THERMAL ENERGY STORAGE

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Contents

1. Introduction

Solar energy is recognized as one of the most promising alternative energy options. In the near future, the large-scale introduction of solar energy systems, directly converting solar radiation into heat, will be available. On sunny days these systems generally collect more energy than necessary for direct use. Therefore, the design and development of thermal energy storage systems, as part of a complete solar installation to provide an optimum tuning between heat demand and heat supply is of vital importance, and one of the greatest efforts in solar research.

The basic concepts, designs, and developments in thermal energy storage are, therefore, discussed in this chapter.

1.1. Solar Energy Storage

Solar radiation is intermittent by its nature. Its total available value is seasonal and dependent on the meteorological conditions of the location. Unreliability is the biggest retarding factor for extensive solar energy utilization: there is no sun at night. Of course, reliability on solar energy can be increased by storage and using the stored energy whenever needed. Energy storage is therefore essential to any system that depends largely on solar energy. It adjusts temporal mismatches between the load and the intermittent or variable energy source, thereby improving the system operability and utility. Solar radiation cannot be stored as such, so an energy conversion has to be brought about and, depending on this conversion, a storage device is needed. Solar energy can be stored by thermal, electrical, chemical, and mechanical methods, but some energy loss will be unavoidable in all these transformations.

In *thermal* storage, the useful energy from the collector is transferred to the storage medium where it is transformed into an increase in internal energy. This may occur with or without change of phase (i.e. in the form of latent heat, sensible heat or both).
Electrical energy can be stored in a battery, a photovoltaic system being particularly suitable for such type of solar energy storage. It can also be stored in a magnetic field (inductive) or an electrical field (capacitative).

Chemical storage may be classified into thermochemical and electrochemical methods. In thermochemical storage, the thermal energy from the collector can be added to suitable chemical reactants in an endothermic reaction to produce chemical products that can be stored. When this stored energy is needed, these products undergo an exothermic reaction, releasing the thermal energy. Solar energy can also be used to generate hydrogen in a thermochemical reaction. This fuel can, then, be used when needed. Hydrogen can also be generated in an electrochemical process by converting the solar energy from the sun into electric energy which, in turn, produces hydrogen by electrolysis of water.

Storage by *mechanical* means can be achieved in the short term by converting the solar energy from the collector into the mechanical energy of a rotating shaft. This mechanical energy can then be stored for longer periods in the form of internal energy, such as compressed air, gravitational energy (like that stored by pumping water from a low to a high level), or kinetic energy, which can be stored in a flywheel. These can all be transformed back to mechanical energy which can be directly applied or used to generate electrical energy.

1.2. Thermal Energy Storage

Conversion of solar energy into thermal energy is the easiest and the most used method. Furthermore, the greatest use of solar energy is in the form of heat.

Thermal energy in the form of hotness or "coldness" can be stored in various media as sensible heat (temperature change), as latent heat (isothermal phase change), or by a combination of the two. It is often stored in identifiable subsystems that typically include a storage medium, container, insulation, heat exchangers, heat-transfer fluid, pumps or blowers, and controls. The features considered when choosing a thermal storage system are the storage temperature(s) and the storage duration. The storage temperature depends on the application. It has an important effect on the performance of the collector as well as the load. The storage temperature may be classified as low (less than 100°C), intermediate (100 to 450°C) and high (higher than 450°C). Storage duration can be classified as short duration (a few hours to a few days) and long duration (a few months to several seasons). For thermal storage the decisive factor for solar duration is the time-dependent thermal losses. These losses can be excessive for a long duration and unless a suitable storage method is applied, the duration should be short.

There is usually some flexibility in choosing the storage temperature and the storage duration. In a system utilizing solar energy, the energy, can be stored not just by the collector but also by other components of the system. Cost, size, and reliability are important factors which the designer should consider before deciding upon the method of storage and the material to be used in a certain application. The designer should always aim to develop a storage system of long duration, of small volume per unit of energy stored, and of low cost. Thermal energy storage system can be broadly characterized by the following parameters (Kreider and Kreith 1979);

- Quantity of energy in and out (first low efficiency)
- Quality of energy in and out (second low efficiency)
- Energy storage cycle duration
- Input and output power
- Energy density per unit volume
- Investment cost per unit energy out
- Operating and maintenance cost.

1.3. Thermal Storage Efficiency

Thermal energy extracted from the storage system is usually less than that stored, as a result of losses and irreversibilities inherent in the storage process. Probably more important than this is the fact that energy degenerates in the process of storage since it is extracted at a temperature lower than that at which it was previously stored. These two factors, quantity and quality, should be considered when defining the efficiency of the storage process. The quality (first-law) efficiency over a complete storage cycle is:

$$\eta 1 = \frac{Q_{out}}{Q_{in}} = \frac{Q_{in} - losses}{Q_{in}} \qquad (1)$$

Efficiency based on quality (second law) considerations of energy quality (or availability) is expressed in terms of absolute input temperature. T_{in}, output temperature T_{out} and a sink temperature T_{sink}. It can be expressed as the ratio of ideal Carnot efficiencies integrated over the discharge period, or simply as (Kreider and Kreith 1979):

$$\eta_2 = \frac{T_{in}(T_{out} - T_{\sin k})}{T_{out}(T_{in} - T_{\sin k})} \qquad (2)$$

A reasonable definition of the storage efficiency was reported by Turner, Dickinson and Cheremisin, see Elsayed et al. (1986), and is expressed as:

$$\eta_s = \frac{Energy\ Extracted \times \eta_{th}(at \cdots T_{out})}{Energy\ Extracted \times \eta_{th}(at \cdots T_{in})} \qquad (3)$$

where η_s is the storage efficiency and η_{th} is the thermal efficiency which can be taken generally as the Carnot cycle efficiency, based on ambient temperature. In this manner, the storage efficiency defined above represents the ratio between the extraction available energy and the input available energy.

1.4. Thermal Insulation

The main characteristics for thermal insulation materials include low thermal conductivity, relatively unchanging with temperature; high thermal capacity, so that additional thermal storage can be obtained; no deterioration at working temperature; and ease of handling. The insulation material must also be available and reasonably inexpensive. Most industrial insulating materials are made from the following basic materials: asbestos, magnesium carbonate, diatomaceous silica, vermiculite, rock wool, glass wool, cork, cattle hair, and wool. Eighty-five per cent magnesia (a mixture of approximately 85 per cent magnesium carbonate and 15 per cent asbestos fiber) is the most commonly used material for insulation applications up to 315°C (600°F). In addition to having a low thermal conductivity, 85 per cent magnesia is lightweight, easily cut and fitted, unaffected by steam or water leakage, and strong enough to withstand ordinary use. Properties of this and other commonly used insulating materials are given in Table 1.

Material	**Apparent density, Kg m^{-3} (lb ft^{-3})**	**Temperature °C (°F)**	**Thermal conductivity k, W m^{-1} °C (Btu ft^{-1} h^{-1} °F)**
85% magnesia	272	38	0.068
	(17)	(100)	(0.039)
	272	260	0.081
	(17)	(500)	(0.047)
Felted rock or glass wool	256	38	0.052
	(16)	(100)	(0.030)
	256	315	0.099
	(16)	(600)	(0.057)
Aluminum foil (3/9-in air spacing)	3.2	38	0.043
	(0.2)	(100)	(0.025)
	3.2	182	0.066
	(0.2)	(350)	(0.038)
Wool felt	136	0	0.038
	(8.5)	(32)	(0.022)

	136	93	0.057
	(8.5)	(200)	(0.033)
Cork (molded)	120	0	0.036
	(7.5)	(32)	(0.021)
	120	50	0.042
	(7.5)	(122)	(0.024)

Table 1. Thermal Conductivity of Insulating Material (Kreider and Kreith 1979).

The rate of heat loss through insulation applied to cylindrical surfaces can be calculated by eqn. (4) below. Some values of h_1 for vertical cylindrical surfaces in a room at 21°C (70°F) are given in Table 2.

Insulation skin temperature		**Combined coefficient h_t**	
°C	°F	Kj m^{-2} h^{-1} °C	Btu ft^{-2} h^{-1} °F
38	100	9.53	1.68
65	150	11.7	2.07
93	200	13.5	2.38
121	250	15.1	2.67
149	300	16.7	2.95

Table 2. Combined Coefficient for Convection and Radiation from Insulating Surface (Kreider and Kreith 1979).

$$Q = \frac{k(2\pi L)(T_S - T_a)}{In(R_2 / R_1) + (k / h_1 R_2)}$$

Where:

Q = rate of heat loss, kj h^{-1} (Btu h^{-1})

k = thermal conductivity of the insulation at average temperature, W m^{-1} °C (Btu ft^{-1} h^{-1} °F^{-1})

L = length of cylindrical surface, m (ft)

T_s = temperature of surface covered with insulation. °C (°F)

T_a = temperature of the ambient air °C (°F)

R_1 = inside radius of insulation, m (ft)

R_2 = outside radius, m (ft)

h_1 = combined coefficient for convection and radiation from insulation surface, W m^{-2} °C (Btu ft^{-1} h^{-1} °F^{-1}), Table 2.

As the thickness of insulation is increased, the rate of heat loss from the surface is decreased, but the cost of the insulation is increased accordingly. The most economical thickness of insulation is that for which the sum of the life-cycle cost of the heat loss plus the life-cycle cost of the insulation materials is a minimum. The heat loss per hour per unit length for a vertical cylindrical tank can be calculated for several assumed thicknesses of insulation by using eqn. (4). The cost of the heat loss equals the product of this heat loss per hour multiplied by the hours of operation per year multiplied by the cost of the heat loss per kj (Btu). The cost of the insulation materials equals the cost of the insulation materials (applied) multiplied by the fraction of this cost to be amortized each year. Results of these calculations can be plotted and the most economical thickness of insulation determined.

2. Sensible Heat Storage

2.1. Introduction

Sensible heat storage is carried out by adding energy to a material to increase its temperature without changing its phase. The material used can be a liquid or a solid. The liquids most often used are water and thermal oil. Solids used include rocks, brick, concrete, iron, dry and wet earth, and many others. Most of these have the characteristics necessary for a good storage material. Two disadvantages are inherent in most sensible storage systems. These are the large size usually required and the temperature swing created from the sensible addition and extraction of energy. If a large temperature swing is permitted, the storage size correspondingly decreases. However, compared with other methods of storage, the size will still be high. The size can also be decreased by using storage materials which have a large thermal capacity (ρC). A large storage size, besides occupying a large space and causing increased cost, also causes large thermal losses. It thus necessitates the usage of a large volume of insulation which in turn increases the cost substantially.

Sensible heat storage material should have high thermal properties which are specific heat C, density ρ, and thermal diffusivity α. The storage material should be reversible over many cycles of heat addition (charging) and extraction (discharging). It should also be chemically stable, non-corrosive, non-combustible, and non-toxic. The storage material should also be mechanically stable.

2.2. Low Temperature Sensible Heat Storage

The thermal properties and thermal capacity of some suitable sensible storage materials are given in Table 3. Data show that water has the highest value of thermal capacity. However, other materials such as rock and earth should not be excluded as potential materials of low temperature storage.

Material	C J Kg^{-1} K	ρ Kg m^{-3}	K W mK^{-1}	$\alpha\times10^{7}$ m^{2} s^{-1}	Thermal capacity $\rho C(1-\varphi)$ MJ m^{3} K	Porosity range of bed φ%	Reference
Water (at 60°C)	4179	983.3	0.654	1.592	4.109	0	Holman 1976
Wrought iron (0.5%C)	460	7848	59	163.4	2.167→3.610	40→0	Holman 1976 Albert et al. 1979
Rock	880	2883	0.48	1.892	1.522→2.537	40→0	Albert et al. 1979
Brick	878	2242	-	-	1.181→1.968	40→0	Albert et al. 1979
	836	1926	0.72	4.47	1.59	-	Saleh 1982
Dry earth	-	-	0.6→1	4→5	1.5→2		Albert et al.

							1979
	840	1698	-	-	-	-	Saleh 1982
Wet earth	-	-	1.5→3	7→8	2→4	-	Albert et al. 1979
Concrete	1120	2242	-	-	1.507→2.511	-	Albert et al. 1979
	961	2408	1.73	7.48	2.29		Saleh 1982

Table 3. Thermal Properties of some low temperature sensible heat storage materials (Elsayed, Taha and Sabbagh 1986).

2.2.1. Storage in Liquids

Water is the most suitable thermal storage liquid for a low temperature range (less than 100°C). It has a high thermal capacity (about 4.2 MJ m^{-3} K) and can be stored at atmospheric pressure in that temperature range. Water is also advantageous over many other storage materials when the collector fluid in the solar energy system is water. However, water is corrosive to some materials and the lifetime of water tanks is only about 10 years A water store can be located above ground or underground. Tanks above the ground may be stationed indoors or outdoors.

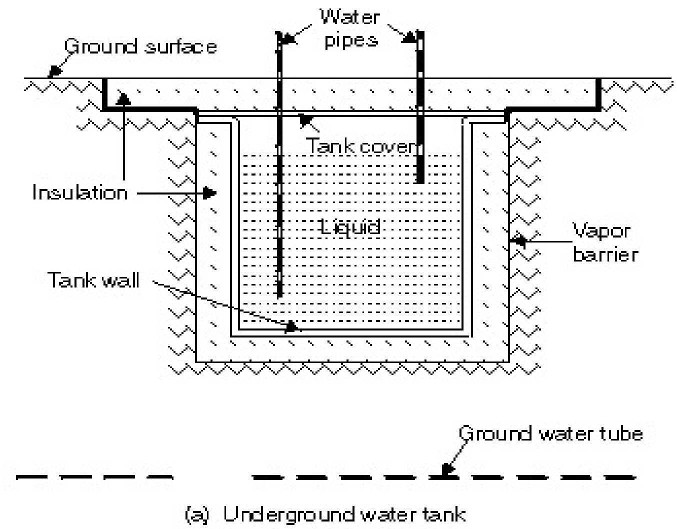
Above ground liquid storage is usually used for short period storage. The cost of the above ground storage system represents a high percentage of the initial cost. The insulation used to decrease the thermal losses represents a large percentage of the storage cost as a result of the large volume of the store. For long term storage, the insulation thickness should be large to avoid excessive energy losses. To cut down this cost it is logical to turn to underground storage and thus make use of the abundant insulating material represented by earth.

Two procedures can be followed for underground liquid storage. These are: (i) burying water tanks in the ground at shallow depths from the surface, Figure (1a), and (ii) injecting water into a cavity in the ground surrounded by a solid, non-porous rock formation, or injecting it into an aquifer, Figure (1b).

The sizing of the storage tank is a major problem. There are many factors which affect the economical and operational size of the storage tank for a certain solar system. These factors include: (i) the purpose of the solar energy system (i.e. the load); (ii) the area of the collector; (iii) the meteorological conditions at the location, and the operational characteristics of the system. The economy of the system is governed by the percentage cost and by the fraction of the total operational energy used by the solar collectors to provide the load.

A simple method which may be followed to estimate the size of the tank is to decide upon a certain interval of time $\Delta\tau$ during which the nominal load Q_L is fulfilled solely by using the stored energy (Elsayed, Toha and Sabbagh 1986). In this case, a temperature swing ΔT in the tank representing the difference between an allowable maximum and allowable minimum temperature of the storage liquid is decided upon. The maximum temperature is usually imposed by the physical properties of the liquid, particularly the boiling point. The minimum temperature is judged by the temperature requirement of the load, or by the expected effect on the overall efficiency of the solar energy system. The storage volume can then be obtained from the following simple equation:

$$V = (QL\Delta\tau)/(\rho C\Delta T)$$



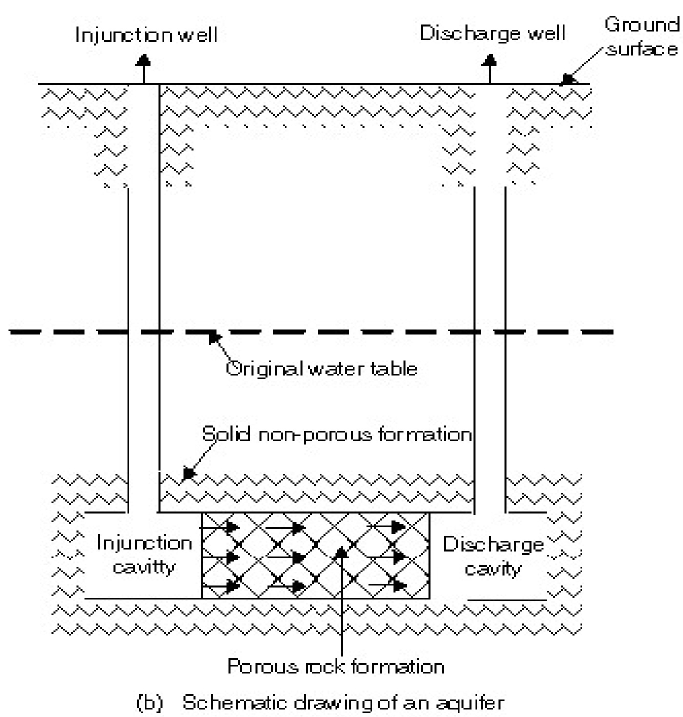


Figure 1. Underground liquid storage (a) underground water tank; (b) schematic drawing of an aquifer.

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Bibliography and Suggestions for further study

General References (Books)

Elsayed M M, Taha I S and Sabbagh J A (1986) Design of solar thermal systems. Scientific Publishing Center, King Abdulaziz University, Saudi Arabia.

Kreider J F and Kreith F (1979) *Solar Energy Handbook*. McGraw-Hill Book Co, New York.

Sayigh A A M (ed.) (1977) *Solar Energy Engineering*, Chapter 15 by M. Ali Kettani. New York: Academic Press, pp. 325-339.

Developments in Sensible and Latent Heat Storage

A. Wokaun. Beyond Kyoto: The risks and how to cope. UN Framework Convention on Climate Change. Bonn, Germany, 16-25 June 2004

Al-Karaghouli A.A., Alnaser W.E. (2004), *Experimental comparative study of the performance of single and double basin solar-stills*. Appl Energy **77**(**3**), pp. 317-25.

Al-Karaghouli A.A., Alnaser W.E. (2004), *Performances of single and double basin solar-stills.* Solar Energy **78**(**3**), pp. 347-54.

Al-Shammiri M., Safar M(1999). Multi-effect distillation plants: state of the art. Desalination , 126:45-59.

Bansal N K and Singh S (1985) Study of three different underground storage systems. *Energy Convs. Mgmt* 25(3), 303-307.

Brousseau P and Lacroix M (1996) Study of the thermal performance of a multi-layer PCM storage unit. *Energy Convs. Mgmt.* 37(5), 599-609.

Chafik, E., 2003. A new type of seawater desalination plants using solar energy. Desalination

Corrado Sommariva ,(2010),COURSES IN DESALINATION, Thermal Desalination

Delyannis E. (2003), *Historic background of desalination and renewable energies.* Solar Energy **75**(**5**), Elsevier pp. 357-66.

Fath, Hassan E S (1991) Heat exchanger performance for latent heat thermal energy storage system. *Energy Convs. Mgmt.* 31(2), 149-155.

Fath, Hassan E S (1995) Thermal performance of a simple design solar air heater with built thermal energy storage system. *Energy Convs. Mgmt.* 36(10), 989-997.

Fath, Hassan E S (1995) Transient analysis of thermosyphon solar air heater with built-in latent heat thermal energy storage system. *Renewable Energy* 6(2), 119-124.

Florides G., Kalogirou S. (2004), *Ground heat exchangers – a review.* Proceedings of third international conference on heat power cycles, Larnaca, Cyprus, on CD-ROM.

García-Rodríguez L. (2003), "Renewable energy applications in desalination: state of the art", Solar Energy 75, 381-393.

García-Rodríguez, L., 2002, Seawater desalination driven by renewable energies: a review. Desalination 143: 103-113

Gregorzewski, A. and Genthner, K., High efficiency seawater distillation with heat recovery by absorption heat pumps. Proceedings of the IDA World Congress on Desalination and Water Reuse, pp. 97-113, Abu Dhabi, November 18-24, 1995.

Kalogirou S. (2004), *Solar energy collectors and applications.* Prog Energy Combust Sci, **30**(**3**), pp. 231-95

Karameldin, A. Lotfy and S. Mekhemar (2003), *The Red Sea area wind-driven mechanical vapor compression desalination system*, Desalination **153**, Elsevier pp. 47-53.

Kaushik S C, Kumar and Garg H P (1995) Effect of baffle plate on the performance of triangular built-in-storage solar water heater. *Energy Convs. Mgmt.* 36(5), 337-342.

Kaygusuz K (1995) Experimental and theoretical investigation of latent heat storage for water based solar heating system. *Energy Convs. Mgmt.* 36(5), 315-323.

Kudish A.I., Evseev E.G., Walter G., Priebe T. (2003),*Simulation study on a solar desalination system utilizing an evaporator/condenser chamber*. Energy Convers Manage 44(10), Elsevier, pp. 1653-70.

M.A. Darwish , Iain McGregor, (2005), *Five days' Intensive Course on - Thermal Desalination Processes Fundamentals and Practice*, MEDRC & Water Research Center Sultan Qaboos University, Oman

Millow B. and Zarza E., Advanced MED solar desalination plants. Configurations, costs, future – Seven years of experience at the Plataforma Solar de Almería (Spain), Desalination 108, pp. 51-58, 1996.

Müller-Holst, H., 2007. Solar Thermal Desalination using the Multiple Effec Humidification (MEH) method, Book Chapter, Solar Desalination for the 21st Century, 215–225.

Nahar N M (1983) Year-round performance of an improved collector-cum-storage type solar water heater. *Energy Convs. Mgmt* 23(2), 91-95.

Parekh S., Farid M.M., Selman R.R., Al-Hallaj S. (2003), *Solar desalination with humidification-dehumidification technique – a comprehensive technical review*. Desalination **160**, Elsevier pp. 167-86.

Sayig A.A.M. (2004), *The reality of renewable energy*. Renewable Energy, pp. 10-15.

Soteris A. Kalogirou (2005), *Seawater desalination using renewable energy sources*, Progress in Energy and Combustion Science **31**, Elsevier, pp. 242-281.

Thomson M., Infield D. (2003), *A photovoltaic-powered seawater reverse-osmosis system without batteries*. Desalination **153**(1-3), pp. 1-8

Tiwari G.N., Singh H.N., Tripathi R. (2003), *Present status of solar distillation.* Solar Energy 75(5), Elsevier, pp. 367-73.

Tripanagnostopoulos Y and Yianoulis P (1992) Integrated collector-storage systems with suppressed thermal losses. *Solar Energy* 48(1), 31-43.

Tzen E., Morris R. (2003), *Renewable energy sources for desalination.* Solar Energy **75**(**5**), Elsevier, pp. 375-9.

United Nations, Water for People, Water for Life – UN World Water Development Report, UNESCO Publishing, Paris, 2003.

Watanabe T, Kikuchi H, and Kanzawa A (1993) Enhancement of charging and discharging rates in a latent heat storage system by use of PCM with different melting temperatures. *Heat Recovery Systems and CHP* 13(1), 57-66.

Wiseman, R., Desalination business "stabilised on a high level" – IDA report, Desalination & Water Reuse 14(2), pp. 14-17, 2004.