CHAPTER 6

Volume Sizing for Desired Energy Storage Tasks

Contents

Abstract

This chapter presents methods for calculating the volume of the thermal storage containers/tank to meet the demand of thermal storage for various approaches to thermal storage, including: heat transfer fluid (HTF) thermal storage, solid and HTF dual-media sensible thermal storage, phase change material (PCM) and HTF dual-media latent heat thermal storage, as well as sensible and PCM (latent heat) combined media with HTF thermal storage. Whereas the thermal storage using only HTF is a single medium approach that has ideal energy storage efficiency, other approaches of dual-media thermal storage involve heat transfer between the HTF and the other medium and thus have energy storage efficiency less than 100%. Analysis and computation of the heat transfer between the HTF and the other medium are needed in order to size the volume of the thermal storage container.

Keywords: Determining mass flow rate for thermal storage, Heat transfer fluid, Solar thermal power plant, Thermal storage volume determination, Thermal storage media

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6.1 REQUIRED MASS FLOW RATE OF HEAT TRANSFER FLUID FOR POWER DEMAND

A thermal storage system essentially provides a hot heat transfer fluid (HTF) and releases the heat to a destination. In this heat releasing process, the HTF experiences a change of temperature from a high temperature T_H to a low temperature T_L. Vice versa, when a heat storage process is concerned, the HTF experiences a change of its temperature from a low temperature T_L to a high temperature T_H. The mass flow rate of the HTF must satisfy the following requirement if the demand of thermal energy, $\dot{Q}_T$, is known:

$$\dot{Q}_T = \dot{m} \cdot C_f(T_H - T_L) \tag{6.1}$$

If a concentrated solar thermal power plant outputs an electrical power of $\dot{Q}_P$, the needed thermal energy can be determined as:

$$\frac{\dot{Q}_P}{\eta_{th}} = \dot{Q}_T = \dot{m} \cdot C_f(T_H - T_L) \tag{6.2}$$

where $\dot{Q}_T$ is the required thermal energy rate that the HTF needs to provide; η_{th} is thermal efficiency in the thermal power plant that relies on the thermal energy from the HTF; $\dot{Q}_P$ is output electrical power from the concentrated solar thermal power plant. From Eq. (6.2), the mass flow rate of the HTF can be decided as follows:

$$\dot{m} = \frac{\dot{Q}_P}{\eta_{th} C_f(T_H - T_L)} \tag{6.3}$$

It is important to note that no matter what thermal storage approach is applied, the mass flow rate of the HTF must satisfy Eq. (6.3) in order to deliver the desired electrical power in a power plant relying on stored thermal energy. Therefore, the mass flow rate of the HTF is independently decided, regardless of the thermal storage approach.

6.2 DETERMINING THE THERMAL STORAGE VOLUMES FOR DESIRED QUANTITY OF ENERGY STORAGE

The analysis and estimation of the thermal storage volume needs to consider various approaches of thermal storage. The approaches include using an HTF alone for thermal storage, using solid and HTF dual media for sensible thermal storage, using a phase change material (PCM) and HTF dual media for latent heat thermal storage, and using sensible and PCM (latent heat) combined media and HTF for thermal storage.

The analysis begins with the case of thermal storage using only an HTF, which is a single medium approach with ideal energy storage efficiency.

6.2.1 HTF as the Only Thermal Storage Medium

If the HTF is used as the only energy storage medium, the needed mass flow rate is still equal to $\dot{m}$ from Eq. (6.3). The total mass and the corresponding volume of the HTF can be decided using:

$$M_{ideal} = \Delta t \cdot \dot{m}; \; V_{ideal} = \Delta t \cdot \dot{m}/\rho_f \tag{6.4}$$

where $\dot{m}$ is decided based on Eq. (6.3). It has been previously discussed that when the HTF is used as the sole thermal storage medium, the energy storage efficiency can reach 100% in an ideal situation, assuming that the storage tank is well thermally insulated.

6.2.2 Solid and HTF Dual-Media Sensible Thermal Storage

When solid material forms a packed bed and an HTF flows through it, the needed mass flow rate will still equal $\dot{m}$ as obtained from Eq. (6.3). The thermal storage volume should satisfy the following equation [1]:

$$\left\{ \left[(\rho C)_s \cdot (1-\varepsilon) + (\rho C)_f \cdot \varepsilon \right] \cdot V_{min} \right\} \geq \left[(\rho C)_f \cdot V_{ideal} \right] \tag{6.5}$$

where the left-hand side is the total heat capacity of the packed bed (porous media) with HTF filled in the void, and the right-hand side is the ideal case that HTF is the only thermal storage medium and the volume of the storage tank is V_{ideal}. Depending on the density and heat capacity of the solid material relative to those of the HTF, the thermal storage volume V_{min} can be smaller or larger than V_{ideal}.

In order to decide the volume (V_{min}) of the thermal storage tank, a study of the heat transfer between the solid thermal storage material and the HTF has to be conducted. This will predict the HTF temperature discharged from the tank in the thermal discharging process. It is typically required that the discharged HTF temperature be equal to T_H, or no less than a predetermined minimum temperature.

However, because the dual-media thermal storage is not ideal, typically only some percentage of the discharged thermal energy can be withdrawn. This means that if the HTF at a temperature of T_H is charged into a thermal storage tank for a period of time, Δt, the temperature of the HTF discharged from the tank cannot be maintained always at T_H, but drops over the period of time Δt.

Therefore, besides the conditions given in Eq. (6.5), either one of the following two approaches must be applied in order to finalize the proper thermal storage volume and cause the discharged HTF to have the same temperature in the same period of time as for the charging process [2]. These approaches include: (1) charge energy with longer period of time than the required discharging time, (2) charge energy with higher flow rate and discharge at the required flow rate in the same period of charging time. This second approach is usually not recommended, because heat collectors are typically designed based on a given or fixed flow rate.

Another issue during the design analysis of the thermal storage volume is to find the temperature distribution in the thermal storage tank at charged status and discharged status for cyclic operations. For example, the thermal storage system may start from a fully cold state, and after a number of cycles of charging and discharging the temperature distribution after discharging will be different from the initial cold state. This temperature distribution in the thermal storage tank after a discharging is needed as the initial condition for the charging process, and vice versa [3].

To decide the dimensions of a thermocline storage tank, the required operational conditions from the power plant include: the electrical power, the thermal efficiency of the power plant, the desired period of operation based on stored thermal energy, the required high temperature of heat transfer fluid from the storage tank, the low temperature of fluid returned from the power plant, the properties of the heat transfer fluid and the thermal storage material, including the nominal radius of packed pebbles if applicable, as well as the packing porosity in a thermocline tank.

The computational analysis will include the following steps:

(1) Decide on an ideal volume using Eq. (6.4) for the ideal case where only an HTF is used for thermal storage. Once the volume of the ideal thermocline tank is determined, a minimum storage tank volume should be determined using the criterion given in Eq. (6.5). This gives the lower limit of the volume, below which one cannot achieve the desired thermal energy discharge. From the determined tank volume, one can choose diameter, *R*, and the corresponding height, *H*, which will be used in the first trial for energy storage effectiveness analysis.

(2) Use dimensions for the determined minimum volume of the container to conduct one-dimensional heat transfer analysis for one charging and one discharging, and examine the discharged fluid temperature. This will make sure that the fluid temperature is above the minimum required temperature in the desired period of discharging. Typically, the minimum volume cannot meet the requirement for the system to have a discharged fluid temperature the same as that of the charged fluid. By considering an enlarged tank volume and also a longer charging time (compared to the discharging time), one may achieve the goal that the discharged fluid temperature from the thermal storage system is the same as that of the charged fluid over the desired period of time.

(3) Since a thermal storage system needs to operate over many charging and discharging cycles, it is best that the system design analysis take the case of steady periodical operation into consideration. During the initial cycle of energy charging and discharging, the storage tank is fully cold and therefore much longer charging is needed. Since the storage system will have residual energy after each discharging, gradually the thermal storage system will warm up until a steady cyclic operational condition is built up. Therefore, the computation needs to consider up to 10 times of charging and discharging [3] in order to reach steady cyclic operation.

These steps for thermal storage volume design are explained in the flow chart shown in Fig. 6.1 [4].

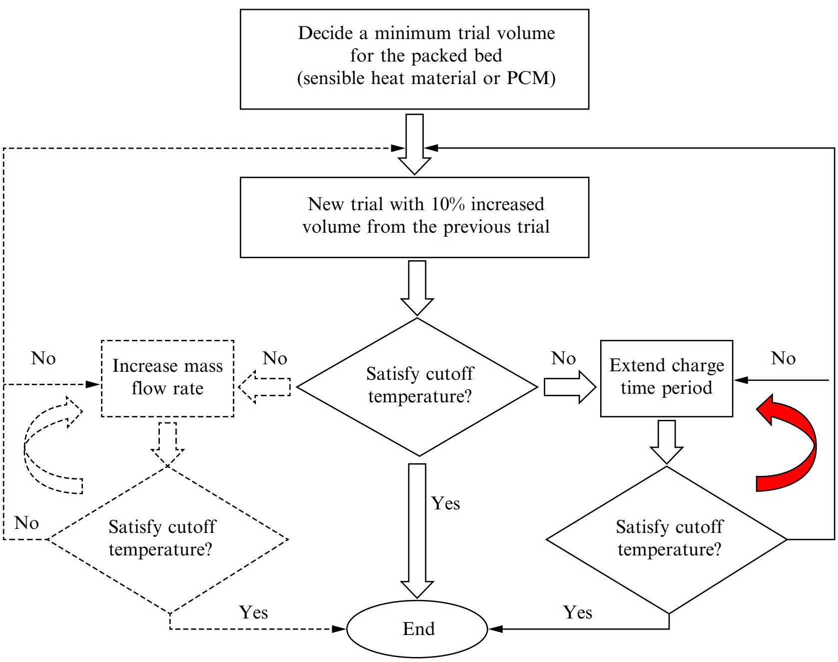

Fig. 6.1 Flow chart for dual-media thermal storage volume design [4].

6.2.3 PCM and HTF Dual-Media Thermal Storage

When an encapsulated PCM is packed in a tank and an HTF flows through it, the needed mass flow rate will still equal $\dot{m}$ as obtained from Eq. (6.3). Because of the latent heat of the PCM, the thermal storage volume should satisfy the following equation:

$$\left\{\rho_{PCM}\Delta H_{fusion}(1-\varepsilon)+(\rho C)_f(T_H-T_L)\varepsilon\right\}\cdot V_{PCM-min} \geq (\rho C)_f\cdot V_{ideal}(T_H-T_L) \tag{6.6}$$

where ΔH_{fusion} is the latent heat of the PCM with the melting point close to or lower than T_H. Assuming that the heat transfer between the PCM and the HTF is ideal, the tank volume, $V_{PCM-min}$, obtained from Eq. (6.6) can be the minimum volume that the heat transfer analysis should start with. Choosing a proper diameter of the storage tank, the height of the tank can be determined based on $V_{PCM-min}$, and heat transfer and energy storage analysis can be conducted using the flow rate determined by Eq. (6.3). The analysis simulates the heat charging and discharging cycles and examines the HTF temperature during a heat discharging process. Typically, if the discharged HTF temperature cannot satisfy the requirement for a certain time period, the $V_{PCM-min}$ will need to be enlarged for the second trial of analysis. In this case, it is also important that an energy charging over a longer period of time than the required discharging time is chosen for the operation of the system.

6.3 EXAMPLES OF SIZING OF THERMAL STORAGE SYSTEM APPLIED TO CONCENTRATED SOLAR THERMAL POWER SYSTEMS

6.3.1 Calibration Analysis for Existing Storage Volume to Meet a Demand

If the dimensions of a storage tank and the operational conditions of a thermal storage system, including the mass flow rate and the high and low HTF temperatures (T_H, T_L) are given, a designer may be required to find a proper time period of energy charge that can satisfy the needed operation time of the thermal energy delivery. The known parameters will be the ideal tank volume, τ_r, as well as H_{CR} at a required operational period of Π_d, as defined in Chapter 4 (Section 4.2).

The first step of the calibration should be the examination of the criterion given in Eq. (6.3), from which a minimum tank volume can be decided. If the minimum tank volume is satisfied, the second step of the calibration is to find a proper ratio of charging time versus discharging time Π_c/Π_d that will allow the energy delivery effectiveness to approach 1.0. The calculated energy storage effectiveness (Eq. (4.16) in Chapter 4) vs. Π_c/Π_d at the given H_{CR} (Eq. (4.12) in Chapter 4) can be quickly found. If at the required Π_d the energy storage effectiveness cannot approach 1.0 at any value of Π_c/Π_d, a new Π_d will have to be selected.

6.3.2 Examples of Storage Tank Size Design for Sensible Energy Storage

Example 1 [1,2]: a pilot solar thermal power plant has 1.0 MW electrical power output at a thermal efficiency of 20%. The heat transfer fluid used in the solar field is Therminol VP-1. The power plant requires high and low HTF temperatures of 390°C and 310°C, respectively. River rocks are used as the filler material and the void fraction of packed rocks in the tank is 0.33. The required time period of energy discharge is 4 h, the storage tank diameter is 8 m. The rock diameter is 4 cm. This example shows how a designer can, upon finding τ_r, Π_d, and H_{CR}, determine whether the design will deliver a high energy effectiveness (Eq. (4.16) in Chapter 4) and how to modify the design. The steps of the analysis are as follows:

First, find a necessary mass flow rate of 25.34 kg/m^3 and an ideal tank height of 9.59 m. The minimum volume of the storage tank can be determined from Eq. (6.5). The ideal volume is used in the first design trial. Using the equations listed in Table 4.1 for spherical rocks, we find the corrected heat transfer coefficient [5,6] to be 32.05 W/m^{2}K. With this information, the values of H_{CR}, Π_d, and τ_r (with definitions in Chapter 4 (Section 4.2)) are obtained as 0.451, 3.03, and 0.0227, respectively. For the condition that $H_{CR} = 0.45$, there is no time ratio Π_c/Π_d that allows the energy delivery effectiveness to approach 1.0. Therefore, the ideal volume will not satisfy the energy storage demand.

One option to improve the ability to store and deliver more energy is to increase the height of the storage tank. When the height is increased to 12 m, the values of Π_d and τ_r change to 2.42 and 0.0181, respectively. It is found that at $H_{CR} = 0.45$ and at the ratio, $\Pi_c/\Pi_d = 1.2$, the energy delivery effectiveness approaches 0.99. This becomes an acceptable design.

Compared to an ideal thermal storage tank, the rock-packed bed thermocline tank uses about 40.0% of the HTF. The longer energy charging time than discharging time indicates that 20% of the charged energy cannot be used, due to the temperature degradation in the discharging process.

Example 2 [1,2]: For the same solar thermal power plant and operational conditions as in Example 1, the thermal storage primary material is molten salt with properties of $\rho = 1680\,\mathrm{kg/m^3}$, $C_s = 1560\,\mathrm{J/(kg \cdot K)}$, and $k_s = 0.61\,\mathrm{W/(m \cdot K)}$. The heat transfer fluid HITEC flows in multiple heat transfer tubes as shown in Fig. 4.3D in Chapter 4. The required time period of energy discharge is 4 h, and the storage tank diameter is 8 m. The study will find the storage tank height.

Following the same procedure as in Example 1, we have a mass flow rate of 40.35 kg/m^3 and the ideal tank diameter and height of 8 m and 6.44 m, respectively. Assume that we have 8448 steel pipes (with an inner diameter of 0.025 m) in the storage tank, and the HTF flows in all the pipes with an equal flow rate. The void fraction ε is found to be 0.33, and the heat transfer surface area per unit of length of the tank is found to be $S_s = 1327\,\mathrm{m}$. Using the equations listed in Table 4.1 for the case of Tubes, we can find the corrected heat transfer coefficient. The minimum volume of the tank is used in the first trial of the design.

The dimensionless values of H_{CR}, Π_d, and τ_r are 0.522, 3.032, and 0.221, respectively. At H_{CR} of 0.50 (close to 0.522) it is impossible to get an energy delivery effectiveness of 1.0 at all the trialed time ratios of Π_c/Π_d.

To increase the energy delivery effectiveness, a new tank height of 2.1 times the ideal volume is used. This makes the values of Π_d and τ_r 1.444 and 0.105, respectively. Now it is seen that at H_{CR} of 0.50 (close to 0.522) and a time period ratio Π_c/Π_d of 1.2, the energy delivery effectiveness can reach 0.96.

Note that after the tank height is increased, the HTF volume takes 69% of the ideal heat transfer fluid volume. The energy delivery effectiveness is able to reach as high as 0.96. In order to improve the energy delivery efficiency, the heat transfer between fluid and thermal storage material must be improved, for example, using pipes with fins.

Example 2 also indicates that when the heat transfer performance (the multiplication of heat transfer coefficient and heat transfer area) between HTF and thermal storage material is poor, the energy delivery effectiveness can be low. If the temperature degradation of the discharged fluid is a big concern, for example in a power plant, heat transfer enhancements in the thermal storage must be made.

6.3.3 Examples of Storage Tank Size Design for PCM Energy Storage

A parabolic trough CSP plant with 60 MW electrical power output at the thermal efficiency of 35% is taken as an example, based on the systematic design in the work of Biencinto et al. [7]. The HTF used in the solar field is Therminol VP-1. The power plant requires high and low fluid temperatures of 390°C and 310°C, respectively. Depending on the packing scheme, the void fraction ε in a packed bed with spheres of a fixed diameter ranges from 0.26 to 0.476 [8]. In this paper, a void fraction of 0.3 was chosen for all the calculations. The diameter of the encapsulated PCM is 4 cm, and the radius of the storage tank is set as 5 m. The required minimum time period of energy discharge is 6 h. The thermal storage system is assumed to be operated within 100 days or 100 charge/discharge cycles without maintenance. The minimum cutoff temperature is set to be 360°C in a discharge process, below which the HTF cannot be effectively used for power generation. This cutoff temperature is based on the conclusion from Modi and Pérez-Segarra [9] that 30°C below the high temperature is acceptable. All the operating conditions and the properties of the HTF and filler material are listed in Tables 6.1 and 6.2. The details of numerical modeling and computational procedures are referred to Chapter 4 as well as to reference [10].

Based on the properties, efficiency of the power plant, and need for power, one can calculate a necessary total mass flow rate for the thermal storage as follows:

Table 6.1 Operational parameters of a 60 MW CSP plant for 6 h thermal storage [4]

$P_{ele}=60$ MW—Electrical output	$\xi=35\%$—Power plant thermal efficiency
$R=5\,\text{m}$—Radius of storage tank	$T_{cutoff}=360°\text{C}$—Cutoff temperature
$T_H=390°\text{C}$—High temperature	$T_L=310°\text{C}$—Low temperature
$N_{cycle}=100$—Number of cycles	$\Delta t_{discharge}=6\,\text{h}$—Time period of discharge
$\varepsilon=0.3$—Void fraction	$d_r=0.04\,\text{m}$—Diameter of filler material

Table 6.2 Properties of HTF and filler materials [4]

HTF (Therminol VP-1)	
$\rho_f=761\,\text{kg/m}^3$	$C_f=2454\,\text{J/(kgK)}$
$k_f=0.086\,\text{W/(m K)}$	$\nu_f=2.33\times10^{-7}\,\text{m}^2/\text{s}$
PCM-1 (KOH, potassium hydroxide)	
$\rho_r=2044\,\text{kg/m}^3$	$C_{r_s}=1470\,\text{J/(kgK)}$solid
$k_r=0.5\,\text{W/(mK)}$	$C_{r_l}=1340\,\text{J/(kgK)}$liquid
$L=149.7\,\text{kJ}$	$T_{melt}=380°\text{C}$

$$\frac{P_{ele}}{\xi} = \dot{m}_{total} C_f (T_H - T_L) \tag{6.7}$$

The required total mass flow rate for a 60 MW electrical supply is calculated as $\dot{m}_{total} = 873.21$ kg/s, which can be divided into four substreams for four tanks, and the mass flow rate $\dot{m}$ in each substream is thus equal to 218.3 kg/s. In the following calculations, only one substream is studied, since the results for one substream will be identical to the other three substreams.

Next, the first step in the design process is to choose an initial trial thermal storage tank volume using Eq. (6.6). The height of the storage tank can be determined as shown in Table 6.3.

The charge time period initially is set to be equal to the discharge time period (6 h). The modeling computation for the thermal performance of the storage system can be obtained. In the next section, the results are examined to obtain an actual storage tank volume, following the general volume sizing strategy.

As a first step, the temperature of outflow HTF versus discharge time at cyclic periodic steady state has been plotted in Fig. 6.2, in which the dashed line represents the cutoff temperature.

It can be observed clearly from Fig. 6.2 that the storage system can only supply HTF above 360°C for approximate 3.5 h, which is much less than the required 6 h. Therefore, based on the general volume sizing strategy, the volume of the trial storage tank is increased by 10%. Also the heat charging time is extended from 6 to 8 h, and a comparison is made in Fig. 6.3.

It is seen from Fig. 6.3 that even if the charging time is extended to 8 h, the 10% increase of the tank height from the trial tank height still would not fully meet the cutoff temperature of above 360°C in 6 h. The 7-h charge with 10% increase of volume can discharge HTF for about 3.9 h with the temperature above 360°C, while the longest time period of 4.1 h is offered by an 8-h charge. Even though these results are better than the 6-h charge at the first-trial tank volume, it is still far from the target of an entire 6-h supply of fluid at temperatures above 360°C. As a result, the next step is to go back and increase the tank volume of the first trial another 10% or more.

Table 6.3 Height of trial storage tank for each PCM when the cutoff temperature is 360°C [4]

PCMs	Tank height of initial trial
PCM-1 (KOH)	25.9 m (total of multiple tanks)

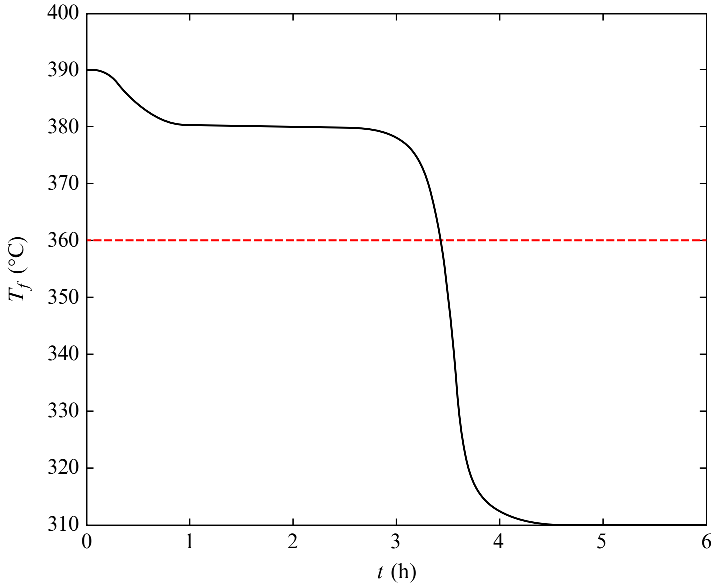

Fig. 6.2 Temperatures of outflow HTF in 6 h discharge based on the tank height of the initial trial analysis [4]

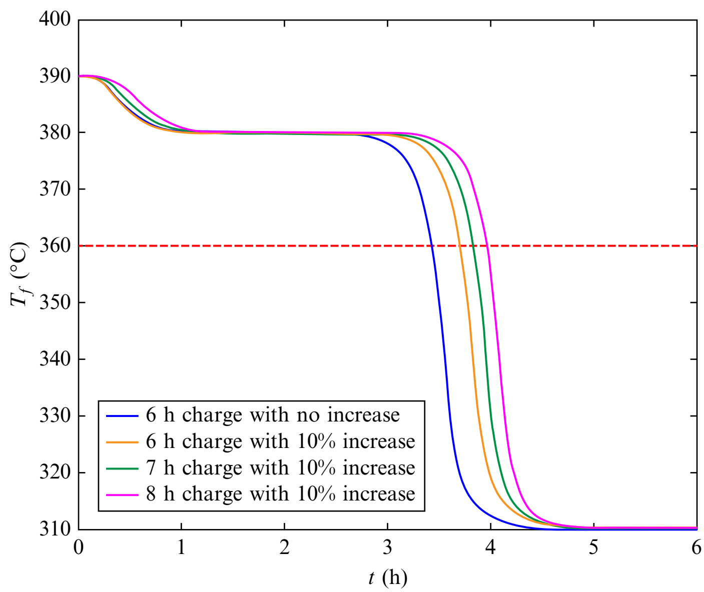

Fig. 6.3 Output HTF temperature in 6 h discharge by varying charge time from 6 to 8 h with 10% increase of the height from the volume of the first trial [4].

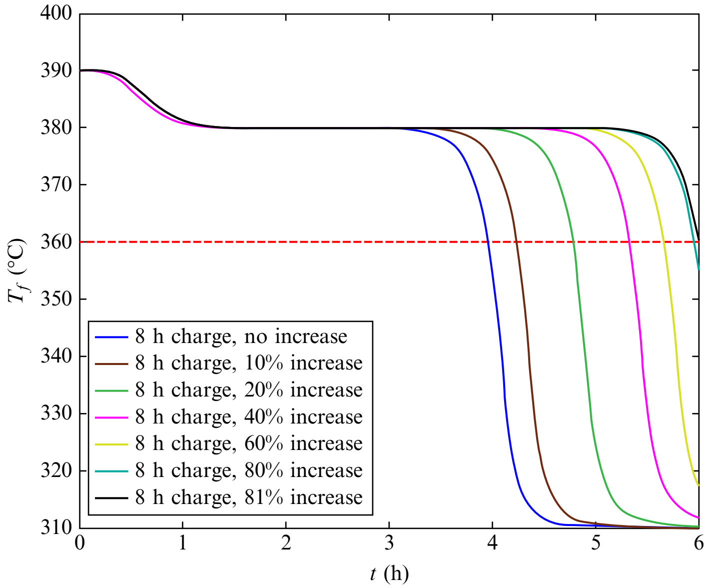

Fig. 6.4 The output HTF temperature in 6 h discharge with enlarged volume from the first trial and 8 h charging time [4].

Following that, the charging time is now chosen as 8 h and the volume is also increased. The results are shown in Fig. 6.4.

Fig. 6.4 demonstrates the output HTF temperature within a 6-h discharge, based on enlarged volume from the first trial storage volume and a fixed charging time of 8 h. It is seen clearly from this figure that before the volume is increased 80%, the output HTF temperature at the end of 6 h of discharge is far from the cutoff temperature of 360°C. Given an 81% increase of the tank volume and 8-h charging time, the results of the discharged fluid temperature could completely satisfy the requirement of above 360°C during the entire discharging time period of 6 h. For this result, the storage tank volume is 3683.5 m^3, which may require multiple tanks in a total height of 46.9 m, if the radius of each tank is fixed at 5 m. In this case, the energy storage efficiency is 88.19%.

For the same thermal storage requirement and PCM material, if the solar radiation collection time cannot be longer than 6 h, the only option to meet the requirement is to further enlarge the storage tank volume. Fig. 6.5 shows the comparison of output HTF temperature during a 6-h discharge with various storage tank volumes at a fixed 6 h of charge. One can observe from the figure that only when a 90% increase of the volume is employed can the

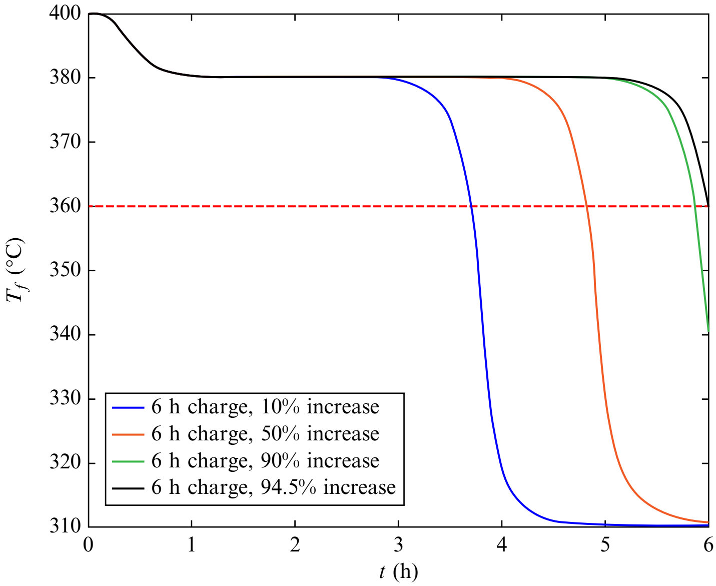

Fig. 6.5 The output HTF temperature in 6 h heat discharging with enlarged volume of storage tank and 6 h heat charging.

output HTF temperature at the end of a 6-h discharge get close to 360°C. At the end of the computation, a 94.5% increase of the trial storage tank volume was found to meet the requirement that the discharged fluid temperature be above 360°C during the entire discharge time period of 6 h. For this result, the tank volume is 3954.2 m^3, and the total height of multiple tanks is 50.4 m if the storage tank radius is fixed at 5 m. The energy storage efficiency for this case is 87.61%. This efficiency is close to that of the last case, which has energy storage efficiency of 88.19%. This means that with a larger volume of the storage tank, one can use a shorter charge time of 6 h to achieve the same goal.

These two cases show that the general volume sizing strategy offers designers multiple options to decide on an appropriate storage tank volume and operation scheme to maintain the HTF temperature above the cutoff temperature during a required 6 h of discharge.

6.4 COLD STORAGE ANALYSIS FOR DESIRED COOLING

Due to development of PCM encapsulation technology, a low melting PCM has been widely used for cold storage in recent years [11]. This is

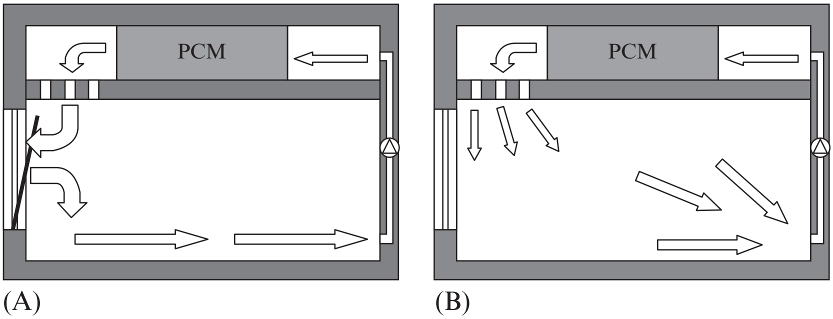

Fig. 6.6 Using PCM for air-conditioning. (A) Cooling of PCM at night; (B) cooling of room in the day. *(Courtesy of Butala V, Stritih U. Experimental investigation of PCM cold storage. Energy Build 2009;41:354–59).*

because encapsulation of the PCM is very important in creating a large heat transfer surface area.

Cold storage can be applied for air conditioning [12], food and vegetable cold storage, transportation, etc., as seen in Fig. 6.6. The heat transfer and energy storage analysis for cold storage is the same as that for heat thermal storage. In this case, a heat charging process is for cold discharging, and the heat discharging process is for the cold charging process. Readers also need to note that the coordinates of all the one-dimensional models presented in this book follow the flow direction of the HTF.

Depending on the application of cold storage, one may also set a limit on the HTF temperature, above which the cold discharging process has to stop.

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