Energy Storage by Sensible Heat for Buildings

Yilin Fan and Lingai Luo

Contents

Abstract

This chapter presents a state-of-the-art review on the available thermal energy storage (TES) technologies by sensible heat for building applications. After a brief introduction, the basic principles and the required features for desired sensible heat storage are summarized. Then, material candidates and recent advances on sensible heat or cold storage adapted for building application are discussed, each with its own characteristics, advantages, and limitations. A large section of the chapter is devoted to the sensible TES technologies for buildings, both for short-term (daily) and for long-term (seasonal) storage. Each technology is described in detail including different aspects: basic principle, development status, performance and costs, potential and barriers, today's R&D activity focus, etc. Comparisons on the advantages and limitations between different TES

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technologies are also made. Finally, conclusions and future directions are summarized.

Keywords
Thermal energy storage (TES) · Sensible · Building · Storage capacity · Thermal loss · Stratification

Introduction

Thermal energy storage (TES) means the temporary holding of excessive thermal energy (in the form of heat or cold) in a storage medium for later use. It helps to balance the mismatch (both in time and in quantity) between heat supply and heat demand. As a result, it plays a more and more important role in various sectors from energy production (e.g., CSP plants) to energy utilization (e.g., buildings), especially for increasing the ratio of renewable energy sources in different countries and regions.

Depending on different technologies, thermal energy can be stored at temperatures between −40 °C to more than 400 °C as sensible heat, latent heat, and thermochemical energy. Sensible heat storage, by its definition, means that thermal energy (heat or cold) is stored in the form of sensible heat in the storage medium, which does not undergo any phase change during charging or discharging process. The single process involved is the temperature variation of the storage medium within one phase. For building applications, TES systems based on sensible heat are currently the most developed and commercially available while latent or thermochemical TES systems are relatively underdeveloped.

This chapter will introduce different TES technologies based on sensible heat for building applications.

Basic Principles

The amount of thermal energy (J) stored or released within a sensible heat storage process may be expressed by Eq. (1):

$$Q = \int_{T_i}^{T_f} mC_p(T)dT \tag{1}$$

where m is the mass of the storage material (kg), C_p the specific heat (J.kg^{-1} K^{-1}), T_i and T_f the initial and final temperature (K) of the storage material, respectively.

The specific heat of certain storage material is usually temperature dependent. However, a constant value of C_p allows to make an approximate calculation when its variation is not so big within the temperature range. Equation (1) can then be rewritten as:

$$Q = m\overline{C}_p(T_f - T_i) = \rho V \overline{C}_p(T_f - T_i) \tag{2}$$

Where $\overline{C}_p$ is the average specific heat of the storage material within the temperature range. Note that constant values of density ρ (kg.m^{-3}) are considered for the majority of storage materials applied in buildings. For packed bed or porous medium used for thermal energy storage, however, the porosity of the material should also be taken into account. Then the energy storage density per unit mass or per unit volume of certain material may be calculated as Eq. (3) or Eq. (4), respectively.

$$Q/m = \overline{C}_p(T_f - T_i) \tag{3}$$

$$Q/V = \rho \overline{C}_p(T_f - T_i) \tag{4}$$

Based on Eqs. 3 and 4, one may observe that high values of C_p render a corresponding high energy storage density. It is thus a key parameter for the selection of proper materials for sensible heat storage use.

The required features for desired sensible heat storage may be summarized as follows.

- *High storage density*: for a certain storage capacity (J or kWh), higher storage density requires lower amount of the storage materials (kg) and smaller size of the storage system (m^3), implying lower capacity cost (€/kWh) of the storage system.
- *High energy efficiency*: high proportion of energy stored in the system could be released to the user. This requires reducing the energy loss during the storage period and the charging/discharging cycle. However, the quantity of energy loss depends on many factors, such as the temperature difference between the stored medium and the environment, the storage duration, the insulation, etc.
- *Wide operation temperature range*: for building application, the working temperature usually ranges between 0–120 °C, except for some specific purposes (e.g., $>$120 °C when combined with high temperature solar panels or $<$0 °C for ice-making). For a certain application, one often searches for a wide temperature variation but without phase change or decomposition of the storage materials.
- *Fast charging and discharging*: less time is needed to reach the storage capacity. This often calls for efficient/intensified heat transfers inside the storage medium (high thermal conductivity, convection effect, etc.) as well as between the storage medium and the heat transfer fluids (large temperature difference, efficient design of the flow paths for the storage unit, etc.).
- *Good stability of the storage material*: for short-term storage (hourly, daily, weekly), it means low degradation of the storage material under hundreds or thousands of thermal cycling; for long-term storage (seasonal), it means stable thermo-physical properties of the storage material during the storage period. On the whole, long lifetime of the storage material (thus reduced capital cost) is favorable.

- *Low or noncorrosiveness, environmental friendly, and inflammableness*: this means good compatibility with the construction around and the environment as a whole, as well as the safety issues.
- *Low cost*: which refers to either low capacity cost (€/kWh) or low power cost (€/kW) of the storage system. It depends also on various factors such as the availability of the storage materials, the capital and operational costs of the storage unit and accessories, and their lifetime.

It should be noted that the above-mentioned features are usually interdependent. And most likely, a sensible heat storage system/technique can not necessarily meet all the requirements. For example, thicker insulation layer could effectively reduce the heat loss but also augments the size of the storage unit and the capital cost. Therefore, some trade-offs or compromises should be made when dealing with specific energy storage issues in buildings. Some multi-objective optimization methods (e.g., [1, 90]) have also been developed which may be associated with life cycle analysis (LCA) or techno-economic analysis.

Materials for Sensible Heat or Cold Storage

A great number of materials have been investigated and proposed for the purpose of sensible heat storage. New materials are also developed every year, which should be further studied for characterizing their properties. Based on their physical status, sensible heat storage materials may be categorized by liquid, solid and gaseous media. Compared to liquid and solid materials, which are widely used for building applications, gaseous materials are rarely used mainly due to their low density thus large volume of reservoirs needed. In this section of the chapter, different materials used for the storage of thermal energy (both heat and cold) in buildings will be discussed, each with its own characteristics, advantages and limitations.

Liquid Storage Materials

Various liquid materials are used for sensible heat storage in buildings, each having its proper operational temperature range. Among them, water is the most commonly used liquid because it meets almost all the aforementioned required features: availability and accessibility, low cost, relatively high specific heat, environmental friendly, stable under cycling operations, etc. Moreover, its operational temperature range (about 20–90 °C) covers a large amount of heating demands for buildings, such as space heating and hot water production. Under atmospheric pressure, the storage temperature limit for water should be below 100 °C. Higher storage temperature above 100 °C is still possible but pressurized tanks should be used. Water can be used in different storage techniques for buildings in terms of storage duration, such as hot water tanks for short-term storage and aquifer or solar ponds for seasonal storage.

Organic oils (e.g., alcobolic or alkane solutions) sometimes appear as alternative to water, so as to achieve a higher working temperature above 100 °C (e.g., up to 118 °C for butanol; up to 126 °C for octane; up to 148 °C for pentanol; up to 160 °C for engine oil; etc.). Compared to water, however, they usually have smaller C_p (typically from 2 to 3 kJ.kg^{-1} K^{-1}) and lower thermal conductivity k (typically from 0.1–0.2 W.m^{-1} K^{-1}), implying lower storage density and poorer heat transfer. Other disadvantages such as the degradation problem and the fire risk when working at high temperature are also identified. Therefore, their utilization is recommended only with caution.

Heat transfer fluids (HTFs) can also be used as liquid storage materials (e.g., [2, 3]). Contrary to the aforementioned pure liquids, they are usually the mixture of synthetic substances. Some commercialized products exist on the market, such as XCELTHERM®, THERMINOL®, DURATHERM®, DOWTHERM®, PARATHERM®, etc., each having a series of candidates with different thermo-physical properties. The interesting feature is that their working temperature could generally exceed 100 °C, so they are mostly used in building-integrated solar energy systems. However, the relatively high cost (with respect to water) also limits their use only in small-sized systems.

Molten salts, liquid metals, and liquid glasses can also be used as HTF as well as sensible storage materials, but for high temperature applications (>150 °C). Hence their intended use fits more the solar thermal power plants rather than for buildings directly.

Table 1 shows a list of liquid materials used or have the potential to be used in sensible heat storage systems for buildings.

Solid Storage Materials

Solid materials are also widely used for the storage of sensible heat for buildings. The building structure itself (concrete, brick, steel, glass, wood, etc.) plays the role as a thermal buffer to attenuate the interior temperature variation using the building thermal inertia [8]. Other common uses are the pecked beds of rocks or pebbles combined with solar energy systems for space heating, the ground and soil storage (such as Chinese Kang). Generally, these solid materials are structured to provide heat transfer surfaces (direct contact) for the HTFs during charging or discharging. Compared to liquid storage materials, solid materials exhibit the advantages like nontoxic, nonflammable, no leakage problem, and thermally more stable. The major drawback is their low specific heat capacity (generally about 1 kJ.m^{-3}K^{-1}), implying low energy density of the storage systems.

Concretes, stones, or sands could usually provide an operating temperature range between 20 °C to 70 °C. Their cost as storage media is acceptable due to their abundant availability. Metals such as aluminum, iron, and copper could be used for high temperature storage applications over 160 °C. They also exhibit good heat conduction property, two or three orders of magnitude higher (e.g., 73 W.m^{-1} K^{-1} for iron, 204 W.m^{-1} K^{-1} for aluminum, 385 W.m^{-1} K^{-1} for copper, etc.) than that of liquid storage materials. Nevertheless, they may be chemically less stable due to the

Table 1 Thermo-physical properties of some liquid materials for sensible heat storage in buildings

Material	Temperature range (°C)	Density ρ (kg. m^{-3})	Specific heat Cp (kJ. Kg^{-1} K^{-1})	Thermal conductivity k (W.m^{-1} K^{-1}) at 20 °C	Reference
Water	0–100	1000	4.19	0.58	–
Ethanol	Up to 78	790	2.4	0.171	–
Propanol	Up to 97	800	2.5	0.161	–
Butanol	Up to 118	809	2.4	0.167	–
Isopentanol	Up to 148	831	2.2	0.141	–
Octane	Up to 126	704	2.4	0.134	–
Engine oil	Up to 160	888	1.88	~0.1	–
XCELTHERM® XT	−55–272	1000	1.70	0.133	[4]
XCELTHERM® XTE	−57–270	968	1.63	0.135	[4]
XCELTHERM® 500	−60–260	789	2.16	0.137	[4]
THERMINOL® VLT	Up to 99	744	1.95	0.112	[5]
THERMINOL® Lt	Up to 181	862	1.79	0.124	[5]
THERMINOL® D12	Up to 192	759	2.10	0.109	[5]
DURATHERM® XLT-50	−45 to 121	820	2.10	0.137	[6]
DURATHERM® HTO	Up to 315	811	1.89	0.137	[6]
DOWTHERM™ 4000	−50–175	1055	3.6	0.442	[7]
DOWTHERM™ SR1	−50–120	1045	3.6	0.442	[7]
DOWFROST™	−45–120	1033	3.8	0.434	[7]
UCARTHERM™	−51–121	n.a.	n.a.	n.a.	[7]
DOWCAL™ 100	−50–175	1047	3.69	0.485	[7]
DOWCAL™ N	−45–120	1026	3.88	0.456	[7]

possible interactions with the HTFs. In terms of cost, they are not naturally available thus should be refined, a factor that also prohibits their large-scale use.

During recent years, researches are focused on the potential of using low-cost alternative materials for solid sensible heat storage (e.g., [9–11]). These recycled materials are generally solid industrial by-products or wastes: asbestos containing wastes (ACW), fly ashes, by-products from the salt industry and from the metal industry, wastes from recycling steel process and from copper refining process and dross from the aluminum industry, and municipal wastes (glass and nylon) [9]. The yearly production of these industrial by-products or wastes is sufficiently abundant to be considered as candidates of storage materials [9]. In terms of thermo-physical properties, recycled materials are comparable, sometimes even more performant than conventional ones, with high thermal and chemical stability and attractive investment cost [12, 13]. In most of the cases, they are targeted to high temperature applications such as concentrated solar power (CSP) plants [14, 15] or compressed air energy storage (CAES), as competitors to molten salts. Recently, it is also reported that these recycled wastes could be used as thermal mass materials for low-energy building construction [12, 16] or combined with solar cooling systems [17], indicating their promising potential as sensible storage materials for buildings.

Table 2 shows indicative thermos-physical properties of some solid materials used or have the potential to be used in sensible heat storage systems for buildings.

Materials for Cold Storage

Chilled water is the most common liquid material for cold thermal energy storage (CTES) in buildings. It is usually stored in specially insulated water tank for daily storage (e.g., [18]) or underground for seasonable storage (e.g., [19]), in connection with the HVAC system of buildings. Ice, as the solid state of water, is also used as storage media, to be stored in special ice storage tanks for daily operation (e.g., [20, 21]). In some cases, ice remains solid during charging/or discharging when it exchanges sensible heat with HTFs (usually air) whereas in other cases phase change may occur to produce chilled water [22], indicating that both sensible and latent heat are involved. For seasonal storage of cold energy, ice or snow can be collected in winter and stored in the form of ice/snow ponds (e.g., [23, 24]). During summer seasons, the stored cold energy could be then recovered by circulating air through the ice/snow ponds. It is also reported that pebbles can also be used (in the form of pebbles bed) for seasonal storage of cold energy [25] in tropical areas (Moroccan).

Short Summary

In summary, the selection of suitable materials with potential for sensible TES in buildings is not an easy task. It is generally application-oriented in which the working temperature range should be firstly considered while other selecting parameters should also be taken into account. The multi-criteria methodology developed by Prof. Ashby [26] associated with Cambridge Engineering Selector (CES) software could be a practical tool. Some case studies were presented in the literature [12, 27] for evaluating materials for sensible TES with the objective of minimized cost.

Sensible TES Technologies for Building Applications

In this section, various building integrated sensible energy (heat or cold) storage systems or technologies will be introduced. Many of the technologies already have their real applications in buildings while some of them are under development

Table 2 Indicative thermo-physical properties of some solid materials for sensible heat storage in buildings [8, 9]

Material	Temperature range (°C)	Density ρ (kg.m^{-3})	Specific heat Cp (kJ. Kg^{-1} K^{-1})	Thermal conductivity k (W.m^{-1} K^{-1}) at 20 °C
Brick	20–70	1600	0.84	1.20
Concrete	20–70	2240	1.13	0.9–1.3
Cement sheet	20–70	700	1.05	0.36
Gypsum plastering	–	1200	0.84	0.42
Granite	20–70	2650	0.90	2.90
Marble	20–70	2500	0.88	2.00
Sandstone	20–70	2200	0.71	1.83
Stone, granite	Up to 160	2640	0.82	1.70–3.98
Stone, sandstone	Up to 160	2200	0.71	1.83
Clay sheet	–	1900	0.84	0.85
Asphalt sheet	–	2300	1.70	1.20
Cork board	–	160	1.89	0.04
Wood	–	800	2.09	0.16
Plastic board	–	1050	0.84	0.50
Rubber board	–	1600	0.20	0.30
PVC board	–	1379	1.00	0.16
Asbestos sheet	–	2500	1.05	0.16
Formaldehyde board	–	30	1.67	0.03
Thermalite board	–	753	0.84	0.19
Fiber board	–	300	1.00	0.06
Siporex board	–	550	1.00	0.12
Polyurethane board	–	30	0.84	0.03
Light plaster	–	600	1.00	0.16
Dense plaster	–	1300	1.00	0.50
Aluminum	Up to 160	2707	0.90	204
Aluminum oxide	Up to 160	3900	0.84	30
Aluminum sulfate	Up to 160	2710	0.75	–
Cast iron	Up to 160	7900	0.84	29.3
Pure iron	Up to 160	7900	0.45	73
Calcium chloride	Up to 160	2510	0.67	–
Copper	Up to 160	8954	0.38	385
Steel slab	20–70	7800	0.50	50
ACW	0–1000	3120	0.8–1.03	1.4–2.1
Fly ashes	25–1100	2600–2962	0.71–1.3	1.2–1.6
Original NaCl	100–200	1384	0.74	0.33
Water shaped NaCl	100–200	2050	0.74	2.84
Astrakanite	0–100	–	0.9–1.2	–

undergoing lab-pilots testing. Each technology will be described in details including different aspects: basic principle, development status, performance and costs, potential and barriers, today's R&D activity focus, etc. For the convenience of description, these sensible TES technologies are classified into two categories: one for short-term storage (daily mismatch) while the other for long-term storage (seasonal mismatch).

Short-Term Sensible TES Technologies

Water Tank

Water tank is a well established and may be the most widely accepted technology for daily TES in buildings. It plays key roles as TES and redistribution. The power source for the water tank could be variable, the most common case is coupled or integrated with conventional gas/electric boilers (e.g., [28]), air-water heat pumps (e.g., [29, 30]), or combined heat & power (CHP) (e.g., [31–35]), as being used in a large number of existing buildings all over the world. Renewable energies could also serve as the power source, including solar energy (flat plate, vacuum tube solar collectors, PV panels, or their hybrid) (e.g., [36–40, 41, 208]), geothermal energy (e.g., [2, 42]), or fuel cells (e.g., [43, 44]). In this case, fossil/electric backup directly integrated or coupled to the water tank is usually a necessary complement. Poly-generations could be another choice (e.g., [45, 46]).

Both hot water and cold water can be stored at water tanks. Hot water tank usually stores water from about 40 °C to 80 °C depending on the heat source and power, mainly for the purposes of space heating and domestic hot water (DHW) production. It should be noted that the stored hot water can also be used for space cooling, usually by running an absorption chiller (e.g., [39, 40, 47–51]) or thermoelectric elements (e.g., [52]) at the downstream of water tank. In cold water tank, chilled water below the room temperature (usually from about 3 °C to 15 °C) is stored, for the purpose of space cooling.

Water tanks could be located either inside or outside the buildings or even underground, with different geometries (vertical/horizontal cylindrical or rectangular) and sizes (from several tens of liters for a single room to a few thousand cubic meters for a district heating and cooling plant). One example of typical hot water storage tank to be combined with solar collectors is shown in Fig. 1. They could be made of a wide variety of materials such as steel, aluminum, or reinforced concrete. By using fiber/plastic composites, expanded polystyrene (EPS) and encasement material, the water tank weight could be one third of that of a compatible storage tank made of steel and is corrosion-free [54]. Generally, they have to be insulated to avoid thermal losses to the ambient, using conventional materials such as glass wool [55], mineral wool, eco cotton-wool [28], polyethylene terephthalate (PET)-fiber fleeces [56], or polystyrene panels [30]. Developing advanced insulation materials having an extra low thermal loss rate ($\lambda = 0.01$ W/m.K) and reasonable thickness for water storage tanks, such as silica aerogel based [57] or vacuum insulation panels [58], is one of today's R&D activities focuses.

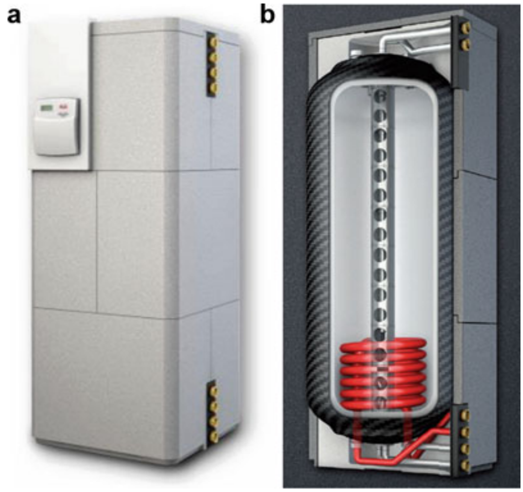

Fig. 1 Roth's Thermotank Quadroline [53]

Another R&D focus is how to maintain the temperature stratification (higher temperature at the top while lower temperature at the bottom) in the water tank (Fig. 2), a key factor that can effectively improve the performance of the energy storage. Ghaddar [59] found that the energy storage efficiency and the whole system may be augmented by up to 6% and 20% by using fully stratified water tank instead of fully mixed one in many solar water heating systems. Various solutions have been proposed to inhibit the turbulence generated from the mixing of the hot and the cold water during charging or discharging. These measures include optimizing the geometrical parameters of the water tank (e.g., tank size; height-to-diameter ratio, etc.) (e.g., [18, 60, 61]), better selecting inlet/outlet positions and shapes (e.g., [62–66]), determining appropriate operating conditions (inlet flow velocity, temperature, cyclic duration, etc.) (e.g., [67–69]), and adding baffle plate or porous mesh at the inlet of the tank (e.g., [70–72]). Recent studies also showed that using partition/stratification plates in the water storage tank could lead to good performance in both energy storage and thermal stratification [73, 74]. A detailed review on the thermal stratification within the water tank was provided by [73].

Packed Bed

Packed beds (also known as rock beds or pebble beds) consist of a bed of loosely or structurally packed solid materials through which the HTF can flow. For buildings applications, it is usually used in conjunction with air-based solar collectors, either directly integrated into the solar collector (e.g., [55, 75, 76]) or standing independently as a tank and connected to the solar collector via pipes or ducts (e.g., [77, 78]). During the charging phase, heated air from the solar collector passes the pebbles bed from the top down to the bottom to release the heat. During the heat-discharging phase, the air from room enters from the bottom to the top of the bed to absorb the stored heat and the heated air is then delivered into the building.

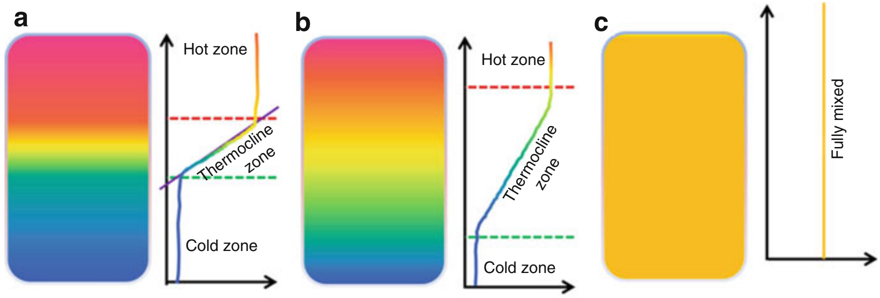

Fig. 2 Differing degrees of stratification within a storage tank with the same amount of stored heat: (**a**) highly stratified, (**b**) moderately stratified, and (**c**) showing fully mixed, unstratified storage [202]

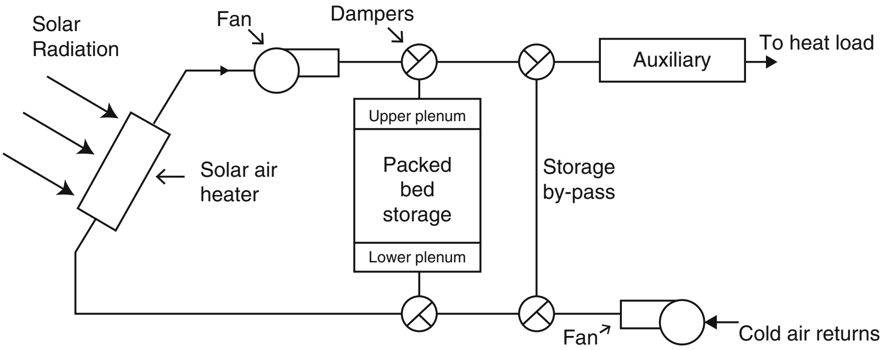

Fig. 3 Schematic of a packed bed energy storage combined with air-based solar system for buildings [80]

Packed beds are generally considered as the most suitable energy storage unit for air-based solar systems for buildings (e.g., Fig. 3) owning to the abundant and low-cost solid storage materials available and the efficient heat transfer through the direct contact between air and the solid particles. Michelson and Shitzer [79] studied a solar air heating system designed for a floor of 120 m^2 offices in Israel and reported that adding a rock bed storage could improve the system's performance. Otherwise, the increased solar collector area is needed. Singh et al. [78] reported that the heat retrieval efficiency of a packed bed could reach about 75–77%, better than that of PCM-based storage system (66.7–72%).

Despite a variety of storage materials available, the shape and size of the packing materials and void fraction are key factors that determine the thermal performance and the pressure drop of the storage unit [80]. Sorour [81] investigated small size (several dozen liters) pebbles bed storage units used in many short-term applications and reported that lower flow-rates of HTF with intermediate particle diameter of pebbles are advantageous to achieve high efficiencies of the storage unit. Ammar and Ghoneim [82] reported that particles with smaller diameter, i.e., with higher values of interfacial surface area per unit volume cause a large degree of thermal stratification in the bed. Nonetheless, Sagara and Nakahara [83] suggested that a trade-off has to be made between the thermal performance and pressure drop in designing packed bed storage unit. For example, a large size material like bricks or concrete blocks may have poorer thermal performance, but the required power supply to run the fans is also small. An economic evaluation might become a decisive factor for the design.

Besides conventional concepts for packed beds storage unit, some new configurations were also proposed to intensify the heat transfer. Audi [84] proposed to use a storage bin with trays to carry the rocks instead of randomly packed rocks. Crandall and Thacher [85] proposed the arrangement of segmented/cascade storage tank system instead of a single tank. Other researchers also proposed to use combined storage systems such as coupled rock bed and water storage unit [86] or combined rock bed – solar pond storage system [87]. A detailed review on packed bed solar energy storage systems was presented by [80].

Thermal Mass

Thermal mass of a building is natural thermal storage media. If controlled or managed appropriately, the use of heavyweight construction materials has various advantages owning to their high TES capacities including (1) dampen the wide range temperature fluctuation from the outdoor [88]; (2) reduce the peak heating or cooling power demands [89]; (3) maintain the indoor thermal comfort [102]; (4) reduce lifecycle CO_2 emissions [91]; and (5) resist to structural damage by severe storms [92].

Akbari et al. [93, 94] reported that the heat storage capacity of the massive structural materials (both external and internal walls) in buildings is affected by the convective heat transfer coefficients of air profile. Yam et al. [95] further developed understanding of the thermal mass effect and found that there is an optimal amount of thermal mass to be used in building passive design as further increase of thermal mass would not increase storage effect. Ma and Wang [96] also found different optimal thicknesses of interior planar thermal mass of various materials for reaching a maximum value of the heat storage capacity. As a result for different buildings, this optimal amount of thermal mass should be determined carefully.

Recent R&D focus on the thermal mass topic lies on the development of optimal operation strategies for building thermal processes, taking the TES by thermal mass factor into account. These thermal mass include the building structure (external and internal walls) [209], earths [92], internal furniture and contents [97, 98], stored products in warehouses [201], or water-filled containers [99]. Some examples are shown in Fig. 4. For commercial buildings, Henze et al. [100] studied the impacts of adaptive comfort criteria and heat waves on optimal building thermal mass control. A model-based demand-limiting control of building thermal mass was developed by Lee and Braun [101]. Recently, Li and Malkawi [102] developed a multi-objective optimization based model predictive control framework that takes both energy cost and thermal comfort into consideration simultaneously. For residential buildings, Le Dréau and Heiselberg [103] found that the thermal mass storage

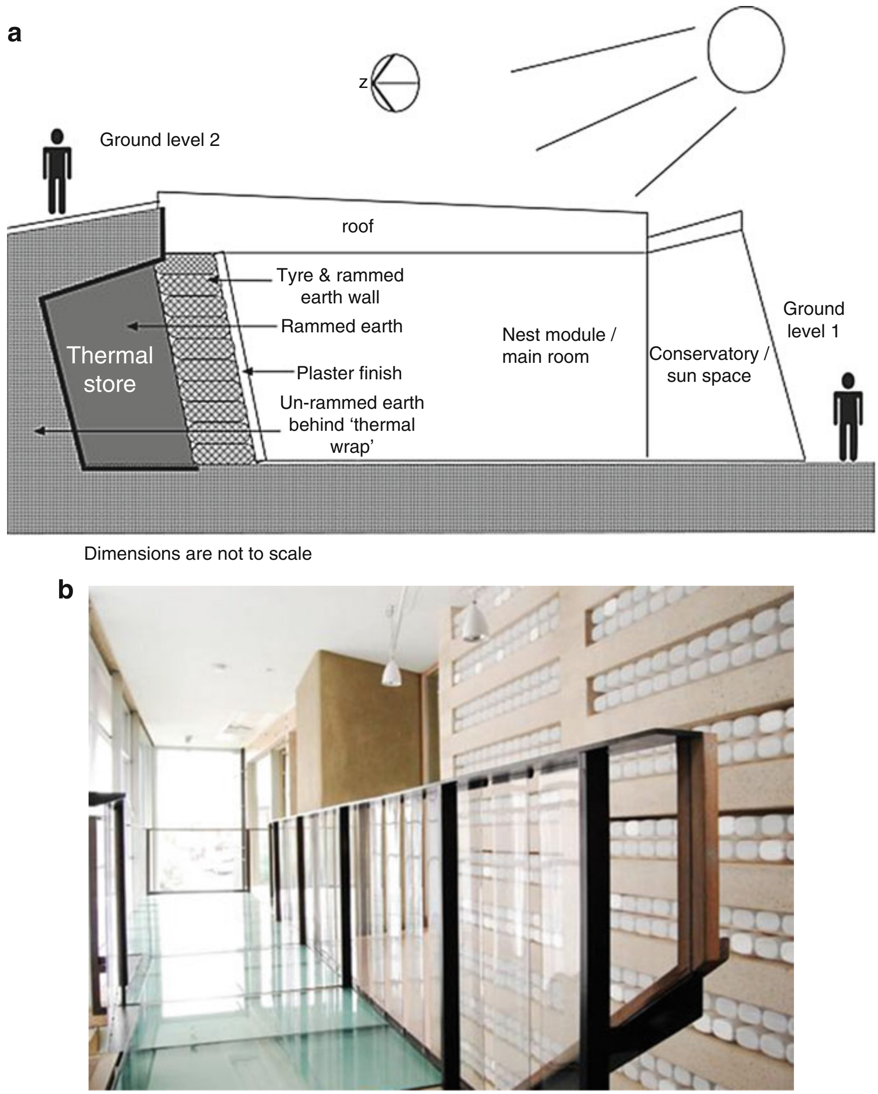

Fig. 4 Thermal mass for TES in buildings. (**a**) Section of Brighton Earthship [92]; (**b**) water filled containers in Marsh House Two [99]

potential depends largely on the insulation level thus the control strategy should be designed differently to make use of the flexibility potential without violating the comfort.

One future direction of thermal mass storage is the development of hybrid adaptable thermal energy storage approach that usually used PCMs integrated-lightweight building construction materials [104] or PCMs integrated-internal furniture [105] to improve the thermal comfort.

Thermally Activated Building Systems (TABS)

Different from the thermal mass, thermally activated building systems involve building surfaces or building structures with water pipes or air ducts embedded. Water or air is used as HTF while the building mass is used as storage media to buffer the room temperature fluctuation by storing or releasing the heat from the thermal mass. TABS is a really ancient concept that can be tracked back to Roman hypocaust, Korea Ondol, and Chinese Kang, using oven, boiler, or stove as the heat source. An historical review on TABS research was presented by [106]. These heating and storage systems in buildings developed by different countries share similar principles and are now still widely used with some conceptual developments. Owing to the advantages such as high thermal inertia, big heat transfer surfaces, and radiative nature, TABS is still applicable in modern buildings.

Hypocaust is a building construction concept originated during ancient Roman in which the hot gases from the furnace are guided to pass through floors (square pillars) and cavity walls and to warm the rooms of buildings. The emissions are then discharged through holes in the roof. In this case, the building structure serves as thermal mass for the sensible heat storage. Bansal [107] analyzed four hypocaust constructions in modern Europe (School of Tournai, Belgium; Meteolabor Laboratories, Switzerland; Sogeco Office Building, Italy and Schopfloch Kindergarten, Germany) and concluded that it is a good alternative even in modern concept of building heating because the heat losses from building walls/floors are first reduced.

In China, the Chinese Kang is a device widely used in cold regions in Northern China by more than 175 million people [109]. It is actually a multi-functional rural domestic system that serves cooking, space heating, bed warming, thermal storage, and natural ventilation purposes. A typical Chinese Kang consists of a stove, a Kang body (similar to a bed), a chimney, and airflow paths for the smokes. The Kang body/plate is heated by the hot smoke flow during cooking time. The thermal energy stored in the thermal mass material of Kang bed (concrete, earth, or stone) can maintain a heating period of several hours or more for the room by convection and radiation [109].

The commonly used Kangs today include the traditional grounded Kang and new elevated Kang. The major difference is that the former is directly built into the floor while the latter is suspended from the floor. The improvements achieved by the elevated Kang include the increased heat utilization of smoke, improved temperature uniformity of the Kang bed, and higher controllability and insulation level [109]. The design of thermal storage by the Kang body is a key factor that affects the indoor thermal comfort level and the biomass energy saving potential. Zhuang et al. [108] had developed an elaborate thermal and airflow model and investigated thermal storage characteristics of a Chinese Kang. A design guide was also proposed to determine the thickness of a Kang plate (quantity of thermal mass) and firing distribution. Recent developments of Chinese Kang concern the combination of solar energy and biomass energy for cooking as the heat source.

Similar architecture also exists in Korea, named as Ondol. Instead of a Kang bed, it is the whole floor of the building that will be heated by the hot smoke from a firebox or a stove (Fig. 5). As a result, it is also called radiated floor of Korea style.

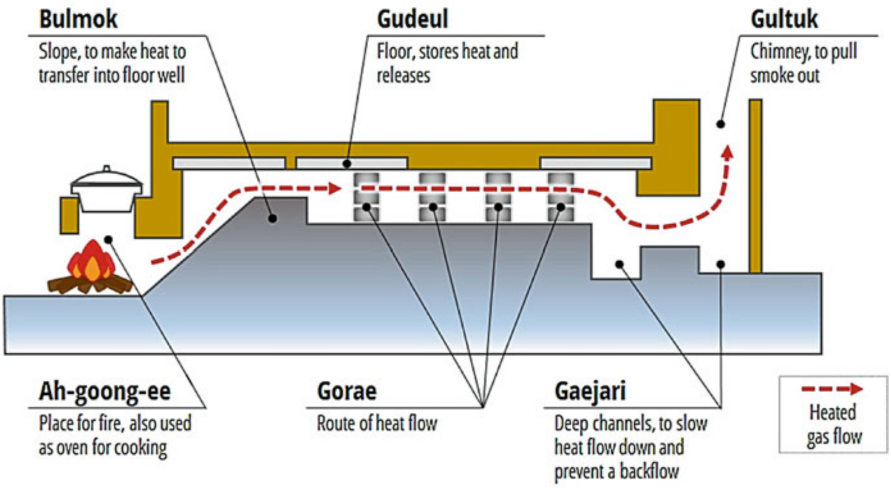

Fig. 5 Schematic view of Korean under-floor heating system Ondol [111]. Similar principles may also be found in other contraries such as ancient Romaine's Hypocaust or Chinese Kang

The heated floor, supported by stone piers or baffles to distribute the smoke, is covered by stone slabs, concreate slabs, clay, or sand layer [110] and an impervious layer such as oiled paper. The improved modern floor/ceiling technology in general involves light-weight TABS placed above the floor structure/at the lower surface of ceilings. It is commonly assumed that the radiant floor/ceiling only exchanges heat with the internal air for heating or cooling of the room while the external layers are well insulated.

Modern concepts similar as Hypocaust are also developed in recent years, including hollow core slabs, concrete core, and pipe-embedded building envelope, as shown in Fig. 6. They are technically prefabricated heavy-weight building walls or slabs with water pipes or air ducts embedded in the slab core.

Recent R&D focus of TABS includes several directions. Firstly, adding PCMs in the building mass is an effective method to increase the heat storage capacity. Some examples include the use of PCMs as thermal storage material for the Ondol system [110]; prefabricated concrete slab with encapsulated PCMs [114]; and PCM-concrete mixture layers [115, 116]. The second direction involves the coupling of TABS with low grade energy sources, owing to the efficient heat transfer between HTF and room air even with small temperature gradient. The investigated low-grade energy sources include solar air collectors [117, 118], solar-collected walls [119], building-integrated photovoltaic-thermal (BIPV/T) system [120–122], ground source [123, 124, 205], and natural wind [125, 126]. Finally, the control strategies for TABS should be carefully determined, which directly affect the comfort conditions and energy saving potential [127]. Supply temperature control with heating and cooling curves is common for most TABS. More advanced controls use heating curves as the base of its control for the determination of the energy to be supplied and the periods

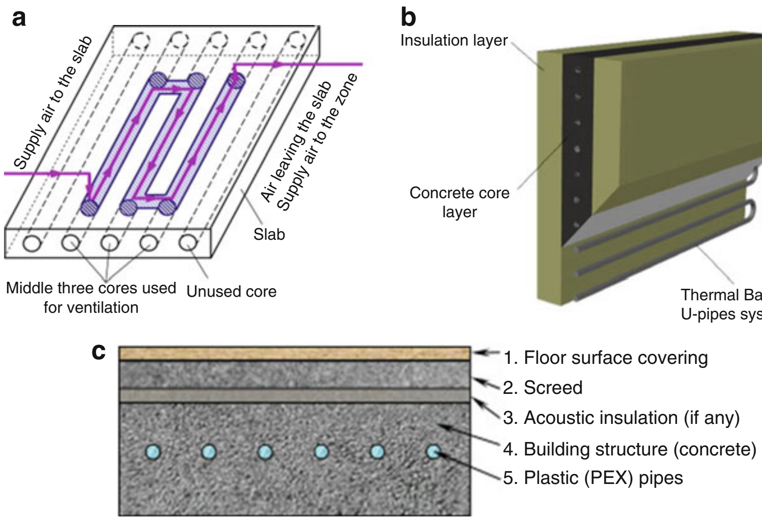

Fig. 6 Different types of prefabricated TABS. (**a**) hollow core slab [206]; (**b**) pipe-embedded building envelope [112]; (**c**) concrete core [113]

of activation. Detailed information on the simulation and control strategies of TABS is provided in the review paper by Romani et al. [127].

Solar Walls

Solar walls, also named as Trombe walls, usually refer to the building envelope walls which are specially designed to absorb solar rays and store thermal energy, so as to reduce a building's energy consumption. If properly installed, a solar wall could be an important green architectural feature that reduces a building's energy consumption up to 30% [128].

The basic principle of a classic or standard solar (Trombe) wall can be tracked back to the Gangway vernacular architecture of the Persian Gulf [129] and was again popularized in modern buildings by a French engineer Felix Trombe in the late 1950s [130]. It uses high heat storage capacity materials (e.g., concrete, brick, stones, etc.) as the external wall of a building, which is covered by an exterior glazing with an air space of several centimeters between both components (Fig. 7). The black-painted surface of the wall absorbs diffused and direct solar radiation during the day and transfers the heat to the heavy thermal mass of the wall by conduction. The stored heat could be released gradually when needed through radiation and convection. Air flow in the gas produced by natural or forced convection usually enhances the heat transfer and improves the thermal comfort of the building.

Standard solar wall can be modified into different configurations depending on different purposes and environment conditions. The conceptual evolution could involve natural ventilated or mechanically ventilated [132], vented or unvented [133], south faced or angled [134], light or dark colored [135, 207], external or

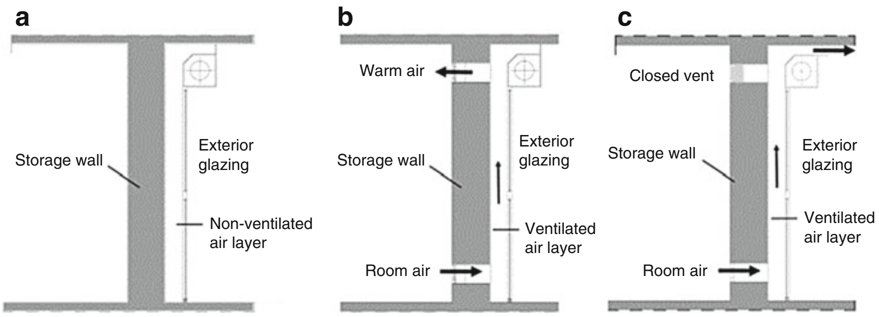

Fig. 7 Various configurations of a solar wall: (**a**) without ventilation; (**b**) winter mode with air thermo-circulation; (**c**) summer mode with cross ventilation [131]

internal insulated [136–139; etc.], pure air circulated in the air gap or with fluidized particles added [140].

One development trend is the solar wall having several different layers, also called as composite Trombe wall. Besides the thermal mass layer (e.g., concrete), the combination could include a water layer [141], another concrete layer with forced air ventilation between two layers [142], PCM plasterboards or bricks [143–145] (Fig. 8a), PCM layer with delta winglet vortex generators [110], or coupled layer of PCM and transparent insulation material (silica aerogels) [146]. The main purpose is to increase the heat storage capacity while reduce the thermal losses. Another innovative development is the PV-Trompe wall (Fig. 8b), in which the front side of the glazing is composed of PV panels [147–149]. The use of PV panels instead of glazing would unfortunately reduce the solar heat gain. However, the cooling of PV panels will increase its efficiency in electricity generation. This conception is also referred to as BIPV/T systems.

Further studies in terms of heat storage are suggested on the determination of the optimal thickness of various materials, such as stone, brick, adobe, concrete, etc., for different climate regions [130]. The coupling with other renewable heat sources is also an issue that needs further efforts.

Long-Term Sensible TES Technologies

Sensible TES technologies can not only be used for short-term (daily) storage in buildings but also for a longer period, i.e., more than several months for inter-seasonal storage. The main purpose is to store the excessive heat in summer season for supplementing the heating demands during winter, or vice-versa, to store excessive cold in winter for the space cooling during next summer. In this regard, the heat source for seasonal TES is in general the solar energy while the cold source is usually the ice or snow produced in nature due to cold weather. The key issue is then how to reduce the thermal losses during the long storage period, i.e., to maintain the temperature of the sensible storage materials. Otherwise, these technologies will

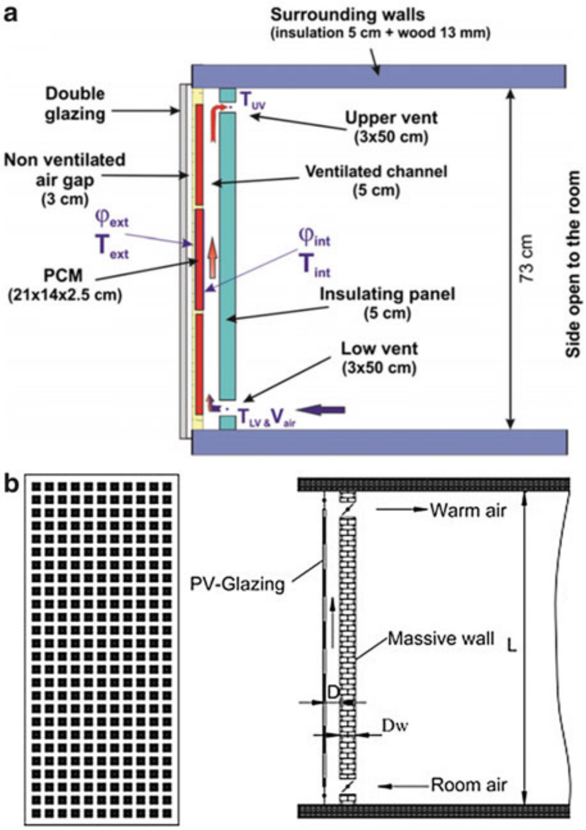

Fig. 8 Hybrid solar wall: (**a**) composite Trombe wall with PCM layers [145]; (**b**) combined PV-Trombe wall [150]

have low energy efficiency thus not be profitable. Since increasing the storage size reduces the loss-to-capacity ratio [151], the development of seasonal TES technologies has been aimed at large-scale district heating and cooling plants instead of single house or apartment.

Generally speaking, there are different ways of sensible seasonal TES. The most common technologies are: water (hot or chilled) tank TES, aquifer TES, borehole TES, and water-gravel TES, as shown in Fig. 9. Among them, the first three use liquid (water) as storage material, the last one (borehole) belongs to the type of sensible solid storage, while water-gravel TES is a combination of liquid and solid storage.

Water Tank

Water tanks still have the widest range of utilization possibilities for seasonal TES. They are usually made of stainless steel or reinforced concrete with insulations at least at the top of the tank and on the vertical walls [153, 154], partially or totally buried underground [155, 156] or outside of a building [157]. Both hot water and chilled water [19, 158] may be stored in the tank, for the purpose of heating or

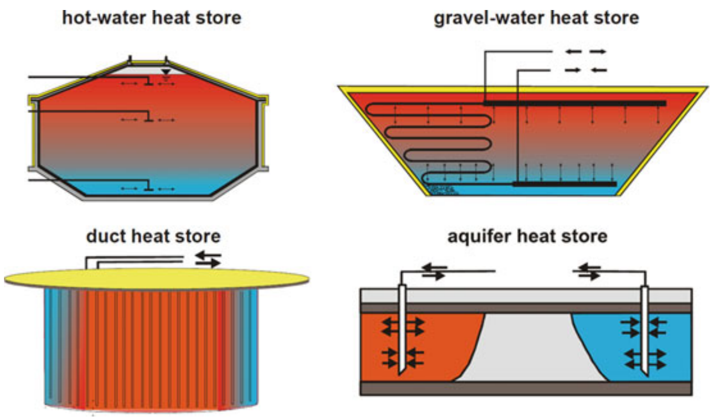

Fig. 9 Different types of sensible seasonal TES [152]

cooling in the next season. Some demonstration projects for buildings with available details on seasonal water storage tanks are presented in Table 3.

Maintaining the temperature stratification inside the water tank is again a key issue for the storage system efficiency. In addition to measures introduced in 4.1.1, multiple charging/discharging [152] was also proposed instead of conventional two levels for charging and discharging (on the top and at the bottom). More precisely, a third charge/discharge device was introduced at variable height in the middle of the water tank, permitting simultaneous charging and discharging at different temperature levels without disturbing much the temperature stratification.

Another research of interest in water tank seasonal TES lies in the insulation materials and methods so as to reduce the heat losses. Some efforts on this point can also be found in Table 3 and in Fig. 10, in connection with the water tightness issue and vapor leakage problem. An optimization method has also been proposed by [160] for determining the optimal amount and distribution of thermal insulation on the water storage tanks to reduce heat losses and improve the cost-effectiveness. A life-cycle assessment of a European apartment building using water tank seasonal TES is performed by [161].

Gravel-Water

The gravel-water seasonal TES concept is similar as the water tank TES but both water and rock/gravel are used as storage mediums. The pit/tank is usually buried underground with insulations on the top and on the side walls so as to reduce thermal losses, as shown in Fig. 11. This type of storage is also named as man-made or artificial aquifer [169]. Pipes are usually installed in different layers of the store for the circulation of HTF to release or absorb heat. Since the gravel-water mixture has lower specific heat than pure water, the volume of the whole basin should be approximately 50% larger compared to water tank TES to obtain the same storage capacity [169]. On the contrary, the lower costs of the envelop structure and storage medium (rock, gravel, sand, etc.) make the gravel-water TES much cheaper. As a

Table 3 Technical data on the seasonal TES plants using water tank

Plant	Heated living area (m^2)	Solar collector area (m^2)	Storage volume (m^3)	Tank geometry and material	Water tightness	Thermal insulation	Reference
Hamburg Germany	14,800	3000	4500	Concrete	1.2 mm stainless steel liner + polyethylene or polyvinylchloride film	0.3 m mineral wool	[152]
Friedrichshafen Germany	39,500	5600	12,500	Concrete			[152]
Hannover Germany	7365	1350	2750	Height density concrete	Without inner steel liner	Granulated blown-up glass packed in large textile bags	[152]
Munich Germany	24,800	2900	5700	Prefabricated concrete elements	Stainless steel liner + welded plates	Expanded glass granules (minimum 0.3 m at the bottom; maximum 0.7 m on the top) + 20 cm layer of foam glass gravel	[162]
Eggenstein Germany	12,000	1600	4500	Cavity	Polyethylene (PE)-liner	Expanded glass granules + foam glass gravel	[162]
Hoerby Denmark			500	Concrete	Bentonite-concrete coating inside		[163]
Herlev Denmark		1025	3000	Concrete and steel sheet piles	Ethylene propylene diene monomer rubber membrane + clay layer	Polyurethane foam	[163]

Ottrupgaard Denmark		560	1500		Clay layer	Polyurethane foam	[163]
Lambohov Sweden	55 houses	2700	10,000	Excavated rock pit	Butyl rubber	Cement bound lightweight sintered clay granules and lightweight concrete	[164]
Säro Sweden	48 hourses	740	640	6 m deep excavation	Stainless steel liner		[165]
Carabria Italy	1750	91.2	500	Reinforced concrete	Spherical cover made from concrete lightened by expanded clay	Foam glass and water proofed by means of a geo-membrane in direct contact with water	[166]
Lisse Netherland		1200	1000	Concrete	HDPE film	Open-cell polystyrene	[167]
Galway Ireland	215	10.6 evacuated tube	23.3	Underground		Spray on soya insulation applied to wall EPS 400 mm wall, 600 mm floor and top	[168]

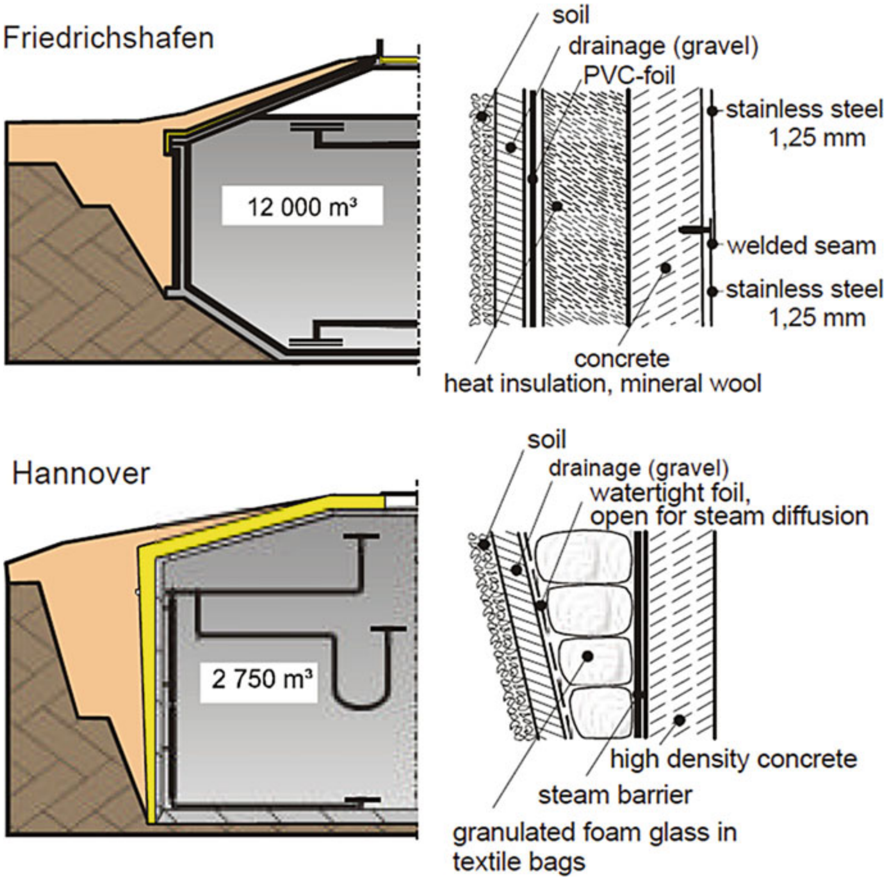

Fig. 10 Insulating techniques for water tank TES systems in Friedrichshafen (*left*) and Hannover (*right*) [159]

result, it also finds its place in for large-scale applications in district heating/cooling plants. Table 4 presents some key parameters of the gravel-water seasonal TES systems realized in Europe.

Aquifer

An aquifer is a geological formation that contains groundwater and permits significant amounts of water to move through it (Bear 1979). Different from the artificial water tank seasonal TES, aquifer TES relies on the natural aquifer layer, avoiding expensive investments of underground excavation and the construction. It was considered as a "promising cost-effective option" for seasonal storage [171].

In an aquifer TES system, the groundwater saturation zone is used for heat storage purposes. It usually consists of at least two thermal wells drilled into the aquifer – one is called the hot well and the other the cold well. During summer

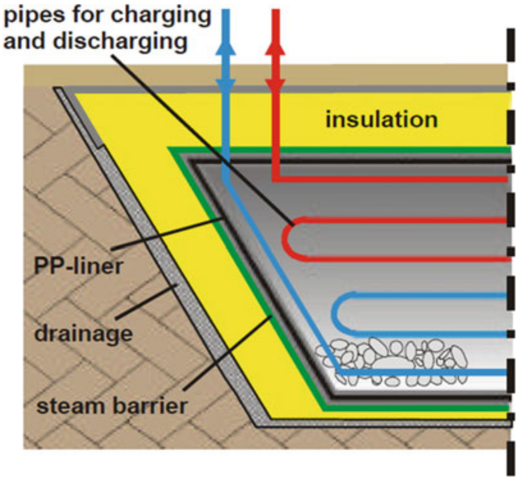

Fig. 11 Construction of the gravel-water TES in Steinfurt, Germany [159]

when space cooling is needed, cold water is extracted from the cold well by pumps, heated by the chosen heat source and rejected into the warm well. The circulation is reversed during winter when heating is required, i.e., hot water is extracted from the warm well, cooled and re-injected into the cold well. Due to the large site requirements, aquifer TES technology is more suitable for large scale district heating and cooling plants rather than single family houses or apartments with small loads.

For aquifer TES, geological conditions at the site are the decisive factors. Some expected features include: high ground porosity, medium to high hydraulic transmission rate around the boreholes, minimum ground water flow through the reservoir, chemical stable for the interactions between ground water and the matrix, etc. Moreover, a good knowledge of the mineralogy, geochemistry, and microbiology in the underground is necessary to prevent damage to the system caused by well-clogging, scaling, etc. [152, 173]. Table 5 presents some key parameters of the aquifer TES systems realized in Germany.

One of the research focuses lies in the influence of groundwater on the efficiency of aquifer TES. Nagano et al. [175] found that large-scale natural convection could occur when high-temperature water is injected into the warm well, which will influence the forced horizontal flow in the saturated porous medium. Zhou et al. [176] numerically studied the influences of the direction and velocity of groundwater on the underground temperature field. They concluded that the groundwater horizontal downstream is favorable to improve the efficiency of combined heat pump and aquifer storage system. Therefore, rational arrangement of well groups should be further considered in the future to achieve a more advantageous effect of groundwater horizontal downstream in practical engineering. Nevertheless, Yapparova et al. [177] found that ground water does not affect the storage efficiency significantly when double concrete walls are provided as thermal insulator.

Table 4 Technical data on the seasonal TES plants using gravel-water concept

Plant	Heated living area (m^2)	Solar collector area (m^2)	Storage volume (m^3)	Pit geometry	Water tightness	Thermal insulation	Reference
Stuttgart Germany		211	1050	Truncated cone	2.5 mm high-density polyethylene liner	Pumice and plyurethane	[170]
Chemnitz Germany	4680	2000	8000	Truncated cone	2.5 mm high-density polyethylene liner	Extruded polystyrene plates	[171, 172]
Steinfurt Germany	3800	510	1500	Truncated cone	Polypropylene liner	Granulated foam glass in textile bags	[159, 172]
Lyngby Denmark			500		HDPE liner	Expanded polystyrene	[163]
Eggenstein Germany	12,000 (school, sport center)	1600	4500		HDPE liner	Fam glass gravel and expanded glass granules	[157, 162]

Table 5 Hydrogeological parameters of the aquifer TES in Germany [174]

Site	Dresden (field test)	Rostock-brinckmanshohe	Buildings of the German parliament in berlin		Neubrandenburg
Geological formation	Quaternary	Quaternary	Hettangian	Quaternary	Upper Postera
Depth	7 m–10 m	13–-27 m	285 m–315 m	30 m–60 m	1234 m–1274 m
Porosity	~25%	~20%	30%	~30%	25%
Permeability	>2 μm^2	8 μm^2	2.8–4.2 μm^2	>1 μm^2	>1 μm^2
Mineralization	Freshwater	Freshwater	29 g/L	Freshwater	133 g/L
Store temperature (initial)	8 °C	10 °C	19 °C	10 °C	54 °C

Another research hotspot is on the thermal interference between hot and cold wells in an aquifer or in a number of aquifers in an area on the storage efficiency. Kim et al. [178] numerically found that thermal interference grows as the borehole distance decreases, as the hydraulic conductivity increases, and as the pumping/injection rate increases. Yapparova et al. [177] reported that storage efficiency increases with the distance between injection and production wells and decreases with increasing injection temperature. Meanwhile, Bakr et al. [179] investigated 19 aquifer TES systems with a total of 76 functioning wells installed in an area of 3.8 km^2 in the Netherlands. They reported that interference among individual wells of an aquifer TES system and wells of other systems may have a positive impact on the efficiency of a well/system since it can help in trapping energy (cold or warm) within the capture zone of all operating aquifer TES systems. Sommer et al. [180] further developed an optimization method for determining the optimal well distances/spatial pattern of large-scale aquifer TES, so as to avoid negative thermal interference and to improve the efficiency of the storage system. A recent numerical study [181] revealed the negative thermal interference caused by the premature thermal breakthrough when the thermal front (generated by the thermal injection) reaches the production well. They also found that permeability of the confining rocks, well spacing, and injection temperature are important parameters which influence transient heat transport in the subsurface porous media. It should be noted that the researches on this topic usually use numerical simulation methods, while field experimental measurements are still rare.

The most promising direction for the future development of aquifer TES is the combination with other heat/cold sources/equipment. In essence, heat pump is usually combined with the aquifer TES in order to reach higher heat source temperature and maintain the storage water at a relatively lower temperature, as shown in Fig. 12. Paksoy et al. [203] found a 60% increase in COP of the combined heat pump and aquifer TES system, when compared to that of a conventional heat pump using ambient air. Ghaebi et al. [182] revealed that the combination of the aquifer TES with the heat pump, to meet both cooling and heating needs of the complex, is an efficient way for building applications. Hill and DeHouche [183] studied the employment of aquifer TES in combination with a commercial water to air heat pump in Afghanistan. They predicted that the annum fuel saving could reach £335,000 with a payback period of less than 2 years. The application of the concept for heating and cooling in buildings is reported, such as for a hospital in Belgium [184]; an office building in Scarborough, Canada [185]; residential and commercial buildings in Rastatt, Germany, with a storage volume of 23,000 m^3 [186]; and multi-family houses in Rostock, Germany, with a storage volume of 20,000 m^3 [152]. More details on the heat pump coupling may be found in the review paper [187]. Recently, Xiao et al. [188] investigated the feasibility of the combination of an aquifer TES and the cooling tower of a seasonally running thermal plant. They found that the aquifer TES system could be optimized by locating the cool water supply well upstream of the storage well.

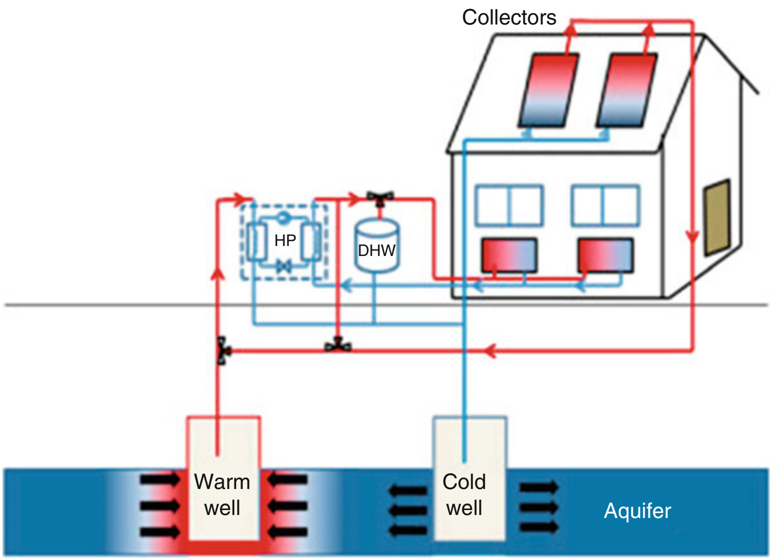

Fig. 12 Aquifer TES combination with a heat pump and solar thermal collectors [187]

Borehole

Borehole TES uses the ground (rock, sand, soil, etc.) itself as heat storage material, which usually comprises vertically or horizontally drilled boreholes in the ground. It is also called as ground/soil storage or duct heat storage in the literature. Tubes are filled in boreholes (also called borehole heat exchangers) through which the HTFs (usually water or glycol if necessary) circulate to release into or absorb heat from the ground. Different types of borehole heat exchangers are used, such as single U-pipe, concentric-pipe, or double U-pipe, as shown in Fig. 13. The top cover of the borehole system should be insulated to reduce heat losses while there is no specific boundaries underground [189]. Due to the small temperature difference between the ground and the HTF for borehole TES systems, the combination with heat pumps is usually recommended to improve the efficiency of the whole system [187].

One of the important issues for borehole TES systems is the control of heat transfer underground: the heat exchange between the HTF inside the tube and the surrounding ground should be enhanced while the heat conduction away from the reservoir (thermal losses) should be reduced. The influencing factors could include the thermal properties of the materials, the arrangement/configuration of tubes, and the geochemical conditions of the location. Some favorable features for a successful borehole TES are rock/soil with high specific heat, medium thermal conductivity, good contact between the tubes and the surrounding soil and favorable groundwater, etc. Lanini et al. [189] also proposed some design guidelines including the definition of spatial distribution by a cylindrical volume with a diameter twice its height, the depth limitation of borehole at 100 m, and a constant distance (5 m) between two

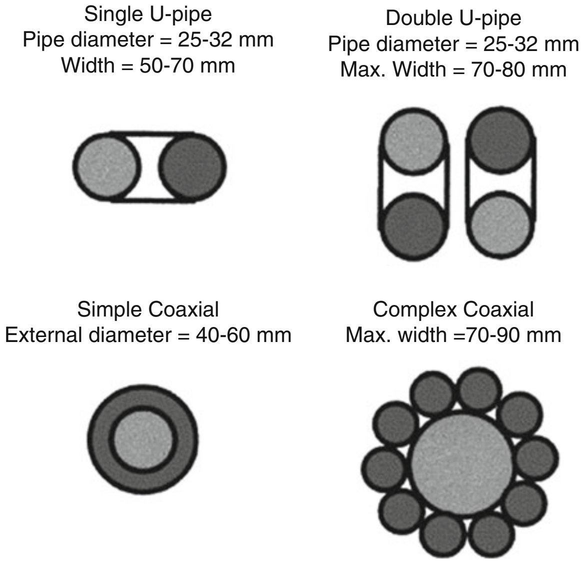

Fig. 13 Different configurations of borehole heat exchangers [190]

boreholes. The possibility of thermal energy storage in shallow trenches filled with encapsulated PCMs is also studied by [191].

Some efforts in the literature focused on reducing the contact thermal resistance between the pipes and the borehole wall by using filling grouting materials with high thermal conductivity. These grouting materials include bentonite or high solid composite (such as 9% blast furnace cement, 9% Poland cement, 32% fine silica sand, and 50% water) [192], water alone [193], and a composite material with graphite additive [194].

Borehole TES concept has received considerable attention for large-scale seasonal TES plants owing to its adaptive feature (no specific requirements for the locations) and its possibility for a modular design [152]. Due to its lower energy storage density than water-based TES concepts, a borehole TES system requires 3–5 times more volume to reach the same amount of stored energy. The payback time estimated ranges between 5 and 10 years, which is also higher than that of aquifer TES systems, mainly due to the significantly high initial cost (cost of borehole tubes and ground work) and the long time to reach typical performance [195]. Table 6 presents the technical data for some typical seasonal TES plants using borehole technology.

Comparison between Different Sensible Seasonal TES Technologies

Based on the above discussion, it may be seen that different sensible TES technologies have been already widely applied for seasonal storage, preferentially in large-scale heating/cooling plants than in single-family houses. This is because the investment cost (per water equivalent) decreases as the storage volume increases [159]. The costs of water-tank or gravel-water concepts are relatively higher due to the construction of water tank/pit and the ground work. Borehole and aquifer TES

Table 6 Technical data on the seasonal borehole TES plants

Plant	Heated living area (m^2)	Solar collector area (m^2)	Borehole storage volume (m^3)	REF
Neckarsulm Germany	20,000	5470	63,360 (doubled in U-shape duct of 30 m deep)	[152]
Attenkirchen Germany	30 homes	863	500 (hot water) + 10,500 (borehole) (90 borehole double-U-loops of 30 m deep)	[196]
Crailsheim Germany	School and gymnasium	7300 (vacuum tubes)	37,500 (double U-pipes, 80 boreholes with a depth of 55 m)	[197]
Anneberg Sweden	50 residential units	2400	60,000 (crystalline rock; double U-pipes; 100 boreholes with a depth of 65 m)	[195]
Lidköping Sweden		2500	15,000 (clay)	[186]
Kungsbacka Sweden	School building	1500	85,000	[197]
Drake landing solar community Canada	52 homes	2313	33,657 (144 boreholes with a depth of 35 m)	[192]
Treviglio Italy	Residential area	2727	43,000	[186]
Groningen Netherlands	Residential area	2400	23,000	[186, 197]
Kranebitten Austria		400	60,000	[198]
Shanghai China	2304 (greenhouse)	500 (vacuum tube)	4970 (130 U-pipes at a depth of 10 m)	[204]
Harbin China	500 (detached houses)	50	5100 (12 single U-pipes at a depth of 50 m)	[199]

technologies are relatively cheaper in terms of initial cost but depend strongly on the geological conditions for their installation. Moreover, the influences of the drilled boreholes or aquifers on the underground hydro-geological and microbiological situations after yearly usage still need to be further investigated. Table 7 summaries the characteristics of each sensible seasonal TES technology and gives a comparison on their advantages and limitations.

Several R&D problems still exist. Firstly, how to adjust the thermal interference (stratification) when heat or cold is charge into or discharged from the store requires further efforts of researchers. Secondly, the development of cost-effective insulation materials to reduce the thermal loss during the storage period is quite important. Since for seasonal TES, the temperature of heat stored is usually low and not sufficient to be directly used for space heating or DHW generation. The temperature

Table 7 Comparison between different technologies of sensible seasonal TES [187, 204]

Concept	Water tank	Gravel-water	Aquifer	Borehole
Storage medium	Water	Gravel and water	Water – Sand/ gravel	Soil, rock, sand, etc.
Storage capacity (kWh/m^3)	60–80	30–50	30–40	15–30
Storage volume (1 m^3 water equivalent)	1	1.3–2	2–3	3–5
Geological requirements	–stable ground conditions –preferably no ground water –5–15 m deep		–natural aquifer layer with high hydraulic conductivity ($k_f > 1x10^{-5}$ m/s) –confining layers on top and bottom –no or low natural groundwater flow –suitable water chemistry at high temperature –aquifer thickness between 20 and 50 m deep	–drillable ground –groundwater favorable –medium to high thermal conductivity –high heat capacity –30–100 m deep
Advantages	– Can be built at almost any location – Most common system – No special geological condition requirements – High stratification – High heat capacity – Easy installation	– Can be built almost everywhere – No special geological condition requirements – More cost effective than water tank – Leaving natural aquifer untouched	– Cost effective – Can be used for both heating and cooling – Ability to produce direct cooling without using any supporting device – Low maintenance cost – Much more efficient heat transfer compared to borehole TES	– Can be used for both heating and cooling – for vertical borehole (30–200 m depth with the spacing of about 2–4 m), less surface area is needed – less sensitive to outdoor climate due to constant ground temperature – For horizontal duct (at depth of 0.8 to 1.5 m), less excavation is needed thus lower cost – Feasible for very large and very small applications

(*continued*)

Table 7 (continued)

Concept	Water tank	Gravel-water	Aquifer	Borehole
Limitations	– High cost in buried water tank – High thermal loss – Corrosion – Leakage	– High cost – Low stratification due to high thermal conductivity – Leakage – Needs 1.3–2 times larger storage volume compared to water tank	– Needs special geological conditions – High thermal loss due to no thermal insulation – Needs 2–3 times larger storage volume compared to water tank – Clogging effects – Long initial process due to extensive geological investigation	– Needs 3–5 times larger storage volume compared to water tank – Not suitable for all locations with ground-water flow – Needs drillable ground – High initial cost – 3–4 years needed to reach typical performance

upgrading via the coupling with a heat pump system or a supplementary boiler is indispensable. Hence, the system integration/regulation and the control strategy should be carefully designed and optimized.

Conclusions and Future Directions

This chapter presents currently available technologies by sensible heat for both short-term and long-term TES for buildings. Based on the literature review, the following conclusions may be achieved:

- Compared to latent or thermochemical TES, sensible technologies are relatively simple, easy to handle, cost-effective, and have found their positions in building applications both for short-term and long-term TES storage.
- Commonly used sensible technologies for daily TES in buildings include water tank, packed bed, thermal mass, thermally activated building system, and solar wall. They are oriented for both single-family houses and for multiple-family districts. The most developed and widely used is water tank, whereas others are good complementary depending on locations, weather conditions, or buildings. The development of super insulation for water tanks and the methods to maintain the thermal stratification inside the tank are currently the main R&D focuses.
- Commonly used sensible technologies for seasonal TES in buildings include water tank, gravel-water, aquifer, and borehole technologies. From the economic point of view, they are more cost-effective for large-scale applications. The selection of the technology mainly depends on the hydro-geological conditions of the sites. The main R&D focuses are the system integration/regulation when they are coupled with renewable sources or heat pumps.

Table 8 Key data and figures for sensible TES technologies (Adapted from Ref. [200])

Technical performance	Typical current international values and ranges
Energy input	Solar heat, waste heat, variable renewable energy sources (PV, wind, geothermal, etc.), cooking heat, etc.
Energy output	Space heating/cooling, domestic hot water generation
Storage capacity	10–50 (kWh/t)
Thermal power	0.001–10 (mw)
Efficiency	50–90 (%)
Storage period	Daily, monthly, yearly
Cost	0.1–10 (€/kWh)
Technical lifetime	10–30+ (year)
Environmental impact	Negligible, with greenhouse gas emission reduction depending on the amount of primary fossil energy saved by using energy storage. *potential environmental impact of large-scale underground TES systems is still not very clear

Table 8 provides an estimation of IEA on the current status of development for sensible TES technologies (Adapted from Ref. [200]).

Several directions for the future development are also identified for sensible TES, for the purpose of augmenting its market share for building applications.

- Coupling with PCMs (layers, encapsulates, etc.) to improve the energy density.
- Coupling with variable heat sources, especially renewable heat sources.
- Coupling with heat pumps for its temperature up-grading, especially for seasonal storage.
- System integration, optimized control strategy for best energy savings.

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