# STSM scientific report

**STSM Applicant:**

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**STSM Topic:**

Thermal energy storage for low temperature applications

**Host:**

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**Period:**

From 16 – 06 – 2011 till 17 – 09 – 2011

## 1. Purpose of the STSM

It is well known that thermal energy storage (TES) plays an important role in both industrial and domestic applications. The northern European countries, such as Sweden, have a high demand of cold during summer time. They normally have installed a district cooling which is based on cold water being distributed in a network of pipes. In a specific location cool water is produced and then fed through a network pipes to homes, offices, hospitals, industries and other environments in need of cooling. To do this, big water caverns are used to cool down the warm water from the network and to store it. Therefore, it is of great interest for the researchers to study this type of storage system, enhancing the stratification and the energy storage density of them.

The main purpose of the STSM is to study numerically and experimentally a TES system developed by the researchers from the KTH in the past that could not be studied deeply. This TES system is a cylindrical storage tank of water which could be added phase change material (PCM) in form of packed bed in order to enhance the energy density of the system and the stratification of it. For that purpose the STSM has been structured to present and compare two different mathematical models of packed bed storage with PK6 as PCM, more specifically the heat transfer during charging the PCM.

- The first numerical model is a continuous model based on the Brinkman equation which describes the flow field inside the porous media and the heat transfer mechanisms present in the packed bed systems.

- The second numerical model treats the PCM capsules as individual particles and describes the temperature gradient inside the PCM capsules.

Both models are validated with experimental data generated during this STSM. In order to carry on the experimentation, experimental set-up has developed in the KTH lab.

## 2. Description of the work carried out during the STSM

### 2.1. Experimental set up

The experimental set up consists of a cylindrical storage tank and a water bath with a capacity of 10 L used for setting the temperature and the HTF flow rate and a water flow meter. The cylindrical storage tank has an internal diameter of 101 mm and a total height of 500 mm, where only 3.73 L are used for storage. To increase the storage capacity of the tank, an organic PCM (PK6) was added. The encapsulation of this PCM in a spherical form (average diameter of 3.6 ±0.1 mm) let it work as a packed bed. PK6 is an organic PCM from Rubitherm GmbH with a storage capacity of 175 kJ/kg between -2 to 13 °C and the permeability of the PCM was calculated experimentally using the above mentioned experimental set up. The encapsulation form of the PCM is not inside a spherical capsule having two thicknesses (PCM and capsule) but doing a mixing between the PCM and some additive making it as a sponge sphere.

Twelve thermocouples type T were placed inside the storage tank in order to measure the porous media temperature at different heights in the vertical plane and two more thermocouples (type T) were located at the inlet and the outlet of the tank. The storage tank is insulated with 40 mm thick polyurethane and the pipes are insulated with 20 mm thick foam. A sketch of the system is shown in Fig. 1 and Fig. 2 shows the storage tank filled with PCM in the experimentation.

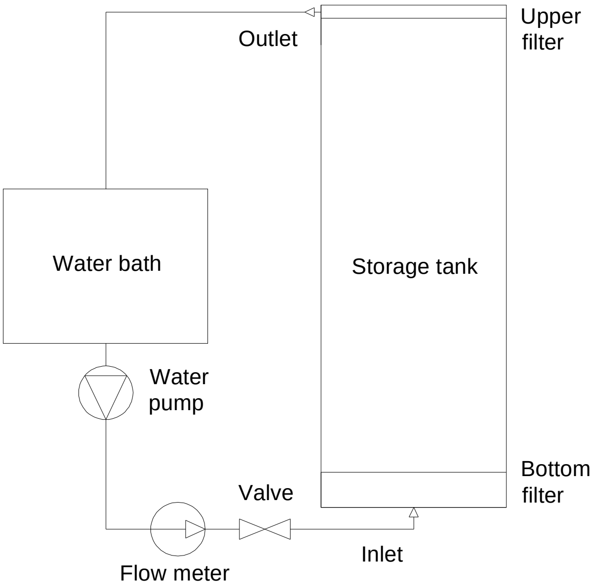


Fig 1. Scheme of the experimental set up used in the experimentation.

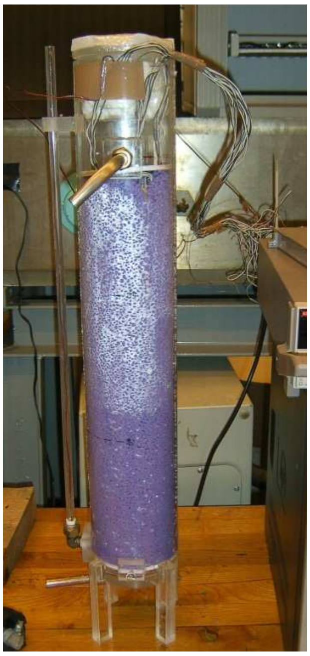


Fig.2 Storage tank full of PCM.

It is important to maintain the stratification and to avoid mixing inside the storage tank, therefore the HTF flow has to be maintained as a plug flow through the storage medium. For that reason, two filters with 100 holes of 2 mm diameter were included, one at the bottom and another one at the top of the water tank in order to constrain the PCM and evenly spread the HTF flow.

A correct inlet velocity profile is crucial in reaching numerical sound simulation. Different numerical models with various velocity profiles were compared with an experimental data. With the same experimental set up described before but without PCM, the tank was filled with water at 11 °C and water at 2 °C was introduced from the bottom at a flow rate of 0.5 L/min. The experimental data was compared with 4 different models which were the same except the velocity profile in each of them. Therefore four different velocity profiles were analysed, from a constant velocity (plug flow) till a very pronounced velocity profile. The results clearly showed that the best velocity profile according to the experimental data was the constant velocity profile. Therefore, the filter used was adequate and all the models studied in this work have used a constant velocity profile.

### 2.2. Numerical model. Brinkman's equation model

Regions with small pores, as it is the case studied in this paper, are treated as a permeable medium and its flow is described by Darcy's law. In the Darcy model it is effectively assumed that all the stress in the flow field is carried by the porous medium and the fluid is not subjected to any strain because of the viscous stresses. This assumption cannot be regarded to be physically realistic for high permeability porous media where at least part of the viscous stress is borne by the fluid itself [1]. Moreover, Darcy's law alone is not sufficient to satisfy these boundary conditions and may affect the flow and heat transfer characteristics inside the porous media. Therefore, the Brinkman equation, which accounts for the transition from Darcy flow to viscous free flow, has selected as the working interface. The Brinkman equations describe fluids in porous media for which the momentum transport within the fluid due to shear stresses is of importance. This mathematical model extends Darcy's law to include a term that accounts for the viscous transport in the momentum balance, and it treats both the pressure and the flow velocity vector as independent variables. In porous domains, the flow variables and fluid properties are defined at any point inside the medium by means of averaging of the actual variables and properties over a certain volume surrounding the point (*Comsol Multiphysics 4.2*). Hence, this is a multiphysics model where the Brinkman equations (*Eq. 1 to Eq. 3*) are combined with heat transfer (*Eq. 4*) equation between the HTF and the porous media. The dependent variables in the Brinkman equations are the directional velocities and pressures and the temperature in the heat transfer equation. The flow porous media is governed by a combination of the continuity equation and momentum balance equation, and for a Newtonian and incompressible fluid are:

Continuity equation:

$$\rho\frac{\partial u}{\partial x}+\rho\frac{\partial v}{\partial y}=0$$

*(Eq. 1)*

*Brinkman-momentum equation in x:*

$$\frac{\rho\,\partial u}{\varepsilon\,\partial t}+\frac{\rho}{\varepsilon^{2}}u\frac{\partial u}{\partial x}=-\frac{\partial P}{\partial x}+\frac{\mu\,\partial\tau_{xy}}{\varepsilon\,\partial x}-\frac{\mu}{\gamma}u$$

*(Eq. 2)*

*Brinkman-momentum equation in y:*

$$\frac{\rho\,\partial v}{\varepsilon\,\partial t}+\frac{\rho}{\varepsilon^{2}}v\frac{\partial v}{\partial y}=-\frac{\partial P}{\partial y}+\frac{\mu\,\partial\tau_{yx}}{\varepsilon\,\partial y}-\frac{\mu}{\gamma}v-\rho g\beta\left(T-T_{ref}\right)$$

*(Eq. 3)*

Related to the heat transfer involved in the problem, the mathematical model for heat transfer in porous media used is (the velocity field comes from the Brinkman's equation):

$$(\rho C_p)_{eq}\frac{\partial T}{\partial t}+\rho C_p u\frac{\partial T}{\partial x}+\rho C_p v\frac{\partial T}{\partial y}=k_{eq}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+Q \qquad (Eq.\ 4)$$

Where

$$(\rho C_p)_{eq}=\varepsilon\rho_{PCM}C_{p,PCM}+(1-\varepsilon)\rho_{HTF}C_{p,HTF} \qquad (Eq.\ 5)$$

$$k_{eq}=\varepsilon k_{PCM}+(1-\varepsilon)k_{HTF} \qquad (Eq.\ 6)$$

In this study, a commercial CFD program COMSOL 4.2 was used to carry out the numerical study. The governing equations for porous media and heat transfer were solved through control-volume-based technique. The effects of time step on the solution were carefully examined in the preliminary calculations, where three time steps (0.01 s, 0.1 s, and 1 s) were tested. Convergence of the solution was checked at each time step, with the convergence criterion of $10^{-6}$ for all the equations solved.

### 2.3. Numerical model. Energy equation

In order to take into account the thermal gradients inside the PCM spheres, and to reflect the influence of the shape and size of the spheres and not only the porosity of the porous media on the heat transfer, a simplified transient two-dimensional model was developed. This mathematical model uses the bases settled in [2] and it is based on dividing the tank into a number of vertical layers whose thickness is always equal than a capsule diameter, $N_L=\frac{H}{D_{sph}}$ (Fig. 4 and Fig. 5).

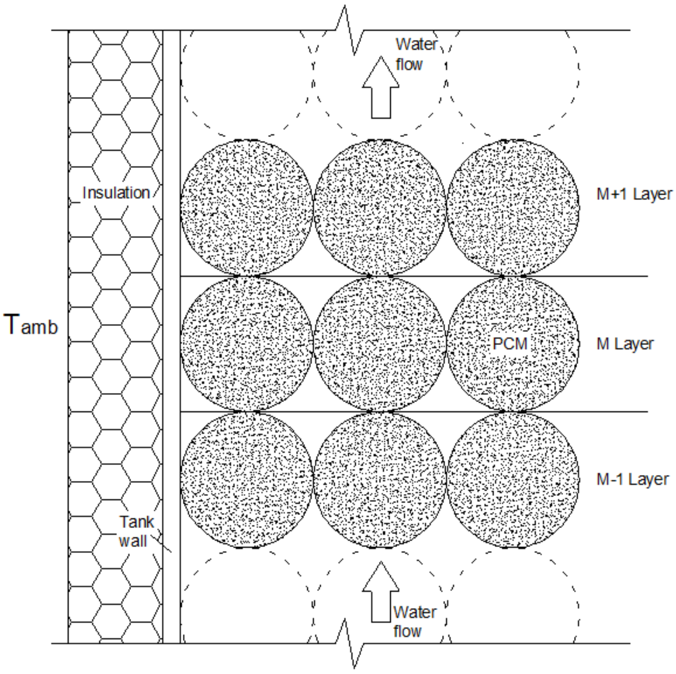


Fig. 4. Sketch of the modeled system.

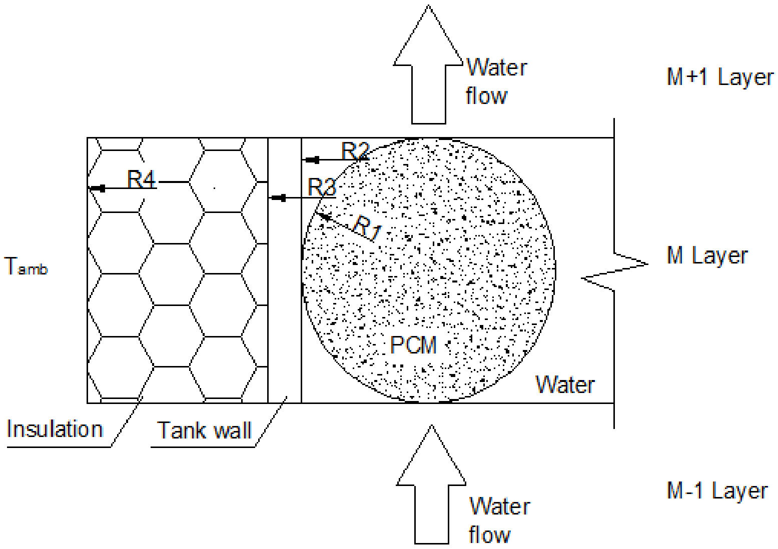


Fig. 5. Sketch of the modelled sphere.

The energy equation during charging and discharging was solved using a fully implicit finite volume method of solution in spherical and cylindrical coordinates system. From the first principle of thermodynamics for a closed isotropic system, the transient two-dimensional heat transfer in PCM, capsules and water during a charging or discharging process and insulation is governed by Eq. 7 and Eq. 8:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(kr^2 \frac{\partial T}{\partial r}\right) \qquad \text{(Eq. 7)}$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p v \frac{\partial T}{\partial y} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) \qquad \text{(Eq. 8)}$$

In the model the number of nodes considered in the radial direction was: 6 nodes in the PCM, 3 for the methacrylate glass envelope of the tank and 4 for the insulation foam. For the two-dimensional conditions 130 nodes in the y-direction were used. The algebraic linear equations system extracted from the finite volume method was solved using Gauss Seidel iterative method with a time step of 1 second. The solution was found to be mesh-independent based on the above nodes selection.

## 3. Description of the main results obtained

In order to prove the credibility of the developed mathematical models, a comparison of both numerical models and experimental data was conducted. For the validation of the numerical codes, experimental data during the solidification of the PCM was used. Initially, all system (PCM and water inside the tank) was at 11 °C and a flow (1 L/min) of cold water at 2 °C entered from the bottom of the cylinder tank while the hot water (11 °C) left from the top. During this process (almost 12 minutes), the melted PCM gave energy to the water increasing the temperature of the new water while the PCM was solidifying.

### 3.1. Validation and simulation results of the Brinkman's equation model

A comparison of the experimental data and the calculated temperature profile of the water during PCM solidification are shown in Fig 7. The temperature profile of the water from the mathematical model demonstrates good agreement with the experimental data not only the phase change temperature range but also in the time at which the packed bed is at constant temperature so the cold charging is done. However, while the temperature profile from the experiments shows almost no phase change at the lowest part of the tank (T_0, T_2, and T_4), the temperature from the mathematical model shows a constant temperature during this period due to the phase change of the PCM (T_2, and T_4). This effect could be due to the difference between the real porosity in the packed bed and the assumed for the mathematical model, which is constant in the entire storage tank. As the PCM used has a lower density than the water, it flows; therefore probably there was more PCM in the upper part of the tank. Moreover, it is impossible to ensure that the quantity of PCM in each layer of the storage tank is the same. Therefore, if at the upper part of the storage tank there is more quantity of PCM than in the lower part, the PCM does not give such amount of energy to the water in the lower part, and the temperature decreases faster while in the upper part of the tank, the PCM gives more energy to the HTF so the temperature decreases more slowly in the experimental data.

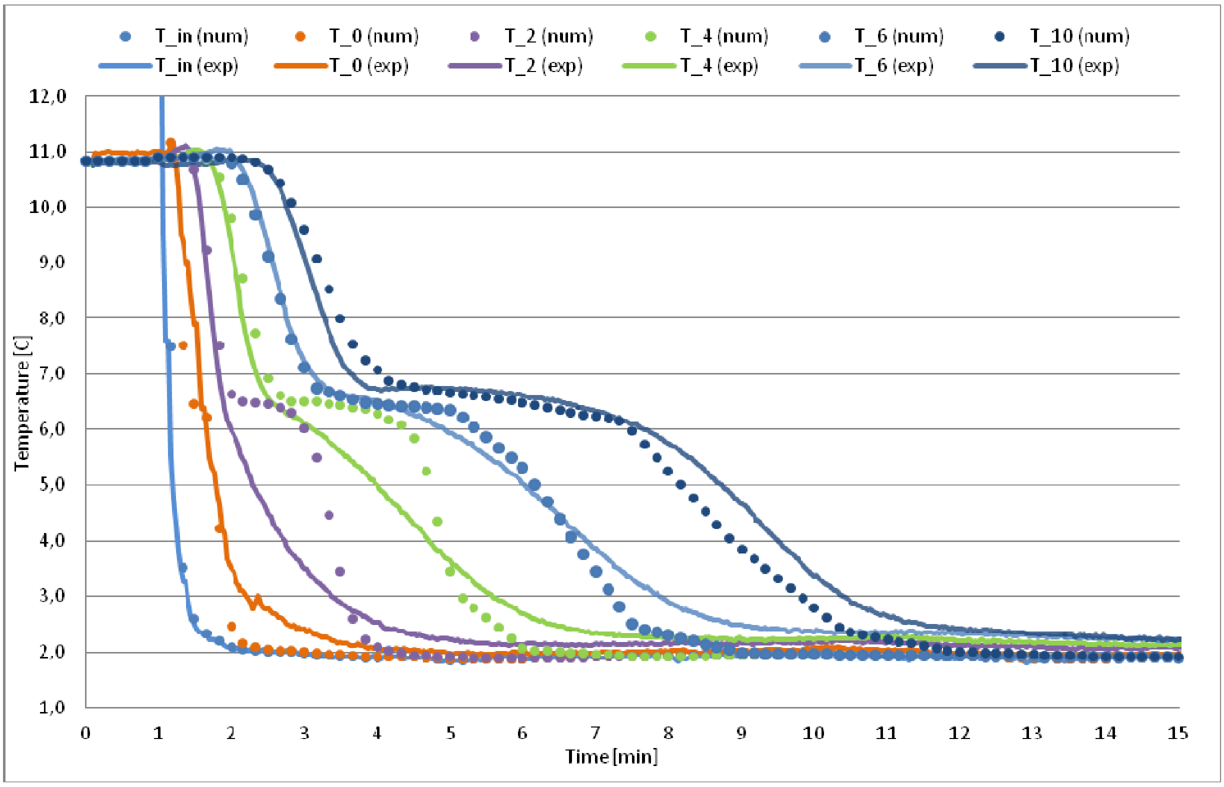


Fig. 7. Brinkman's equations model validation during PCM charging.

Using the continuous phase model described by the Brinkman's equation, the porosity and the permeability of the packed bed are the main parameters that describe the system. Moreover these parameters could affect the velocity of the HTF and the pressure drop inside the packed bed, hence it could further influence the heat transfer between the HTF and the PCM capsules and the design of the packed bed storage tank. Therefore it is important to evaluate the velocity (Fig. 8) and the pressure drop (Fig. 9) inside the packed bed tank, which only the implementation of the continuity and momentum equation allows, hence the Brinkman equation model does. Fig.10 shows the velocity of the HTF inside the packed bed storage tank at different heights (h1 = 4 cm; h2 = 20 cm; h3 = 31 cm; h4 = 44 cm) from the bottom of the tank, and at different radius (r0 = 0 cm, r1 = 1 cm, r2 = 2 cm, r3 = 3 cm, r4 = 4 cm and r5 = 5 cm). As it is expected in packed beds, the velocity profile is almost constant unless when the flow goes near the lateral wall where the velocity decreases till 0.

Fig. 11 shows the temperature profile inside the packed bed in different instants of time after (1 to 12 minutes) after starting the cold charging. During the PCM charging (between 1 to 8 min) the temperature of the main part of the storage tank is within the phase change temperature of the PCM (7-5 °C).

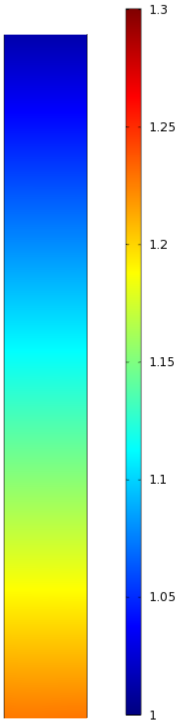


Fig. 8 Pressure profile at steady state, after15 min of cold charging.

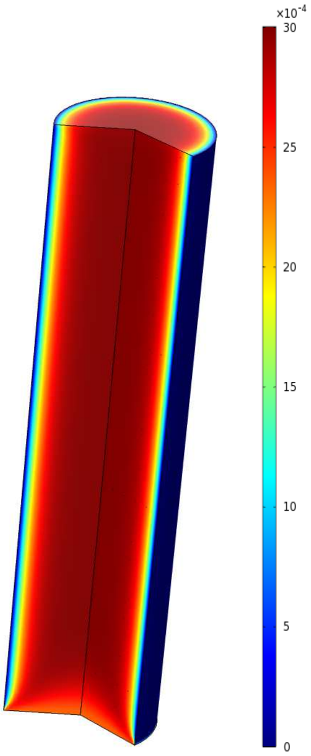


Fig. 9. Velocity profile at steady state, after15 min of cold charging.

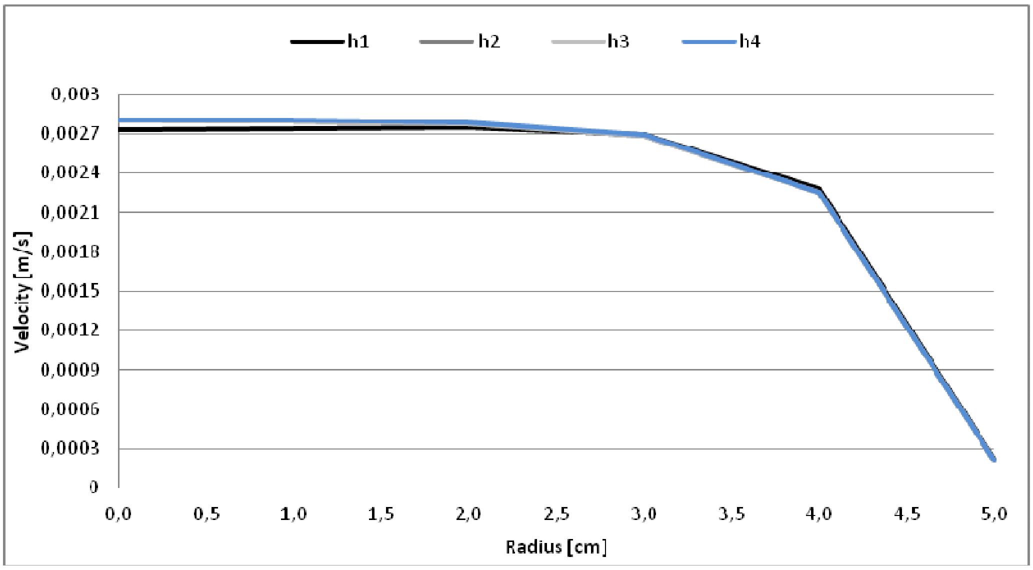


Fig.10. Velocity inside the storage tank at different heights and different radius.

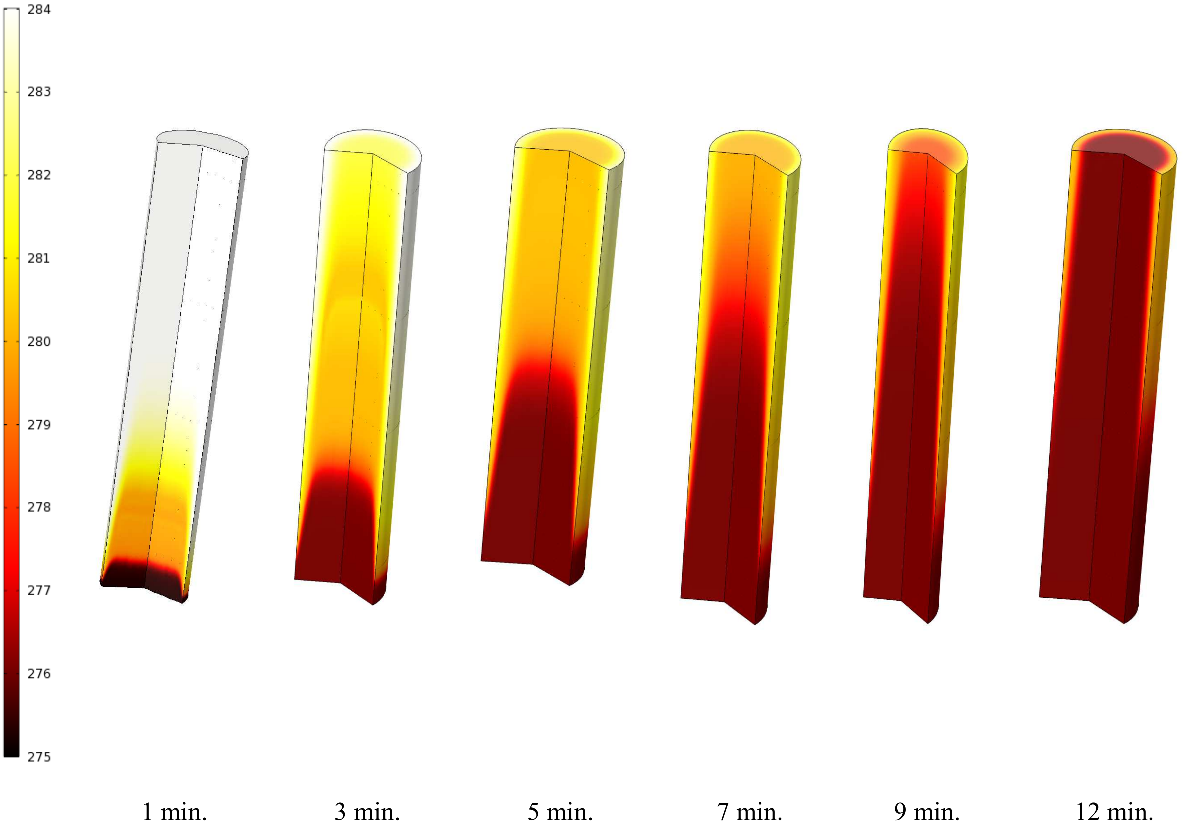


Fig. 11. Temperature distribution inside the packed bed after 1, 3, 5, 7, 9, and 12 minutes of cold charging.

When working with vertical water storage tanks, one of the most common assumptions is that there is no temperature gradient in the horizontal direction in water [3]. Therefore, the storage tank could be divided in N layers and it could be assumed that the temperature in the r direction is the same in each layer [4-5]. Fig. 12 shows the temperature of the packed bed during the cold charging at different heights (h1, h2, h3, and h4) and in different radius of the storage tank (r1, r2, r3, r4, and r5). The temperature of the packed bed is the same in the radial direction while the velocity profile is the same. As it was shown before, the HTF velocity is almost constant till the radius is 30 mm and then it starts to decrease slowly till 40 mm and then very fast till the wall of the storage tank. Therefore, the temperature of the packed bed starts to change in the radial direction too. Hence, the assumption of having no temperature gradient in the horizontal direction would be a good approximation when the velocity profile is constant in the radial direction, which is function of the permeability of the porous media. Fig. 13 shows the temperature gradient (K/m) in the radial direction of the packed bed in different instants of time after (1 to 12 minutes) after starting the cold charging.

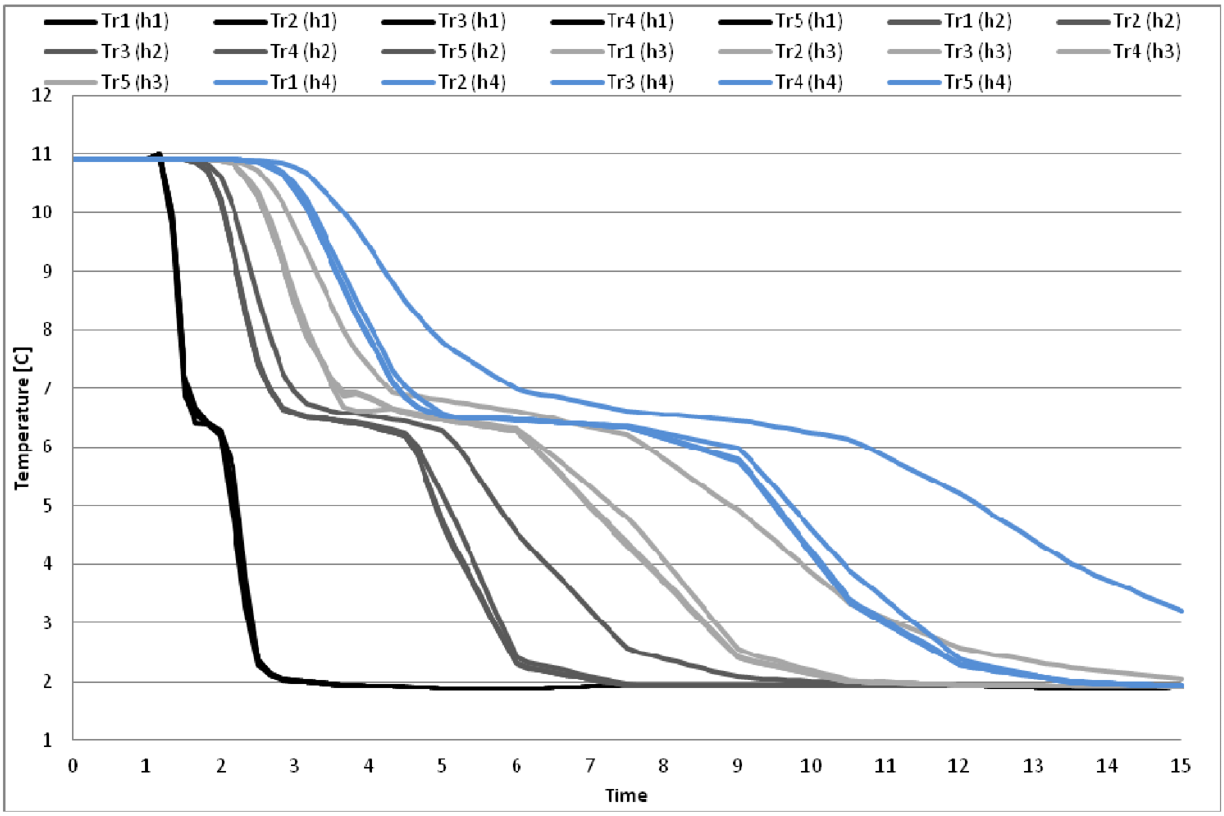
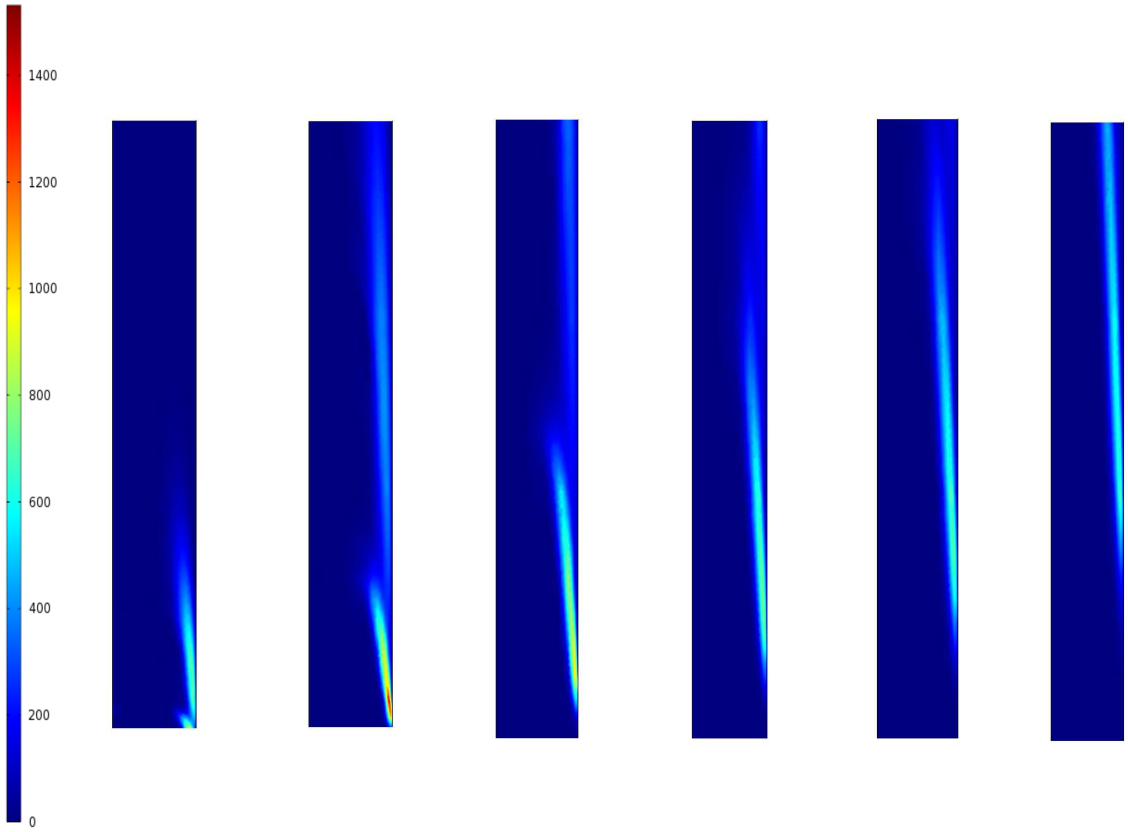


Fig. 12. Temperature of the packed bed at different heights and radius.



1 min. 3 min. 5 min. 7 min. 9 min. 12 min.

Fig. 13. Temperature gradient (K/m) in the radial direction inside the packed bed after 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 minutes of cold charging.

### 3.2. Validation and simulation results of the energy equation model

The energy equation model developed in this study allows for thermal gradients inside the PCM capsules, which could not be shown in the Brinkman's equation model. However it cannot describe the flow of water through the voids among the PCM capsules but the Brinkman's equation model does. Fig 14 shows the comparison between the experimental and the calculated temperature profile of the water during PCM solidification. The agreement between both water temperature profiles is a good support to the mathematical model developed and the different correlations used to predict the different heat transfer coefficients. However, also the same effect which could cause the difference between the real and the assumed porosity inside the different layers of the storage tank that was commented in the validation of the Brinkman's equation model can be observed. Nevertheless, the agreement between both the experimental and the calculated packed bed temperature profile is really good.

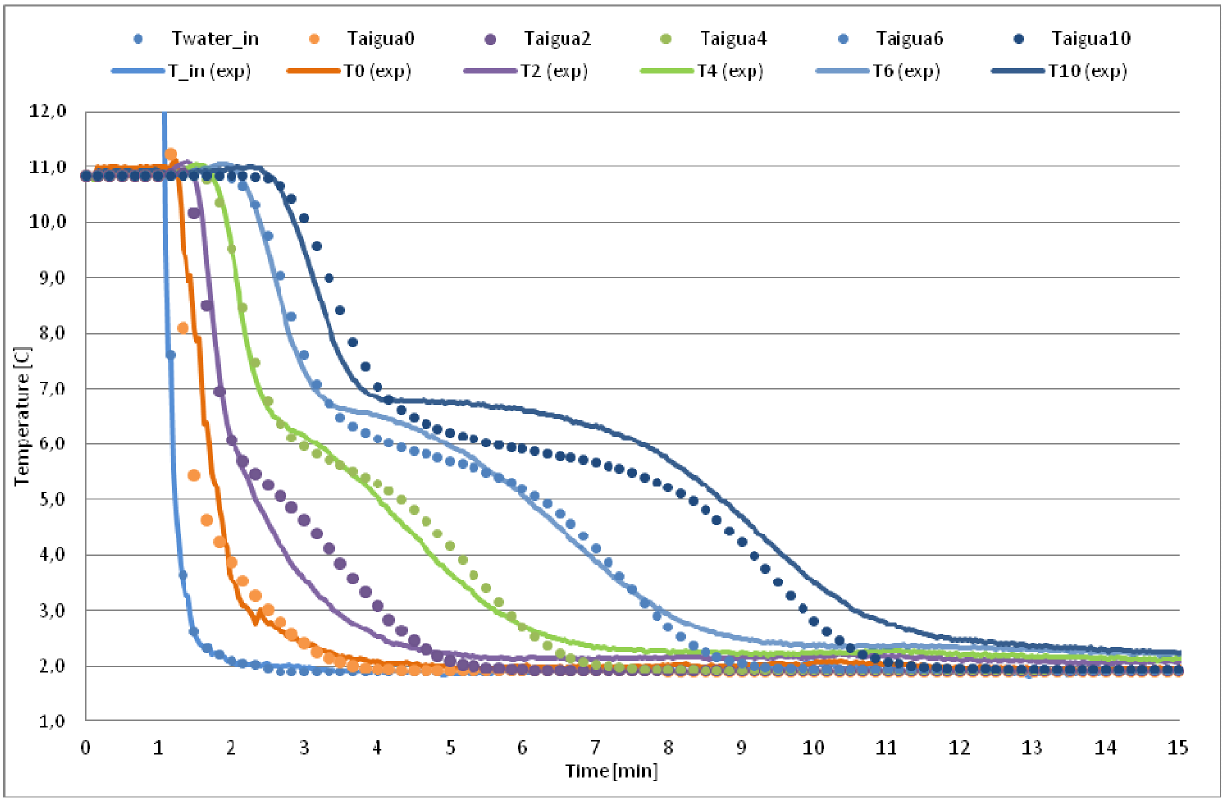


Fig. 14. Energy equations model validation during PCM charging.

The PCM temperature decreases gradually at the beginning of the cold charging of the sensible heat storage period, and then remains nearly constant during the phase change (7-5 °C) which is followed by a temperature decrease during cooling of the solid PCM. The energy equation model developed allows analysing the temperature gradients inside the PCM capsules, which could be done using the continuous phase model developed using the Brinkman's equation. For that purpose, a specific correlation of the Nu number in order to calculate the heat transfer coefficient between the HTF and the PCM capsule was used. However, different heat transfer coefficients have been used in the recent literature [4-5]. Therefore, three different scenarios with three different heat transfer coefficients have been analysed and compared:

- Scenario 0 (used to validate the code). The heat transfer coefficient is from natural convection through a sphere [6]:

  $Nu = \left(2 + 0.4\,\mathrm{Re}^{0.5} + 0.06\,\mathrm{Re}^{2/3}\right)\mathrm{Pr}^{0.4}\left(\dfrac{\mu}{\mu_s}\right)^{0.25}$. All properties at $T_\infty$ except $\mu_s$ which is at $T_s$ of the sphere. This equation is valid only when: $0.71 \le \mathrm{Pr} \le 380$ ; $3.5 \le \mathrm{Re} \le 7.6 \cdot 10^4$ ; $1.0 \le \dfrac{\mu}{\mu_s} \le 3.2$.
- Scenario 1. The heat transfer coefficient proposed by [7] depends on the porosity of the bed, the HTF properties and the Re number of the HTF flow:

$$Nu = 2 + 1.1\left[6(1-\varepsilon)\right]^{0.6} \mathrm{Re}^{0.6}\, \mathrm{Pr}^{1\!/\!3}$$

- Scenario 2. The heat transfer coefficient is from an empirical correlation proposed by [8] for the case of spherical capsules arranged in a random form:

$$Nu = 3.22\,\mathrm{Re}^{1\!/\!3}\, \mathrm{Pr}^{1\!/\!3} + 0.117\,\mathrm{Re}^{0.8}\, \mathrm{Pr}^{0.8}$$

Fig. 15 shows the temperature profile of different PCM capsules (at r=0) at different heights in each of the three scenarios analysed. As it was expected, the temperature of the PCM at the lowest part of the tank presented faster phase change due to the high power from the HTF (inlet temperature at 1 ºC). On the other hand, the PCM at the upper part of the storage tank presented the slowest phase change time due to the heat exchange between the HTF and the PCM was much slower here, where the HTF temperature was higher than at the bottom part. However there was no difference in the PCM temperature even if different Nusselt correlations were used. Hence, in terms of heat transfer there was no difference between the three different correlations.

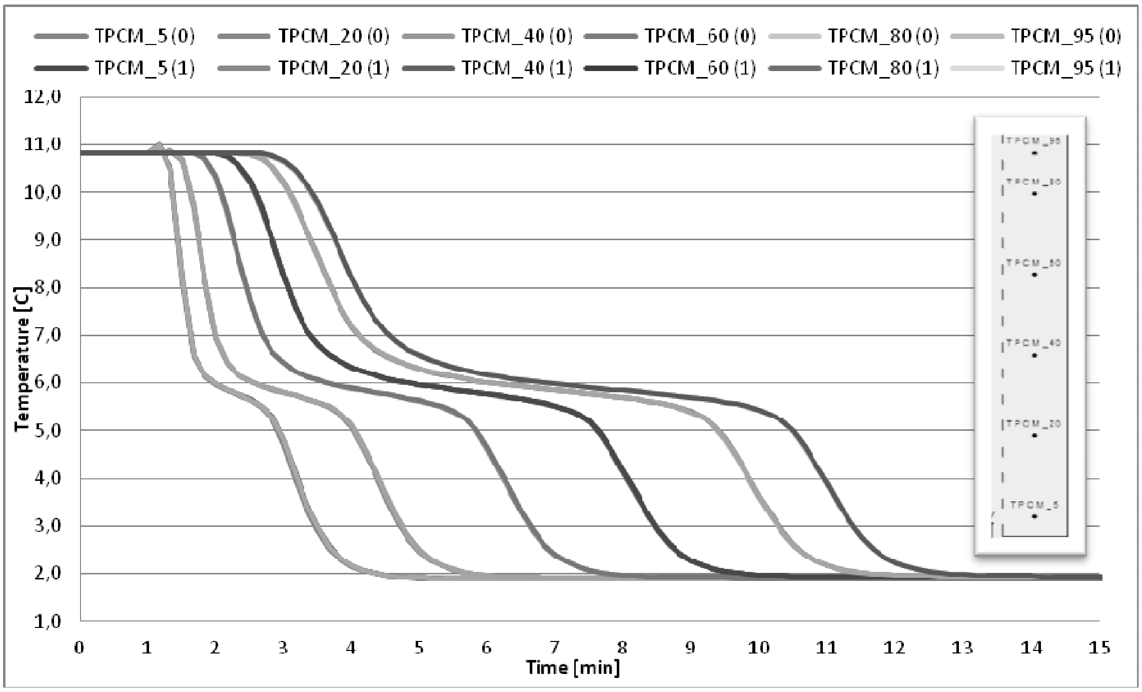


Fig 15. PCM temperature profile during cold charging.

The gravitational force is due to the combined presence of a fluid density gradient and a body force that is proportional to density and it could cause free convection, increasing or decreasing the heat transfer between the HTF and the PCM packed bed. Due to the characteristics of the experimentation done, forced convection was present in the heat transfer process and probably free convection as well. However the proportion both of them participated in the heat and mass transfer during the cold charging was to be more specified. The effect of buoyancy on heat transfer in a forced flow is strongly influenced by the direction of the buoyancy force relative to that of the flow (same direction-assisting flow, opposite direction-opposing flow, and perpendicular directions-transverse flow). In assisting and transverse flows, buoyancy acts to enhance the rate of heat transfer associated with pure forced convection; in opposing flows, which is the case (during cold charging), it acts decreasing this rate. In the problem settled, the buoyancy effect will decrease the heat transfer rate between the HTF and the PCM spheres. It is known that free convection is negligible if $\left(\frac{Gr}{\mathrm{Re}^2}\right) << 1$ and that force convection is negligible if $\left(\frac{Gr}{\mathrm{Re}^2}\right) >> 1$. The combined free and force (or mixed) convection regime is then one for which $\left(\frac{Gr}{\mathrm{Re}^2}\right) \approx 1$. Moreover, in the case studied, the $\left(\frac{Gr}{\mathrm{Re}^2}\right)$ number goes from 0 to 3.24 as the temperature difference between the HTF and the PCM capsule surface varies from 0 to 10 °C. Therefore, the heat transfer between the HTF and the PCM packed bed are, with a theoretical point of view, both free and forced convection.

As explained above, the Brinkman's equation model allows the incorporation of the gravitational force but not the energy equation model. However, the temperature profile from both models in comparison with the experimental data does not show difference between adding or not the gravitational force into the momentum equation. Therefore in the situation studied, free convection is not as important as forced convection. Another point would be when no flow situations or very low flow rate happen, then Re decreases and the problem becomes a free convection problem.

## 4. Future collaboration with host institution

From the work developed in the STSM this summer, future collaboration between the University of Lleida and the KTH – Royal Institute of Technology will be carried on. In fact next November the researchers from KTF which Dr. Viktoria Martin is the principal investigator, are coming to the University of Lleida to celebrate a meeting to discuss future collaboration between both universities.

## 5. Foreseen publications/articles resulting or to result from the STSM

In the 3rd Experts Meeting and Workshop for Annex 25: "Surplus Heat Management using Advanced TES for $CO_2$ mitigation" that will be celebrated the 13th and the 14th of October 2011 in Osaka will be presented the work developed during the STSM: "*Comparative study of different numerical models of packed bed thermal energy storage systems*".

Moreover, I am editing with the collaboration of different authors the first paper from the work done during the STSM:

*Comparative study of different numerical models of packed bed thermal energy storage systems*

Authors: E. Oró, J. Chiu, V. Martin, L.F. Cabeza

## 6. Confirmation by the host institution of the successful execution of the STSM

Attached

## 7. References

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