STSM scientific report

STSM Applicant: Antoni Gil, GREA – University of Lleida, Lleida (Spain)

STSM Topic: High temperature energy storage in thermal applications

Host: Prof. Dr. Xavier Py, CNRS – Promes, University of Perpignan (France)

Period: 15 – 02 – 2011 to 15 – 05 – 2011

Purpose of the STSM

The work plan purposed initially was divided on three consecutive tasks:

1.- Selection of the storage material and characterization of the selected material.

2.- Experimental part, testing the material in a storage module available at CNRS – PROMES.

3.- With the data obtained in the experimental period a simulation of the application will be done.

Description of the work carried out during the STSM

The objectives of the work plan were achieved during my stay in PROMES-CNRS, but due to confidentiality problems about the future results of the tasks planed before the stage, the objectives where changed to the following:

1.- Study of thermal energy storage (TES) systems modeling in periodic regime, using a mathematical model based on transfer functions.

2.- Theoretical analysis of the possibility to scale up the results obtained on laboratory or pilot plant to industrial scale.

3.- Evaluation of the physical sense of the results obtained during the theoretical analysis.

This task consisted on performing a theoretical study on a scale up in thermal energy storage systems for solar power plants and industrial applications. This study was based on articles published by Fourcher et al. [1], J. Brasnier et al. [2] and B. Bourouga et al. [3], who used mathematical transfer functions to evaluate the behavior of thermal energy storage systems. Thanks to the transfer functions described by J. Brasnier et al. and B. Fourcher et al., in this study it was possible to determine systems of equations that allow extrapolating the results obtained in the laboratory to industrial scale. This tool opens the possibility to guarantee the behavior of materials and thermal energy storage technologies tested in the laboratory, when they are applied on an industrial scale in both size and time. In other words, this tool can accurately predict the lifecycle of a system of energy storage and behavior of their thermophysical properties from laboratory tests with quantities about few kg and experiments of a few weeks.

Description of the main results obtained

The present work is focused on thermal energy storage (TES) systems and the possibility to find a reliable method to scale up the results obtained at laboratory scale to industrial scale. Nowadays the TES systems are an essential part in solar thermal power plants and, more and more, in industrial applications. But the choice of these systems would be rather inexact if there is no data about the behavior of a potential storage material after several thermal cycles. Until today only laboratory or small scale experiments were performed to obtain information about the behavior of the system at higher scale. Unfortunately, this type of experiments cannot predict the behavior for years of operation at full scale with accuracy, leading the selection of the TES system for an industrial plant to a high risk decision.

Fourcher et al. [1] published in 1980 a theoretical study on a TES system based on sensible heat storage. The mathematical model of the TES system proposed was done through the thermal transfer equations, which includes 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 [2]. 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 distribution of the solid storage material and the HTF consequence of this signal can be written as shown in eq. 1 and eq. 2 (the axes x, y and z of the equations will be fixed depending on the geometry of the TES system) according to Bourouga et al. [3]:

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

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

Bourouga et al. in 1985 applied the transfer functions developed by Fourcher et al. to TES systems with three different geometries: plates, cylinders and balls (Fig. 1). This theoretical study demonstrated that the storage performance is independent to the geometric parameters of the module and to the thermo-physical properties of the HTF.

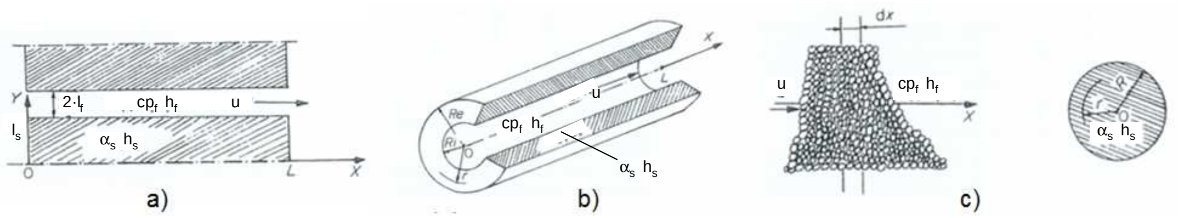

Fig. 1. Three different geometries studyied by Bourouga et al. (1985): a) plates; b) cylinders; c) balls

In this work only the geometry of plates was studied (Fig. 2). The study of the harmonic response of the TES system considering the mechanisms of thermal transfer in dynamic leads to the use of transfer functions based on the mathematical model equations of the system.

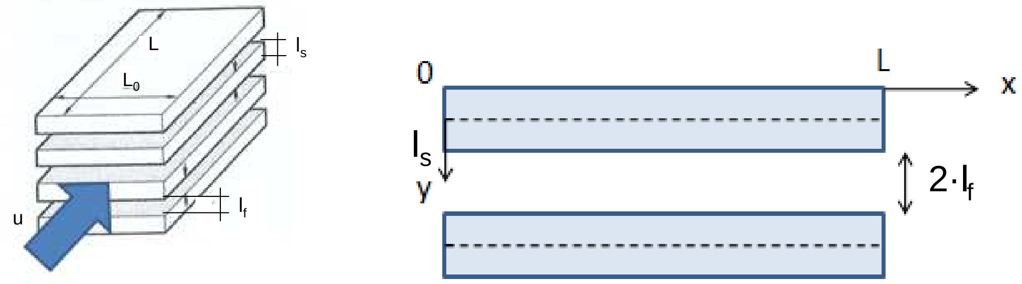

Fig. 2. Parameters of the storage system based on the geometry of plates

According to Bourouga et al. 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.

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

where μ is the damper function defined as it may be seen in eq. 4

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

This model takes into account the assumption that the thermal properties of the TES material and HTF were considered constant and uniform, according to Fourcher et al.

The non-variation of the damper function is the key to be able to scale-up the experimental results obtained in laboratory and to predict the behavior of an industrial scale TES system. If the value of the damper is varied the prediction is not possible.

Damper function describes the dynamic behavior of the TES system depending on four dimensionless numbers (β, γ, St*, Re and τ*) as eq. 4 shows. The interaction between the dimensionless numbers and the thermo-physical properties and geometrical parameters (L, l_s, l_f, u, or τ) is very strong. It is not possible to vary some of them in a dimensionless number without having a variation in many others. To be able to extrapolate the results in laboratory scale to industrial scale the variation of the thermo-physical properties or geometry must lead to no variation of the four dimensionless numbers. Otherwise, the results obtained can not be scaled up directly. In this work a systematic study of the possibilities was carried out to reach these solutions where the dimensionless numbers rest invariable.

The analysis of the system of possibilities is based on a tree of combinations. Every combination is a sequence of dimensionless numbers ordered and defined. 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.

In order to carry out these 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 where all dimensionless numbers remain constant had to be considered as valid solutions. On the other hand, combinations that imply a variation on the final value of one of dimensionless numbers lead to a distorted solution not considered in this work. Variation in physical and temporal parameters is introduced multiplying them by a constant (K).

RESULTS

A scale-up analysis of the storage tank varying the length of the plates was carried up as first approach. First of all is necessary to define the length of the laboratory scale model (L_{lab}). The new length (L) was obtained multiplying the length of the laboratory scale model by the constant K (eq. 11).

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

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

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 (ls) 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 HTF velocity (u) decreases in a factor of 10.

Table 1. Combinations that lead to a system of equations varying the 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	

Concerning to 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 case shows that appropriated K values for geometric scale up can be inadequate for temporal scale up.

CONCLUSIONS

As a conclusion, 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. The scale up can be done in space, changing the geometry of the TES system, or in time, 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.: plates, cylinders and spheres. The present work is focused on the plates geometry.

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 developed.

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

The analysis of the 10 combinations shows that there is an only 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, the scale up can be done assuming that dimensionless numbers will be not constant. In these cases the equation systems lead to distorted solutions that have to be studied in detail one by one.

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
HTF velocity 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
HTF velocity 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

REFERENCES

[1] Fourcher, B., Saint-Blanquet, C., 1980. Transfer function of a storage sensible heat element in periodic regime. Int. J. Heat mass transfer. Vol 23, pg 1251-1262.

[2] Bourouga, B. Fourcher, B., 1985. Comparison des functions de transfert d'un stockage en régime périodique pour trois géometries fondamentales. Examples d'optimisation. Int. J. Heat mass transfer. Vol 28 nº8, pg 1425-1439.

[3] Bransier, J., 1979. Periodic storage by latent heat on the fundamental aspects of the kinetics of transfers. Int. J. Heat mass transfer. Vol 22, pg 875-883.

Future collaboration with the host

At the present moment CNRS-PROMES and GREA are collaborating to publish a scientific article focused on the work developed during my stage in PROMES.

In order to continue the collaboration GREA Universitat de Lleida will host Antoine Meffre, a PhD student from CNRS – PROMES, in their installations during some weeks.

Foreseen publications/articles resulting of the successful execution of the STSM

Thanks to this collaboration work between GREA University of Lleida and CNRS-PROMES University of Perpignan a scientific publication is in preparation. On the other hand, this work will be presented in the next Annex 25 meeting in October 13th-14th 2011 at KEPCO Osaka (Japan) as "*Evaluation of thermal energy storage systems scale up: from laboratory scale to industrial applications"* and in the ISES congress in Kassel (Germany), August 28th to September 2nd 2011 as "*Theoretical study on scale up of thermal energy storage systems in solar power plants*".