficiency in Rankine cycle is high and can be close to that in Carnot cycle. However, the heat efficiency is significantly affected by the types and properties of working fluids and irreversibilities in different thermal dynamic processes in the systems [19–21]. Theoretically, the optimum working fluids in Rankine cycle should have high enthalpy drops, low critical pressure, low saturated temperature before pumping and high chemical stability [22].

Except for selection of proper working fluid in the Rankine cycle, an effective approach for improving the heat efficiency is the waste heat recovery [23–27]. Sprouse and Depcik [23] reviewed the studies of engine exhaust waste heat recovery in organic Rankine cycles (ORC). They concluded that ORC was highly efficient in using low-to-medium grade of waste heat. Nelson [24,25] investigated the engine efficiency of Class 7–8 highway trucks with efficient waste heat recovery. They claimed that the engine performance was potential to be improved by more than 50%. Apart from waste heat of engine, solar energy, geothermal energy, and waste heat from condensers in steam power plants or other industrial processes can be utilized for improving the heat efficiency of the Rankine cycle. Auld et al. [26] investigated the influence of different waste heat sources from industrial processes on the heat efficiency of organic Rankine cycles. It was pointed out that both mechanical work output and heat efficiency are essential for system optimization.

Although fundamental studies in charging/discharging behaviour of cold energy storage, thermal dynamic analysis of Rankine cycle and engine performance are largely involved in open literatures, integrated CES systems in practical conditions have scarcely been reported according to the authors' knowledge. This study concerns a small-scale (~5 kW) CES system, which uses eutectic PCM as the cold storage medium, and carbon dioxide as the working fluid in Rankine cycle. Feasibility analysis of the developed CES system was conducted based on experimental measurements.

2. Development of small-scale CES system

2.1. Comparison with high-temperature thermal energy storage

High-temperature heat thermal energy storage has gained increasing attention due to the benefits of high energy storage density, long life time, little environmental concern and low capital cost of the heat thermal energy storage system [2]. As one of the thermal energy storage technologies, cold energy storage was proposed for peak-shifting purpose and has been extended to be used in different areas. Compared with heat thermal energy storage, the cold thermal energy storage is more valuable due to the higher exergy efficiency in the discharging process in the condition of the same temperature difference between the PCM and the environment [28].

This can be elaborated in two cases that the PCM temperature T_{PCM} is maintained (case one) or varied (case two) in the heat/cold discharging processes. For energy storage systems, exergy (ΔE) refers to the maximum useful power that can be obtained in the discharging process; while exergy efficiency (η_{ex}) is defined as the ratio of the exergy to the heat release/absorption (ΔQ) to the environment in the discharging process of the energy storage system. In both case studies, the ambient temperature was T_a and the initial temperature difference between the PCM and the environment for heat/cold thermal energy storage system wasΔT. As a result, the temperature of the cold PCM was $T_a - \Delta T$, while the temperature of the heat PCM was $T_a + \Delta T$. For case one, the exergy efficiency in the discharging process was calculated as:

$$\eta_{ex,cold} = \frac{\Delta E_{cold}}{\Delta Q} = \frac{T_a}{T_a - \Delta T} - 1 \tag{1a}$$

$$\eta_{ex,heat} = \frac{\Delta E_{heat}}{\Delta Q} = 1 - \frac{T_a}{T_a + \Delta T} \tag{1b}$$

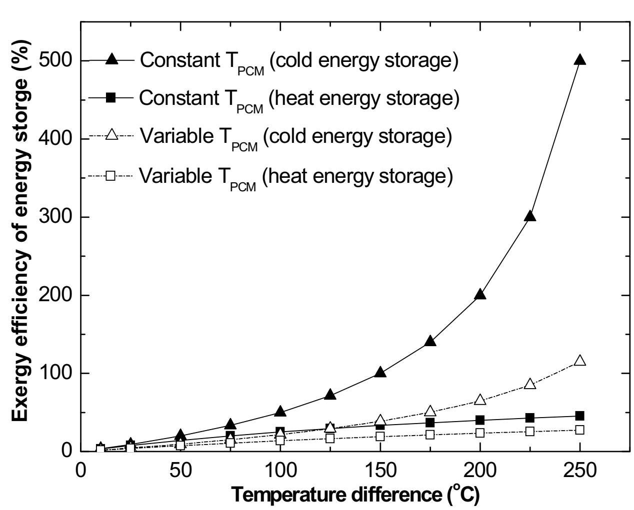

Fig. 1. Evaluated exergy efficiency for heat/cold thermal energy storage systems.