STORAGE OF SENSIBLE HEAT

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Summary

Storage of thermal energy is going to be a decisive factor for the future problem of managing energy. The most direct way is storage of sensible heat. Here we have most experience, it is least complicated compared e. g. with latent or chemical heat and it is inexpensive. There are draw-backs of course; sensible heat requires e. g. large quantities of materials and volumes. In the past few years, a great number of new developments occurred and our knowledge of thermal storage has considerably widened.

The use of solar energy has brought forth new concepts of seasonal storage and new ideas for better small water stores. And this is certainly not the end. It is rather the

beginning of an awareness of energy and that we do not only have to save it but that we also can store it.

1. Introduction

Ever since mankind used heat as an energy source, it used stores provided by nature in natural resources such as wood, coal and oil. In principle, these represent stores for solar energy, generated during decades or thousands of years. With increased demand for energy and an increased rate of consumption, mankind, nowadays, lives exceedingly from the energy capital rather than from the growth (the interest).

The technical storage of heat is a pressing problem, therefore. Seldom is there a perfect coincidence in demand and supply of energy; formerly, in the daily life, stores for sensible heat were commonplace: heavy built houses, massive tiled stoves, or a hot brick in the bed in winter. The problem of technical storage has been tackled ever since energy is used industrially: regenerators with ceramic materials have been applied since more than 100 years in the metallurgic and glass industry, in order to recover high temperature heat from flue gas. In 1873, McMahon received a patent for a "storage boiler" /1/, an early predecessor of the present-day sliding pressure steam accumulator patented in 1913 by J. Ruths /1/. For rational use of energy in the future heat storage will be an absolute necessity.

2. Classification and Principles of Storage of Sensible Heat

Thermal energy storage can basically be classified according to the way heat is stored: as sensible heat, in hot liquids and solids, as latent heat in melts and vapour and as chemical heat in chemical compounds. Only the first one is treated here.

Heat - in the physical sense - is a form of energy and can be stored in a variety of ways and for many different applications.

A characteristic property of heat is its temperature: according to this it can be distinguished in low-temperature heat and high-temperature heat. The former is usually applied for domestic hot water supply; it is usually stored in small hot water tanks when used for single family houses, or in large underground containers for large housing projects with hundred and more apartments.

High-temperature heat is applied for all sorts of power processes and in chemical engineering. In these cases, heavily insulated tanks - often pressurised - will be used. There is another criterion for thermal storage, depending on the time involved: short-term storage for a couple of days or long-term storage over a period of months; this is also called seasonal storage. All these terms are found in literature.

Criteria for low- and high-temperature heat are not specified; usually temperatures below 100 °C are named low-temperature. A schematic of various concepts of stores for sensible heat is shown in Figure 1.

The water displacement store has a volume of some hundred litres and is used for hot water supply in houses. The pebble/water reservoir is for the seasonal storage of heat; it is sometimes named "man-made aquifer" and comes in sizes of up to 10.000 m³. The Cowper Regenerator is the device used in steel- and foundry-industry for many years. It consists of a large container filled with ceramic pellets which are alternately heated by flue gases coming from e. g. the blast furnace and cooled by air which is preheated for the furnace.

The solar pond is a special arrangement for an easy store of solar heat. This heat is absorbed at the bottom of the pond and heats the brine there. The salt concentration in the pond increases from top to bottom so that density increases and natural convection is suppressed. Ground Stores, Multiple Well Stores, Aquifers and Storage Reservoirs are seasonal stores which are supposed to transfer summer heat into the winter demand. The Ruth Accumulator stores hot water under high pressure. When the discharge valve is opened, the pressure is released and the superheated water will evaporate until equilibrium at the corresponding saturation temperature is reached (the water cools down since it provides the evaporation heat to the steam).
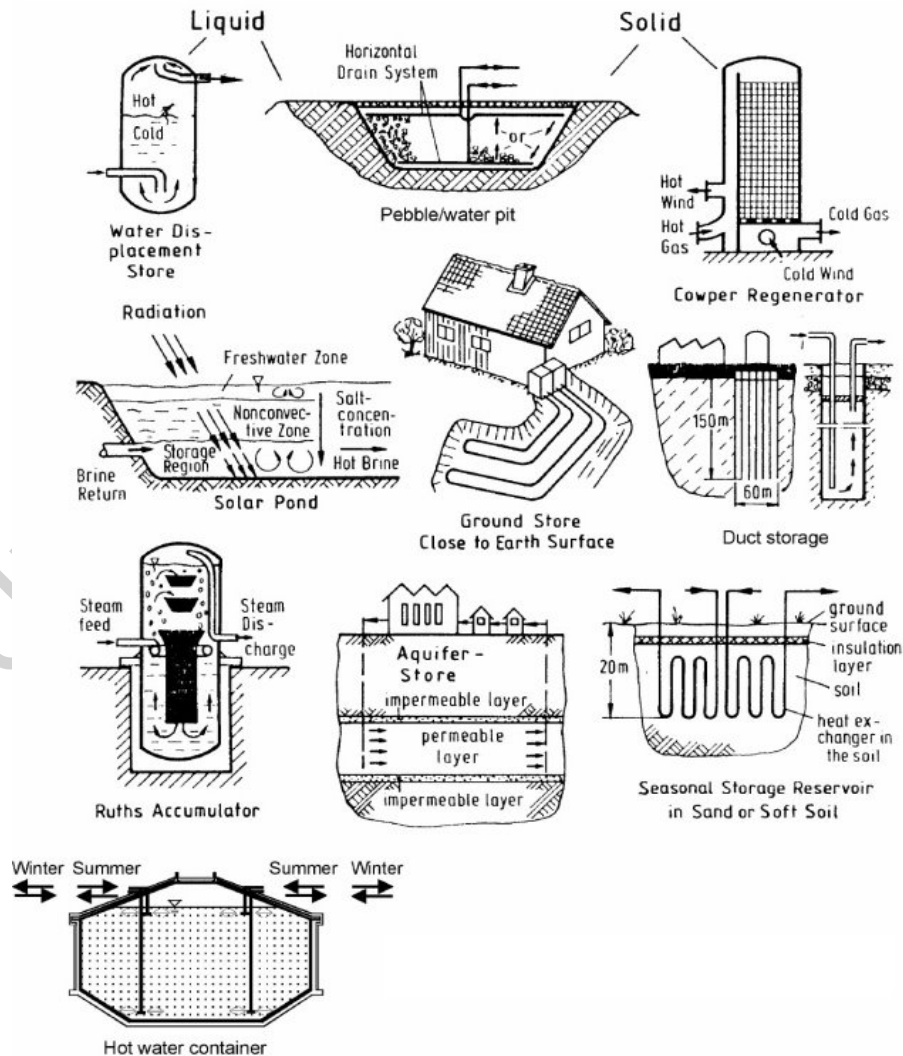

Figure 1:   Different Concepts for the Storage of Sensible Heat

An effective store depends very much on the store material. The following requirements should be met:

- long service life, non-corrosive, non-toxic, non-flammable - large heat storage capacity
- high thermal diffusivity $\alpha = k / \rho c_p$ in e. g. m²/s and heat diffusivity $b = \sqrt{k \rho c_p}$ in J/m²Ks$^{1/2}$; with k being the thermal conductivity, ρ the density and c_p the specific heat capacity
- capability to withstand charging / discharging cycles without loss in performance, store capacity or change in structure
- wide availability, simple handling, storage in simple containers
- low cost

The price of the storage medium and / or the cost of the containment are decisive for the utilisation. Long life and a high cycling stability are pre-requisites for an economic application; i.e., at a price competitive with existing facilities. High temperature diffusivity of the heat storage material provides a quick response to temperature differences; i.e., quick charging and discharging. High heat diffusivity yields a high amount of heat being stored.

Heat transfer processes have to be considered: the heat may be either transferred directly to the storage material as, e. g. in a dry pebble bed with air flows or by way of a heat exchanger as in a solar domestic hot water store where the water- antifreeze mixture flowing through a solar collector has to be separated from the hot water for consumption. Other aspects of selecting a heat store material may be operational advantages in energy supply systems or a larger flexibility in application.

2.1 Thermodynamic Considerations

The storage of sensible heat is based - thermodynamically speaking - on the increase of enthalpy of the material in the store, either a liquid or a solid in most cases. The sensible effect is a change in temperature. The thermal capacity - this is the heat which can be put in the store or withdrawn from it - can be obtained by the equation

$$Q_{12} = m \int_{T_1}^{T_2} c_p(T) dT \tag{1}$$

with the specific heat capacity c_p being a function of temperature T, and m mass.

For a temperature independent c_p this becomes simply

$$Q_{12} = m c_p (T_2 - T_1) \tag{1a}$$

where the unit of Q_{12} is, e. g., **J**. The symbol m stands for the store mass and T_2 denotes the material temperature at the end of the heat absorbing (charging) process and T_1 at the beginning of this process. This heat is released in the respective discharging process.

For pure solids (especially heavy elements), the specific heat per mole of a substance is approximately $3R$ (Dulong-Petite rule), with R being the molar gas constant (R=8.31441 kJ/kmolK). Thus, the molar thermal energy q_{mol} stored in solids can be approximated by

$$q_{mol} \approx 3R \cdot \Delta T \tag{2}$$

and q_{mol} is measured e. g. in kJ/kmol. Thus, approximately 25 kJ/kmol can be stored with a temperature difference of $\Delta T = 1K$. With the molar mass M (kg/kmol), the thermal energy q stored per mass (store capacity in kJ/kg) is obtained

$$q = c_p \Delta T = q_{mol} / M = 3R \cdot \Delta T / M \tag{3}$$

Heat has a quality, namely its temperature. This determines how much of the heat can be usefully applied according to the second law. This available energy is called Exergy E_x and can be obtained from

$$E_x = Q_{12} - \frac{T_{am}}{T} Q_{12} \tag{4}$$

when the Kelvin temperature of the store T = constant during delivery of the heat, with T_{am} being the ambient temperature, e.g. 293 K.

For varying temperatures of the store (i.e. stores of a finite size) the exergy change is expressed by

$$\Delta E_{x12} = (H_2 - H_1) - T_{am}(S_2 - S_1) - (p - p_{am})(V_2 - V_1) \tag{5}$$

with H being enthalpy, S entropy, V volume and p being pressure.

Under atmospheric pressure $p = p_{am}$ and with the 1st and 2nd law this reduces to

$$\Delta E_{x12} = mc_p \left[(T_2 - T_1) - T_{am} \ln \frac{T_2}{T_1} \right] \tag{6}$$

From equation (6) it can be observed that exergy changes are not linear with temperature as energy changes (see eq. (1a)).

Exergy is low at low temperatures but increases steeply with an increase in temperature while the energy increase remains the same at low or high temperatures.

A second law evaluation of stores (i.e. by exergy) is more useful than a first law evaluation (by energy). This becomes obvious in *the following example* on the importance of temperature stratification in warm water stores:

Let us assume a container which is half filled with water of 50 °C (upper half) and 20 °C (lower half). If the two water layers will be fully mixed, the mean temperature is 35 °C. The energy in this container remains the same, provided no heat losses occur to the surroundings. Following now equation (4), assuming an ambient temperature of T = 293 °K, a loss in exergy can be calculated. It amounts to $\Delta E_x = 1.23 mc_p$. The energetic consideration does not show any change by the destruction of a thermal layering in the store; the exergetic consideration, however, does indicate the quality of the stored water which, with respect to temperature, has certainly decreased. Half of the container water with 50 °C is of more use - e. g. for taking a shower - than all of the water with 35 °C.

3. Solid Storage Materials

Properties of some solid materials are given in Table 1.

Material	M	θ	ρ	c	k	$10^6 \alpha$	$10^{-3}b$
	kg/kmolg	°C	kg/m³	kJ/kgK	W/mK	m²/s	J/m²ks$^{1/2}$
Aluminium 99.99 %	27	20	2700	0.945	238.4	93.3	24.66
Copper (commercial)	63.5	20	8300	0.419	372	107.	35.97
Iron	56	20	7850	0.465	59.3	16.3	14.7
Lead	207	20	11340	0.131	35.25	23.6	7.24
Brick (dry)		20	1800	0.840	0.5	0.33	0.87
Concrete (gravelly)		20	2200	0.879	1.279	0.66	1.57
Granite		20	2750	0.892	2.9	1.18	2.67
Graphite (solid)	12	20	2200	0.609	155	120	14.41
Limestone		20	2500	0.741	2.2	1.19	2.02
Sandstone		20	2200	0.710	1.8	1.15	1.68
Slag		20	2700	0.836	0.57	0.25	1.13
Soil (clay)		20	1450	0.880	1.28	1.00	1.28
Soil (gravelly)		20	2040	1.840	0.59	0.16	1.49

Table 1: Thermophysical properties of some solid materials

Metals and graphite have high values of temperature diffusivity α and heat diffusivity *b*. Thus, these materials are best suited for quick charging and discharging. Other materials such as bricks and stones are less advantageous in this respect, it takes longer for them to heat and cool but in volume storage capacity $(\rho \cdot c)$ granite can compete with aluminium.

Solid materials can be heated to very high temperatures (e. g. magnesia bricks in Cowper regenerators to 1.000 °C). They are usually chemically inert and, in the form of rocks and pebbles, abundant and cheap.

Pebble bed and rock pile stores consist of loosely packed material in a container. Heat has to be carried to or from such stores by a heat carrier such as air or water. These beds provide a large surface area for heat transfer in their dispersed materials; the internal heat losses are only small because the particles have little surface contact to surrounding particles and thus, little conduction losses.

Reduced insulation around the store container is sufficient when air - with a small thermal conductivity - is used as a heat carrier and fills the gaps between the particles. Such particle beds, however, cause a large pressure drop in the fluid flow. This has to be compensated by pumps or compressors. Another drawback is the large storage volume required. Conveniently, this is provided in underground installations.
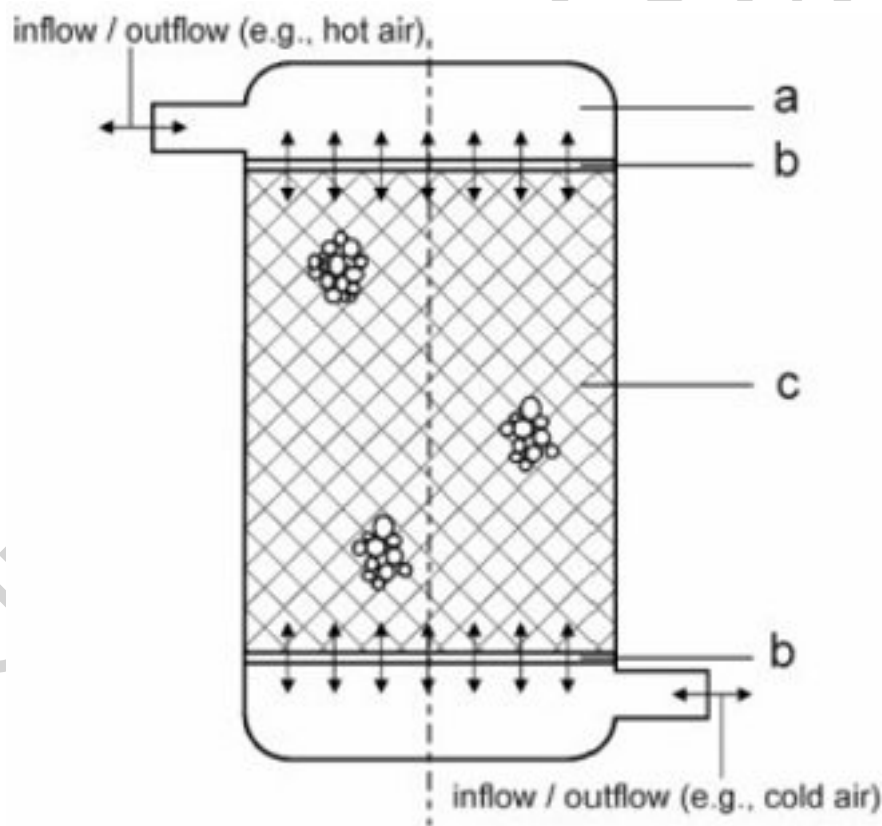
Figure 2: Container with solid particles for thermal storage: (a) air distribution chamber, (b) grating, (c) particles

In ground stores, heat is stored in soil, stones or solid rocks, especially for low-temperature storage. Cast iron is an inexpensive material with a high volume storage capacity $(\rho \cdot c)$. It is used for high temperature storage together with oil as the heat carrier. As solid materials for storage always have to be combined with fluid heat

carriers, properties of the solids have to be taken into account which affect fluid flow and heat transfer, e. g., particle and container size, mechanical durability against abrasion and thermal cycling, hygroscopy, etc. In Figure 2, a storage bin for solid materials with gas as a heat carrier is shown. If the packing density is high, e.g. for small solid particles, the store capacity is high, but the pressure drop is also high. A proper particle size which should be rather uniform has to be found.

The thermal stratification is well maintained in a solid-material heat store because natural convection in the heat carrier is suppressed by the granulate, and internal heat conduction is low. Containers as shown in Figure 2 are used - in form of pillars - as architectural components in buildings. The combination of hollow bricks and air has been known as hypocaust-heating systems since antiquity.

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Biographical Sketch

Professor Dr.-Ing. Erich Hahne was born in Athens, Greece, he studied Mechanical Engineering in Munich, Germany at the Technical University. There, as a student of Professors Ernst Schmidt and Ulrich Grigul he received his Diploma-and Doctor's Degree (1964). Following was a one year NASA research fellowship at CalTech in Pasadena, Calif. With Ernst Schmidt und his successor Ulrich Grigull he was working for almost 15 years in the Institute for Thermodynamics, Technical University Munich as Assistant and then as Academic Director. In 1973 he was appointed full professor and director of the Institute for Thermodynamics and Thermal Engineering in the University of Stuttgart.

His research activities are mainly in the areas of phase change heat transfer, thermophysical properties solar thermal energy utilization and heat storage. As an outcome of this work he authored or co-authored more than 400 journal publications.

For over 30 years he taught a wide range of undergraduate and postgraduate courses such as Technical Thermodynamics, Heat and Mass Transfer, Solar Energy Technology, Heat Exchanger-Design and Optimised Energy Conversion. His textbook "Technische Thermodynamik" is now in its 3rd edition.

He is a well know member of the International Heat Transfer Community. Being one of the Founding members of the International Center for Heat and Mass Transfer (ICHMIT)- since 1968 as German representative, later as a member of the Scientific Council and between 1978 and 1981 as chairman of the Executive Committee.