Numerical study of a thermal storage tank enclosed PCM capsules

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Abstract. Low-temperature thermal storage has a huge potential in residential use for regulating the energy supply. This paper proposes a new thermal storage system consisting of modular units. Users can combine different numbers of the units to achieve the desirable energy demand. In this study, a single unit was studied. The hydrated salt was used as the phase change material (PCM) and it was packed in spherical capsule. The phase change situation of each PCM balls were analysed with numerical simulation method. The results showed that the PCM balls in different position had different change rate. In the charging process, the thermal stratification happened after the middle part of the unit, the down layer PCM balls took 30% more time than upper layer to be melted completely. In discharging process, considered the user requirement, the low inlet velocity may fit the single unit. The thermal stratification also happened in the discharging process, and it is most obvious in the middle part.

Keywords: phase change material; low-temperature thermal storage; hydrated salt; numerical calculation

1. Introduction
To overcome time and space restrains of energy use, energy storage plays an increasingly important role in energy systems [1-3]. In some situations, energy storage systems can be proposed which allow for a high energy density and a small temperature drop during the heat storage processes [4]. The confirmed capacity of phase change materials (PCMs) to store high density energy, by making use of latent energy, allows to shrink the volume of storage containers and employ this energy storage technique at large scale [5].

Encapsulating PCM in spheres is a method which has been widely adopted to avoid any instability within the PCM as well as preventing corrosion [6]. F.L. Tan [7, 8] conducted a study on the melting process of spherical PCM capsules in constrained and unconstrained situations, analysing with experimental and computational approaches the heat transfer characteristics of PCM. E. Assis [9] investigated experimentally and numerically the melting of a spherical PCM capsule formed of mixed salt materials.

With the development of computational fluid dynamics (CFD), more details of phase change materials and its behaviour have been studied [10]. This study proposed a new thermal storage system and developed a CFD model of the device, numerical analysis was used in this paper as a theoretical foundation for the future design and experiment.

2. The scheme of systems and simulation model
2.1. Scheme of the latent thermal storage system

A prototype model was designed in this work. Figure 1 (a) displays the three-dimensional (3-D) structure of the latent thermal storage component. The PCM is packaged within a spherical shell shown as Figure 1 (b). The diameter of each PCM ball is 42 mm and every four PCM balls are defined as one group. Each component have nine groups of PCM balls. In this case, it was assumed that all PCM balls are motionless and they are arranged orderly with a 2 mm distance between each other. The size of each storage component is 90 mm×90 mm with a height of 405 mm.

![Figure 1. Scheme of the latent thermal storage system.](image)

(Gravity acts along the positive Z direction, underline flow direction represents discharging process.) The inlet tube, with a diameter of 10 mm, is placed between the first and second group. The outlet tube is placed in the symmetric place between the eighth and ninth group. During the charging process, the HTF (water in 353K) flows into the component from the top, which is shown as a solid line arrow in Figure 1 (a). While during the discharging process, the CTF (water in indoor temperature, 300K in this case) flows from the bottom, represented by a dotted line arrow. A complete cycle of the charge and discharge process is considered for the analysis in this study.

2.2. Physical situation and mathematical model

The following assumptions were made for the mathematical model: 1) Both solid and liquid PCM phases are homogeneous and isotropic. 2) The shell of the PCM balls is not built in the model, while its thermal conductivity is calculated in the simulation process and its thickness is 0.5 mm. 3) The liquid phase is a viscous Newtonian fluid. 4) The PCM balls are full of phase change material. 5) The changes of density and heat conductivity coefficient during the melting and solidification process are neglected. 6) The walls of the storage component are assumed as heat insulation.

The PCM balls were offered by Jinli New Energy Technology. The material they used is called SXC-CZ, which is a hydrated salt. Water is used as HTF and CTF, their properties are shown in Table 1. Moreover, phase change shell material is hard plastic, which properties are shown in Table 2.

| Material | Density \((kg/m^3)\) (Boussinesq) | \(C_p\) \((J/kg \cdot K)\) | Thermal conductivity \((W/m \cdot K)\) | Viscosity \((kg/m \cdot s)\) |
|----------|---------------------------------|-----------------|-------------------------------|---------------------|
| Water    | 998                             | 4198            | 0.6                           | 1.03 \times 10^{-3} |
| SXC-CZ   | 900                             | 3000            | 0.95                          | 5.1 \times 10^{-3}  |

| Pure solvent melting heat \((J/kg)\) | Solidus Temperature(K) | Melting Temperature (K) | Thermal expansion coefficient \((1/K)\) |
|-------------------------------------|------------------------|-------------------------|-----------------------------------|
| Water                               | /                      | /                       | /                                 |
| SXC-CZ                              | 202000                 | 331                     | 331                               | 2 \times 10^{-3} |

Table2. Physical properties of solid materials.
This case used ANSYS FLUENT as numerical calculation software. With the Boussinessq model [11], the natural convection is considered in this case. Also, the solidification & melting model with enthalpy-porosity [12-13] were used to calculate the variation of PCM.

3. Results and discussion

3.1. Comparison of experiment and simulation
To understand the results thoroughly, the PCM balls were marked for further analysis with serial numbers to reference their typical location, which is shown in Figure 2. In X direction, every second group was indexed from one to five as shown in Figure 2 (a). In the cross section in Y-Z plane, each group is formed by four balls, with a letter code assigned to each unit (a, b, c, d) as shown in Figure 2 (b).

In the experiment, the temperature of PCM balls are took into comparison with simulation, which represent the beginning, middle and the end of the component. There are three sets of phase change heat storage data. The simulation results are represented by full line, and the experimental results are shown in hollow points. It can be seen from Figure 3 that the experimental and simulation results were matched well. However, to study the phase change situation of each PCM balls, the simulation method was used in the study.

3.2. Charging process
The figure 4 shows the change of the liquid fraction for each PCM balls during the charging process which the inlet velocity is 1m/s. All curves on the figure shows a very similar tendency but with different melting rate. In general, along the flow direction the melting rate is decreased. It is because that the temperature difference and fluid velocity decreased along the flow direction.

Overall, the curves in figure4 (a) (b) is different like in (c) (d). The PCM balls in down layer (3, 4, 5 in group c, d) had slower melting rate than upper layer (3, 4, 5 in group a, b). It is because that the thermal stratification happened after the middle part of the unit. The warmer water tend to flow to the top and the cooler water stay at the bottom. This phenomenon will accelerate the melting rate of the upper layer PCM balls, but also extend the time for the unit to melt completely. In the middle part of the unit, the upper layer took 33% less time than down layer PCM balls to melt completely.
3.3. Discharging process

Different like in charging process, the discharging process is face to the users. So the outlet temperature need to be considered. In Figure 5 the outlet temperature variations are shown versus different inlet flow velocities. The inlet and outlet was reset and it was further assumed that the discharging process just happened after charging process. The initial temperature of the component is 353 K and the CTF is 300 K.

The curves plotted in Figure 5 can be divided into three stages. During the first stage, the CTF replaced remaining hot water in the tank, which temperature was dropped to a lower rate and sensible heat of the PCM balls started to release at this stage. In the second stage, the tank was filled with CTF and the outlet temperature dropped rapidly. Then the latent heat started to release and reached an equilibrium point which the temperature of the outlet stabilized at a relatively constant temperature. However, the heat was continuously transferred to the CTF, solidifying slowly the PCMs which would form a shell [14], which eventually would become thicker during the discharging process. Therefore, the internal heat exchange area became smaller and the process arrived at the final flat stage where the temperature dropped fast to meet the temperature of the component inlet.

The curves in Figure 6 shows when the CTF velocity is low the flat stage will show up at higher temperature. In Table 3 different standard inlet velocities have been listed in a comparative way and were set in relation to the total flow volume and time. Considered the user requirement, the 313K was set as lowest temperature for the outlet temperature. The scenarios with a low-velocity inlet had achieved a total flow with relatively minor difference, while as the flow velocity increased, the total hot flow started to decrease rapidly.

Table. 3 The comparison of total (lowest 313 K) heat flow in different inlet velocities.

| Inlet velocity (m/s) | Flow time (s) | Total flow (L) |
|----------------------|--------------|----------------|
| 0.1                  | 711          | 5.584          |
| 0.2                  | 324          | 5.089          |
| 0.3                  | 232          | 5.466          |
| 0.5                  | 81           | 3.181          |
| 1                    | 37           | 2.906          |
Like charging process, the liquid fraction change situation of group 3 (middle of the unit) under three inlet velocity (0.1m/s to 0.3m/s) are shown in Figure 6. The upper layer PCM balls (group a, b) had slower solidification rate than down layer PCM balls (group c, d). It shows that the thermal stratification happened in the discharging process. Warmer water gather near the upper layer which guaranteed outlet temperature. However, it made the upper layer small temperature difference between PCM balls and CTF which extend the discharge time.

Figure 6. The variation of liquid fraction in (a) $v_{inlet}=0.1 \text{ m/s}$, (b) $v_{inlet}=0.2 \text{ m/s}$, (c) $v_{inlet}=0.3 \text{ m/s}$

Figure 7 shown the phase change situation change in a single unit with inlet velocity of 0.3m/s. It picked up group 5, 3, 1 PCM balls which is the beginning, middle and end of the unit. From the Figure, the thermal stratification change along the flow direction. At the beginning of the unit, the CTF had the negative Z direction velocity near the inlet which it can reach the upper layer PCM balls as shown in Figure 8, so the solidification rate of these PCM balls almost same. At the middle part, after the CTF fully developed the thermal stratification appeared. At the end part, because of the outlet, the stability of CTF is broken. The solidification rate of each balls tend to be uniform.

Figure 7. The variation of liquid fraction in different locations ($v_{inlet}=0.3 \text{ m/s}$)

Figure 8. The distribution of temperature in the energy storage component at 300s

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4. Conclusions
This study uses numerical analysis to study one single unit of the detachable latent heat storage system, using hydrated salts as PCM filling in the sphere and water as HTF/CTF. The results show that during the charging process, the HTF heat the PCM balls rapidly and keep a relatively small thermal drop (about 4K in the steady situation) at the outlet. The melting rate of each PCM balls decrease along the flow direction. Moreover, the study showed that the thermal stratification phenomenon appeared after the middle section of the component and resulted in longer melting time for down layer PCM balls.
Different inlet velocities were compared during the discharging process. In comparison to high inlet velocities, lower inlet velocities resulted in prolonged periods of high outlet temperatures and a higher quality of total flow (higher than 313 K). However, thermal stratification took place throughout the low inlet velocity cases, resulting in a longer discharging time and partly heat waste at the end stage of the discharge. Combining these two factors, a flow velocity between 0.2 m/s to 0.3 m/s might result to be the better choice for one single unit.

Overall, this 3-D numerical model of the energy storage tank offered a high efficiency approach towards a thorough understanding of the phase change process and heat transfer in energy storage tank. To enhance the heat storage performance in this system, more works are expected to be carried out by optimizing the complex system, including choosing more appropriate geometric configurations and suitable sizes.

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Acknowledgement

This work is supported by National Natural Science Foundation of China (No.51406121 and No.51736007) and Eastern Scholar (No.QD2015017).