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# EXPERIMENTAL STUDIES OF PHASE CHANGE MATERIALS IN A BUBBLING FLUIDIZED BED

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## ABSTRACT

The aim of this work is to experimentally study the behaviour of three micro-encapsulated PCM in a bubbling fluidized bed for thermal energy storage. Different experiments, heating and cooling the granular PCM with fluidizing air, are carried out with different superficial gas velocities. When achieving their phase change temperature two of the three materials present agglomeration. For this reason, the material flowability and wear resistance are studied by measuring the angle of repose and attrition, respectively. Nevertheless, the angle of repose does not seem to be influenced by the temperature of the material and the particle size distributions after the attrition tests indicate that the bed particles are just slightly smaller than the original ones.

## INTRODUCTION

The use of phase change materials (PCM) for latent heat thermal energy storage (LHTES) has gained considerable importance in a wide variety of applications such as solar energy utilization, industrial waste heat recovery, and electrical power load shifting. A great number of studies have been concerned with packed beds as a common LHTES system (1,2). Like packed beds, fluidized beds can be utilized for thermal energy storage with some unique properties such as a uniform temperature in the bed and a high rate of heat transfer to a solid object immersed in the bed, which can be advantageous in several applications. Izquierdo-Barrientos et al. (3) studied the behaviour of a fluidized bed filled with micro-encapsulated PCM showing that this material can be used to increase the efficiency of stored thermal energy in the form of latent heat.

The utilization of encapsulated PCM of small particle diameter is advantageous in terms of heat transfer rates and material handling requirements (4). Rubitherm® offers a PCM with a particle size in the range of 0.2-0.6 mm and the possibility to choose between three different phase change temperatures of 42, 50 and 80 °C for different applications.

This paper presents a preliminary study of these three granulated materials, GR42, GR50 and GR80 in terms of fluidization, flowability and mechanical resistance to check their feasibility of being used in a fluidized bed for thermal storage.

## EXPERIMENTAL SET UP AND MATERIAL PROPERTIES

A schematic diagram of the experimental set-up is illustrated in Figure 1. The bed consists of a cylindrical tube of stainless steel of 2 mm wall thickness filled with particles. The air enters to the plenum of the column and then flows into the bed through a distribution plate of thickness 1.5 mm with 300 orifices of 2 mm of diameter, resulting in a 3% of open area. In this way, the air is uniformly distributed in the bed. A fine mesh screen is mounted at the bottom of the distributor plate to prevent solid particles from entering the plenum chamber. The instrumented test section is 500 mm height, has an internal diameter of 200 mm and is insulated with glass wool of 2 cm thickness. Also the piping is insulated with 1 cm thickness of a thermal insulator. The free board of the column is divided into two parts, one cylinder with an internal diameter of 200 mm and another with an internal diameter of 300 mm. Its purpose is to assure homogeneous velocity distribution of air at the exit from the test section and to reduce the elutriation and entrainment of particles from the bed.

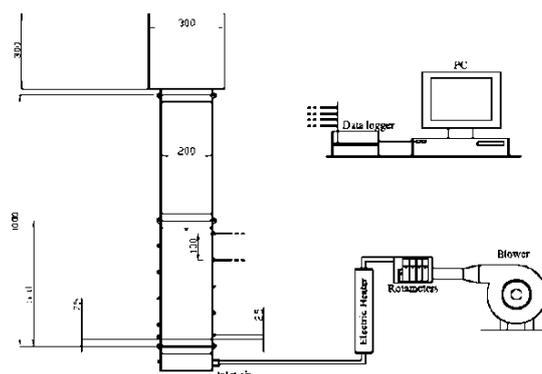


Figure 1: Schematic of the experimental set-up. Dimensions are in mm.

The air flow is supplied by a blower, with variable mass flow rate, and heated by electrical heaters prior to flowing to the column. Type K thermocouples are used to measure the temperature at specific locations inside the test section and in the plenum chamber. Air temperatures are also measured at the inlet and at the outlet of the test section. The thermocouples are connected to a data acquisition system for continuous monitoring and recording of the data. The materials used for the experiments are GR42, GR50 and GR80, granular phase changing composites from Rubitherm®. The numbers represent the material's corresponding phase change temperature, which is, at first, the only difference between the three materials. These materials are commercially available and correspond to Geldart's Group B classification (5). Particle density ( $\rho_p$ ), measured minimum fluidization velocity ( $U_{mf}$ ), phase change temperature ( $T_{pc}$ ) and mean particle size ( $d_p$ ) of the PCM's are shown in Table 1. The differences between the  $U_{mf}$  are due to the different particle size distribution (PSD) and density.

Table 1: Material properties for GR42, GR50 and GR80.

|             | $\rho_p$ (kg/m <sup>3</sup> ) | $U_{mf}$ (m/s) | $T_{pc}$ (aprox.) (°C) | $d_p$ (mm) |
|-------------|-------------------------------|----------------|------------------------|------------|
| <b>GR42</b> | 1531.7                        | 0.094          | 42                     | 0.566      |
| <b>GR50</b> | 1550.5                        | 0.133          | 50                     | 0.642      |
| <b>GR80</b> | 1594.7                        | 0.076          | 80                     | 0.569      |

## EXPERIMENTS

Heating and cooling experiments have been carried out for the three materials (GR42, GR50 and GR80) at different flow rates (375, 500 and 625 L/min). The bed temperature is uniform and equal to the ambient temperature at the beginning of each experiment. The experiment starts by blowing air at the desired rate into the column and switching on the electric heaters with the required power. The air is heated from room temperature up to a temperature higher than the  $T_{pc}$  of each material (65°C for the GR42 and GR50, and 95°C for the GR80). A static bed height of 200mm has been defined for all the tests which correspond to approximately 5 kg of material. Figure 2 shows the temperatures measured at different heights during the heating and cooling process for the GR50 at different gas flow rates. Under fluidizing conditions the temperature along the bed is uniform because the system is well fluidized and behaves as a well-mixed tank (typical Geldart's B particles behavior). Three of the four thermocouples inside the bed (i.e., located at 7.5, 12.5 and 17.5 cm above the distributor) measure the same temperature during the charging process. The first thermocouple, located at only 2.5 cm above the distributor presents a higher temperature during the heating period. These results could be attributed to the influence of the air jets from the distributor orifices (6). The length of these jets could be enough to modify the temperature measured by the first thermocouple.

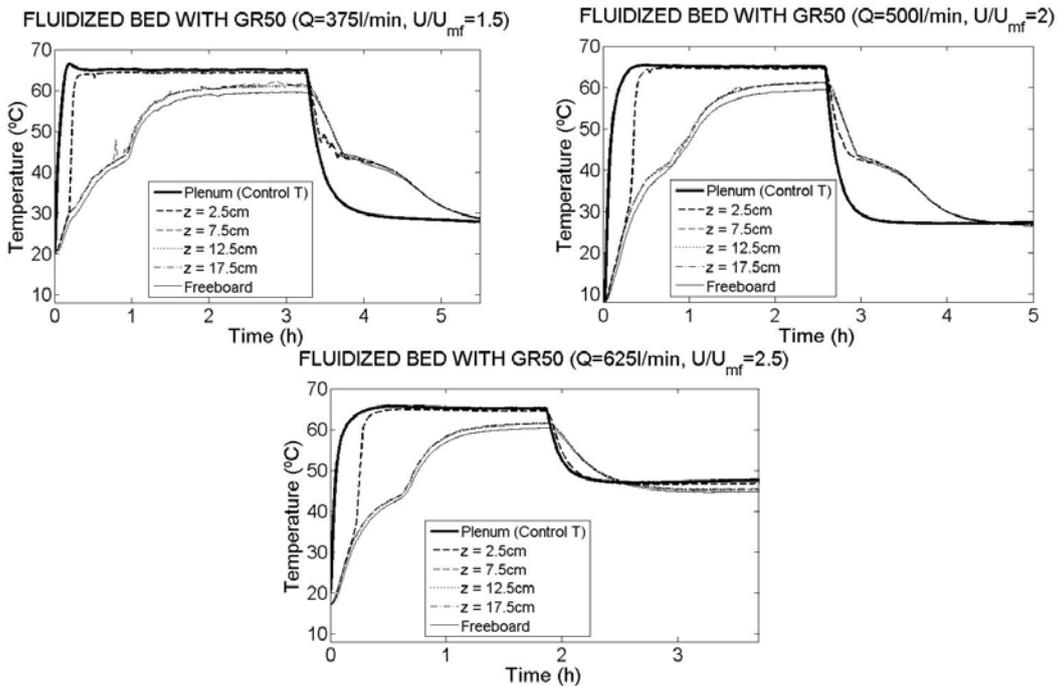


Figure 2: Temperature profiles for the GR50 ( $T_{pc} = 50^\circ C$ ) at different flow rates.

The same experiments performed for the GR50 have been repeated for the materials GR42 and GR80. The results obtained are shown in Fig. 3. For these materials, despite using a flow rate higher than two times the flow rate at minimum fluidization conditions, the granular PCM is not properly fluidized when the bed temperature is over  $T_{pc}$ , specially during the heating period, the material seems to be agglomerated. The thermocouples placed inside the bed record different temperatures at different heights instead of showing a uniform temperature. Their behaviour could be compared to the one of powders of Group C (Geldart's Classification), which are incapable of fluidization in strict sense. Bubbles, as such, do not appear, instead the gas passes up interconnected vertical and inclined cracks/channels extending from the distributor to the bed surface (7). Nevertheless, it can be appreciated that the higher the flow (i.e.,  $U/U_{mf}$ ) the better mixing is obtained (although without achieving complete fluidization). Thus, most of the agglomeration could be overcome increasing the flow rate.

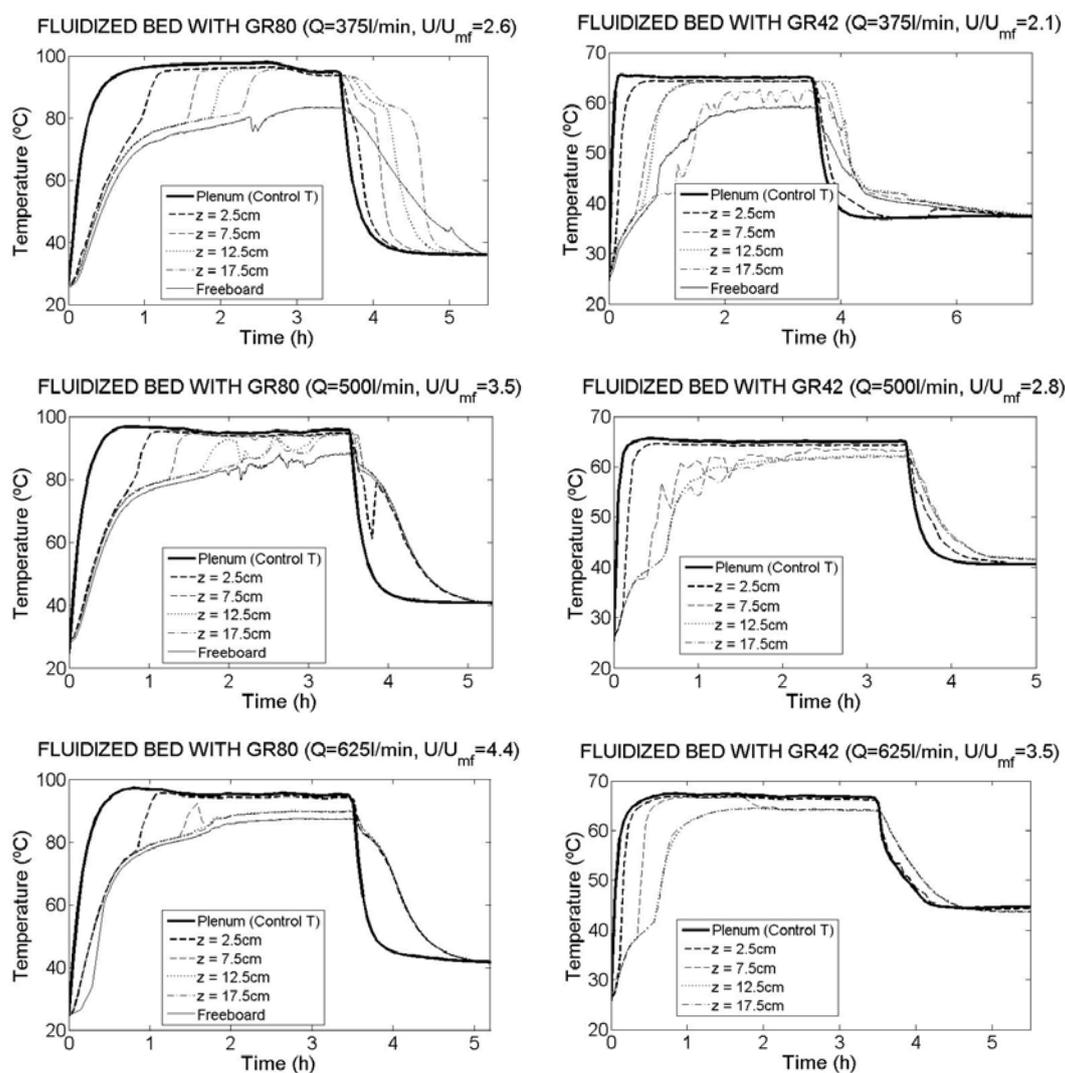


Figure 3: Temperature profiles for GR42 ( $T_{pc} = 42^\circ C$ ) and GR80 ( $T_{pc} = 80^\circ C$ ) at different flow rates.

In order to interpret the different fluidization behaviour of the materials, the angle of repose and attrition tests have been performed.

### Angle of repose

The angle of repose (AOR) measurement has a major influence on the flowability and dynamic behaviour of a powder material, which influences on the fluidizing performance of the material (8). The equipment used to measure the AOR is the same proposed by Geldart et al. (9) where 100 g sample is poured slowly on to an upper converging chute. The three materials GR42, GR50 and GR80 have been tested. Figure 4 shows the AOR, obtained as the average value of seven runs, for the three materials at room temperature. It takes around 25 seconds to pour the entire sample. No noticeable differences appear between the three materials. Due to the larger error bars, it is not possible to delineate a clear trend with AOR. This is because the AOR measurement inherently has human errors associated. Nevertheless, the Chauvenet's criterion (with a 90% of confidence) has been applied to assess whether one piece of experimental data from the set of observations is likely to be spurious.

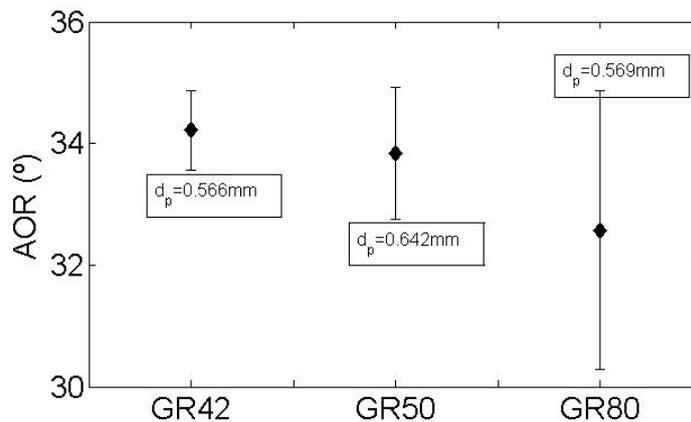


Figure 4: AOR at room temperature for GR42, GR50 and GR80.

As GR42 and GR80 became difficult to fluidize when heated close to its  $T_{pc}$ , further analysis of the AOR against temperature is presented in Figure 5. No significant conclusions can be drawn as no remarkable changes appear in the AOR when heated beyond  $T_{pc}$ . Although, when the materials are heated (specially beyond  $T_{pc}$ ), their flowability retards and present signs of cohesiveness. The pouring time is decreased to 12 seconds because the materials do not flow continuously, but in clumps.

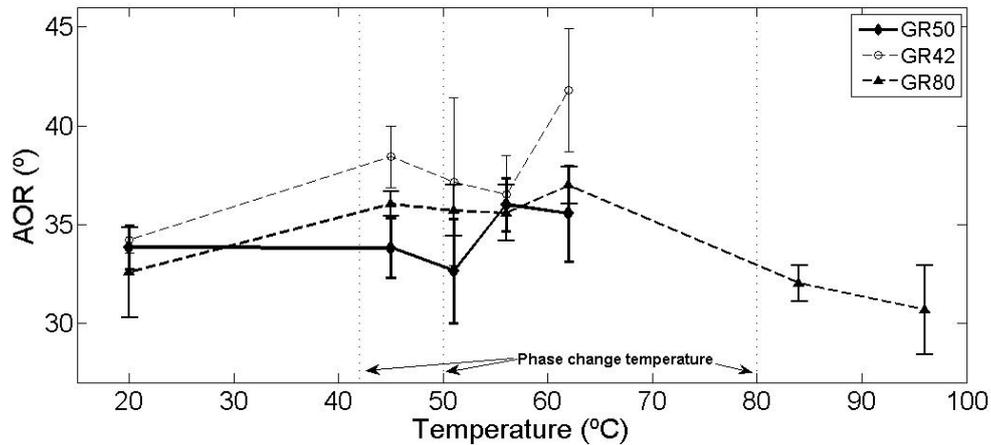
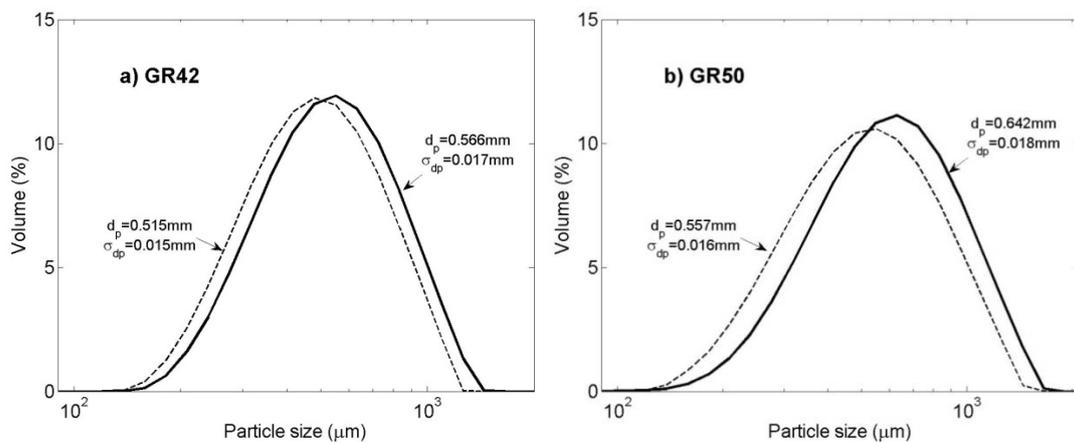


Figure 5: Evolution of the AOR with temperature for the GR42, GR50 and GR80.

### Attrition test

In order to further analyze the fluidizing characteristics of the materials and explain the possible causes of agglomeration found in the materials GR42 and GR80, attrition tests have been performed. The attrition testing apparatus follows the ASTM D5757-00 standard (10), with the four main stainless steel components: the three orifice (0.397 mm) distributor plate, the attrition column (710 mm in height, 35 mm *ID*), the conically divergent/convergent freeboard settling chamber (630 mm in height), and the fines collector containing a ceramic filter (0.1 mm pore size). The unit is loaded with 50 g of the particulate sample, and operated at 10 L/min of air at room temperature and pressure for a run period of 5 hours. More details are reported in (10).

The PSDs before and after the attrition tests for the three materials and their corresponding mean particle diameter (with the standard deviation) are presented in Figure 6. The distributions are Gaussian and have similar width. Although the mean particle diameter is slightly higher for the GR50, the shape of the distribution has been shown to have a higher influence than the mean particle size on the defluidization of a fluidized bed (11).



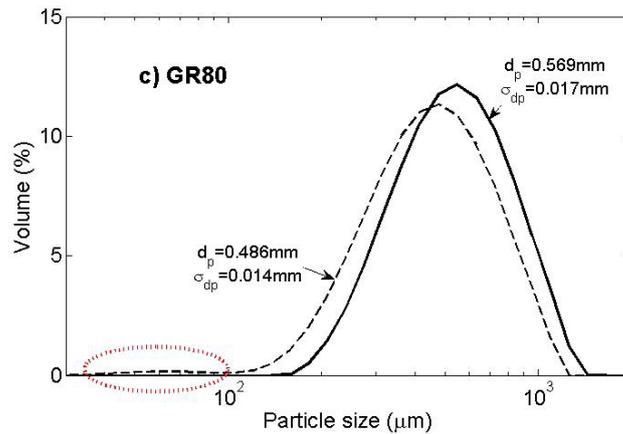


Figure 6: PSD for a) GR42, b) GR50 and c) GR80 before (continuous line) and after (dashed line) the attrition tests.

It has been proved that attrition increases the number of particles and decreases their size (the mean diameters are smaller than before the attrition tests). As a consequence, the PSDs are modified, being the degree of variation of the PSD after the attrition test very similar for the three materials. Fines, of a size smaller than  $50\mu\text{m}$ , are only detected for the GR80 with a fraction of 0.33 wt.% of the total mass, which is not very significant. Nevertheless, because of the abrasion of the material, some leakages of the PCM might happen and influence on the agglomeration of the material.

## CONCLUSIONS

The PCM GR42, GR50 and GR80 have been used in heating experiments in a fluidized bed obtaining well fluidizing behaviour for the GR50 but agglomeration and segregation for the GR42 and GR80. The bed stops being well fluidized when the  $T_{bed}$  is close to the  $T_{pc}$  for the GR42 and GR80. In order to analyze wear resistance and flowability of the materials, attrition and angle of repose tests have been performed. The angle of repose is not significantly influenced by the temperature of the material. The PSDs after the attrition tests indicate that the mean bed particles are slightly smaller than the original ones. Just for the GR80 the amount of fines is appreciable albeit with a small impact (0.33% of the total volume). Due to the abrasion of the material the PCM could have some leakages contributing to stickiness, thus agglomeration.

## ACKNOWLEDGMENT

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## NOTATION

|                |   |
|----------------|---|
| $d$            | Bed diameter [m]  |
| $d_p$          | Mean particle size [m]  |
| $ID$           | Internal diameter [m]   |
| $T_{bed}$      | Temperature of the bed [°C]                                       |
| $T_{pc}$       | Phase change temperature of the granular PCM [°C]                 |
| $U$            | Superficial gas velocity [m/s]                                    |
| $U_{mf}$       | Superficial gas velocity at minimum fluidization conditions [m/s] |
| $\sigma_{d_p}$ | Standard deviation of the particle size distribution [m]          |
| $\rho_p$       | Density of the granular PCM [kg/m <sup>3</sup> ]                  |

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