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Review

Mobilized thermal energy storage: Materials, containers and economic evaluation

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ABSTRACT

The transportation of thermal energy is essential for users who are located far away from heat sources. The networks connecting them achieve the goal in efficient heat delivery and reasonable cost, especially for the users with large heat demands. However, it is difficult to satisfy the heat supply of the detached or emergent users with the existing pipelines. Therefore, a promising alternative, called mobilized thermal energy storage (M-TES), was proposed to deliver the heat flexibly without the restriction of networks. In this paper, a review of studies on M-TES is conducted in terms of materials, containers and economic evaluation. The potential candidates of materials, such as sugar alcohols, hydrated salts, alkalies and zeolite are reviewed and compared based on their thermophysical properties, price, advantages and disadvantages. Various containers, including the shell-and-tube, encapsulated, direct-contact, detachable and sorptive types, are discussed from the aspects of configuration, performance and utilization. Furthermore, the studies on the economic evaluation of M-TES systems are summarized and discussed based on the analysis of the economic indicators, including initial cost, operating cost, revenue, subsidy and energy cost. Finally, the challenges and future perspectives for developing M-TES are presented.

1. Introduction

The demand for space heating and domestic hot water is essential for most residential buildings in temperate and cold regions. The energy consumption in this respect accounts for a high proportion in the total energy consumption in many countries [1]. For example, In China, space and water heating accounts for approximately 71% of the total energy consumed in the residential sector [2]. In European Union (EU), 45% of the total final natural gas (NG) demand is due to building space heating [3]. Clearly, to achieve the goals of energy reduction and environmental protection, the efficient and sustainable satisfaction of the heat demand of space heating and hot water usage is essential.

At present, the method of district heating (DH) is preferred due to its advantages of high efficiency and stability. In EU, there are about 6000 DH systems with an overall length of 200,000 km [4]. Most existing DH systems are built in Scandinavian and Baltic Member States [5,6]. Though the market share for DH in other regions of Europe still remains low because of the historical development of the national energy systems. It is believed that the numerous consumers and high density heat demand provide an opportunity for the expansion of DH in Europe. However, the development of long-distance pipelines is undesirable, especially for remote areas, due to the enormous costs of pipelaying [7]. Hence, the approach of direct heating using boilers is widely used for sparse users or those who live far away from DH networks. Compared with a DH system, it is convenient to operate a small-scale boiler. Nevertheless, it is more costly and lower inefficient than DH by approximately 15% and 10%, respectively [5,8]. Moreover, the heating system with small-scale boiler releases extra CO_2 (around 15%) when using fossil fuels [9,10]. To address this issue, other clean and sustainable heating methods were proposed by researchers. Herein, the introduction of renewable energy in heating system, is attractive, owing to the benefits of decarbonizing the heating sector [11–13]. To overcome the shortcomings of most renewable energy, i.e. intermittency and fluctuation, the instillation of energy storage units is necessary. For

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example, the water pit thermal storage is considered as one of the most reliable and widely used technologies for solar heating systems [14].

Notably, the renewable energy resource is regional distributed. The heating method integrated with renewable energy is not suitable for the resource-poor regions. Another flexible heating method, mobilized thermal energy storage (M-TES)—without the limitation of DH pipelines and renewable resource availability—is therefore proposed.

The concept of M-TES was described earlier within the framework of the International Energy Agency/Energy Conservation through Energy Storage (IEA/ECES) [15]. The project Annex 18, "Transportation of energy by utilization of Thermal Energy Storage Technology", was in operation from June 2006 to December 2009. A series of experimental studies were carried out by the Annex participants [15]. Meanwhile, M-TES pilot projects were operated by several companies [16,17]. Herein, the primary task was conducted for seeking appropriate storage materials. The characterization of thermodynamic and kinetic properties was conducted to examine the suitability of the selected material [18]. Afterwards, the storage container should be designed and optimized to achieve the good charging and discharging performances. This content included the optimization of conventional shell-and-tube storage container and also the exploration of novel storage devices such as direct-contact type [19,20]. Moreover, to identify the feasibility and potential of an M-TES system, it is essential to carry out the system economic analysis including the evaluation of economic indexes such as net present value (NPV), payback period (PBP) and energy cost [21]. Though the investigations of the above three points have been reported in many researches, there is still lack of a summary of the state of the art of M-TES, which leads to the necessity of this review. In addition, the challenges and outlook are also presented here based on the literature review. The purpose of this article is to address the progresses in the study of M-TES and show an insightful prospect for its further development.

2. The concept and principle of mobilized thermal energy storage (M-TES)

The M-TES concept is shown in Fig. 1. First, the M-TES container packed with storage material is transported to the heat source site—for instance, a power plant—and charged with the waste heat from steam exhaust. The heat is absorbed by the storage material and stored in the container; then, the fully charged container is transported by a truck over a long distance to the sparse residential heat user. At the user site, the M-TES container is used to completely or partly replace the boiler in the existing heating system; after discharging, the container is sent back to the heat source site for the next cycle.

As mentioned above, the whole procedure of M-TES can be divided into the charging and discharging processes. The principles are illustrated in Fig. 2. At the heat source site, the steam exhaust from a turbine is partly extracted before the condenser. Then, it flows in a heat exchanger and releases heat to the M-TES container. Considering the solubility of the material solution, the thermal oil is normally used as

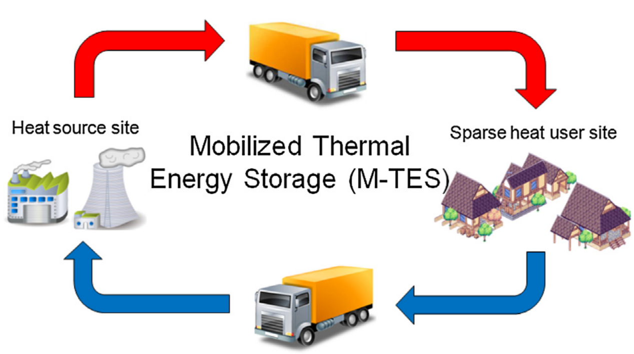

Fig. 1. Diagram of M-TES concept [22].

the heat transfer medium. Thus, an oil-water heat exchanger is installed here; at the user site, the stored heat in the M-TES container is released through an oil-water heat exchanger to heat the return water of the existing heating system. When using radiators as endpoints, an assistant boiler is installed to heat the return water up to at least 70 °C [23,24]. For a system with fan-coil units or under-floor pipes, a water mixing valve is used to mix the return and supply water [25]. In contrast, the M-TES is recommended for the existing heating systems with fan-coil units or under-floor pipes because it is more cost-effective, environmental friendly and convenient to operate a water mixing valve than a boiler.

To make the M-TES system run continuously, there are at least two containers with a given number of return trips per day. One container is being discharged at the user site, while the other is being charged at the heat source site or transported on road. The dwell time of vehicles at heat source site and user site depends on the charging and discharging performances of containers. Therefore, the operating strategy of M-TES is generally optimized according to the conditions of heat source, the heat demand of end-users and also the distance between them.

3. Materials

The invisible heat is capable of transportation by virtue of the heat storage material. The heat can be stored in the material as a form of sensible heat, latent heat or chemical reaction/adsorption heat. Therefore, the material of M-TES will be summarized based on this classification. Because the M-TES is designed for both domestic hot water supply and space heating, the low- and medium-temperature (50–350 °C) thermal energy storage materials are mainly involved.

3.1. Sensible heat storage (SHS) materials

When raising the temperature, the thermal energy is stored as a change in the internal energy of the material itself. This inherent characteristic exists in all material and is called "sensible heat storage". The amount of stored sensible heat depends on physical variables, such as mass, specific heat capacity and the temperature difference [26,27].

The most common SHS materials are rock, brick, concrete, water and oil [28,29]. With a high specific heat capacity that reaches up to 4190 $J\,kg^{-1}\,°C^{-1}$, and the advantage of being low cost, water is usually considered as an ideal SHS material. Chan et al. [30] proposed a heat delivery scheme by using a truck to supply hot water for a hotel. The waste heat generated in a power plant was used as the heat source. The results showed that although it would evidently offset the original energy consumption, the disadvantages, such as large volume and low energy density, seriously restricted its potential of application. Obviously, the other SHS materials are not suitable for the utilization in an M-TES system likewise because of their lower volumetric thermal capacities [31].

3.2. Latent heat storage (LHS) material

To improve the heat storage density and make the transportation feasible, the LHS technology was designed for the M-TES. During charging and discharging, the LHS material undergoes a solid-liquid phase transition [32].

According to the literature, the potential candidates can be divided into two categories, i.e., organic sugar alcohols and inorganic hydrated salts. Therefore, the following summary of LHS materials for M-TES will be described based on this classification. The key properties are listed in Table 1.

3.2.1. Organic sugar alcohols

In the early days, Kakiuchi et al. [33] examined the feasibility of using erythritol as heat storage material based on the lab-scale measurements. Results showed that erythritol could be used as an excellent