# CHAPTER 2

# Thermal Storage System Configurations and Basic Operation

## Contents



## Abstract

A thermal storage process typically involves energy collecting, storage, and delivery using a heat transfer fluid (HTF). We can use the HTF alone as a thermal storage medium, or use dual media (with HTF and another material in a packed bed). System operation, configurations/arrangement of all possible packed-bed and fluid flow for the single medium or dual media thermal storage systems are presented and discussed in this chapter.

**Keywords:** Heat transfer fluid, Ideal thermal storage, Packed bed thermal storage, Phase change material, Thermal storage system, Thermocline thermal storage

## 2.1 THE SCENARIO OF IDEAL THERMAL STORAGE (HEAT OR COLD)

As the goal of thermal energy storage, it is always desirable that the stored "heat" or "cold" be delivered with no degradation of temperature [1]. A decrease of the temperature of "hot" thermal energy introduces a loss of exergy, or a reduction in efficiency, when the thermal energy is converted to mechanical or electrical energy. Increase in the temperature of a "cold"


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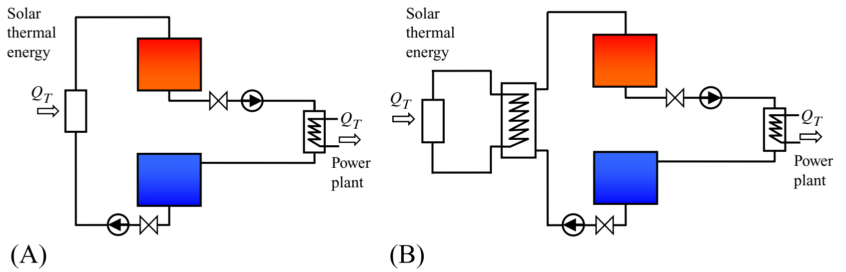


**Fig. 2.1** Thermal energy stored in HTF using two tanks [2]. (A) The heat transfer fluid in solar collection system is also used for thermal storage. (B) The heat transfer fluid in solar heat collection system is different from the thermal storage fluid.

thermal storage material will cause extra electrical energy to be expended to drive the refrigeration system to compensate for the loss of cold.

To avoid degradation of temperatures of thermal energy, the best-case scenario is that the energy-carrying fluid in the thermal storage system, called the heat transfer fluid (HTF), be withdrawn at the same temperature at which it was originally stored. Therefore the ideal situation for the most efficient thermal energy storage system is to include two storage tanks for a heat transfer fluid (HTF), as shown in Fig. 2.1A. The thermal energy–carrying hot fluid is stored in a hot tank. To withdraw the energy, the fluid is pumped out, and after heat exchange, the fluid temperature is lowered and then stored in a cold tank. When there is a need to store thermal energy, the fluid from the cold tank is pumped out to be heated up and then stored in the hot tank. Assuming that the tanks are very well thermally insulated, the round-trip energy storage efficiency can approach almost 100%, meaning that the stored thermal energy temperature will not be degraded.

When implementing this energy storage and delivery system in a concentrated solar thermal power (CSP) plant, the thermal energy for storage is from solar concentrators [2]. The power generation system uses the stored thermal energy at times when sunlight is not available, whether at night or during bad weather.

A different version of thermal storage using fluid only is shown in Fig. 2.1B, where the fluids for thermal storage and HTF are different. One example, which is found in some concentrated solar power plants, uses parabolic trough collectors; synthetic oils are used as the HTF, while molten nitrate salts are used as thermal storage fluids. This arrangement is due to the different features of the two types of fluids; in particular, the HTF may not be suitable for thermal storage, either because of the cost or due to inadequate properties, such as density and heat capacity being too low.

Finally, it should be pointed out that the flow direction of the HTF during the heat discharging process is inverse to that of the heat charging process. This feature of flow direction inverse between heat charging and discharging processes is generally true, which will also be explained later in discussions for all other thermal storage systems.

## 2.2 THERMOCLINE THERMAL STORAGE SYSTEM USING HTF ALONE

Although its energy storage efficiency is ideal, the two-tank thermal energy storage system shown in Fig. 2.1 always keeps one tank space empty, which to some extent is a waste of tank space and thus is not cost-effective. Therefore, a so-called thermocline thermal storage system has been proposed, using only a single tank. There have been two types of designs using a single tank and only the HTF as the thermal storage material, as shown in Fig. 2.2. The operation of these two types of thermocline thermal storage requires that the hot fluid charges into the tank always from the top, while during hot fluid delivery, the flow direction is reversed so that cold fluid flows into the tank from the bottom and thus hot fluid is discharged out from the top. As a result of this operation, during both energy storage and delivery processes, hot fluid is always kept on top and cold always at the bottom, which creates hot-cold stratification due to the temperature gradient and buoyancy effect. This phenomenon is called a thermocline, and this technique has become well-accepted by the thermal storage community.

In Fig. 2.2B a thermal insulation baffle is used between the hot and cold fluids to separate the hot from mixing with cold, which makes the hot-cold separation or stratification even more ideal [3]. The concept of separating

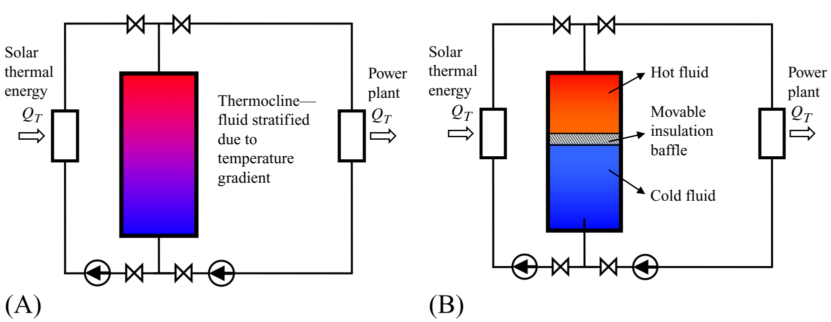


**Fig. 2.2** Thermocline thermal storage system using a heat transfer fluid only. (A) Thermocline; (B) hot and cold fluid separated/insulated with a movable baffle.

hot from cold HTF using a movable thermal insulation baffle in a single tank is not necessarily limited to the vertical style.

Although the benefit of cost reduction using only one tank in thermocline thermal storage is attractive, destruction of the temperature stratification due to flow disturbance is a difficult issue for the system shown in Fig. 2.2A [4]. In the case of Fig. 2.2B, the proper separation of the hot and cold fluid using the baffle requires a moving and control mechanism, which can be inconvenient. Therefore, the systems in Fig. 2.2 have not been adopted in large-scale thermal storage systems in CSP industry so far.

## 2.3 THERMOCLINE THERMAL STORAGE SYSTEM WITH PACKED BED AND A HEAT TRANSFER FLUID

It also needs to be pointed out that, under certain circumstances, the HTF itself may not be suitable to be used as a thermal storage material [5], particularly if the HTF is too expensive, or the energy storage capacity ($\rho \cdot Cp$) of the HTF is not sufficiently high. Or, if the HTF needs a very high pressure to be kept in the liquid state, a large storage tank will suffer from large mechanical stresses, which will drive the cost of the thermal storage tank higher. Therefore, thermal energy storage with HTF flowing through a packed bed of another thermal storage material is also frequently used. In this case, the second thermal storage material must have much higher energy storage capacity ($\rho \cdot Cp$) for sensible energy storage, or a high value of ($\rho \cdot \Gamma$) for latent heat energy storage. It is noted here that the latent heat is represented by $\Gamma$. Even when a second material is used in a packed-bed thermal storage system, the system still has a certain amount of HTF inside which still stores a certain amount of energy. Therefore, this mode of energy storage is also called dual-media thermal storage.

The packed bed may be a sensible thermal storage material or phase change material (PCM). The general goal of using a packed bed with HTF fluid flowing through is to use low-cost materials, or to reduce the storage volume for a large quantity of thermal storage [6]. Heat transfer between the heat-carrying HTF and the other thermal storage material is inevitable in this case, such as is seen in Fig. 2.3. This means that when the thermal energy from the HTF is stored in another medium, a temperature decrease is inevitable and the energy storage efficiency cannot reach 100%. As the result, the discharged HTF from the thermal storage tank will suffer a degradation of the temperature after a certain time.

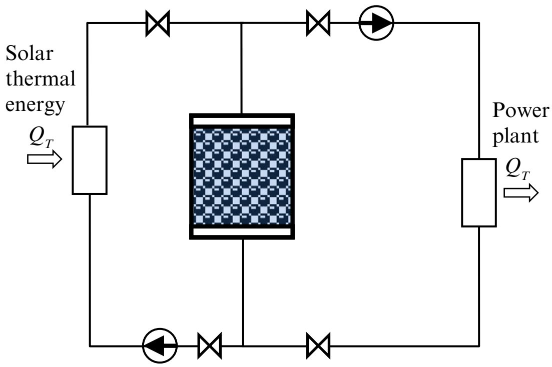


**Fig. 2.3** Dull media thermal storage, where an HTF flows through a packed bed of another thermal storage material.

Similarly, the HTF flow directions in a dual-media thermal storage system also need to be inversed between the energy charging and discharging processes. A brief proof of this arrangement is given here, as illustrated in Fig. 2.4. Assuming that the HTF is charged into the tank from the top, it will result in a final temperature distribution in the tank as indicated by the "after-charge" curve. If cold fluid flows in from the top of the tank to take the stored heat out, its temperature variation is indicated by the curve of the discharge scheme (b). It can be seen that the cold fluid temperature will reach a point equal to that of the thermal storage material as it passes through the storage tank. After that point, the HTF has to release its heat

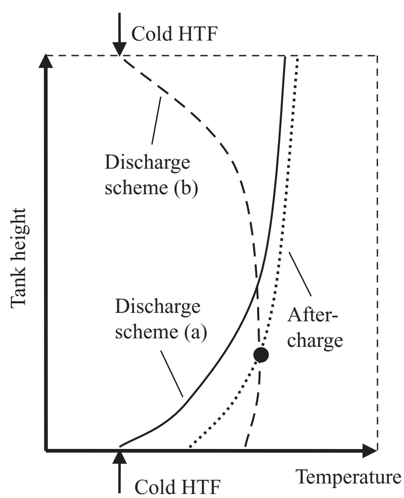


**Fig. 2.4** Illustration for the need of inversion of flow direction of HTF.

to the thermal storage material, which is now colder than the fluid as the HTF continues flowing through the remainder of the storage tank. If the cold HTF enters in the tank from the bottom to extract stored heat, its temperature variation will be as illustrated by the curve of the discharge scheme (a). In this case the temperature of the HTF will keep rising throughout its path to the top end of the storage tank.

One needs to check and manage the convective heat transfer between the HTF and the material of the packed bed in order to achieve the best energy storage efficiency. The Newton cooling equation for heat transfer rate is

$$\dot{Q} = Ah\left(T_f - T_s\right) \tag{2.1}$$

It is understandable from this equation that for the HTF to give energy to a solid material with minimum temperature degradation, both a large heat transfer area between the fluid and the solid and a large convective heat transfer coefficient $h$ are necessary. For better accommodation of this requirement, the advantages and disadvantages of the packaging schemes of thermal storage materials should be evaluated before doing the system design and engineering.

There are four typical schemes for thermal storage material packaging, as shown in Fig. 2.5. These are: (A) packed rocks/pebbles of sensible thermal storage materials; (B) packed capsules which have PCM encapsulated inside; (C) multiple zones with different types of capsules having different phase change temperatures, or even a hybrid package in which rocks/pebbles of

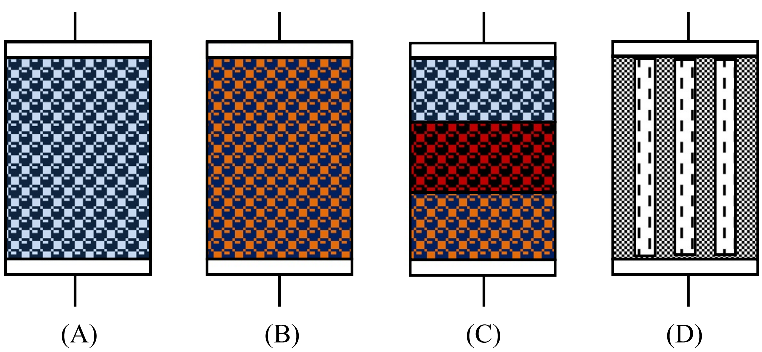


**Fig. 2.5** Packaging schemes of packed-bed thermal storage. (A) Rocks or pebbles in packed bed; (B) PCM capsules in packed bed; (C) multizones of PCM capsules and rocks/pebbles packed bed; (D) "block" thermal storage material (sensible or PCM) with HTF pipes embedded inside.

sensible thermal storage materials are on top and capsules of PCMs are packed underneath; (D) heat transfer fluid flowing in pipes that are embedded in a "block" of thermal storage material, either sensible thermal storage material or PCM. Detailed discussions about these packaging schemes are provided in the following sections.

### 2.3.1 Packed Bed Using Pebbles of Solid Material for Sensible Energy Storage

Sensible thermal energy storage materials such as rocks, pebbles, sands, or fabricated concrete pebbles may be used to fill a packed bed, as shown in Fig. 2.5A. These materials are easy to obtain at a low cost and their thermal energy storage capacity $\rho \cdot Cp$ is also sufficiently high. Thermal/physical properties of these materials are given and discussed in Chapter 3. When the grain size (of pebbles, rocks, or sands) is approximately uniform, the porosity of the packed bed may range from 0.35 to 0.41 [7]. A packed bed with nonuniform grain size, such as rocks of different sizes, could have a porosity as low as 0.326 [8], and rocks mixed with sand could have a porosity even lower, around 0.22 [4].

Due to the very large surface area of the rocks, pebbles, or sands that form the porous media, the heat transfer between the HTF and the thermal storage material will be very good, so that the temperature difference $\left(T_f - T_s\right)$ can be rather small, which contributes to high thermal energy storage efficiency.

As schematically shown in the structure of the thermal storage tanks in Fig. 2.5, the top and bottom fluid chambers of the tank need to be designed carefully to ensure that the fluid is distributed uniformly in the radial direction and also that the packaging is uniformly placed, leaving no channeling in the porous media [8]. Fortunately, some studies have shown that the flow of HTF in a packed bed can reach uniformity in a relatively short length of the tank [9,10].

### 2.3.2 PCMs Encapsulated as Fillers for Packed Beds

Due to the relatively large latent heat (in the phase change process) compared to sensible heat, PCMs are attractive for large quantity thermal energy storage with small volume. This introduces another type of dual-media thermal storage with HTF flowing through a packed bed of PCM materials, as shown in Fig. 2.5B. Again, in order to have a large heat transfer area between the PCM and HTF for better heat transfer, PCM materials are better encapsulated into small capsules [11]. Technologies of encapsulation of PCMs have been significantly developed in recent years, particularly for low to medium thermal storage applications up to temperatures of 250°C. Encapsulation technologies for high temperature PCMs, above 500°C, are still under development [12,13].

### 2.3.3 PCMs and PCM-Sensible Hybrid Packed Bed Thermal Storage

It is known that during the energy charging process, the temperature of the HTF must be higher than that of the PCM. When thermal energy is discharged, the temperature of the HTF is lower than that of the PCM. This nature of a significantly lowered temperature of the HTF from charging to discharging is a disadvantage. To avoid any large degradation of the temperature of the HTF, multiple PCMs packed in multiple zones (as shown in Fig. 2.5C) with cascade melting points have been proposed and studied. It has been proven that the thermal storage efficiency can be improved using cascade PCMs packed in a single tank or multiple tanks [14,15].

To further expand the benefit of using cascade PCMs, sensible thermal storage materials may be placed on the top of the storage system [16].

### 2.3.4 Solid Block Thermal Storage With HTF Pipes Embedded

Other than the porous packed bed using particles, pebbles, or PCM capsules, thermal storage may also use integrated material, referred to as "blocks." Concrete [17,18], sands saturated by thermal conductive liquid [7,19], and "blocks" of PCM materials [20] have been used and reported for thermal energy storage. In this case, pipes of HTF are embedded into the thermal storage block material, as shown in Fig. 2.5D. The material can be either for sensible thermal storage or for latent heat thermal storage.

There are three types of configurations of HTF and solid block materials, as shown in Fig. 2.6. The first configuration uses plate type thermal storage blocks that form 2D flow channels. The second type has thermal storage material as rods and HTF flows in the gap of the bundle of the rods. The third type has a large block of thermal storage material with pipes of HTF embedded through it.

Unlike the case of the HTF flowing in a porous thermal storage material, the heat transfer surface area of the channels/pipes embedded in thermal storage material is much smaller. Therefore, enhancement of heat transfer in the solid block and at the surface of the channels/pipes is needed.

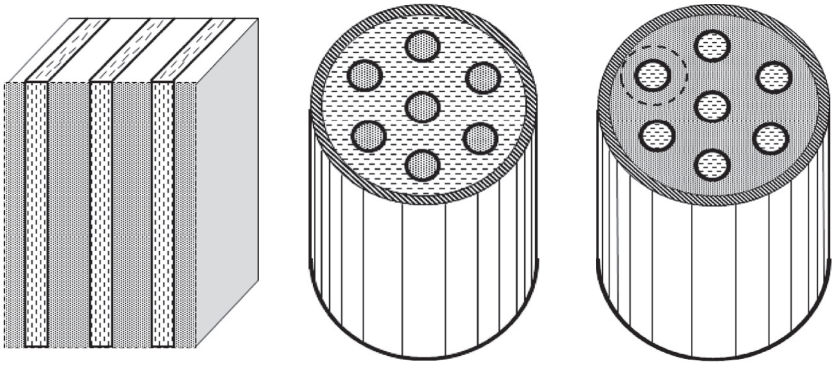

**Fig. 2.6** Configurations of HTF channels in thermal storage block material. Areas shadowed with dashed lines show the region of the HTF. (A) Fluid flows in between solid slabs. (B) Fluid flows in between solid rods. (C) Fluid flows in pipes embedded in solid.

Measures such as putting metal foam and metal coils in the thermal storage material and fins at the outside of the pipes are typically recommended [20].

The thermophysical properties of the block thermal storage materials, such as concrete, sands saturated with thermal conductive liquid, PCM, and issues of heat transfer enhancement in these materials are presented in Chapter 3.

Convective heat transfer coefficients of HTF in a variety of porous media and in the flow channels as shown in Fig. 2.6 are discussed in Chapter 4, where heat transfer and energy storage performance are analyzed.

## 2.4 THERMOCHEMICAL ENERGY STORAGE TECHNOLOGIES

Although either sensible heat or latent heat thermal storage technologies make it possible to store a large amount of energy for electrical power generation, on the order of 300 MWe for 6–8 h, it is still very challenging to use these technologies for thermal energy storage for a much longer period of time, say a season or from summer to winter. The major challenge is the heat loss due to imperfect thermal insulation, or the high cost for highly reliable thermal insulation. Therefore, researchers have been looking for other technologies, such as thermochemical energy storage, to solve the demand for long-term thermal energy storage.

The basic idea of thermochemical energy storage is to use the heat to drive an endothermic chemical reaction and dissociate material A to material B and C ($A + heat \rightarrow B + C$). The materials B and C are able to be stored for a desired length of time and can even be transported to different locations. When desired at another time, one can use the reverse reaction ($B + C \rightarrow A + heat$), which is exothermic, to release heat for utilization. Depending on the chemical reaction chosen, thermochemical approaches can provide energy storage and return back heat both at low temperature (for room heating) or rather high temperatures, up to several hundred degrees Celsius.

Some reduction-oxidation (redox) reactions with significant heat effects have been surveyed in Ref. [21] for application in thermochemical energy storage. Metal oxides such as $MnO_2$ and $Co_3O_4$ may be redox cycled so that thermal energy storage and retrieval can be accomplished. When input with heat, the following reduction reactions may occur:

$$2MnO_2 + heat \rightarrow Mn_2O_3(s) + \tfrac{1}{2}O_2 \tag{2.2}$$

$$Co_3O_4 + heat \rightarrow 3CoO\,(s) + \tfrac{1}{2}O_2 \tag{2.3}$$

The oxidation reactions of $Mn_2O_3$ and CoO release heat and thus thermal energy is retrieved. These technologies are considered for large-scale thermal storage deployment in concentrated solar power (CSP) plants that use air as the heat transfer fluid. The convenience of using oxygen as the reactive gas is because of the supply of ambient air, which thus avoids storage of gaseous material. The redox temperature range of these reactions is suitable for new generation solar tower-based CSP plants, which have a temperature of 900°C under atmospheric pressure. For example, the reaction, Eq. (2.2), also has a high energy density of (844 kJ/kg $Co_3O_4$) and its performance was reported to be very stable during cycling reactions [22,23].

The cycling between metal hydroxide to metal oxide is also suitable to be applied for thermochemical energy storage. The reaction, such as:

$$Ca(OH)_2(s) + heat \rightarrow CaO(s) + H_2O(g) \tag{2.4}$$

has been reported in Ref. [23] for energy storage in a fluidized reactor.

Dehydration reactions can also be utilized for thermochemical energy storage; the following reaction:

$$CaCl_2 \cdot 6H_2O + heat \rightarrow CaCl_2 + 6H_2O \tag{2.5}$$

has been adopted for thermal storage at low temperature range.

Chemical reactions with gaseous materials such as the association-synthesis system:

$$2NH_3 + heat = N_2 + 3H_2 \tag{2.6}$$

has also been considered for thermochemical energy storage. Since this system uses catalysts and operates at rather high pressures (80–200 bar), it needs storage of $H_2$ and $N_2$ gases, which is not cost effective for large quantity thermal storage.

Some more complicated chemical processes have also been utilized for thermochemical energy storage. The following series reactions are examples to accomplish the goal of thermal energy storage:

$$2H_2SO_4 + \text{Heat} \rightarrow 2H_2O + 2SO_2 + O_2 \ (\text{Sulfuric acid decomposition}) \tag{2.7}$$

$$2H_2O + 3SO_2 \rightarrow 2H_2SO_4 + S \ (\text{disproportionation producing sulfur}) \tag{2.8}$$

$$S + O_2 \rightarrow SO_2 + \text{Heat} \ (\text{Combustion of sulfur for heat}) \tag{2.9}$$

Here $SO_2$ and S are recycled in the entire processes to achieve the goal of energy storage.

Thermochemical hydrogen production has also been considered for thermal energy storage in hydrogen fuel. One example of a thermochemical cycle for $H_2$ production based on $CeO_2/Ce_2O_3$ oxides was described and demonstrated in [24]. The thermochemical reaction consists of two steps:

$$\text{Reduction}: 2CeO_2 \rightarrow Ce_2O_3 + 0.5O_2;$$

$$\text{Hydrolysis}: Ce_2O_3 + H_2O \rightarrow 2CeO_2 + H_2.$$

The thermal reduction of Ce(IV) to Ce(III) (endothermic step) can be performed in a solar reactor under a controlled inert atmosphere. The first step reaction has been demonstrated at operating conditions of $T = 2000°C$, $P = 100$–$200$ mbar. The hydrogen generation step for water-splitting with Ce(III) oxide has been accomplished in a fixed-bed reactor and the reaction is complete with a fast kinetic in at a temperature range of 400–600°C. The recovered Ce(IV) oxide is then recycled to feed the first step. In the entire process, water is the material input and heat is the energy input. The output material is hydrogen fuel and oxygen. Importantly, these two gases are obtained in different steps that avoid a challenge of high temperature gas-phase separation. Pure hydrogen is produced that can be stored as fuel. Although the operation at a temperature of 2000°C faces a big material challenge, the cerium oxide two-step thermochemical is still a promising process for hydrogen production.

Details of heat values (additions and retrieves) involved in the previously discussed chemical reactions and the devices accommodating the reactions and heat addition/retrieves studied by various research groups/researchers are introduced in Chapter 4.

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