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Sensible Heat Storage: Overview

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1.1. Introduction

Heat and cold are two very important fields of the energy economy. They are used for the air-conditioning of living spaces, but they are also essential in the industry in the transformation and generation of materials and products. Nowadays, they are obtained from fossil fuels, either directly or using electricity, which is also often generated by power plants. But this combustion generates CO_2 emissions, contributing to the global warming, and these fuels are not sustainable, since they are not renewable, posing serious risks to the future development of humanity.

At the scale of humanity, sun is an inexhaustible source of heat. However, solar energy lacks concentration, it is intermittent and even lacking for a part of the year and its availability is often shifted with respect to the needs, particularly depending on the season. This explains the potential interest in the efficient storage of heat and also cold.

Two very different types of heat storage can be identified: low-temperature storage, the most widespread and mainly used for domestic air-conditioning and water heating, and high-temperature storage, more complex, essentially used to smooth power generation subjected to the intermittence of renewable energies. This work describes the processes of sensible heat storage, by far the most developed, but

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does not cover the processes using phase change materials, which will be described in the following chapters, or the sorption processes, which will be dealt with in Volume 2.

1.2. General principles

Sensible heat is the heat stored in a material, except for phase changes (solid–liquid–gas transitions). Sensible heat storage in a material consists of its enthalpy increase during the storage phase, heat being released during the discharge phase. The material can be a liquid or a solid. The perceptible effect is temperature change. Stored energy is written as follows:

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

Here, Q_{12} (Joule) is the sensible heat, $T_1$and T_2 (K) are the initial and final temperatures, c_p (J/kg·K) is the specific heat capacity of the body and it may be temperature dependent. If the specific heat capacity c_p remains constant, the relation (with ρ density, V volume) is written as follows:

$$Q_{12} = mc_p(T_2 - T_1) = \rho V c_p(T_2 - T_1)$$

It can be noted that for a given specific heat capacity and for a given amount of stored heat, the storage volume V is inversely proportional to the density of the material. These relations can be easily transposed to sensible cold storage. Sensible heat storage is by far the easiest to implement and also the oldest. If the material remains stable during temperature changes, the system is indefinitely reversible.

1.3. Storage configurations

There are various storage configurations that use liquid or solid materials for storage, in association or not with a gaseous or liquid heat-transfer fluid, carrying or not solid particles. The dimensioning depends on the type of configuration, operating temperatures, heat transfer modes involved, flow rates of the heat transfer fluid, thermophysical properties of the materials used, geometry of the storage tank and objectives in terms of energy and power. Depending on the storage technology, phenomena such as stratification may be predominant in the operation mode, dimensioning, management and efficiency of the storage.

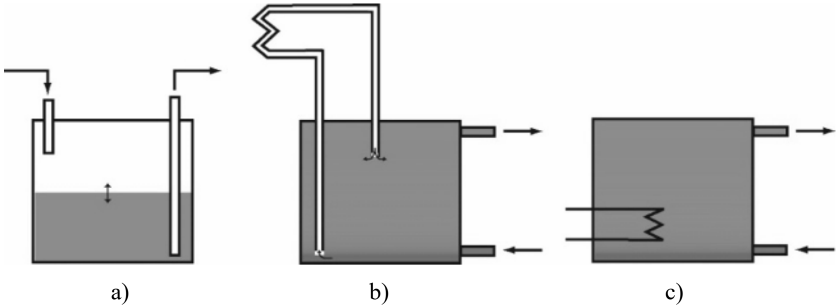

Figure 1.1. *Various sensible heat storage configurations. For a color version of this figure, see www.iste.co.uk/odru/heat1.zip*

Figure 1.1 shows three types of liquid storage configuration. In configuration (a), the storage involves filling the tank with heat-transfer fluid, which is also used as storage material. The release therefore involves emptying the tank and using the heat contained in the liquid. The recovered energy is therefore directly linked to the quantity of liquid and the available power is given by its circulating flow. After passage through an exchanger that may use the heat supplied by the storage, the liquid may then be stored at lower temperature in a so-called "cold" tank. Therefore, storage and release consist of the fluid passage from one tank to another. This configuration is currently used in concentrated solar power plants. The storage material is then quite often a mixture of molten salts, such as the binary mixture $NaNO_3/KNO_3$. In configuration (b), the storage consists of extracting the liquid from the bottom of the tank in order to heat it and then injecting it back at the top. The liquid is used both as heat-transfer fluid and storage material. The same is applicable to configuration (c) where, in contrast, a system placed inside the tank provides the heat to be stored. This can be done in various ways: flow of heat-transfer fluid, electric resistance, etc.

Configurations (b) and (c) are typically present in water heaters using electric power, solar power, etc. Specific studies have been conducted on these, particularly on stratification. For high temperature applications (>120°C), water is no longer the preferred fluid. Oils and molten salts are rather used. Given its high cost, a lower volume of liquid is used by associating it with inexpensive solid materials. At very high temperatures, air may prove to be the only viable technical solution. Considering the average air storage capacity, choosing solid materials for storage then becomes inevitable. Hence, the storage tank is filled with a solid material that takes up a part of the volume. The remaining volume (porosity) allows the heat-transfer fluid to supply with or extract the heat essentially stored in the solid material. This material can have a bulk granular form or an organized form. Granular materials of centimetric size can be natural rocks or ceramic materials (alumina, bauxite, recycled ceramic materials from industrial or municipal solid waste, etc.). Organized materials can be self-supported structured elements such as bricks or a material such as concrete, in which a set of tubes are inserted.

1.4. Modeling of thermocline storage

Operating this storage referred to as *dual media* involves the control of three zones: two high and low temperature zones separated by a high gradient zone, the thermocline.

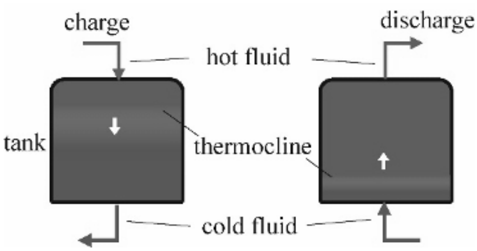

Figure 1.2. *Dual media heat storage. For a color version of this figure, see www.iste.co.uk/odru/heat1.zip*

The thermal modeling of storage on solid material relies on the coupling of convection heat transfer around the material and conduction transfer inside. There are two possible cases:

– The temperature of the medium can be considered homogeneous, and in this case the lumped heating or cooling method known as the *lumped capacitance method* can be used.

– There is a temperature distribution in the material, which requires complete or approximate calculation.

The first approach, very useful in storage, uses the lumped capacitance method. This highlights the influence of the material and of its thermophysical properties, and also of its geometry. Figure 1.3 shows a schematic representation of the lumped heating of a solid immersed in a fluid.

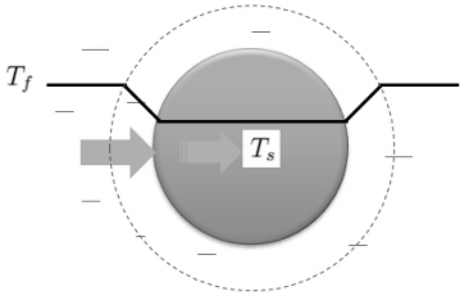

Figure 1.3. *Lumped heating of a solid by a fluid*

The energy supplied by the fluid is transferred by convection and leads to an increase in the internal energy of the solid:

$$h.S.(T_f - T_s).\mathrm{d}t = \rho.V.C_p.\mathrm{d}T_s \qquad [1.1]$$

When the solid is at an initial temperature $T_{s,i}$ and it is subjected to a step in temperature at the initial moment, the result of integration is:

$$Ts = T_f + (T_{s,i} - T_f).\exp\left[-\left(\frac{h.S}{\rho.V.C_p}\right)t\right] \qquad [1.2]$$

Let us consider $\theta = T_s - T_f$, $\theta_i = T_{s,i} - T_f$, which leads to the following expression:

$$\frac{\theta}{\theta_i} = \frac{T_s - T_f}{T_{s,i} - T_f} = \exp\left[-\left(\frac{h.S}{\rho.V.C_p}\right)t\right] \qquad [1.3]$$

which yields:

$$\frac{\theta}{\theta_i} = \exp(-Bi.Fo) \qquad [1.4]$$

The dimensionless form of this equation features Biot and Fourier numbers:

$$Bi = \frac{h.L_c}{\lambda} \qquad [1.5]$$

and:

$$Fo = \frac{\alpha t}{L_c^2} \qquad [1.6]$$

The characteristic length is the ratio between the volume of the required material and the surface through which transfer takes place:

$$L_c = \frac{V}{S} \quad [1.7]$$

This yields the following:

– For a plate of thickness e:

$$L_c = \frac{e}{2} \quad [1.8]$$

– For a cylinder of radius R:

$$L_c = \frac{R}{2} \quad [1.9]$$

– For a sphere of radius R:

$$L_c = \frac{R}{3} \quad [1.10]$$

Therefore, the stored energy is:

$$\frac{Q_{sto}}{Q_{max}} = 1 - \frac{\theta}{\theta_i} = 1 - \exp(-Bi.Fo) \quad [1.11]$$

It should be noted that this relation is also an expression of the storage efficiency.

These relations are valid for Biot numbers $Bi < 0.1$, therefore for thermally thin materials. Nevertheless, Xu et al. (2012) propose an extension of the lumped capacitance method to Biot numbers $Bi > 0.1$. An effective Biot number is introduced. In summary, for a flat plate, this effective Biot number is written as follows:

$$Bi_{eff} = \frac{Bi}{1+\frac{3}{5}.Bi} \quad [1.12]$$

For a cylinder, the correction is given by the following relation:

$$Bi_{eff} = \frac{Bi}{1+\frac{1}{2}.Bi} \quad [1.13]$$

Finally, for a sphere, we have:

$$Bi_{eff} = \frac{Bi}{1+\frac{1}{3}.Bi} \qquad [1.14]$$

Generally speaking, the expression of the stored energy and therefore of the efficiency is given as follows:

$$\eta = \frac{Q_{sto}}{Q_{max}} = 1 - \exp\left(-Bi_{eff}.Fo\right) \qquad [1.15]$$

This extension is interesting and quite precise in many cases. In the end, this situation corresponds to a storage that is limited by the convective transfer properties and therefore by the convective coefficient and the transfer surface. This explains the interest in granular medium as storage material. When the transfer in the solid is limiting ($Bi >> 0.1$), the equation of heat in the solid must be solved:

$$\frac{\partial^2 T_S}{\partial x^2} = \frac{1}{\alpha_S}\frac{\partial T_S}{\partial t} \qquad [1.16]$$

for $x = L_c$:

$$\lambda_S \frac{\partial T_S}{\partial x} = h(T_f - T_s) \qquad [1.17]$$

and for $x = 0$:

$$\frac{\partial T_S}{\partial x} = 0 \qquad [1.18]$$

Then the general solution is:

$$\frac{T_S - T_f}{T_{s,i} - T_f} = \sum_{n=1,3,5\ldots}^{\infty} A_n \exp\left[-\left(\frac{n.\gamma_n}{L}\right)^2.\alpha.t\right]\cos\left(\frac{n.\gamma_n.x}{L}\right) \qquad [1.19]$$

where the values of A_n and γ_n are tabulated (Bergman et al. 2011). For a Fourier number $Fo > 0.2$, the following approximations can be used:

– For a flat plate:

$$\frac{T_S - T_f}{T_{s,i} - T_f} = A_1 \exp(-\gamma_1^2.Fo)\cos\left(\frac{\gamma_1.x}{e}\right) \qquad [1.20]$$

– For an infinite cylinder:

$$\frac{T_S - T_f}{T_{s,i} - T_f} = A_1 \exp(-\gamma_1^2.Fo)\mathrm{J}_0\left(\frac{\gamma_1.r}{R}\right) \qquad [1.21]$$

– For a sphere:

$$\frac{T_s - T_f}{T_{s,i} - T_f} = A_1 \exp(-\gamma_1^2 . Fo) \frac{\sin\left(\frac{\gamma_1 . r}{R}\right)}{\frac{\gamma_1 . r}{R}} \quad [1.22]$$

For Fourier numbers $Fo < 0.2$, Heissler charts may prove useful (Bergman et al. 2011).

Let us now integrate to the storage the transfer between the material and the flowing fluid. It is typically the case of thermocline storage that is used in industrial waste heat recovery, in concentrated solar power plants, or still in the glass industry, being then called regenerators. Figure 1.4 shows the charge of such a storage.

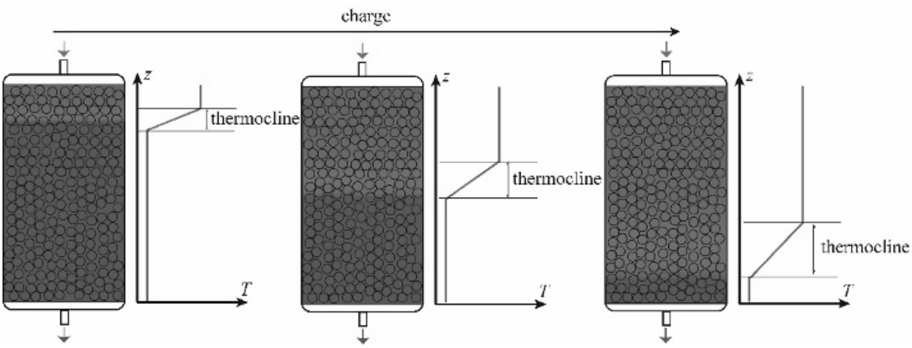

Figure 1.4. *Charge of a packed granular bed thermocline storage system. For a color version of this figure, see www.iste.co.uk/odru/heat1.zip*

Willmott (2001) established the equations that model this storage using two coupled equations: it is a two-temperature model. Two large types of models can be distinguished: a 1D-1D model and a 1D-2D model. Esence et al. (2029) present all the necessary elements on the numerical differences of models.

An illustration of the 1D-1D model is Schumann's (1926) model. This model, used once again by Hughes et al. (1976), was established for a particle bed. The effective conductivity of the bed is assumed to be infinite in the radial direction; there is no temperature gradient in the particles; the fluid flows in a single direction; the conductivity of the particle in the axial direction is zero; the fluid has no axial thermal dispersion; the properties do not depend on temperature; no heat loss in the environment is considered. The radiative transfer between fluid and solid and between the particles in the bed is negligible.

Then the model is written as follows:

– In the fluid phase:

$$\varepsilon C_{pf}\rho_f \frac{\partial T_f}{\partial t} = -u_f \varepsilon C_{pf}\rho_f \frac{\partial T_f}{\partial x} + h_c A(T_s - T_f) \qquad [1.23]$$

where A is the surface of a particle and ε is the porosity.

The interstitial velocity v_f can be written using the mass flow rate. Then we have:

$$u_f = \frac{v_f}{\varepsilon} \qquad [1.24]$$

$$v_f = \frac{\dot{m}_f}{\rho_f A_{cs}} \qquad [1.25]$$

where A_{cs} is the fluid passage section area.

– In the solid phase:

$$(1-\varepsilon)C_{ps}\rho_s \frac{\partial T_s}{\partial t} = h_c A(T_f - T_s) \qquad [1.26]$$

The system of equations is accompanied by the initial conditions, which are often a uniform temperature and the boundary conditions that can be a jump in the temperature of the ingoing fluid.

Let us introduce a volume exchange coefficient $h_v = h_c.A$. Then the number of transfer units (NTU) associated with the particle bed can be defined as follows:

$$NTU = \frac{h_v A_{cs} L}{\dot{m}_f C_{pf}} \qquad [1.27]$$

For a low heat capacity fluid such as air, the term $\rho_f C_{pf}\partial T_f/\partial t$ can be ignored. Then the equation related to the fluid becomes:

$$\frac{\partial T_f}{\partial x} = \frac{h_v}{v_f \rho_f C_{pf}}(T_s - T_f) = \frac{h_v A_{cs} L}{\dot{m}_f C_{pf} L}(T_s - T_f) \qquad [1.28]$$

hence:

$$\frac{\partial T_f}{\partial x} = \frac{NTU}{L}(T_s - T_f) \qquad [1.29]$$

Duffie and Beckman (2006) introduced a time constant:

$$\tau = \frac{\rho_s C_{ps}(1-\varepsilon)A_{cs}L}{\dot{m}_f C_{pf}} = \frac{m_s C_{ps}}{\dot{m}_f C_{pf}} \qquad [1.30]$$

This time constant is characteristic for the ratio of heat stored by the solid and transferred by convection by the fluid. Then we have:

$$\frac{\partial T_s}{\partial t} = \frac{NTU}{\tau}(T_f - T_s) \qquad [1.31]$$

If there is a temperature gradient through the particles ($Bi_D > 0{,}1$), Duffie and Beckman (2006) propose a modified NTU:

$$NTU_{eff} = \frac{NTU}{1+Bi_D/5} \qquad [1.32]$$

with:

$$Bi_D = \frac{h_c D}{2\lambda_s} \qquad [1.33]$$

The Schumann model can be completed by a term describing axial diffusion. Hence:

$$\varepsilon C_{pf}\rho_f \frac{\partial T_f}{\partial t} = \lambda_{eff,f}\frac{\partial^2 T_f}{\partial x^2} - u_f \varepsilon C_{pf}\rho_f \frac{\partial T_f}{\partial x} + h_c A\left(T_s - T_f\right) \qquad [1.34]$$

and:

$$(1-\varepsilon)C_{ps}\rho_s \frac{\partial T_s}{\partial t} = \lambda_{eff,s}\frac{\partial^2 T_s}{\partial x^2} + h_c A(T_f - T_s) \qquad [1.35]$$

where $\lambda_{eff,f}$ and $\lambda_{eff,s}$ are the effective conductivities of the fluid and solid, respectively.

If, from now on, radial dispersion is considered in the solid, the model becomes 1D-2D (1D fluid, 2D solid). This model was implemented in the works conducted particularly at PROMES-CNRS Laboratory and at CEA-Liten (Couturier et al. 2014; Hoffmann 2015; Kéré et al. 2015; Esence et al. 2017; Fasquelle 2017; Lopez-Ferber 2018; Touzo 2021) to describe heat storages at relatively high temperatures (from 200 to 850°C).

Finally, some remarks can be made on the performances of sensible heat storages. The group of dimensionless numbers that are naturally involved in this analysis is $Bi.Fo$. It corresponds to the ratio between transferred power and stored power. $Bi.Fo$ can also be expressed as the product of the number of transfer units NTU and the ratio between the energy transferred by convection by the fluid) and the energy stored by the solid. Then we introduce the Stanton number St that compares the heat transferred by convection to the heat carried by the flowing fluid. NTU is then proportional to the Stanton number via the ratio between the transfer surface and the flow section:

$$NTU = St\frac{S_{ech}}{S_{eclt}} \quad [1.36]$$

The group $Bi.Fo/St$ can be formed as follows:

$$\frac{Bi.Fo}{St} = \frac{h.V_S}{\lambda_S.S_{ech}}.\frac{\lambda_S.t.S_{ech}^2}{\rho_S.C_{pS}.V_S^2}.\frac{\rho_f.C_{pf}.u_f}{h} = \frac{\rho_f.C_{pf}.u_f.t}{\rho_S.C_{pS}.V_S}.S_{ech} = \frac{\dot{m}_f.C_{pf}.t}{m_S.C_{pS}}.\frac{S_{ech}}{S_{eclt}} \quad [1.37]$$

This introduces the ratio between the energy transferred by convection by the fluid and the stored energy. In other terms, this group is characteristic for the time required for the fluid to extract or supply the storage energy taking into account the available transfer surface/flow section ratio. This highlights four dimensionless numbers, Bi, Fo, St and S_{ech}/S_{eclt}, that can be used to analyze and qualify the sensible heat storage.

1.5. References

Bergman, T.L., Lavine, A.S., Incropera, F.P., Dewitt, D.P. (2011). *Fundamentals of Heat and Mass Transfer*. John Wiley & Sons, Hoboken.

Couturier, R., Bruch, A., Fourmigué, J.F. (2014). Experimental and numerical investigation of a pilot-scale thermal oil packed bed thermal storage system for CSP power plant. *Solar Energy*, 105, 116–125.

Duffie, J.A. and Beckman, W.A. (2006). *Solar Energy Thermal Processes*. John Wiley & Sons, New York.

Esence, T. (2017). Étude et modélisation des systèmes de stockage thermique de type régénératif solide/fluide. PhD Thesis, Université Grenoble Alpes, Grenoble.

Esence, T., Desrues, T., Fourmigué, J.-F., Cwicklinski, G., Bruch, A., Stutz, B. (2019). Experimental study and numerical modelling of high temperature gas/solid packed-bed heat storage systems. *Energy*, 180, 61–78.

Fasquelle, T. (2017). Modélisation et caractérisation expérimentale d'une boucle solaire cylindro-parabolique intégrant un stockage de type thermocline. PhD Thesis, Université de Perpignan Via Domitia, Perpignan.

Hoffmann, J-F. (2015). Stockage thermique pour centrale solaire thermodynamique à concentration mettant en œuvre des matériaux naturels ou recyclés. PhD Thesis, Université de Perpignan Via Domitia, Perpignan.

Hughes, P.J., Klein, S.A., Close, D.J. (1976). Packed bed thermal storage models for solar air heating and cooling systems. *J. Heat Transfer*, 98, 336–338.

Kéré, A., Goetz, V., Py, X., Olives, R., Sadiki, N. (2015). Modeling and integration of a heat storage tank in a compressed air electricity storage process. *Energy Conversion Management*, 103, 499–510.

Lopez-Ferber, N. (2018). Validation expérimentale d'un système de stockage thermo-cline air/céramique à échelle pilote - développement d'un matériau de stockage. PhD Thesis, Université de Perpignan Via Domitia, Perpignan.

Schumann, T.E.W. (1929). Heat transfer: A liquid flowing through a porous prism. *Journal of the Franklin Institute*, 208, 405–416.

Touzo, A. (2021). Intégration d'un stockage thermocline à des procédés énergétiques. PhD Thesis, Université de Perpignan Via Domitia, Perpignan.

Willmott, A.J. (2001). *Dynamics of Regenerative Heat Transfer*. Taylor & Francis, London.

Xu, B., Li, P.-W., Chan, C.L. (2012). Extending the validity of lumped capacitance method for large Biot number in thermal storage application. *Solar Energy*, 86(6), 1709–1724.