Current situation and research progress of mobilized thermal energy storage technology

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Abstract. To match the disharmony and imbalance between heat supply and demand in time and space, mobilized thermal energy storage technology has emerged, which can achieve the full and effective utilization of industrial waste heat and clean heating in the industrial and civilian fields. This article provides a review of the current development status and research progress of mobilized thermal energy storage technology from the perspectives of heat storage materials, heat accumulators, case studies, and engineering demonstrations. Meanwhile, some suggestions were put forward for the future development of mobilized thermal energy storage technology.

Keywords: Mobilized thermal energy storage, Low grade thermal energy, Waste heat utilization, Heat supply.

1 Introduction

Since the reform and opening up, with the rapid development of society and economy, China's energy consumption level has also been increasing year by year. Currently, the energy consumption of industrial sector accounts for about 65% of the total national consumption for China. Compared with developed countries, China's industrial waste heat utilization technology is not mature enough. In the context of energy-saving and emission reduction policies, the improvement of industrial energy efficiency in China has achieved initial results. However, the large amount of heat generated in the production process of high energy-consuming industries such as electricity, cement, steel, nonferrous metals, and petrochemicals has not yet been fully and effectively utilized [1]. A large amount of low-grade waste heat, represented by flue gas and hot water, is directly discharged into the external environment, causing serious energy waste and environmental pollution.

Meanwhile, with the continuous improvement of people's living standards, China's energy demand is constantly increasing. On one hand, there is a huge heat demand in China's industrial sector. Traditional printing and dyeing industries mainly produce

A. E. Abomohra et al. (eds.), *Proceedings of the 2023 9th International Conference on Advances in Energy Resources and Environment Engineering (ICAESEE 2023)*, Atlantis Highlights in Engineering 29,
https://doi.org/10.2991/978-94-6463-415-0_18

steam by burning fossil fuels such as coal and natural gas. On the other hand, residential heating and domestic hot water have always been the main components of energy consumption in civil buildings in China, accounting for approximately 71% of residential energy consumption [2]. The winter is extremely cold in northern China, and most residential areas nowadays use heating networks. The heating network is stable and has a high energy utilization efficiency, but its initial investment is large and maintenance costs are high [3]. Moreover, it mostly uses coal and oil as fuels, emitting a large amount of harmful gases and dust during the combustion process, which is the main cause of atmospheric pollution. Considering the cost, it is difficult for the heating pipeline network to cover remote areas. Dispersed and emergency users have to use small boilers for heating, resulting in lower energy utilization efficiency and more severe greenhouse gas emissions. Therefore, how to achieve clean heating for civil buildings is of great significance for China to successfully achieve the goal of "carbon peak and carbon neutrality".

To fully and effectively utilize industrial waste heat and achieve clean heating in both industrial and civilian fields, a technology called mobilized thermal energy storage (M-TES) has emerged. A M-TES system generally includes two parts: a heat storage container and a transportation vehicle. As shown in Figure 1, the M-TES system obtains energy from heat sources such as steel mills, power plants, and chemical plants, and then transports the heat storage device to heat users such as residential areas, hotels, hospitals, and industrial plants to release heat. Transportation methods include road, rail and maritime. The M-TES systems are different from traditional heating networks, and their unique flexibility can effectively alleviate the time and space imbalance between energy supply and demand [4, 5]. The M-TES systems can recover industrial waste heat and supply clean heating, effectively reducing fossil fuel consumption and greenhouse gas emissions, and improving energy efficiency. When the heat source is renewable energy electricity, using M-TES technology can effectively solve the problem of new energy electricity consumption, which is conducive to peak shaving and valley filling as well as supply and demand balance in the power grid.

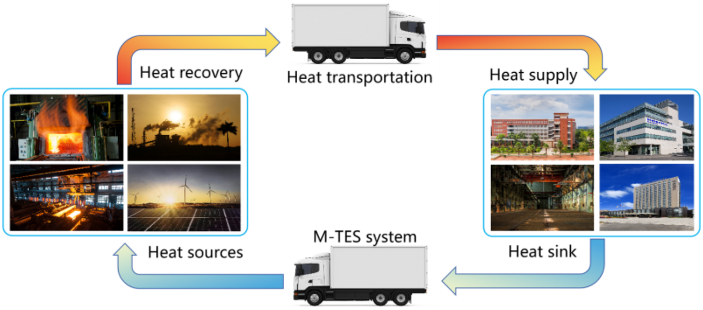


Fig. 1. Concept diagram of mobilized thermal storage technology.

Most research on M-TES has less discussion about the concept of thermal storage systems, and focuses on thermal storage materials, container design, thermal storage forms, and technical and economic evaluation [1-8]. This article provides a review of the current development status and research progress of M-TES technology from the perspectives of heat storage materials, heat accumulators, case studies, and engineering demonstrations. Meanwhile, some suggestions were put forward for the future development of M-TES technology.

2 Fundamental research

The selection of thermal storage materials and the design of heat accumulators are the two most critical factors affecting thermal storage performance. The basic research in the field of M-TES focuses on developing higher quality thermal storage materials and better heat accumulators.

2.1 Heat storage materials

One of the eternal key research topics in the field of thermal storage is to seek low-cost thermal storage materials that can meet the needs of heat storage. According to the principle of heat storage, heat storage materials can be divided into three types: sensible heat, latent heat, and thermochemical heat storage materials. Sensible thermal energy storage technology is the most mature and cost-effective, but the energy storage density is also the lowest. Common sensible thermal energy storage materials include water [9], solid thermal storage bricks [10, 11], basalt [12, 13], etc. Phase change energy storage has a high energy storage density and stable exothermic temperature, which is currently the focus of research and engineering applications. Phase change heat storage materials mainly include three types: sugar alcohols (erythritol, mannitol, xylitol, etc.) [2], hydrated salts/alkalis (sodium acetate, barium hydroxide, etc.), paraffin and fatty acids. The most widely used phase change materials (PCM) currently are erythritol and sodium acetate trihydrate (SAT) [14]. Erythritol is suitable for thermal storage applications above 120 °C, and SAT is suitable between 20 °C and 100 °C. Thermochemical energy storage is still in the laboratory development stage. Thanks to the extremely high energy storage density, thermochemical energy storage has great potential for engineering applications. Common thermochemical heat storage materials include zeolite[15], silica gel[7], etc. Table 1 lists some common energy storage materials in the field of M-TES reported in the literature.

Table 1. Common heat storage materials, heat transfer fluids, and types of heat exchangers in the field of M-TES.

Heat storage type	Heat storage material	Heat transfer fluid	Types of heat exchangers	References
sensible	MgO solid thermal storage brick	water/air	direct	[10, 11]
sensible	basalt fiber	air	direct	[12, 13]
sensible	water	water	—	[9]
latent heat	tombarthite	water/steam	indirect (phase change ball)	[16]
latent heat	$Ba(OH)_2 \cdot 8H_2O$	—	indirect	[17]

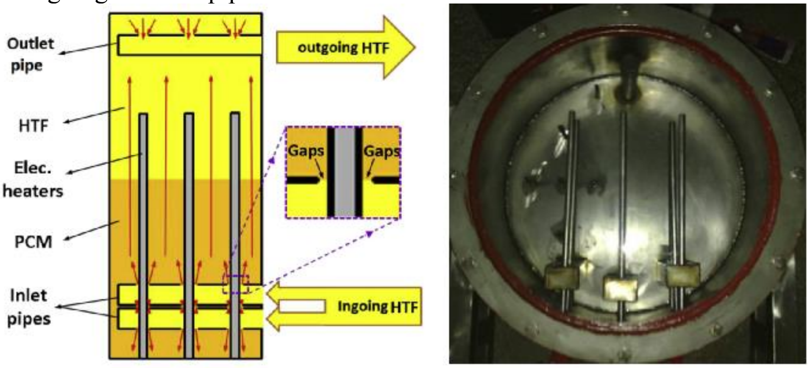
Heat storage type	Heat storage material	Heat transfer fluid	Types of heat exchangers	References
latent heat	$Ba(OH)_2 \cdot 8H_2O$	water	(shell-and-tube) indirect	[18, 19]
latent heat	$Ba(OH)_2 \cdot 8H_2O$	water	indirect (shell-and-tube)	[20]
latent heat	NaOH	heat transfer oil	—	[21]
latent heat	paraffin wax	water	indirect (shell-and-tube)	[22]
latent heat	erythritol	water/heat transfer oil	direct/indirect (shell-and-tube)	[23, 24]
latent heat	erythritol	heat transfer oil	direct	[9, 25-27]
latent heat	erythritol	water	indirect (shell-and-tube)	[28]
latent heat	erythritol	silicone oil	Indirect (phase change ball)	[29]
latent heat	erythritol	heat transfer oil	indirect (shell-and-tube)	[30]
latent heat	SAT	—	Indirect (shell-and-tube)	[31]
latent heat	RT70HC	water	Indirect (shell-and-tube)	[32]
thermochemical	—	—	—	[33, 34]
thermochemical	zeolite	air	direct (packed bed)	[15]
thermochemical	$CaSO_4 \cdot 1/2H_2O$	—	direct (packed bed)	[35, 36]

Sensible thermal energy storage is achieved by increasing or decreasing the temperature of the thermal storage material itself to store and release thermal energy. Therefore, when using sensible thermal energy storage materials, the exothermic temperature will gradually decrease during the exothermic process. Zhu [12] proposed two ways, including manual adjustment and automatic adjustment, to adjust the inlet flow rate, thereby improving the heat release stability. The biggest problem faced by phase change energy storage is the low thermal conductivity of PCM. Composite materials can be made by adding thermal conductivity enhancers (such as graphite, nanometals, etc.) to thermal storage materials, thereby improving the thermal conductivity of the materials [3, 5, 29]. However, the doping inevitably increases costs and reduces heat storage density. Meanwhile, many PCM face problems such as high-temperature thermal decomposition, supercooling, and phase separation, which hinder the large-scale application of PCM. Thermal decomposition refers to the phenomenon of material degradation caused by high-temperature environments during continuous heating/cooling cycles. Kakiuchi et al. [37] claimed that the lifetime of erythritol depends more on heating temperature than on repeated melting/solidification processes. Therefore, it is necessary to select heat storage materials reasonably based on the temperature of the heat source for different application scenarios. Supercooling refers to the phenomenon where phase change materials do not solidify or crystallize at temperatures below the solidification point. Supercooling is a metastable state, which is broken when there is slight disturbance in the liquid, and the phenomenon of material supercooling disappears. The methods of forming disturbances include adding nucleating agents, stirring, ultrasonic irradiation, etc. [38, 39]. P. ONA et al. [39] attempted to solve the supercooling problem of erythritol as a PCM through physical methods. The research results indicate that ultrasound irradiation is the most effective method compared to bubbling and stirring. Phase separation refers to the separation and deposition of a portion of the dehydrated material after repeated melting/solidification, which to some extent hinders the next hydration process. Wang [19] conducted an experimental study on the effects of different nucleating agents and thickeners on the undercooling and phase separation of barium hydroxide octahydrate. The results indicate that iron powder, copper powder, and potassium dihydrogen phosphate can effectively improve the undercooling of barium hydroxide octahydrate, while sodium carboxymethyl cellulose, polyacrylamide, and magnesium oxide can inhibit the phase separation phenomenon of barium hydroxide octahydrate.

2.2 Heat accumulators

The research on heat accumulators/exchanger focuses on the improvement of traditional heat exchangers and the development of new types of heat exchangers. Table 1 lists the common forms of heat exchangers used in the field of M-TES in literature reports. Heat accumulators can be divided into two types according to the heat exchange form: direct-contact type and indirect-contact type. For direct-contact type, the heat storage fluid and the heat transfer fluid must be immiscible and chemically compatible, meanwhile there needs to be a significant density difference between the two fluids [3]. Compared with indirect-contact type, direct-contact heat exchangers eliminate complex heat transfer structures such as pipelines and fins, resulting in higher heat storage density. Meanwhile, due to the elimination of the thermal resistance of the heat exchange structure, the heat transfer rate is faster [3]. However, direct-contact heat accumulators face problems such as dead zones and fluid inlet blockage during the initial stage of charging [24]. To reduce the melting dead zone, Guo et al. [27] proposed to heat the container wall near the dead zone, successfully reducing the charging time by 29%. To address the blockage during the initial stage of charging, Guo et al. [23, 25, 27] proposed using electric heaters to generate fluid channels (Fig. 2). The heating process only requires about 5% of the energy stored in the heat accumulator, and the fluid channels are formed in 90 seconds, which can significantly reduce the charging time. However, it is worth pointing out that using an electric heater may cause the PCM around the electric heater to overheat and undergo high-temperature decomposition [2]. Through laboratory scale experimental research, Wang et al. [24] demonstrated that increasing the flow rate of heat transfer oil (HTO) can effectively enhance the charging/discharging process. However, increasing the flow rate of HTO may cause the HTO to carry the PCM out of the heat accumulator, resulting in the loss of PCM. When the PCM solidifies after entering the circulating pipeline, pipeline blockage may occur [3].

Kaizawa et al. [26] conducted experimental studies on mass transfer and phase transition behavior of PCM using a small heat exchanger model with transparent glass, explaining the different heat transfer mechanisms during charging and the three solidification mechanisms of PCM during discharging. To reduce dead zones and maximize heat storage density and heat transfer rate, the influence of the position, number, and nozzle angle of the inlet pipe on heat transfer and liquid flow should be fully considered when designing the inlet pipe.



(a) (b)

Fig. 2. The heat accumulator developed by Guo et al. [25]: a) Section view of the heat accumulator with electric heater; b) Photo of the heat accumulator with electric heater.

Indirect-contact heat storage devices achieve heat exchange through internal pipelines, and the heat exchange rate is limited by the heat exchange area and the thermal conductivity of the storage material, resulting in a lower heat exchange rate. According to the packaging form of thermal storage materials, indirect-contact heat accumulators can be divided into two types: shell-and-tube type and packaging type. The shell-and-tube heat exchanger is currently the most widely used heat exchanger in M-TES. Its technology is mature, with the advantages of flexible design and convenient maintenance. As shown in Figure 3, the shell-and-tube heat exchanger can be optimized and upgraded by improving the structural form and arrangement of heat exchange tubes [17, 30, 40], adding fins [22, 30, 40], baffle plates, and other methods to improve heat exchange performance [3]. Zhang et al. [17] used commercial simulation software to conduct numerical analysis of the storage performance of a M-TES device. By optimizing the geometric configuration and arrangement of the fins, as well as using storage materials with higher thermal conductivity in the sidewall area of the device, the total charging and discharging time was successfully reduced by nearly one-fifth. By means of the simulation tool, Tian et al. [40] demonstrated that compared to the sparse arrangement of large-diameter pipe, the compact arrangement of small-diameter pipe can enhance the heat transfer performance and reduce the "dead zone" area of the heat exchanger due to the increased heat transfer area. Yan [22] conducted tests to investigate the effects of waste heat temperature and quantity on the charging and discharging process of a mobile phase change heat storage device. The results indicate that compared to the changes in flow rate, the stored and released heat is more sensitive to the temperature changes. Therefore, a reasonable flow rate should be selected to avoid unnecessary pump power consumptionin in practical applications. Meanwhile, compared to optimizing the size of fin openings and cross section, optimizing the spacing and thickness of fins has a better improvement effect on the storage performance. It is worth noting that upgrading the internal pipeline layout of the heat accumulator often leads to more complex structures, which may have a negative impact on heat transfer. For example, increasing heat exchange tube bundles not only improves heat transfer performance but also reduces heat storage capacity [28]; adding fins can improve heat transfer efficiency while suppressing natural convection [41].

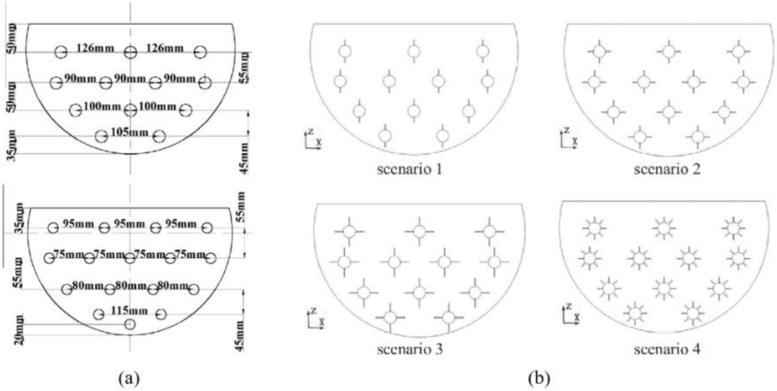


Fig. 3. TES container developed by Guo et al. [30]: a) Layouts of the tubes in the different scenarios.; b) Layouts of the fins in the different scenarios.

Due to the absence of pipes and fins, packaged heat accumulators are lighter in weight. Common packaging structures include heat storage balls [29], heat storage bags [42], heat storage plates [43], etc. The typical packaged heat accumulators are shown in Figure 4. They are generally made of materials with good thermal conductivity and corrosion resistance. Compared to the shell-and-tube type, packaged heat accumulators have a larger heat transfer area, resulting in a relatively higher heat transfer rate [3]. However, frequent charging and discharging is a challenge for packaging materials, and attention should be paid to preventing leakage [2].

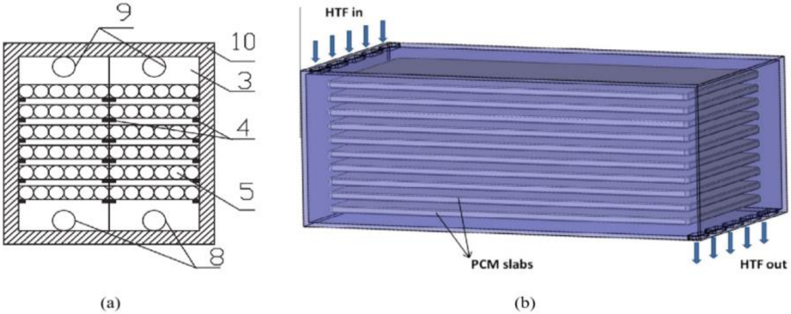


Fig. 4. The typical packaged heat accumulators with (a) heat storage balls [29] and (b) heat storage plates [43].

3 Case studies

To confirm the feasibility and application potential of M-TES systems, it is essential to conduct economic analysis. The M-TES is an alternative to traditional heating networks. Overall, when the heat source and heat user are relatively fixed and the heating load is large, the heating network has more advantages. When facing non fixed heat sources and users, the M-TES is more flexible. Different scholars have explored the economic and social benefits of M-TES technology in specific cases through case analysis methods. Li et al. [9] conducted an economic evaluation of M-TES, indicating that the heating cost is directly proportional to the transportation distance and inversely proportional to the heat demand. Compared with other heating methods such as biomass particle/bio-oil/biogas/oil boiler systems and electric air-source heat pumps, M-TES systems are more suitable for users with short transportation distances and high heat demand. Compared to using water as a heat storage material, using PCM is more suitable for situations with high heat demand or long transportation distances. Taking Taiyuan city as an example,Yue [16] elaborated on the importance of using M-TES systems based on the distribution of waste heat resources and heating conditions. He analyzed the economic and social benefits of using waste heat from thermal power plants for surrounding domestic heat. Zhang et al. [10,11] proposed the use of imported composite magnesium oxide solid thermal storage bricks as storage materials, utilizing abandoned wind power to provide heating for household users, in order to solve the problems of wind power consumption and coal-fired pollution. In addition to selecting storage materials, considering waste heat conditions and the specific needs of heat users, the impact of operating strategies on economy is also crucial. For example, when designing the storage capacity and transportation cycle number of a M-TES system, if both the number of heat storage units and the number of trips can be minimized, the economic benefits can be maximized. Chiu et al. [28] explored the economy of using M-TES technology to apply industrial waste heat to low-temperature district heating networks. In seasons with low heating demand, thermal storage modules should be fully stored to minimize transportation costs, while in seasons with high heating demand, partial storage should be carried out to provide sufficient heat rate and reduce the number of storage units. The impact of transportation methods on costs is also crucial. The prediction results indicate that under the optimal operating strategy, the cost of highway transportation is still 75% higher than that of waterway transportation [28].

As an energy supply method, the comparison between M-TES technology and traditional energy supply methods such as fossil fuel combustion is a common focus of attention in academia and engineering. Thermodynamic analysis [18, 21, 44] is a powerful tool in this field. Wang et al. [18] selected $Ba(OH)_2 \cdot 8H_2O$ as the storage material to recover waste heat below 100 °C. The effects of environmental temperature, initial and final temperatures of storage materials on storage capacity and exergy efficiency were studied through thermodynamic analysis. The results indicate that the final temperature of the material has a decisive impact on its thermodynamic properties. Nomura et al.

[21] studied the feasibility of using high-temperature PCM NaOH to recover heat from steel plants for use in chemical plants using thermodynamic analysis methods. The results indicate that M-TES systems using PCM have a higher energy storage density and less exergy loss compared to burning fossil fuels or using sensible heat storage. Kaizawa [44] established a thermodynamic model to compare and analyze the differences in energy consumption, heat loss, and CO_2 emissions when using different energy supply methods. The results show that when supplying hot water at 50 °C, compared to the traditional method of using kerosene combustion for heating on site, the energy demand of the M-TES system containing erythritol is 7.7%, the energy loss is 8.1%, and the CO_2 emissions are 20.2%. When supplying cold water at 7 °C, compared to the absorption refrigeration method using natural gas as the heat source, the energy demand of the M-TES system containing erythritol is 12.0%, the heat loss is 12.0%, and the CO_2 emissions are 26.6%.

4 Engineering demonstrations

The limitation of the above research is that there is a large amount of data from assumptions and estimates, and no prototype has been developed to obtain accurate cycle efficiency and economic results. Furthermore, most studies have not taken into account the cost of waste heat and heat loss, which is undoubtedly crucial in practical engineering applications.

The Fraunhofer Institute of Environment, Safety, and Energy Technology conducted six months of actual operational test on a prototype of a 2 MWh M-TES system to evaluate its economic and technical feasibility [31]. The system uses SAT as the storage material and a shell-and-tube heat exchanger. The results indicate that the impact of transportation distance, number of cycles, and weight of storage materials on the heat production cost gradually increases. The author emphasizes the importance of low-cost waste heat and shorter charging and discharging time for the profitability of the M-TES systems. Most of the reported literature estimates the economic performance based on certain assumptions. In contrast, the economic evaluation based on the actual test data of the prototype under longer operating cycles is more convincing in this article.

Krönauera et al. [15] proposed a demonstration factory scale M-TES system based on zeolite that extracts heat from steam from a waste incineration plant and provides heat to customers 7 kilometers away for drying processes (Fig. 5). The designed heat storage capacity is 2.3 MWh, but the on-site test data did not reach the required output power due to the uneven distribution of zeolite packed beds. Sensitivity analysis shows that the impact of transportation time, annual cycle times, and storage capacity on energy costs is gradually increasing. Kuta [32] verified the feasibility of using the M-TES technology to use geothermal energy for heating single family residential buildings through on-site experiments in real situations (Fig. 6). The system uses 700 kg of RT70HC PCM as storage material, with a heat storage capacity of 45 kWh, which can provide nearly 8.5 hours of heating for a single household 13.2 kilometers away. The results indicate that in terms of PCM selection, the phase change temperature of PCM should be at least 15 °C lower than the temperature of the heating medium to ensure sufficient phase change and heat storage.

Fig. 5. M-TES prototype developed by ZAE Bayern Research Centre [15].

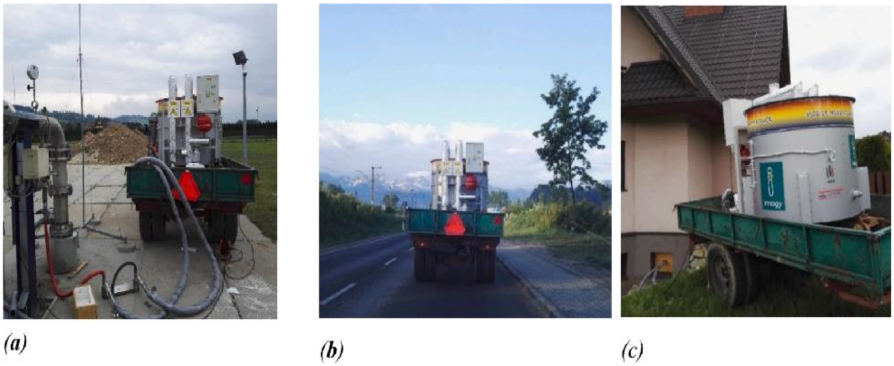


Fig. 6. M-TES developed by AGH University of Science and Technology [32]: a) charging; b) transport; c)discharging.

Multiple countries, including China, Germany, and Japan, have already implemented on-site applications of the M-TES technology [45]. A M-TES application project located in Köln, Germany [45] uses barium hydroxide to recover waste heat from power plants and supply heat for kitchens. The volume of the heat accumulator is 25 m^3， and the heat storage capacity is 4 MW. In China, the two most representative suppliers in the field of the M-TES are CYENER (Beijing) Technology Co., LTD (CYENER) and Qingdao Aohuan New Energy Group Co., Ltd (Aohuan). Figure 7 shows their typical products. CYENER developed the first M-TES vehicle in 2005 [46], using alkali-oxide composite PCM for heat storage. The latest generation of heat storage vehicles have a storage capacity of up to 6.5 GJ and a heating distance of up to 20 kilometers. The storage vehicles mainly recycle residual heat from steel plants, thermal power plants, chemical plants, etc., providing hot water, heating, and emergency heating services for residential buildings, hospitals, schools, and hotels. Aohuan has two forms of M-TES products: tank containers and tank semi trailers, with a maximum heat storage capacity of 25 GJ. It successfully utilized the heat from the thermal power plant to heat the office building and warehouse of Dongjiakou Station on Qingdao Metro Line 13 20 kilometers away[47].

(a) (b)

Fig. 7. M-TES developed by (a) CYENER [46] and (b) Aohuan [47].

5 Conclusion

As a clean energy supply method, the mobilized thermal energy storage and heating technology has enormous application potential in industrial waste heat utilization, industrial and residential heating, power grid peak shaving and valley filling, etc. This article provides a review of the current development status and research progress of the M-TES technology from the perspectives of heat storage materials, heat accumulators, case analysis, and engineering demonstration. PCM represented by erythritol and SAT have received significant attention in the M-TES research. Thanks to mature design and manufacturing experience, shell-and-tube heat exchangers have become the most widely used heat storage device in the field of M-TES. To increase the heat transfer rate, heat accumulators represented by packaged and direct-contact types have gradually become research hotspots. The economic analysis of M-TES is becoming increasingly comprehensive. Thermodynamic analysis methods are widely used to compare M-TES with other traditional energy supply methods. Manufacturers represented by CYENER and Aohuan have successfully commercialized M-TES technology. In a word, scholars' research has strongly promoted the continuous development of M-TES technology. It can be foreseen that M-TES will have a brighter application prospect in the future.

Acknowledgments

This work was financially supported by Science and Technology Project of State Grid Corporation (5108-202218280A-2-444-XG).

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