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A review of available methods for seasonal storage of solar thermal energy in residential applications

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ABSTRACT

There is generally agreement among the HVAC (Heating Ventilating and Air Conditioning) community that one of the main issues impeding solar thermal technologies from achieving their full potential for space heating and domestic hot water (DHW) production applications is the development of economically competitive and reliable means for seasonal storage of thermal energy. This is particularly true at high latitude locations, where seasonal variations of solar radiation are significant, and in cold climates, where seasonally varying space heating loads dominate residential energy consumption.

This review presents the principal methods available for seasonal storage of solar thermal energy. It concentrates on residential scale systems, and particularly those currently used in practice which mostly store energy in the form of sensible heat. Some newer methods that exhibit promise, like chemical and latent storage, are also briefly discussed and pertinent reviews are referenced.

Contents

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1. Introduction

Solar thermal energy technologies offer good potential for production of heat for residential space heating and domestic hot water production. It can be shown that the amount of solar radiation incident on the roof of a typical home exceeds its energy consumption over a year. The relatively low temperatures required for heating and DHW applications make solar collection efficiency relatively high: for example, according to Cruickshank [1], thermal systems are typically two to four times as efficient as photovoltaic (PV) systems. Furthermore, space and water heating are responsible for a large portion of the energy needs of residential buildings: about 80% in Canada [2] and 82% in Europe [3]. There is therefore a large potential in using solar thermal technologies to convert solar radiation into usable sensible heat.

As is generally well known, offsets and intermittence make achieving the potential of solar technologies relatively complex. The bulk of energy production occurs at midday, if the sky is clear; and during summer. Meanwhile, consumption is higher during winter, especially at morning and night when space heating loads tend to be at their peak and occupants use more hot water. The diurnal offset is relatively easy to compensate for with water tanks (buffers) and other short term storage methods like the use of the building's thermal mass [4]. At the seasonal scale however, solutions are more complex and expensive.

There are many methods available to compensate for the seasonal offset. For example, increasing the tilt angle of solar collectors augments winter production, resulting in an increase of directly usable heat for space heating; even if this decreases the total annual collected heat. Using heat collected during the summer to charge sorption or desiccant systems to cool or dehumidify buildings [5] is a way to use excess summer production that is gaining considerable attention in the research community. Finally, seasonal thermal energy storage (TES) can make the availability of heat match the demand.

Seasonal storage systems are much larger than short-term ones. Braun [6] evaluated that storage capacities per unit of collector area must be two to three orders of magnitude (100–1000 times) larger for seasonal storage than for overnight storage. Nevertheless, Fisch et al. [7] reported investment costs per square meter of solar collector for large scale solar plants only twice as high for systems with seasonal storage than for systems with short-term storage.

According to Braun et al. [8], significant reductions in solar collector requirements for heating could be achieved by using seasonal storage at northern latitudes, where seasonal variations are large, and in cold climates, where DHW loads are much smaller than space heating loads. Similarly, Hooper [9] stated that a solar heating system with a 100% solar fraction[1] for a Canadian home using seasonal storage would require 25% of the collector surface needed for the same system type equipped with short-term storage. Since solar collectors tend to be expensive, there is definitely potential in developing more economical storage systems in order to obtain higher solar fractions for these heating tasks.

Sillman [10] evaluated that performance of systems equipped with seasonal storage increases linearly as the storage size increases up to the point of unconstrained operation, i.e., the point where the storage size is sufficient to store all the heat collected during summer. He concluded that this point of unconstrained operation is the likely economic optimum. He also evaluated that systems with seasonal storage providing nearly 100% solar space heating may cost the same or less per unit heat delivered than systems equipped with diurnal storage providing only 50% of the space heating.

This review presents the methods available for seasonal storage of solar thermal energy in residential applications. It discusses technical aspects of these systems, and summarizes the research and implementation work accomplished to date. Emphasis is placed on past and present systems, which mostly store energy in the form of sensible heat. Some newer promising methods, like chemical and latent storage, are also briefly discussed and pertinent reviews are referenced.

2. Storage principles

According to Pilkington Solar International GmbH [11], thermal energy storage can be classified by storage mechanism (sensible, latent, or chemical) and by storage concept (active or passive). These concepts and mechanisms are described in the following subsections.

2.1. Storage concepts

Active thermal storage systems are characterized by forced convection in the storage material: the storage medium itself circulates. They can again be subdivided in two sub-systems: (1) direct (or closed loop) systems, for which the heat storage medium also circulates in the solar collectors and (2) indirect (or open loop) systems, for which different mediums are used to collect and store the heat.

For passive systems, a heat transport medium passes through the store to carry energy to and from a storage medium. The storage medium can be a solid, a liquid, a phase change material (PCM), or the reactants of a chemical or sorption reaction. The main disadvantage of this type of system is that, for sensible storage, the temperature differential driving the heat transfer decreases as the store is charged or discharged. Such systems can also be limited by the low thermal conductivity of some storage mediums.

Active and passive storage systems should not be confused with active and passive solar thermal systems described by some authors like Dincer and Rosen [12] and Cruickshank [1] and illustrated in Fig. 1. An active solar system (Fig. 1b) is a system that uses a mechanical system (pump or fan) to circulate the heat transport fluid while a passive system (Fig. 1a) uses density gradients (gravitational forces) to circulate the fluid.

2.2. Storage mechanisms

Storage mechanisms have been researched quite intensively in the frame of Task 32 [13] of the IEA (International Energy Agency) SHC (Solar Heating and Cooling) programme. A new joint IEA project [14], involving SHC Task 42 [15] and ECES (Energy Conser-

[1] The solar fraction is the ratio of the heat used for space heating and DHW production coming from the solar heating system to the total heat requirements for these tasks.

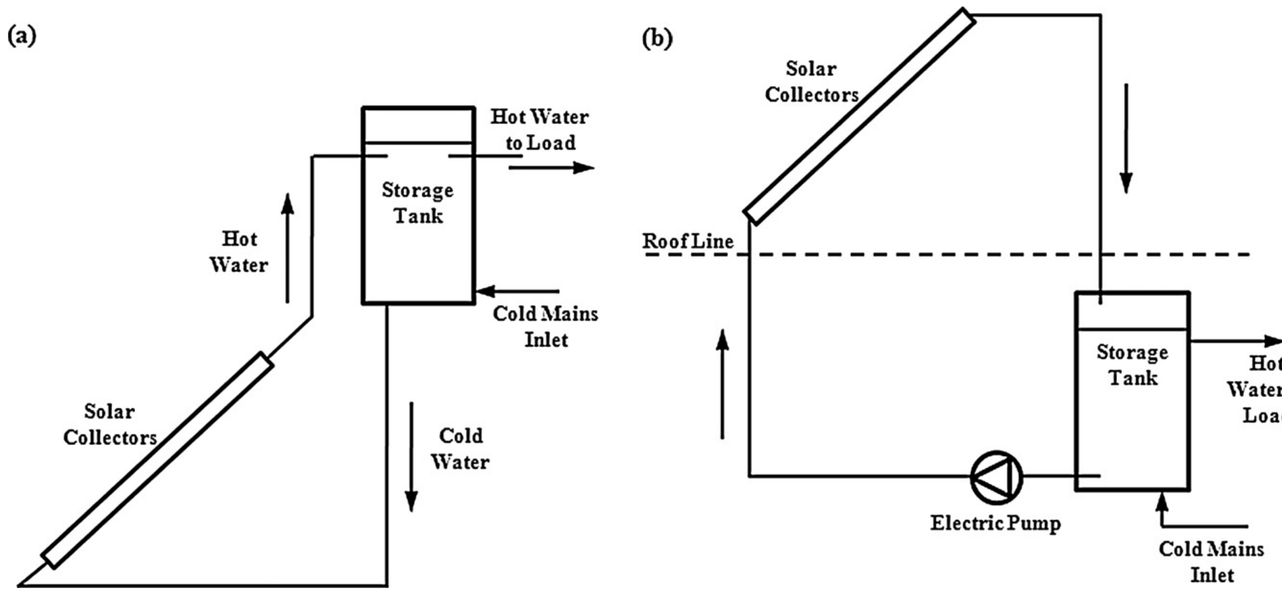

Fig. 1. Typical passive (a) or thermosyphon, and active (b) solar thermal systems (reproduced from Cruickshank [1]).

vation through Energy Storage) [16], concentrates on the storage materials involved.

Hadorn [17] approximated the theoretical storage volumes required to store 6.7 MJ of heat, assuming 25% of the heat is lost, using different mechanisms. His approximations, illustrated in Fig. 2, show the great potential of some relatively recent concepts like the use of chemical reactions.

It is worth noticing that the calculated water volume in Fig. 2 is for a 70 °C temperature increase, a reasonable assumption for space heating applications: the space temperature is about 20 °C while water can easily be stored at temperatures up to ≈100 °C. For storage of cold, where temperature differences are smaller (≈20 °C between the application temperature and the 0 °C limit of water), latent and chemical mechanisms are even more advantageous.

2.2.1. Chemical

Bales et al. [18] separate chemical storage in chemical reactions and thermo-chemical (sorption) processes. These principles are described in the following subsections.

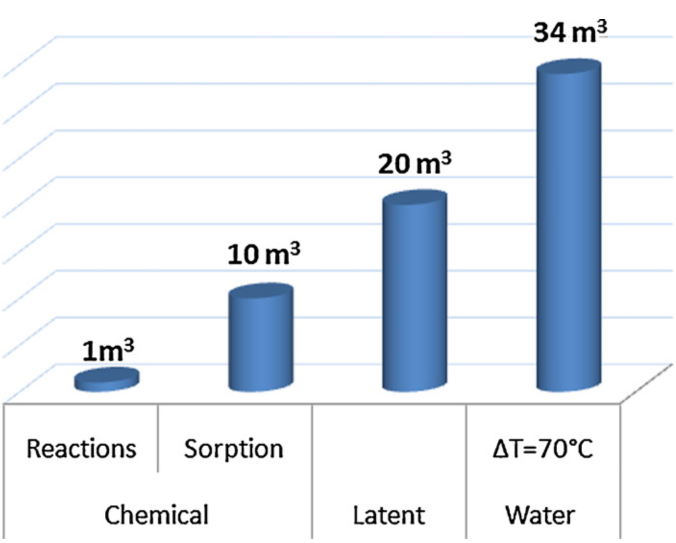

Fig. 2. Volume required to store 6.7 MJ (from Hadorn [17]).

2.2.1.1. Chemical reactions. Chemical reaction storage consists of using the collected heat to excite a reversible endothermic chemical reaction. The stored heat can be recuperated by reversing the reaction, sometimes by adding a catalyst.

A prototype system using one such reaction was proposed during Task 32 of the IEA SHC programme [19]. It involves the separation and recombining of magnesium sulphate seven hydrates, a desorption–adsorption reaction, which could theoretically store 2.8 GJ/m^3 of energy. This prototype is illustrated in Fig. 3. The chemical reaction is:

$$MgSO_4{\cdot}7H_2O(s) + heat \Leftrightarrow MgSO_4(s) + 7H_2O(g) \quad (1)$$

Task 32 identified potential candidate reactions for this type of storage [20]. They are summarized in Table 1. Although the very high storage density of silicon oxide is attractive, the endothermic part of the reaction is quite complex and must be performed in an industrial environment: it involves side reactions including HF and electrolysis of NaF and H_2O. The exothermic reaction of silicon oxide, as well as all other reactions involving the reactants enumerated in Table 1 can be performed in residential areas.

2.2.1.2. Thermo-chemical processes. Thermo-chemical storage consists of storing energy by using it to break the bonding of water with a relevant substance (desorption), evaporate one of the products, and condense it for future use. The heat is recuperated by re-evaporating the condensed product and re-bonding it (sorption) with the other substance. Some molecules, referred to as sorbents, have a high affinity for water (sorbate) with which they develop a strong bond. The breaking of that bond (desorption), and subsequent evaporation of one of the constituents, is therefore an endothermic reaction. The reverse reaction, sorption, is exothermic. Sorption processes can be classified in three types: adsorption (by a solid), absorption (by a liquid) and solid/gas reactions.

Table 2 presents potential molecule pairs for thermo-chemical storage identified as showing potential for residential solar thermal applications in the frame of IEA SHC Task 32 [20]. The energy densities presented in the table are for the weight of the pair and not just for the weight of the sorbent as presented by some authors. These pairs were selected as the best candidates from a more complete list provided by Mugnier and Goetz [21].Zeolites, sometimes used for adsorption processes, are aluminosilicate minerals of alkali

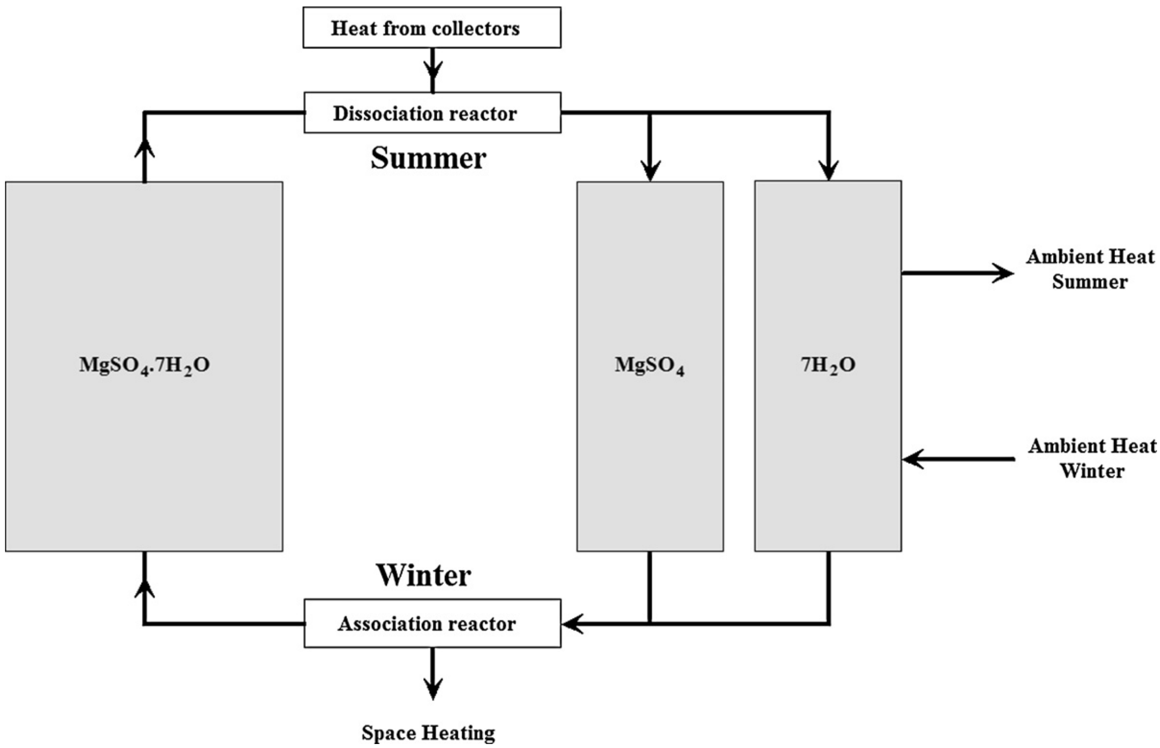

Fig. 3. Chemical reaction storage prototype from IEA SHC Task 32 (reproduced from bales et al. [19]).

Table 1
Potential materials for chemical reaction storage identified during IEA SHC Task 32.

Material	Dissociation reaction	Storage density (GJ/m^3)	Turnover temperature (°C)
Magnesium sulphate	$MgSO_4{\cdot}7H_2O \Rightarrow MgSO_4(s) + 7H_2O$	2.8	122
Silicon oxide	$Sio_2 \Rightarrow S_i + O_2$	37.9	4065 +HF: 150
Iron carbonate	$FeCo_3 \Rightarrow FeO + CO_2$	2.6	180
Iron hydroxide	$Fe(OH)_2 \Rightarrow FeO + H_2O$	2.2	150
Calcium sulphate	$CaSO_4{\cdot}2H_2O \Rightarrow CaSO_4 + 2H_2O$	1.4	89

Table 2
Sorption pairs identified during IEA SHC Task 32.

Absorption	Adsorption	Solid–gas reaction
NH_3–H_2O 0.40 GJ/kg	H_2O–zeolite 4A0.08 GJ/kg	H_2O–Na_2S 1.27 GJ/kg
H_2O–NaOH1.00 GJ/kg	H_2O–silica gel 0.14 GJ/kg	H_2O–$MgCl_2$0.84 GJ/kg
		H_2O–$CaCl_2$ 0.98 GJ/kg
		H_2O–LiCl 0.71 GJ/kg

or alkaline earth metals which contain crystal water. Their general chemical formula is:

$$A_mX_pO_{2p}{\cdot}nH_2O \tag{2}$$

where A represents the chemical elements Ca, Na, K, Ba, or Sr; X represents the chemical elements Al or Si; m, n and p represent the number of atoms of each element in a molecule.

Fig. 4 presents a closed loop sorption storage principle that was studied in the frame of IEA SHC Task 32. In this closed principle heat, but not matter, is exchanged with the ambient and the sorbate (water) needs to be condensed in the charging phase and then evaporated in the discharge phase.

The evaporation process of this system requires low grade heat (≥5 °C) to evaporate the water during discharge. This low grade heat can be extracted from the building, thus cooling it, or from the ambient or other “free” sources. The exothermic sorption into the sorbent is used for heating the building. The thermal storage can therefore be used to provide either cooling or heating.

Open loop thermo-chemical processes are generally integrated into the ventilation system of buildings in a similar way as desiccant systems are. In this concept, illustrated in Fig. 5, the sorbent is located as a packed bed or in a porous (honeycomb) structure in which the ventilation air of a building is circulated. The sorbent removes the humidity from (dries) this air. Heat is used to dry (recharge) the sorbent. Considering that the sorbent can be used to remove humidity from air at a later time, this recharge constitutes a form of energy storage. One such system was studied in the frame of Task 32.

IEA SHC Task 32 also evaluated the storage system implemented in the ClimateWell [22] absorption chiller. To understand the storage method of the ClimateWell chiller, one must also understand the cycle of a typical one stage sorption chiller illustrated in Fig. 6. In this example, a liquid sorbent–water solution is pumped from a low pressure absorber to a generator. In the generator, this solution is heated, breaking the sorbent–water bond (desorbing) and evaporating the water: the generator increases the pressure of the solution which is why it is often referred to as a thermal compressor. A higher concentration solution is returned from the generator to the absorber while the excess water, in vapour form, is transferred to the condenser. Heat is extracted from the condenser, liquefying the water. This liquid water is then transferred to the

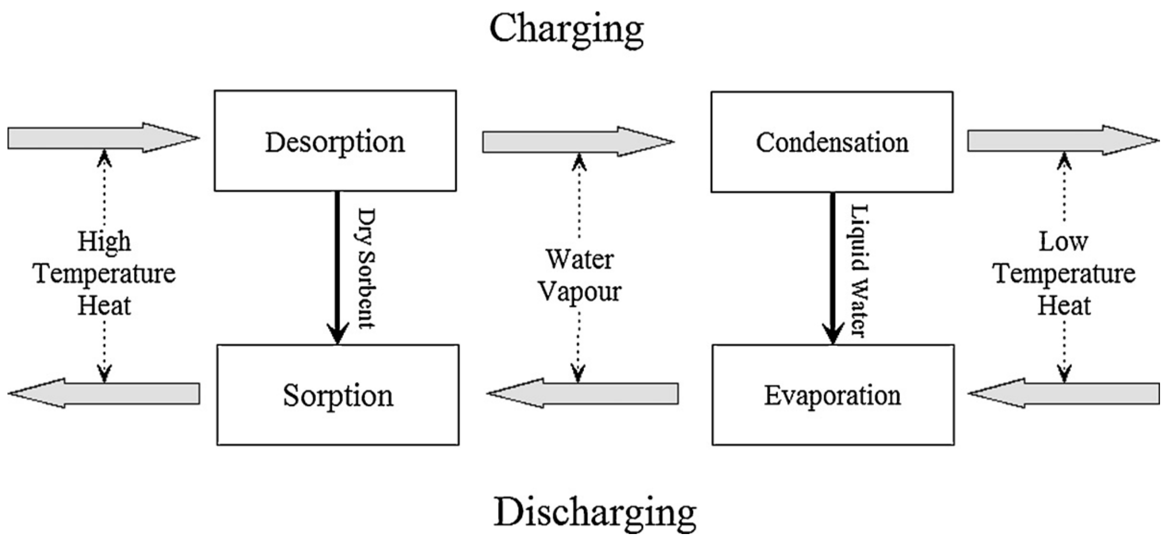

Fig. 4. Closed loop sorption storage principle (reproduced from Bales et al. [19]).

lower pressure evaporator, where it is evaporated with low temperature heat: the low pressure in the evaporator is due to the sorbent–water solution in the absorber. This water vapour is then transferred to the absorber where it is again absorbed. The cycle can be compared to the cycle of a typical mechanical compression heat pump where water would act as the refrigerant: the condenser and evaporator serve the same purpose while the generator replaces the compressor and the absorber serves as the expansion valve.

The main difference between the ClimateWell system and this typical absorption process is that the ClimateWell process is not continuous, i.e., sorption and desorption do not occur at the same time. This allows ClimateWell to separate the system in two vessels [23], represented by the dotted lines on Fig. 6: one vessel, the

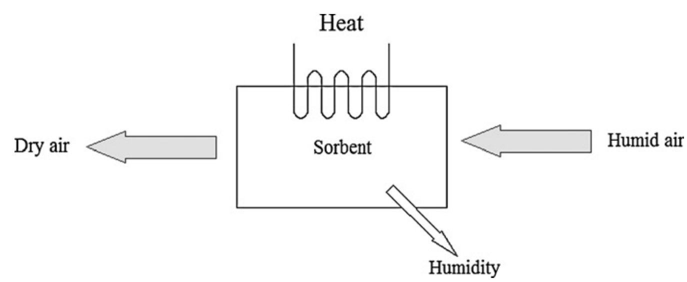

Fig. 5. Open loop thermo-chemical storage.

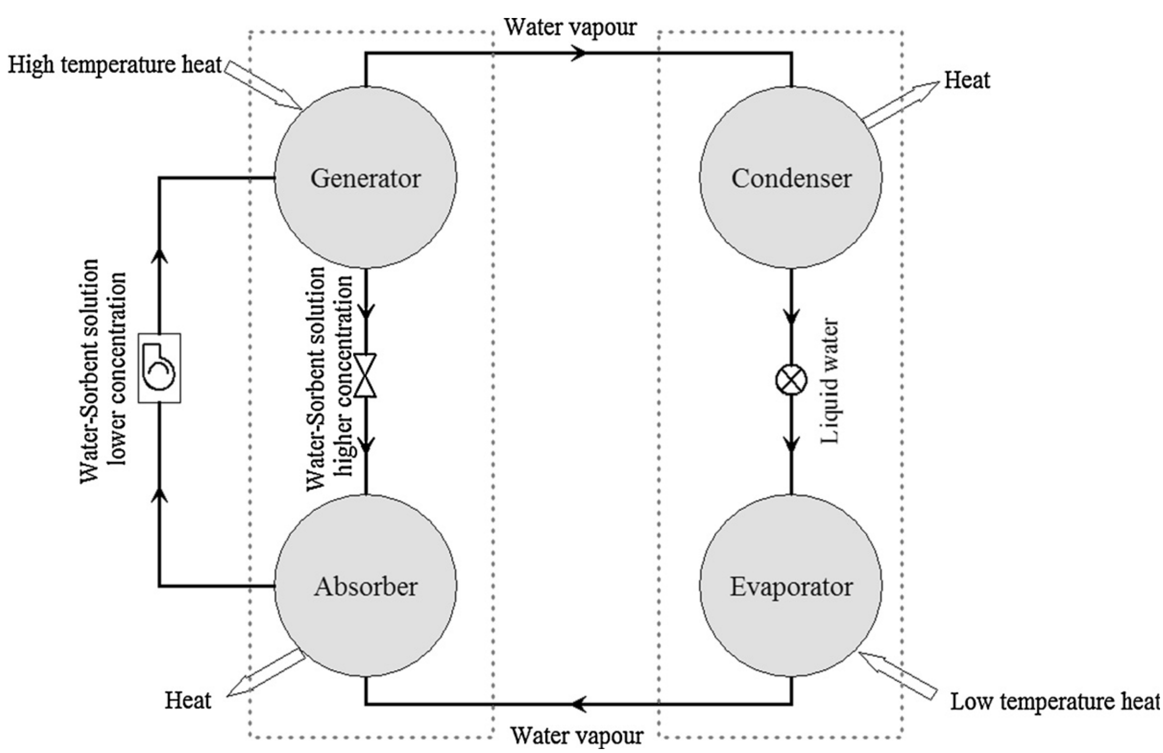

Fig. 6. Typical one stage absorption cycle with water as a sorbate.

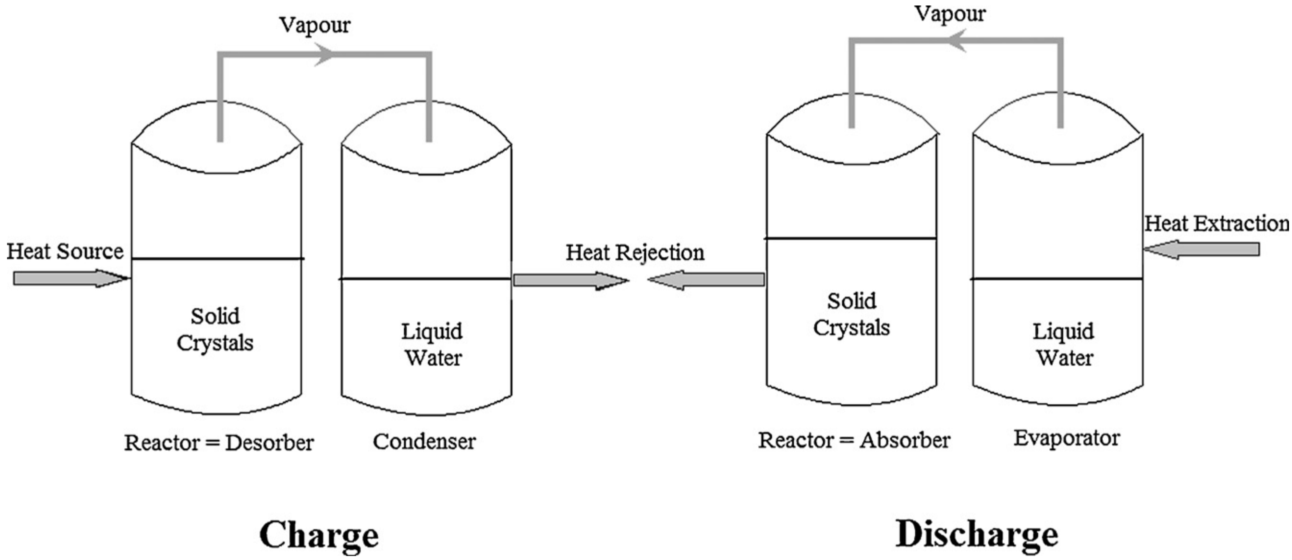

Fig. 7. Charge and discharge processes of the ClimateWell chiller.

reactor (vessel on the left of Fig. 6), handles the absorption and desorption while the other (vessel on the right) acts as the evaporator and condenser. Another major difference is that during the desorption (or charge) process the sorbent, lithium chloride ($LiCl_2$), crystallizes, resulting in a three phases sorption process instead of the two phases process illustrated in Fig. 6. These solid crystals act as a storage medium as they can be diluted in the water during the sorption, or discharge, process. Fig. 7 illustrates these discontinuous charge and discharge processes where solid crystal acts as a thermo-chemical store.

2.2.1.3. State of the research. Chemical storage has the undeniable advantage of allowing storage of reaction products at ambient temperature, resulting in no long-term self discharge of the storage unit: a significant benefit for seasonal storage applications. Other advantages are the very high storage density obtained, good control of reactions involving catalysts and the possibility to use sorption reactions for cooling purposes.

Chemical storage systems have been researched, as previously mentioned, in the frame of the IEA SHC Task 32 programme [13]. A European project, numbered NNE5-2000-00385 [24] and entitled SOLARSTORE, is also preoccupied with them. The SOLARSTORE [25], a solid–gas sorption short-term storage system using bromide strontium as a sorbent and water as a sorbate, has been built and tested and some short-term absorption storage systems, like the one implemented in the previously described ClimateWell chiller, have reached market. Nevertheless, the main conclusion from Task 32 is that there are a number of promising technologies and materials for the seasonal chemical storage of solar heat, but that much research remains before they become practical and economical. The main area of research should be on materials, which are either too expensive, do not have the right properties or have not yet been shown to work in prototypes with realistic boundary conditions. Numerical modelling of the heat and mass transfer processes in thermo-chemical materials is still very basic and also needs to be further developed to improve understanding of how these systems work and make possible their optimization.

2.2.2. Latent

Latent storage consists of storing heat nearly isothermally in some substances, referred to as Phase Change Materials (PCMs), as the latent heat of phase change. In practice, this type of storage generally consists in melting ice, paraffin, fatty acids, salts or mixtures depending on the storage temperature required. PCMs are usually classified as organic (paraffin, fatty acids, alkanes) or inorganic (salts).

Fig. 8 illustrates the enthalpy evolution of a typical compound as a function of temperature. The regions of the curve where the temperature is lower or higher than the fusion temperature are regions where it is possible to store heat in sensible form: the amount of heat stored is the product of the specific heat and the temperature increase (assuming that the liquid form is incompressible and the specific heat is constant). At the fusion temperature, the compound undergoes a change of phase and can absorb or release energy at a nearly constant temperature as long as the change of phase is not completed, i.e., as long as the energy injected or extracted is not equal to its enthalpy of fusion (h_{sf}). So the latent heat storage potential of a compound is equal to its enthalpy of fusion.

This type of TES demonstrates relatively high energy density: for example, the temperature of a volume of water ($Cp \approx 4.2\,MJ/m^3K$) would have to be increased by 43 °C to store the same amount of energy as the same volume of typical paraffin, like the C13–C24 compound ($h_{sf} \approx 180\,MJ/m^3$, $T_{fusion} \approx 23\,°C$), melting and by 270 °C to store the same amount of energy as the phase change of NaCl ($h_{sf} \approx 1144\,MJ/m^3$, $T_{fusion} \approx 800\,°C$). They also have the advantage of constant temperature discharge. According to Zalba et al. [26], disadvantages include:

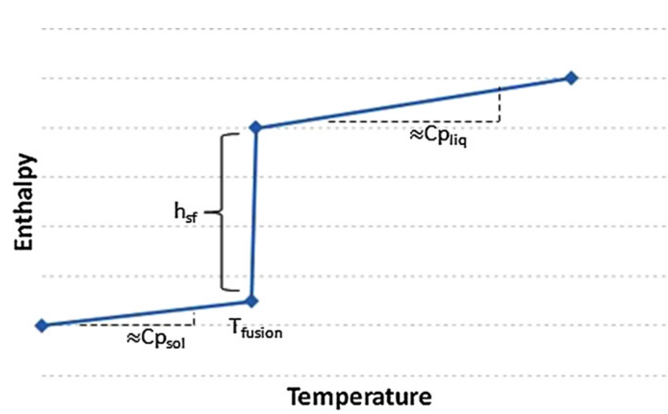

Fig. 8. Enthalpy evolution of a compound undergoing a change of phase.

- Inorganic PCMs: undercooling, containment difficulties (corrosion), phase separation, phase segregation, lack of thermal stability.
- Organic PCMs: lower phase change enthalpy than inorganic ones, low thermal conductivity which makes extracting heat at a high rate problematic, inflammability.

A common way around the thermal conductivity problem consists of encapsulating PCMs to increase their heat exchange area and circulating a heat transport fluid through a bed of these capsules. This results in a combined sensible/latent active/passive store exhibiting a higher storage density and more stable storage temperature than a tank filled with only the heat transport fluid. Another advantage of encapsulation consists in easier management of volume changes, which can be relatively important especially for organic PCMs. It is also possible to integrate PCM particulates in the structure of other compounds in order to obtain more advantageous heat transfer characteristics.

Extensive reviews of available PCMs and research work concerning latent storage are provided by Kenisarin and Mahkamov [27], Tyagi and Buddhi [28], Sharma et al. [29], Zalba et al. [26], and Cabeza et al. [30]. An interesting research topic from the point of view of using latent mechanisms for seasonal storage consists of subcooling a PCM as described by Streicher et al. [31]. Subcooling consists of storing heat in a PCM by liquefying it and then reducing its temperature while keeping it in liquid phase, i.e., conserving the energy stored in the phase change. It could theoretically be possible to reduce the temperature of a PCM in liquid phase to the ambient conditions, eliminating long-term heat losses.

The main conclusion of IEA SHC Task 32 [31] was that the improvement of using PCM in heat stores are very limited compared to water stores for most of the applications looked at by the taskforce: space and water heating. According to the task participants, the only concept that can, in theory, achieve significant improvement is long term storage using subcooling: but the resulting system would probably be excessively complex due to the need of several stores insulated against each other and a reliable mechanism to activate crystallization. The investment cost may also not be justified. Nevertheless, they recommend pursuing research in the screening of better PCM materials – the design of stores resulting in larger PCM fractions in the storage materials, higher heat transfer between heat transport fluids and PCMs as well as hydraulic layouts and control strategies better adapted to this type of storage – and development of better simulation models.

2.2.3. Sensible

Finally, sensible storage consists of storing heat, as internal energy, in the temperature increase of a medium: generally a liquid or a solid. Sensible systems are usually simpler and cheaper than their alternatives. They are well demonstrated, clearly understood, reliable and widely used concepts. According to Hadorn [17], storage in the 20–80°C range has been done for centuries with water, and water will remain the storage of choice for solar combisystems[2] for the years to come: in fact, no seasonal chemical or latent seasonal storage systems have been applied to date for residential application. Furthermore, Sections 2.2.1 and 2.2.2 clearly indicate that, despite the large potential of chemical and latent mechanisms, further research and development is required in order for these concepts to result in reliable and economically competitive seasonal storage systems. Therefore, the remainder of this article focuses on sensible TES.

[2] A solar combi-system is a system that provides heating and domestic hot water, as well as possibly space cooling, from an array of solar thermal collectors. This system is usually backed up by an auxiliary non-solar heat source.

3. Mediums for sensible heat storage

According to Hariri and Ward [32], the principal characteristics of a TES system limiting the variety of choices are:

- Its energy capacity per unit volume or weight;
- the temperature range over which it operates;
- the energy transport medium properties (toxicity, corrosiveness, heat capacitance);
- the temporary stratification of the storage unit;
- the power requirement for the addition or removal of heat;
- the material container associated with the storage system;
- the means of controlling thermal losses from the storage system;
- its cost.

Obviously, an important requirement of a good storage medium is a high thermal capacity (density multiplied by specific heat). Space limitations are often an issue, especially for residential applications. This limits the mediums used to liquids and solids. Another important quality is the capacity to absorb or release heat at a rate sufficient for the required application. This rate is dependent on the thermal diffusivity of the medium for solids and the possibility of obtaining high convective heat transfer rates for liquids. In general, it is easier to exchange heat with liquids, but solids are easier to stratify and contain.

Stratification allows an increase of the energy quality (exergy) within a store and makes it easier to store collected heat. Many authors, including Dincer and Rosen [12,33], Rysanek [34], Cruickshank [1], Badar et al. [35] and Krane [36] evaluate the exergy, or useful work potential, content of TES systems. Stratification is discussed in Section 4.

For sensible TES systems, the relatively high heat exchange area and temperature difference between the store and its surroundings can lead to considerable self discharge through heat losses, especially over the long periods involved in seasonal storage. Reduction of self discharge is addressed in Section 5.

The cost of the storage medium is obviously a major incentive in the selection of a storage medium. This is especially true for seasonal systems which tend to be large. For this reason, large thermal storage systems for residential applications have typically used water, soil or rocks as storage mediums. These mediums have been used in a number of system configurations. Some of these configurations are discussed in the following sub-sections. Other storage mediums are also briefly discussed.

3.1. Water

Water is the storage medium of choice for storage in the 20–80 °C temperature range due to its high thermal capacity (∼4.2 kJ/kgK) and low cost. Its main inconvenience is its limited temperature range but this does not affect residential applications much since the upper temperature of that range is more than sufficient for space heating and DHW production. Additionally, it is close to the upper temperature limit of the fluid exiting typical solar collectors. The possibility to obtain high convective heat transfer rates from water is both an advantage, as it allows high heat injection and extraction rates, and an inconvenience, as it makes stratification more difficult.

3.1.1. Water tanks

Water tanks can be either artificial constructs made of steel and/or concrete or geological cavities. Heat is transported to or from the tank by a flow of water in and out of the tank or by a fluid circulated in a heat exchanger inserted in the tank. Fig. 9 presents some commonly used heat transport configurations reproduced from

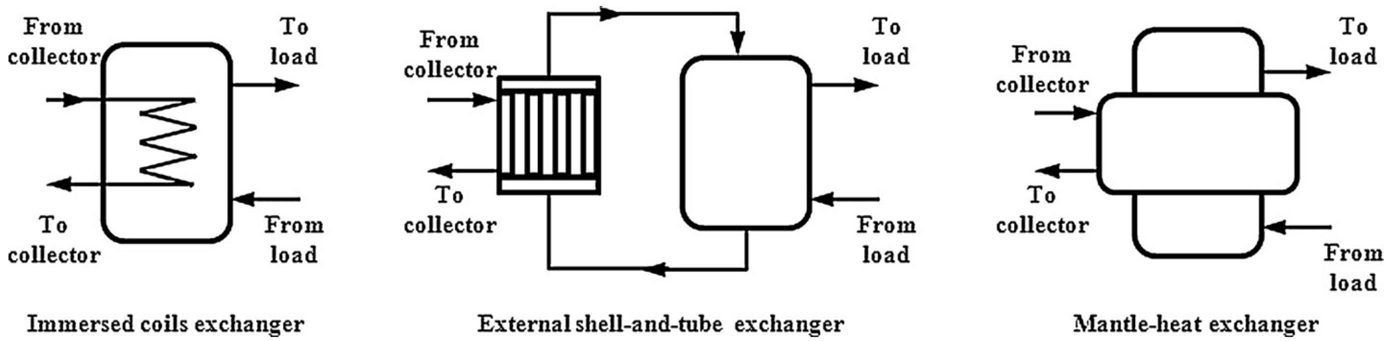

Fig. 9. Common configurations to transport heat into a water tank (reproduced from Han et al. [37]).

Han et al. [37]: immersed coils, external (side-arm), and mantle types heat exchangers.

Immersed coil heat exchangers are generally located at the bottom of thermal storage tanks to take advantage of the greatest temperature differences between the solar heated fluid and the incoming water on the load side. These designs tend to produce uniform temperatures in the storage tank (i.e., unstratified temperature distributions); this is undesirable, as explained in Section 4. Solar thermal systems configured in this way often use specialized (and more costly) thermal storage tanks fitted with special internal heat exchangers.

External heat exchangers represent flexible options for indirect systems as they allow standard, less expensive storage tanks and heat exchangers to be used. Most solar thermal systems used in North America are indirect systems with external heat exchangers and two circulation pumps: one to circulate an anti-freeze solution through the solar collectors and the other to circulate water from the storage tank through the heat exchanger. Numerous studies have been completed to optimize the performance of this type of system and, in particular, to characterize the performance of natural convection heat exchangers used to eliminate the need of a circulation pump in the exchanger-tank hydraulic circuit: including those by Purdy et al. [38], Lin et al. [39], and Cruickshank and Harrison [40]. Commercially available for a number of years, this configuration has led to increased reliability, cost-effectiveness, and improved thermal performance due to its potential for increasing thermal stratification in the storage tank.

Mantle heat exchangers consist of a double walled storage tank that allows the heat transfer fluid to be circulated through the storage mantle (i.e., cavity formed by the two walls) transferring heat to the stored water. Mantle tank storage systems tend to have a large heat transfer surface area that increases performance but require specialized tanks that may be more costly. Used mostly in Denmark and Australia, mantle tank systems have been extensively studied by Rosengarten et al. [41], Andersen and Furbo [42] and Knudsen [43] among others.

3.1.2. Aquifer

Aquifer thermal energy storage is a concept that has received considerable attention because of its potential for economical large scale and long term energy storage. In this concept, wells are used to carry water to/from the aquifer, allowing transport of heat as illustrated in Fig. 10.

Aquifer storage is considered to be best suited for high capacity systems. The amount of energy that can be stored depends on the allowable temperature change, the thermal conductivity, and the natural ground water flow. Designers must also take into account

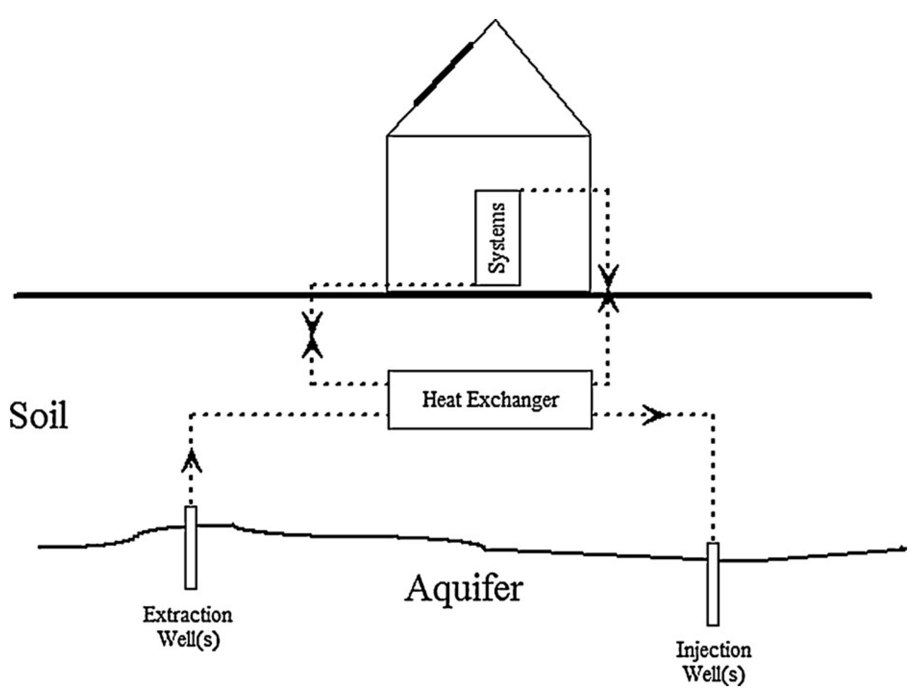

Fig. 10. Aquifer storage.

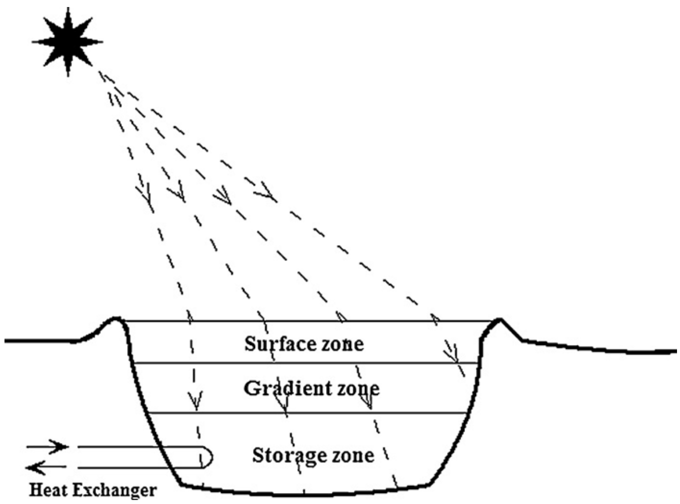

Fig. 11. Solar pond.

potential environmental consequences. Dincer and Rosen [12] and Lee [44] provide more complete reviews of aquifer storage systems.

3.1.3. Solar ponds

Surface water (ponds or lakes) can be used to collect and store solar heat. In this concept, pioneered in Israel during the 1960s, an existing natural pond is used or an artificial pond is constructed (Fig. 11). Solar ponds contain salt solutions. The salinity gradient results in higher salt concentration at the bottom of the pond, so heat absorbed at the bottom remains trapped there. In other words, the salinity gradient inhibits natural convection and the cooler water at the surface acts as an insulator. Darkening the bottom of the pond also results in more solar radiation being absorbed.

According to Dincer and Rosen [12], salinity-gradient solar ponds may be economically attractive in regions with little snow fall and areas where land is readily available. They require certain maintenance, similar to that of a swimming pool, in order to control algae and bacteria growth. Kamal [45] and Duffie and Beckman [46] provide literature reviews on solar ponds covering issues like performance predictions, design, maintenance, sample projects, and economics.

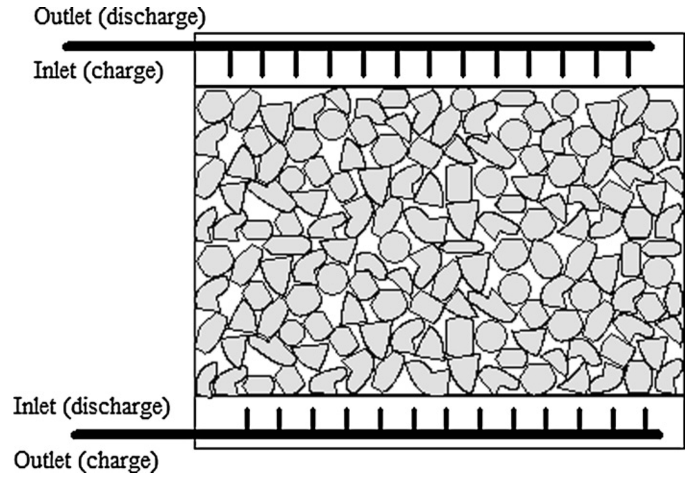

Fig. 12. Rock bed storage system.

3.2. Rock beds (or gravel)

Rock bed storage consists of having a heat transport fluid, usually water or air, circulate through a bed of rocks, discharging/charging heat to/from it as illustrated in Fig. 12. In cases where air is used to transport heat, the transport medium does not contribute to the storage and the resulting storage system is nearly passive. When water is used, it contributes to the storage and the resulting system is a hybrid active/passive system.

Rocks have lower thermal capacity than water but can easily operate at higher temperatures and are easier to contain. Nevertheless, it is usually recognized that rock bed storage offers relatively low energy density, especially if the heat transport medium does not contribute to the storage [11], as is the case with air based systems. According to Dincer and Rosen [12], it takes about three times more space to store the same amount of heat in rocks than in water but the economics favour solar air collectors with rock bed storage over liquid collectors with water based storage for short-term storage applications. For seasonal storage in residential applications, available space is quite often a critical aspect. It is also an important factor for insulated and buried systems since the costs of insulation and excavation are proportional to the size of the installation. Finally, larger systems experience higher heat losses. For these reasons, rock bed storage should be considered for seasonal

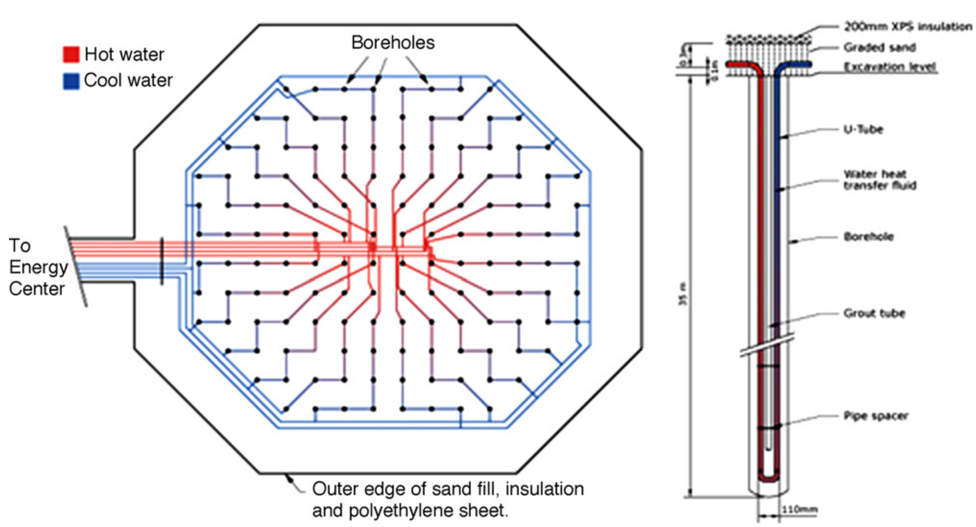

Fig. 13. Drake Landing Solar Community seasonal TES [47] Bore field configuration (left) and boreholes details (right).

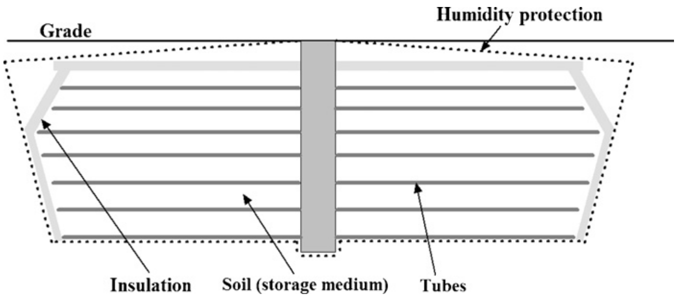

Fig. 14. Vaulruz system (horizontal tubes).

applications mostly when geological conditions favour this type of system.

3.3. Ground (soil or solid rock)

The use of ground as a passive storage medium has the potential to result in low-cost systems since soil is free. In this concept, the ground is excavated or drilled to insert tubes (vertical boreholes[3] like the Drake Landing Community system [47] illustrated in Fig. 13 or horizontal pipes like the Vaulruz [48] system illustrated in Fig. 14) in which a heat transport fluid circulates, injecting/extracting heat in/from the ground material. Soil can also be used as an insulator for water tanks. In this concept, discussed in more details in Section 5, the ground is excavated to insert a water tank and the setup is backfilled.

Although soil is free, excavation or drilling required for the completion of many systems is relatively expensive. Tubes, tanks or even insulation and water barriers used in some systems also represent a significant cost. For the Vaulruz system, Chuard et al. [48] reported a cost breakdown where excavation is responsible for 40% of the TES system's cost. Schmidt et al. [49] reported cost breakdowns of many systems in Germany. For systems that are either buried or using soil as a storage medium, the groundwork represents 21–24% of the total storage systems cost. The total TES systems costs vary between 0.4 and 1.35 million Euros for these projects.

Givoni [50] compared the applicability of three different soil conditions for use as storage mediums. According to him, long-term storage in dry ground is limited to desert and arid zones. In regions with limited amount of rainfall, this system could be applied where adequate protection of the storage area and its periphery from water penetration can be provided. The water table should also be at sufficient depth. It is also possible to use wetted soil in dry surroundings to take advantage of the fact that wet soil demonstrates higher volumetric storage capacity and thermal conductivity than dry one. To construct such a system, a certain ground area in a dry region should be covered by an impermeable cover and insulated. Heat transfer from the point where the heat transport fluid circulates to the rest of the storage medium is accomplished both by direct conduction and by water migration within the ground. Expansion of wet soil relative to its volume in dry conditions should also be considered during design.

3.4. Other mediums

Oil or salt solutions are also commonly used as liquid heat storage mediums. Oil being more expensive than water, it is generally used for applications requiring higher storage temperatures. Salt solutions, or brines, are commonly encountered when old salt mines (caverns) are used as storage tanks and flooded, or when using salinity gradient solar ponds (see Section 3.1.3).

Blocks or plates made of different solid materials can also be used for sensible storage of heat. For example, graphite [51] and concrete [11,52] storage systems have been built. Pellets or balls of iron and iron oxide have also been used. These mediums are generally more expensive than soil, rocks or water so their typical application is storage of high temperature heat destined for generation of electricity where their stability and capacity to endure high temperatures are important properties.

Concrete, present in the structure of a building or added in the form of slabs, is also commonly used for short-term sensible storage [4] of low temperature heat for space heating applications. Constructing a dedicated large concrete seasonal heat storage system would intuitively be less economically competitive than using free materials like soil or rocks.

4. Stratification of sensible stores

Sensible TESs have the disadvantage that a relatively large temperature increase of the storage medium is required to obtain a satisfactory energy density. This can result, if the storage medium is not well stratified, in difficulties to transfer heat to the storage system when it is almost charged and to obtain much use from the lower quality heat available when the system is almost discharged. Stratification, illustrated in Fig. 15 for vertically standing tanks, allows continuous possibilities to transfer heat to the cooler regions of an almost fully charged store while it also results in a proper energy quality being available from the warmer regions of an almost discharged store. Another advantage of stratification, as indicated by Duffie and Beckman [46], is that the lower temperature of the flow returning from a stratified storage increases the solar collectors' efficiency by reducing the convective and radiative heat losses from the collectors to the ambient. Phillips and Dave [53], Castell et al [54], Cabeza et al. [55], and Haller et al. [56] discussed methodologies to evaluate stratification coefficients indicating the level of stratification of storage systems.

Phillips [57] calculated that stratification can increase the amount of useful energy available by 20% in a rock bed TES with air acting as the heat transport fluid. Lund [58] analysed water tanks and determined that stratified stores resulted in solar fractions higher than those obtained with fully mixed stores by as much as 35–60% for central solar plant designs of practical interest. Sharp and Loehrke [59] evaluated that stratification could improve solar system performance by 5–15% compared to well mixed storage. Hollands and Lightstone [60] reported that a perfectly stratified water tank could make a solar system produce 38% more heat than a fully mixed tank.

Many strategies or mechanisms have been explored to improve stratification of sensible storage systems. Rysanek [34], Hugo [61] and Altuntop et al. [62] considered baffles and/or devices named stratifiers inserted into water tanks to reduce mixing of the fluid in order to favour stratification. Work has also been performed on the shape of stores: for example, according to Dincer and Rosen [12] increasing the depth of water based TES favours stratification through gravitational forces acting on the density gradients resulting from temperature differences. Other researchers, like Chung et al. [63], Davidson and Adams [64], Shah and Furbo [65], Jordon and Furbo [66], Lavan and Thompson [67], Zurigat et al. [68], Cataford and Harrison [69], Ghajar and Zurigat [70], Kleinbach et al. [71], as well as Andersen et al. [72] explored the configuration of fluid inlets and outlets for water tanks. Hollands and Lightstone [60] and Newton [73] studied the effect of water flow rate on stratification and solar system performance. Buckles and Klein [74], McCarthy [75], Tabarra and Bowman [76], Bannerot and Wu [77],

[3] Ground storage systems using boreholes for transport of heat are often referred to as "duct" systems.

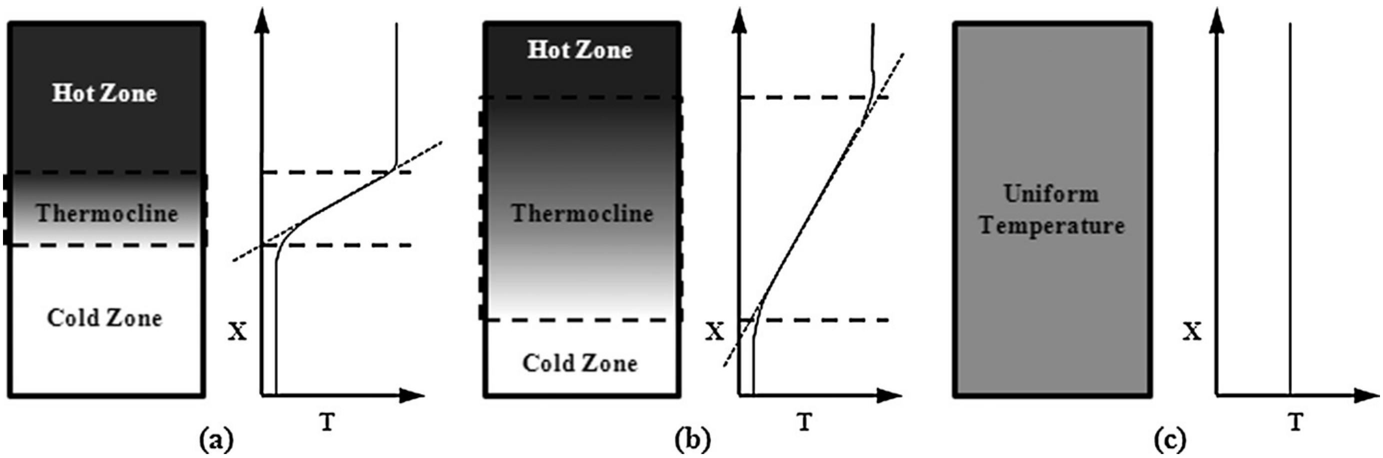

Fig. 15. Differing levels of stratification within a storage tank with equivalent stored energy: highly stratified, (b) moderately stratified, and (c) fully mixed (or unstratified) (reproduced from Cruickshank [1]).

Elliot [78], Andersen and Furbo [42], Knudsen [43], and Jordon and Furbo [79] studied the effect of load profiles on thermal stratification and solar system performance.

Some water tanks have used variable position inlets, like described by Dalenback [80], allowing the injection of heat at locations in the tank where the temperature is similar to that of the heat transport fluid; this avoids destruction of the exergy in the warmer regions of the tank. In a similar way, some passive systems have also used targeted injection of heat to improve stratification: for example, the Drake Landing Solar Community's [81] (Fig. 13) seasonal storage system uses boreholes connected in series from the center to the periphery of the bore field, allowing injection of higher temperature heat in the center of this soil based system while the Vaulruz [48] (Fig. 14) system used 7 buried layers of horizontal tubes superposed vertically allowing injection of incoming heat transport fluid at a height in the soil corresponding to its temperature.

Some researchers have also proposed segmenting storage systems to increase stratification: Crandall et al. [82] used the strategy on a rock bed system, Taylor and Krane [83] used it with a flat slab system while Bejan [84], Arata and de Winter [85], Sekulic and Krane [86], Mather et al. [87], Tacchi [88], Ragoonanan et al. [89], Han et al. [37], and Cruickshank [1] explored it for water tanks.

5. Reduction of self discharge in sensible stores

The generally large volume and high temperature at full charge of sensible stores result in higher heat losses (self discharge) than alternative systems discussed in Sections 2.2.1 and 2.2.2. As observed by Vasseur [90] and Hess and Miller [91] for water tanks, larger heat losses also result in more natural convection in the tank leading to loss of stratification. To compensate, sensible systems are generally insulated and often buried in order to reduce self discharge. It is also recommended [12] to design such systems with geometries resulting in low surface over volume ratios in order to reduce relative heat losses.

When a system is buried, the temperature of the soil surrounding the storage region eventually increases while its thermal conductivity decreases due to its humidity content diffusing along thermal gradients. This results in decreased heat losses from the store. Givoni [50] highlighted the following advantages and limitations for insulated buried tanks:

Advantages

- Smaller volume required for a given thermal storage capacity than with rock beds;
- simplicity of heat transport in and out of the storage by water flow;
- can be used in any climatic conditions and soil types;
- relative ease of insulating a tank;
- effect of water flow within the ground on the heat transfer in the store is small.

Limitations

- The ground surrounding the tank does not contribute to the storage progress;
- leakage due to corrosion or cracking of the tank could cause expansion of the ground, leading to differential pressures and movements and potentially leading to more leakage;
- when heat is withdrawn from the store and the tank could get colder than the surrounding ground, condensation may occur in the insulation around the tank, reducing performance.

Dalenback [80] studied the buried system at the Sarö Solar Plant and determined that, if the storage system would be above ground, it would need to be about 1.9 times its actual height or have approximately twice its insulation level in order to provide the same performance. Ucar and Inalli [92] compared the performance of three different cylindrical storage tanks: (1) un-insulated above ground; (2) insulated above ground and; (3) un-insulated below ground. Their results, for three different scale systems (25, 250 and 1000 houses), show that the underground storage tank consistently reach higher solar fractions than the above ground alternatives, especially after the first years of operation since the ground around the store warms with time, reducing heat losses even more.

Dincer and Rosen [12] cite two studies concluding that bermed tanks perform better economically than completely buried tanks; even if they do not perform as well at reducing thermal losses. Berming a tank consists in partially burying it and covering the section from the top of the tank to the ground level with soil as illustrated in Fig. 16. The top of the tank is insulated. Bermed tanks require less excavation, resulting in lower initial cost, and allow easy access to the tank for maintenance.

6. Past projects

A large number of seasonal storage projects have been completed and studied since the 1940s. Some of these are discussed in the following sections.

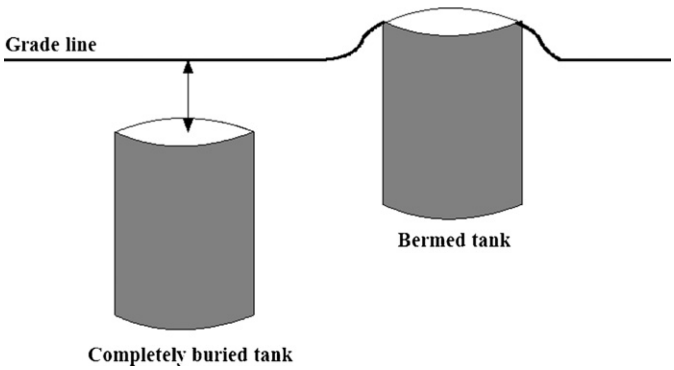

Fig. 16. Bermed tank VS completely buried tank.

6.1. Larger systems

For a high latitude country like Sweden, where seasonal variations result in small solar heat production during winter, the pertinence of seasonal storage is clear. This, relatively high energy prices, and the strong commitment of the Swedish government to phasing out nuclear energy and reducing oil dependency, resulted in Sweden leading the way during the 1980s in the construction of solar thermal plants with seasonal storage as well as the conception of simulation models allowing the study, design, and optimization of such systems. A large portion of this work was accomplished in the frame of Task 7 of the IEA SHC Programme [93]. Larger systems benefit from economies of scale: Fisch et al. [7] found that the investment cost per square meter of collector area for larger systems is between 20% and 30% of the cost for single house systems – well designed larger sensible storage systems are generally more efficient than smaller ones of the same energy density since larger sizes result in smaller area/volume ratios and therefore in lower relative heat losses as pointed out by Kozlowski et al. [94] – and Sweden has a strong tradition of district heating. This resulted in most of these projects (Studvisk, Ingelstad, Lambohov, Lyckebo, Nykvarn, Falkenberg, Sarö, Malung, Kunsbacka, Kullavik, Luleå, etc.) being community size systems. These plants used many different means of seasonal energy storage including typical steel or concrete tanks that are insulated and/or buried, rock pits or caverns filled with water, aquifer storage, or duct (ground) storage.

Such large scale seasonal storage systems have also been constructed in other countries including Switzerland [48], Denmark [95], Finland [96], France [97], The Netherlands [98] [99], the United-States [100–102], Turkey [103], Korea [104], Germany [105,106] and Canada [81]. Dalenback [80], Bankston [107] and Boysen [108] provide rather complete overviews of the state of research and different projects during the 1980s. According to Dincer and Rosen [12], if Sweden lead the way during the 1980s, Canada took over during the 1990s with the implementation of many aquifer TES systems, including those at Sussex Hospital, Carleton University, and Saskatoon Airport; these storage systems were not used for storage of solar energy but to extract extra heat from buildings during summer and use it for space heating during winter. More recently, Germany, where 11 large scale solar systems with storage were constructed since 1996 according to Schmidt and Mangold [109], has been occupying a leadership role.

Schmidt and Mangold [109] reported 65 solar heating plants with more than 500 m^2 of installed collectors in Europe concentrated mostly in Germany, Austria, Denmark, and Sweden. Schmidt et al. [49] reported investment costs, per equivalent water storage volume, for storage systems using four different principles; these costs are reproduced in Fig. 17 where filled markers represent realised projects and empty markers represent projects that were only studied. Even if this sample is limited, some clear trends emerge with larger systems costing less per equivalent storage capacity; and aquifer storage being more economically attractive while water tanks are less.

The European APAS [7] project, "Large-scale Solar Heating Systems", evaluated thirteen large scale solar plant in six European countries. Meanwhile, the Drake Landing Solar Community [110], built in the city of Okotoks, Canada, and operational since the 2006–2007 winter, was the first solar heated community built in North America and the first in the world with a predicted solar fraction over 90% [81].

6.2. Single detached house scale

Even if seasonal storage is more economically competitive at the community scale, single detached housing represents a large fraction of the building stock: according to Natural Resources Canada (NRCan) [111], they account for 68% of the total floor area of all housing and 49% of the floor area of all buildings in Canada. If the building community is to meet ambitious greenhouse gas (GHG) emissions reduction targets, this significant sector must also be addressed.

Givoni [50] credits the MIT (Massachusetts Institute of Technology) solar house as being the first application of seasonal storage to detached single family houses in 1939. The storage system consisted of a 68 m^3 (about 2 m^3/m^2 of collector area) cylindrical steel tank, insulated and buried under the house. Storage temperatures reached 90 °C in August, making it impossible to store collected solar energy during the autumn and early winter since the collectors could not produce higher temperatures. Storage temperatures decreased to 55 °C by the end of February. The system's performance also suffered from condensation in the tank insulation. Many such smaller systems have been built, including those described by Bourret and Javelas [112] (underground rock bed), Oliveti and Arcuri [113] (underground water tank) and Wildmer [114] (above ground water tank), or studied by Ucar and Inalli [92,115] (above and under ground water tanks) and Hugo [61] (above ground water tank) among others.

Smaller scale TES systems have been (or are) also studied, among other storage related concepts, in the frame of IEA SHC Task 26 [116], concerned with solar combi-systems, and Task 32 [13,17], on advanced storage concept for solar and low energy buildings. Task 26 was accomplished in collaboration with the European Commission (EC) Altener project [117], which resulted in more than 200 solar combi-systems installed in 7 EC countries. Other EC projects, like the High-Combi project [118] which plans construction of 5 demonstration plants in 4 countries, are also concerned with using storage to achieve very high solar fractions for space conditioning and DHW production.

Seasonal storage systems for single family houses have also been explored in Canada. One such project, called Providence House, was conceived by Hooper [9]. The Providence House was built in 1976 [119] in the Toronto region with a 277 m^3 storage tank buried under the house. The system ended up providing only 60% of the house's heat requirements due to higher than expected heating loads, collector performance lower than manufacturer ratings, and higher than predicted storage heat losses: according to Hooper, the most probable reason for these high storage losses is heat transfer by convection in the soil surrounding the storage tank, which was neglected by the calculation procedure used for design.

Many solar heated houses, equipped with various storage systems – mostly rock beds, water tanks, and combinations of the two – were built during the 1970s in the north of the U.S. and in Canada. Some of these houses, with claimed solar fractions ranging from 55% to 100%, are described by Carriere and Day [120].

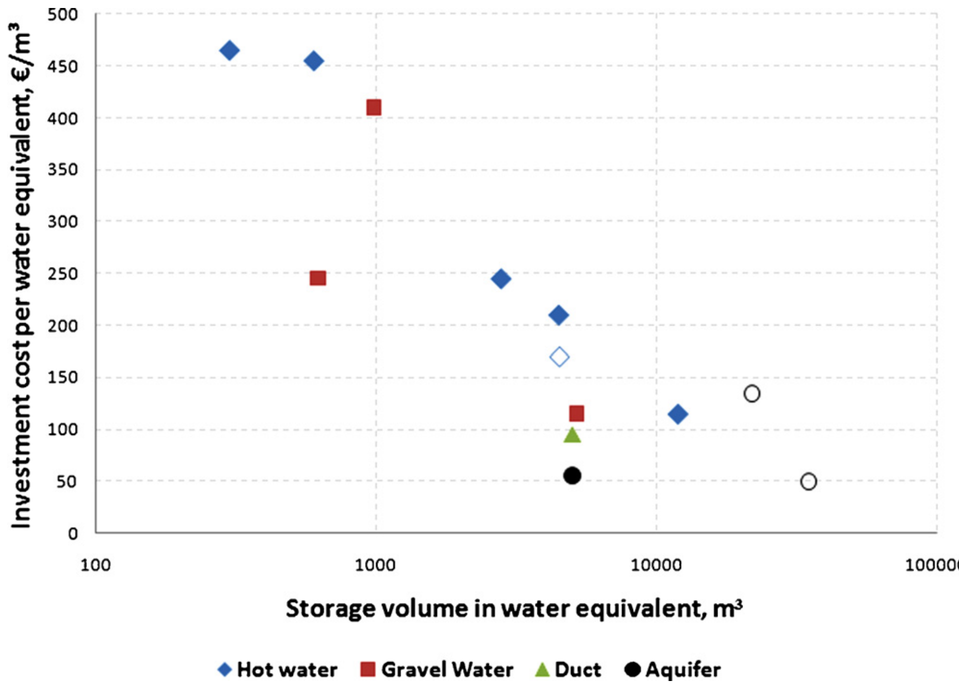

Fig. 17. Investment costs reported by Schmidt et al. [49].

Some projects developed in the frame of the equilibrium sustainable housing demonstration initiative [121] also included relatively large TES systems; notably the Riverdale NetZero duplex [122], built in Edmonton, Canada, which included a 300 l DHW tank and a 17 m^3 storage tank for space heating: the active solar thermal systems provide 64% of the space heating and 93% of the water heating.

Besant and Winn [123] simulated the performance of solar systems with seasonal storage for various North American locations and concluded that these systems could be economically competitive with commonly used heating fuels in regions with low winter cloud cover. More recently, Hugo [61] simulated a solar combisystem for a house in Montreal and concluded that a 100% solar fraction is possible but not economically competitive due to the low cost of electricity and lack of government incentives in the province of Quebec.

7. Modelling of sensible storage

Through the 1970s and 1980s, a certain number of researchers (e.g., Lunde [124], Hooper and Cook [125], Braun et al. [126], and Lund [127,128]) created simplified models which can be used for the design of entire solar heating systems with seasonal storage: Duffie and Beckman [46] provide details for some of these methods, including their well known f-chart method. Most of these models are based on different simplifications of the TES system's behaviour in order to simplify and speed up calculations: for example, typical simplifications involve considering the store as a single temperature and heat capacity node and/or in calculating variations of the store's temperature on a monthly basis. These methods were extensively used at a time when computing resources were more limited and are still used nowadays for the design of smaller systems when the extra cost and required time of more complex modelling is sometimes difficult to justify.

Task 7 of the IEA SHC Programme [93] resulted in the creation of the MINSUN [80] solar system simulation software. MINSUN incorporated: (1) a storage tank model, the Tank Storage Temperature (TST) model; (2) an advanced buried tank model, the Stratified Storage Temperature (SST) model, capable of representing systems of various geometries; and (3) a borehole model, the Duct STorage (DST) model [129].

In more recent years, many different models have been developed and implemented in whole building simulation packages like TRNSYS [130], EnergyPlus [131], and ESP-r [132]. These implementations allow the models to reproduce transient dynamic interactions between the systems and their surroundings. Such simulation packages are now used extensively to design, optimize, and study solar systems components, configurations, and control strategies. The use of simulations offers a cheaper and faster alternative to prototyping and produces numerous outputs that could be difficult to obtain experimentally, allowing better understanding of systems' behaviours and interactions.

Some researchers, like Rysanek [34] and Ucar [92], have used commercial numerical calculation codes to evaluate the performance of storage systems. These numerical codes accomplish very detailed studies of complex phenomena within the store but do not allow easy connection to other models (buildings, systems, etc.) in order to obtain precise dynamic boundary conditions for the TES systems models.

The following sections discuss some of these models, the calculation techniques they use as well as some of their inherent limitations. Since there has been a very large number of models developed over the years, only the main ones and some examples are listed.

7.1. Water tanks

Water tanks have been simulated extensively with models ranging from simplified plug-flow models to very complex models solving the full Navier–Stokes momentum equations. It would be unrealistic to attempt to review a significant part of the modelling work that has been performed over the years, especially the enormous amount of work concerning free standing water tanks. Instead, principles are described and some example works are provided.

7.1.1. Free standing water tanks

As previously mentioned, the most complex water tank models resolve the Navier–Stokes momentum equations in the required coordinate directions as well as an energy balance equation on the flow. This type of model can be used to determine the effect of baffles or diffusers on the flow inside the tank and its stratification. Rysanek's [34] work is a good example of application of such models. Determination and resolution methods of the complete Navier–Stokes equations and their many simplifications can be found in classic fluid textbooks such as those from White [133], Versteeg and Malalasekera [134] and Patankar [135].

Resolution of the full Navier Stokes formulation is, at best, tedious and its resolution in a complete model involving all components of a building and solar system interacting dynamically over long periods of time would be bulky and, for most situations encountered in practice, unnecessary. Many simplified models of storage tanks have therefore been developed. A commonly encountered simplification for these models consists in assuming a flow direction and velocity. These models, often referred to as plug-flow models, only require resolution of an energy balance equation.

Current storage algorithms are often based on one-dimensional numerical formulations which incorporate basic models of tank heat loss, thermal diffusion, flow, and buoyancy induced mixing (Newton [73]). These approaches have been shown to adequately represent the performance of stratified thermal storage tanks in cases when the charge and discharge flow rates into the storage are low and therefore mixing of the tank fluid is minimal (Cruickshank and Harrison [136]). The suitability of 1-D approaches is based on the assumption that the temperature distribution through the thermal storage can be treated as one-dimensional, implying that temperature gradients exist in the longitudinal direction but are negligible in the radial direction, i.e., that the tank is well insulated. Such models are presented by Cruickshank [1], Duffie and Beckman [46], Dincer and Rosen [12], and Van Berkel et al. [137] among many others: Van Berkel et al. also compared analytical and numerical models to experimental results.

7.1.2. Buried water tanks

There were many versions of the previously mentioned SST (Stratified Storage Temperature) model developed as explained by Kozlowski [138]. All used a one-dimensional representation of a plug flow in the tank coupled to a two-dimensional representation of conduction heat transfer in the soil around the tank. Other researchers also simulated buried stores. Shelton [139] considered a half spherical, uniform temperature store, located just below an adiabatic plane representing an insulated building's bottom slab as illustrated in Fig. 18. This store exchanges heat in the radial direction by pure conduction with the portion of a uniform ground located below the foundation slab. Yumrutas and Unsal [140] also considered buried tanks as hemispheres around which they evaluated heat conduction in the radial direction using a hybrid analytical–numerical procedure; the main difference is that their tank is located at the surface and the insulation at its top is subjected to ambient conditions. Inalli et al. [141] modelled a buried tank as a complete sphere buried deep enough so that its boundary condition in all directions is the soil far-field[4] temperature.

[4] The far-field temperature, also referred to as the undisturbed ground temperature, is the temperature of the ground at a location: (1) far enough from a system not to be affected by its presence; (2) deep enough not to be affected by conditions at the ground surface.

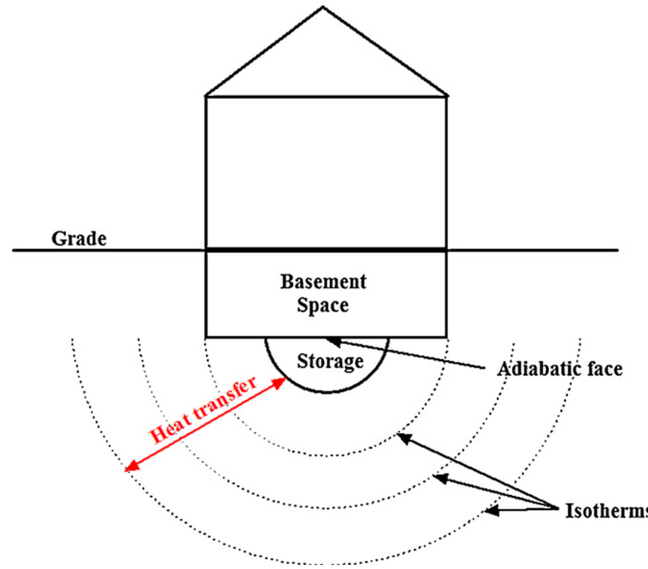

Fig. 18. Shelton's [139] model.

Hopper and Attwater [142] created a method based on 3 indices of performances which were obtained from a numerical simulation: the resulting model approximated conduction heat losses from a partially buried (bermed) tank. Metz [143] developed the GROCS (Ground Coupled System) model, which resolves the heat conduction equation for 30 soil elements located around a storage container by finite difference assuming boundary and initial ground conditions calculated by the ground temperature relationship developed by Kusuda and Archenbach [144]. Salagnac [145] proposed a graphical method, with graphs developed from combinations of numerical simulations and response factors, to evaluate heat losses from buried stores. Kozlowski [138] and Kozlowski et al. [94] describe and compare many different models of buried water tanks.

7.1.2.1. Limitations of these models. Of these models, only the one presented by Shelton [139] accounts, in a limited and unidirectional (it does not account for the effects of the store on the heat transfer from the building's foundation) way, for thermal coupling between a buried storage system and a building's foundation. This thermal coupling is potentially non-negligible for stores located close to buildings: a probable configuration for single detached housing applications.

Furthermore, all these models assume pure heat conduction in the soil while it is well known that humidity diffusion plays a role in the heat transfer and affects soil properties in and around the store as explained by Givoni [50], Hillel [146], Farouki [147] and Campbell [148] among others. These authors discuss complete models of heat and mass transfer in soils: which include a mass balance equation, based on Darcy's law for liquid diffusion and Fick's law for vapour diffusion, as well as an energy balance equation.

A commonly used assumption for design purposes is that a warm store will result in diffusion of humidity in the soil away from the storage zone: and therefore corresponding dry soil properties are used in pure conduction models. Another technique consists in using time and/or space varying ground properties to account for the effect of humidity diffusion: the use of this technique requires a prediction of the humidity level and its effect on ground properties in the store region at all times, which are difficult to predict accurately without a full heat and mass transfer model.

Improperly accounting for humidity diffusion can have a significant impact on results. As previously mentioned (Section 6.2), Hooper [119] blamed convection in the soil for higher than expected heat losses from the Providence system and the MIT solar house suffered from condensation problems in the insulation: phenomena which could have been foreseen with more detailed modelling. Similarly, Ewen and Rogers [149] reported many systems suffering from higher than expected heat losses, potentially due to convection. Hellstrom [150] discussed the differences between common modelling practices and the real physics of heat transfer in soils: this discussion covers tanks, ducts (boreholes), and aquifer storage models.

According to Tsang [151], one of the points raised during Session 3 of the International Conference on Subsurface Heat Storage in Theory and Practice (1983) is that the practice of neglecting convective terms in computational models needs to be critically studied, both in theory and laboratory, to determine errors introduced for a wide range of soils and conditions. Piechowski [152] compared a heat and mass transfer model of a buried heat exchanger to a conduction only model. His conclusion was that there are few differences in the results from both models, except when using low initial soil moisture content since thermal conductivity is more sensitive to wetness in this condition. Leong et al. [153] also found a large influence of soil moisture content on the performance of buried heat exchangers only for dryer soils: for soils with water saturation exceeding 50%, the influence becomes small. As explained by De Vries [154], the main mode of heat transfer in most soils is conduction. Therefore, for many cases, neglecting mass transport could lead to acceptable results if this does not induce significant differences in the evaluated thermal conductivity. Despite these pertinent analyses, there is still no clear definition (list) of soils and conditions for which the pure conduction assumption is applicable.

Surface conditions, like ground freezing, rain and snow cover also potentially have an effect on the heat transfer around shallow systems like those commonly used at the single house scale: frost significantly increases soil thermal conductivity [147] while rain affects humidity diffusion [146]. For example, Tarnawski [155] evaluated from simulations that snow cover has an influence on the performance of horizontal ground heat exchangers: that influence is greater for shallower exchangers. According to another study from Janson and Lundin [156], water movement (discussed in the previous paragraphs) must be considered for freezing soil since freezing causes substantial flows. These phenomena also tend to be either neglected or simplified in most models. This could lead to unrealistic simulation results for shallow systems.

7.2. Ground based systems

Since the 1940s, many models have been developed to evaluate systems using vertical boreholes or horizontal tubes for injection and extraction of heat in the ground. Early modelling generally consisted in solving the infinite line source equation, based on the work of Kelvin et al. [157] and applied to the evaluation of heat transfer around buried tubes by Ingersoll and Plass [158], or the cylindrical heat source equation, developed by Carlslaw and Jaeger [159] and applied to buried tubes by Ingersoll et al. [160]. More recent analytical solutions to the heat conduction problem around buried tubes include the finite line source equation of Eskilson [161], which was further developed by Lamarche and Beauchamps [162] and Sheriff and Bernier [163], and the cylindrical heat source solutions of Beaudoin [164] and Lamarche and Beauchamp [165].

Recently, increased computational capacities lead to the development of more complete vertical borehole models integrated in whole building and energy simulation packages. These newer models are either numerical or hybrid (combining analytical and numerical solutions) models. The Duct STorage (DST) model [129], was originally implemented in MINSUN and eventually, by Pahud and Hellstrom [166], in the TRNSYS [130] simulation environment. The Oklahoma State University model, based on long-term ground temperature reactions to thermal impulsions evaluated numerically by Eskilson [161] and completed with short-term reactions evaluated by Yavuzturk [167], was implemented by Fisher et al. [168] in the EnergyPlus [131] software. Many other borehole models were implemented in simulation software including those from Pinel [169] and Purdy and Morrison [170], which were integrated in the ESP-r [132] package, and the one from Liu and Hellstrom [171] which was integrated in DOE-2 [172]. Spitler et al. [173] compared a number of such simulation models with experimental results. Lundha and Dalenback [174] compared results from the DST model to experimental measurements from a project in Sweden while Breger et al. [100] compared the DST's simulation of a borehole to a finite element model of a U-tube.

Bourret and Javelas [112] coupled a finite difference model of conduction heat transfer around horizontal tubes buried under a building to the building slab: the heat stored in the ground was transferred to the buildings' space through the slab. Gauthier et al. [175] reviewed models of horizontal tubes located below the slab of greenhouses; they also presented their own finite difference model and validated it experimentally. Philippe [176] proposed models combining numerical and analytical solutions to resolve conduction heat transfer around horizontal exchangers; these models were also validated.

Again, all of the previously enumerated models assume heat transfer by pure conduction in the soil so the discussion from Section 7.1.2 applies. Some more complete models, like the ones developed by Lund and Östman [177], Reuss et al. [178] and Tarnawski and Leong [179], also consider water diffusion in the ground. Reuss et al.'s model, based on the pioneering work of Philip and de Vries [180] on heat and mass transfer in porous soils, was validated experimentally.

7.3. Rock bed systems

The geometrical complexity of the rocks arrangement in a rock bed and the resulting complexity of the flow of heat transport fluid make a realistic CFD (Computerized fluid Dynamics) analysis of such systems somewhat difficult. So most existing models used in practice assume linear forced (plug) flows.

Many simplified models, generally referred to as Schumann [181] models, assume the flow to be linear and the rock bed to be a two-phase (rocks and heat transport fluid) system. Each phase has its own distinct energy balance equation with convection heat transfer occurring between the two phases. Certain models assume a very high convection coefficient between the heat transport fluid and the rocks, resulting in both phases being at the same temperature and therefore being treated as a single phase, i.e., with only one energy balance equation. The resulting models are plug-flow models that neglect radiation heat transfer between rocks and thermal gradients within solid particles. Duffie and Beckman [46], Hariri and Ward [32], Phillips [57], Riaz [182], and Hughes et al. [183] describe such models. Zarty and Juddaimi [184] compared a finite differences solution to such a model to a solution obtained with Laplace transforms. Persons et al. [185] and Al-Nimr et al. [186] compared predictions from such models to experimental measurements and found good agreement.

Some more complex two-phase, two or three dimensional models, which take into account heat losses to the surrounding environment, have also been developed. For example, Beasley and Clark [187] and Coutier and Farber [188] developed numerical models while Sowell and Curry [189] proposed a bi-directional model based on temporal superposition of thermal events and response factors.

7.4. Aquifers

Aquifer models generally account for heat and mass transfer. They are often based on classical saturated soil physics theory described by Hillel [146], Campbell [148] and Philip and de Vries [180]. In general, these models consist of a continuity equation based on Darcy's law and an energy balance equation.

Carotenuto et al. [190] compared a simplified aquifer model to a numerical one and found that, for some specific conditions, the simplified procedure provides satisfactory results while providing a fast and useful pre-design tool. According to Tsang [191], analytical solutions are applicable only to the simplest cases and/or in the preliminary design phases; qualitative calculations and, in general, numerical simulation models, must be used for most cases.

A certain number of heat and mass transfer models were proposed during the International Conference on Subsurface Heat Storage in Theory and Practice held in Stockholm in 1983. Among those are the models from Huyakorn et al. [192], Olsen and Reffstrup [193], and Van Meurs and Hoogendoorn [194]. Tsang [191] offered a discussion comparing common modelling assumptions to real life physics of such systems.

More recently, Kangas and Lund [195] described the aquifer storage simulation model AQUYST, which includes a porous medium simulation model, THETA: a full heat and mass transfer model. Lee [196] presents a tri-dimensional model taking into account anisotropy. Bridger and Allen [197] describe a tri-dimensional model of an unconfined heterogeneous aquifer. Lee [44] reviews the main models currently used in practice.

8. Conclusions

This paper has reviewed techniques and mediums for the seasonal storage of collected solar heat for residential applications. Three storage principles (chemical, latent and sensible) were discussed. Chemical and latent principles still present difficulties and need to be further researched. Among these difficulties are the identification of suitable materials; such materials should offer good thermal stability (cyclability) and low cost. Nevertheless, these technologies offer numerous alluring advantages, the main one pertinent to seasonal storage being the possibility to eliminate long-term self discharge.

Most past and present systems have therefore stored heat in sensible form. Since cost is an issue and sensible seasonal storage systems tend to be large, these systems use mostly water, rocks, and soil as storage mediums. A certain number of these projects were reviewed. Much scientific work, also discussed in this paper, has been concerned with improving the stratification of these systems and decreasing their self discharge. Finally, many calculation methods to evaluate, design and optimize sensible systems have been developed through the years and were also reviewed.

Future research work should concentrate on identification of materials and development of more detailed simulation techniques for chemical and latent storage systems. For sensible systems, work should concern the improvement of simulation techniques of soil based system, particularly the precise identification of conditions under which certain simplifications are applicable.

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