THEORETICAL STUDY ON SCALE UP OF THERMAL ENERGY STORAGE SYSTEMS IN SOLAR POWER PLANTS

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1. Introduction

One of the main targets to reach maximum effectiveness of solar power plants is the mismatch between the curve of energy demand and that of energy production. Thermal energy storage (TES) systems are among the best solution to manage this mismatch, but they may also help to reach a more stable electric energy production, prevent possible decreases of the heat transfer fluid (HTF) temperature and reduce the start up time of the power plant. On the other hand, the selection of a suitable TES system for a solar power plant or an industrial application would be rather debatable if there is no data available about the behavior of the corresponding storage material under cumulated thermal cycles. Until today, the current way to carry out such short and middle time predictions is composed of limited experiments at laboratory or pilot scale. Those tests are usually achieved using kilograms of materials cycled during few weeks up to few months. In comparison, corresponding industrial operation concerns several thousands of tons used for about 35 years. Therefore, the above approaches cannot predict accurately the behavior of the real system for years of operation at full scale. Without this needed level of expertise, the investment in new TES materials and systems and their use at industrial scale for the electric production companies could lead to a very high risk.

Fourcher et al. (1980) published an original theoretical study on TES systems based on sensible heat storage. In this publication the TES system was considered trough the transfer function approach and the output signal of the TES system was studied, using a periodic sinusoidal input signal. A publication by Bransier (1979) developed a simple model to study the interaction of the main parameters involved in a periodic heat transfer process. This work was focused on the optimisation of a TES system using mathematic models based on transfer functions.

After these first steps of modeling the thermal storage systems with transfer functions, Acker et al. (1981) studied the convection and conduction of a fluid in laminar flow and in contact with a wall. This study compared the periodic response of two different storage modules: one using air as HTF and a second one using a commercial organic oil called Sanotherm. The obtained results showed that the performance was very similar between the cases of air in turbulent flow and organic oil in laminar flow.

Bourouga et al. (1985) applied the transfer functions developed by Fourcher et al. (1980) to TES systems for three different geometries: plates, cylinders and spheres. This theoretical study demonstrated that the storage performance is rather independent to the geometric parameters of the module and to the thermo-physical properties of the HTF.

The present work, based on the modelization of TES systems through transfer functions, is focused on a potential method to scale up properly TES systems with a high level of accuracy in order to predict their behavior at industrial scale using lab-scale experiments. The scale up can be done in space, changing the metric scale and geometry of the TES system, or in time, changing the duration and number of cycles of charging and discharging allowing the prediction of the life cycle of an industrial TES system from laboratory scale experimentation.

2. Methodology and matehmatical model

Mathematical model

The mathematical model of the TES system used by Fourcher et al. (1980) was done through the thermal transfer equations, which include the thermo-physical properties of the storage material and the HTF, and geometrical characteristics of the system. The thermal equations describe the dynamic behavior of the

TES system taking into account that it is a solid sensible heat storage system, and considering the HTF is in direct contact with it. On the other hand, the model assumes sinusoidal signal as input signal with an output signal that is a function of the thermo-physical properties of the HTF and storage material, and the geometry of the system. The temperature distributions within the solid storage material and the HTF can be written as shown in eq. 1 and eq. 2 according to Bourouga et al. (1985):

$$\theta = \theta(x, y) \cdot \sin[\omega \cdot t + \Psi_s(x, y)] \qquad \text{(eq. 1)}$$

$$T = T(x, z) \cdot \sin[\omega \cdot t + \Psi_f(x, z)] \qquad \text{(eq. 2)}$$

The axes x, y and z are defined depending on the geometry of the TES system. Three geometries of TES system were modelized by Bourouga et al. (1985) (Fig. 1). In the present work, only the geometry of plates is presented (Fig. 2).

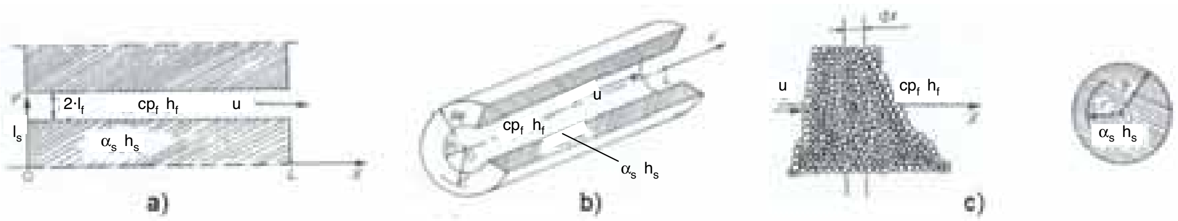

Fig. 1. Three different geometries studyied by Bourouga et al. (1980): a) plates; b) cylinders; c) balls

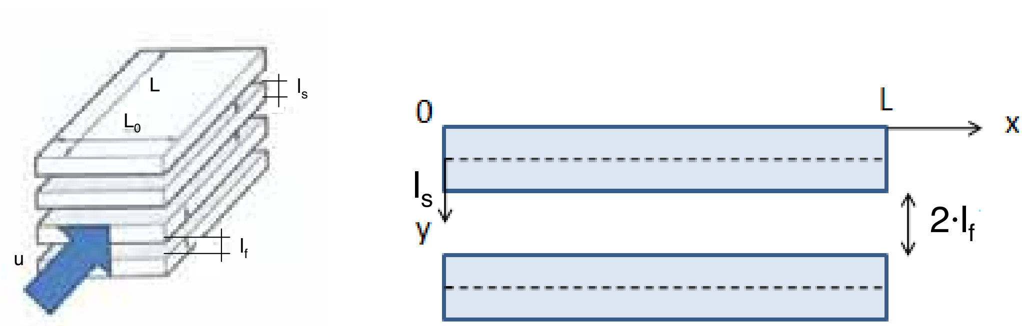

Fig. 2. Parameters of the storage system based on the geometry of plates

The study of the harmonic response of the TES system considering the mechanisms of dynamic thermal transfer leads to the use of tranfer functions based on the mathematical model equations of the system.

TES system based on plates geometry

According to Bourouga et al. (1985), applying the boundary conditions of the TES system for the case of plates and using complex formulation for the temperatures, the equation system leads to the eq. 3.

$$\tilde{T}(x) = T_0 \cdot e^{-\mu x} \qquad \text{(eq. 3)}$$

where μ is the damping function defined as

$$\mu = i \cdot \frac{2\pi}{\tau^*} + St^* \cdot \frac{(1+i) \cdot \sinh(\beta(i+1))}{(1+i) \cdot \sinh(\beta(i+1)) + \gamma \cdot \cosh(\beta(i+1))} \qquad \text{(eq. 4)}$$

This model takes into account the assumption that the TES system is based on sensible solid heat storage, having a direct contact between the storage material and the HTF. On the other hand the thermal properties of the TES material and HTF were considered constant and uniform, according to Fourcher et al. (1980).

Considering a specific change of scale (in space or in time), according to eq. 3 and eq. 4 if the damper function is kept constant, the change of scale is done under perfect analogy. This means that the answer of the TES system to the same incoming signal will lead to a similar value. Otherwise, the change of scale will be associated to a modification in the system behavior. Therefore, the ability of a system to accept a perfect analogy configuration can be easily studied using the damper function.

The damper function defined in eq. 4 describes the dynamic behavior of the TES system depending on four independent dimensionless numbers (β, γ, St* and τ*). This dimensionless numbers are strongly related to the geometry of the TES system and the thermo-physiscal properties of the HTF and storage material. Therefore, the perfect analogy based upon the non variation of the damper function can be extended to the non variation of the four dimensionless numbers. Otherwise, the results obtained can not be scaled up directly. The proposed method is based upon the study of the concerned four dimensionless numbers and the possibility to keep all them constant during a change of scale.

Coefficient β is a relation between the thickness of the plate and the diffusivity of the storage material (eq. 5):

$$\beta = l_s \sqrt{\frac{\pi}{\alpha_s \cdot \tau}} = \sqrt{\frac{\pi \cdot \rho_s \cdot Cp_s}{h_s}} \cdot \frac{l_s}{\sqrt{\tau}} \qquad \text{(eq. 5)}$$

Coefficient γ establishes a relation between the external heat transfer between the HTF and the storage material and its effusivity (eq. 6):

$$\gamma = \frac{Bi}{\beta} = 0{,}023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.4} \cdot \frac{h_s}{\sqrt{h_s \cdot Cp_s \cdot \rho_s \cdot \pi}} \cdot \frac{\sqrt{\tau}}{4 \cdot l_f} \qquad \text{(eq. 6)}$$

The modified Stanton number (St*) is a relation between the heat transferred to the fluid and the heat capacity of the fluid for the case of the system studied (eq. 7):

$$St^* = St \cdot \frac{L}{l_f} = \frac{0{,}023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.4}}{\mathrm{Re} \cdot \mathrm{Pr}} \cdot \frac{L}{l_f} \qquad \text{(eq. 7)}$$

The characteristic time of variation of the inlet temperature (τ*) is the period of variation of the fluid inlet temperature during the time that it remains inside the storage system (eq. 8):

$$\tau^* = \frac{\tau \cdot u}{L} \qquad \text{(eq. 8)}$$

Depending on the main parameter to scale up (L, l_s, l_f, u, or τ) the optimal solution must be calculated combining the dimensionless numbers in the right sequence. This assumption means that there are different possibilities to reach a solution of the equations system but only one will lead to the right solution (perfect analogy). Therefore, in this paper a systematic study of the possibilities was carried out to reach these solutions where the dimensionless numbers rest invariable.

Analysis of possible combinations

The analysis of the system of possibilities is based on a tree of combinations. Every combination is a sequence of following dimensionless numbers ordered and defined as illustrated in Fig. 3 in the particular case of choosing β as first choice. To simplify the resolution of the equations system, both HTF and storage material properties were considered constant. Therefore, only the geometry of the storage system, the flow rate of the HTF, and the period of the input temperature signal would be the parameters to be varied. This approach is consistent with real cases for which lab scale experiments are achieved using industrial HTF and TES material. In addition, and in order to have an easier systematic analysis, the Reynolds dimensionless number is introduced in the system eq. 9, due to its dependency with the thermo-physical properties of the fluid, the geometry of the TES system, and the HTF mass flow rate:

$$Re = \frac{4 \cdot u \cdot l_f}{\upsilon_f} \quad \text{(eq. 9)}$$

In the present study, physical and temporal parameters of the system (L, l_f, l_s, u and τ) are varied. The effect of these variation on final value of dimensionless numbers (β, γ, St*, Re and τ*) is analyzed. Combinations for which all dimensionless numbers remain constant have to be considered as valid solutions. On the other hand, combinations that induce a variation on the final value of at least one of dimensionless numbers lead to a distorted solution not considered as valid in this work.

Variation in physical and temporal parameters is introduced multiplying them by a constant (K). The value of constant K is greater than 1 when a scale-up is desired and less than 1 when scaling-down.

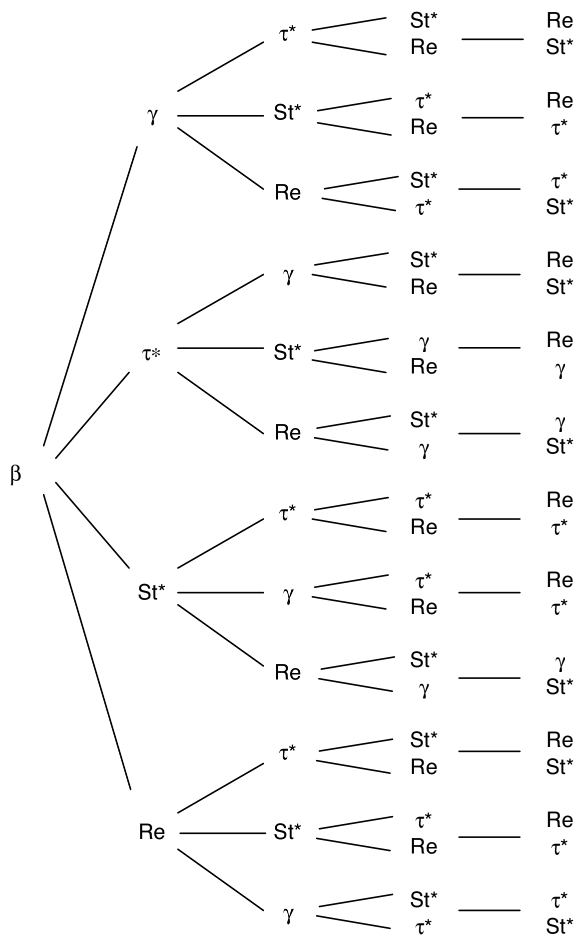

Fig. 3. Tree of possibilities giving β as first step

For a particular dimensionless number to remain constant, the variation of one of its internal parameters has to be balanced by a proportional variation of one of the other involved parameters.

Eq. 10 shows an example for which the plate thickness (l_s) has been modified by a scale change factor *K*:

$$l_s^{'} = l_s \cdot K \rightarrow \beta = \sqrt{\frac{\pi \cdot \rho_s \cdot Cp_s}{h_s}} \cdot \frac{l_s \cdot K}{\sqrt{\tau^{'}}} \Rightarrow \tau^{'} = \tau \cdot K^2 \Rightarrow \beta = const \quad \text{(eq. 10)}$$

Considering the dimensionless number β, its final value can be kept constant by a modification of the τ parameter by a factor K^2.

This kind of internal balance has to be done on each four dimensionless numbers successively taking into account the already modified parameters done on the previous ones. Obviously, each dimensionless number needs at least one internal available parameter to achieve its own balance. This can be done only if all its internal parameters have not been used already by the previous balances. Therefore, some (or even all) successions of the four dimensionless numbers could lead to a non possible combination.

According to this observation, the dimensionless parameters composed of very few internal parameters are much constrained and should be considered before the others.

3. Results and discussion

Scale-up changing the TES length (L)

As a first example, a current space scale-up of a TES system using plates can be viewed by the modification of the plate length. Then, in this case, the change of scale is defined by the ratio K between the industrial and the lab scale plate lengths (eq. 11).

$$L = L_{lab} \cdot K \qquad \text{(eq. 11)}$$

In this case the study of the possibilities leads to 10 possible combinations for which the dimensionless numbers remains constant for length scale-up of the TES system (Table 1). Everyone of these combinations leads to the same system of equations depending on K.

Table 1. Perfect analogy in the case of space change of scale for TES based on plate geometry.

Combination of dimensionless numbers	System of equations for the variation of geometry (L)
St* - γ - β - τ* - Re	$l_s = l_{slab} \cdot K$ $l_f = l_{flab} \cdot K$ $\tau = \tau_{lab} \cdot K^2$ $u = \frac{u_{lab}}{K}$
St* - γ - β - Re - τ*	
St* - γ - τ* - β - Re	
St* - γ - τ* - Re - β	
St* - γ - Re - β - τ*	
St* - γ - Re - τ* - β	
St* - Re - τ* - β - γ	
St* - Re - τ* - γ - β	
St* - Re - γ - β - τ*	
St* - Re - γ - τ* - β	

All combinations that lead to the system of equations for this case starts by the St* dimensionless number.

Table 1 shows that having a laboratory scale storage tank with determined parameters (L_{lab}, l_{slab}, l_{flab}, u_{lab}, and τ_{lab}) if K is defined as 10 the length (L) and the thickness of the plates (l_s) and the distance between plates (l_f) of the industrial scale storage tank will be 10 times higher than these of laboratory scale tank. On the other hand, the flow rate (u) has to be decreased by a factor of 10.

Concerning the period (τ_{lab}), for a value of K defined as 10, the number of cycles in industrial storage tank is increased by a factor of 100. That means that for an experiment of 10 cycles the results can be extrapolated to 1000 cycles.

This illustrates that a relevant change of scale in space can induce a modification in time scale. This effect has to be taken into account and highlights that even if perfect analogies are possible in space or time scales, it would be probably very difficult in the two scales simultaneously.

4. Conclusions

The present work describes a relevant method to scale up properly TES systems. This method may help to predict the behavior results at industrial scales obtained using lab-scale experiments with a high level of accuracy. It can be used also to design properly a lab-scale experimental set-up to offer directly a perfect analogy when possible. The scale up can be done in space scale, changing the geometry of the TES system, or in time scale, changing the number of cycles of charging and discharging.

The TES system studied is based on solid sensible heat storage material in direct contact with the HTF. Three geometries were analyzed by Bourouga et al. (1985): plates, cylinders and spheres. The present work is focused on the plates geometry only.

In order to apply the modeling of the storage system based on solid sensible heat storage material through transfer functions, carried out by Bourouga et al. (1985) to other storage systems, it will be necessary to determine the governing equations of the storage system and to develop the transfer function for the storage system. Systems based on storage by liquid sensible heat or latent heat may be also developed.

Concerning to the case studied, only 10 different combinations lead to a system of equations where the dimensionless numbers remain constant as Table 1 shows. All the other combinations introduce a variation in the dimensionless numbers.

The analysis of the 10 combinations shows that there is only one system of equations to scale up the TES system having results for a laboratory scale.

Values of K adequate for geometric changes could drive to variations of period or flow rate not desired or even lead to values without physical sense. In other words, not all K values lead to convenient values of the geometric and temporal parameters.

On the other hand, a specific scale up can be done also assuming that some dimensionless numbers will not be kept constant. In these cases the equation systems lead to distorted solutions that have to be studied in detail one by one.

5. Nomenclature

	Symbol	Unit
Thermal diffusivity of the solid storage material	α_s	$m^2\ s^{-1}$
Prandtl dimensionless number	Pr	-
Biot dimensionless number	Bi	-
Damper function	μ	-
Heat transfer coefficient	h_s	$W\ m^{-2}\ K^{-1}$
Specific heat capacity	cp_s	$J\ g^{-1}\ K^{-1}$
Density of the storage material	ρ_s	$kg\ m^{-3}$
Temperature of the HTF	$T(x,y)$	ºC
Temperature of the solid storage material	$\theta(x,y)$	ºC
Temporal variation of the sinusoidal signal of temperature	$\omega \cdot t$	rad
Phase of the sinusoidal of temperature in the solid storage material	$\Psi_s(x,y)$	rad
Phase of the sinusoidal of temperature in the HTF	$\Psi_f(x,y)$	rad
Modified Stanton dimensionless number	St^*	-
Characteristic time	τ^*	-
Coefficient β	β	-
Coefficient γ	γ	-
Reynolds dimensionless number	Re	-
Thickness of the plate	l_s	m
Distance between plates	l_f	m
Length of the plate	L	m
Speed of the flow rate of HTF inside the plates	u	$m\ s^{-1}$
period of the input temperature signal	τ	s
initial period	T_0	s
thickness of the plate of the model at laboratory scale	$l_{s\,lab}$	m
distance between plates of the model at laboratory scale	$l_{f\,lab}$	m
length of the plate of the model at laboratory scale	L_{lab}	m
Speed of flow rate of HTF inside the plates of the model at laboratory scale	u_{lab}	$m\ s^{-1}$
period of the input temperature signal of the model at laboratory scale	τ_{lab}	s

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