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# CONVECTIVE HEAT TRANSFER COEFFICIENT IN A BUBBLING FLUIDIZED BED WITH PCM

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## ABSTRACT

This work presents an experimental study to determine the capacity of a Phase Change Material (PCM) in granular form to be used in a bubbling fluidized bed for thermal energy storage. The experimental measurements are focused on the determination of the heat transfer coefficient between a heated surface and the granular PCM in fluidized state. The results obtained indicates that the heat transfer coefficient notably increases (up to values three times higher) when the granular PCM is in solid form because it changes its phase when touches the heated surface.

## INTRODUCTION

In the recent years the development of renewable energies, as solar thermal energy, has been accompanied with the evolution of new and more efficient energy storage systems in order to equilibrate the energy supply with its demand. In this way, the integration of Phase Change Materials (PCM hereafter) in these systems improves the energy storage capacity for the same volume and permits to maintain the system in a narrow interval of temperatures (1).

PCM in granular form is commercially available for different particle sizes. For example Rady (2) used a granular PCM (Rubitherm GR42) with a particle size in the range 1-3 mm in a fixed bed for thermal energy storage. In a recent work, Izquierdo-Barrientos et al. (3) used the same material, with a smaller particle size (0.2 -0.6 mm), in a bubbling fluidized bed with success. The main advantages of the fluidized system over the fixed one is the uniform temperature in the bed (3) and the higher heat transfer coefficients between an immersed surface and the mean temperature of the bed, defined as

$$h_w = \frac{\dot{q}}{T_s - T_\infty} \quad (1)$$

where  $\dot{q}$  is the heat transfer rate and  $T_s$  and  $T_\infty$  are the temperature of the immersed surface and the temperature of the bed respectively.

Along the years there has been an extensive research on evaluating the convective heat transfer coefficient. Mickley and Trilling (4) and Vreedenverg (5) carried out two of the first experimental researches. They measured the heat transfer coefficient using a heated cylinder immersed in the bed and obtained some simple correlations that fitted properly their data. Both of them remarked the difficulties in extrapolating these correlations to different experimental conditions due to the lack of knowledge about the heat transfer mechanisms in fluidized beds. Mickley and Fairbanks (6) proposed the “renewable model”, in which the heat is transferred from the surface to a group of solids in the bed that are in contact with the surface a time  $t$ . In this way, the instantaneous heat transfer coefficient can be obtained solving the transient heat transfer diffusion in the direction normal to the surface which results in

$$h_{w,t} = \sqrt{\frac{k \rho c}{\pi t}} \quad (2)$$

Other researchers have extended and modified the simple model of Mickley and Fairbanks, including a thermal resistance layer between the surface and the packet of particles. This idea overcomes the shortcoming that the thermal resistant  $1/h_{w,t}$  tends to zero when the contact time approaches to zero. Masoumifard et al. (7) introduced a gas film of thickness  $\delta \sim 0.1 d_p$  between the wall and the cluster of particles, which adds the new resistance in the thermal circuit defined as

$$R_g = \frac{\delta}{k_g} \quad (3)$$

Kunii and Levenspiel (8) proposed a region of thickness  $d_p/2$  adjacent to the surface with a voidage  $\varepsilon_w$ , higher than the one of the solids touching the surface. The thermal resistance of this region can be calculated as follows

$$R_{d_p/2} = \left( \frac{2 k_{ew}^0}{d_p} + \alpha_w c_{pg} \rho_g U \right)^{-1} \quad (4)$$

where  $k_{ew}^0$  is the thermal conductivity of the region adjacent to the wall and the second term on the right hand side of the previous equation takes into account the lateral mixing of the gas between the void spaces.

Most of the experimental research and the proposed models in the literature concerning heat transfer between a surface and the solids particles in a fluidized bed have been focused on the case when the heat transferred to the particles increases the internal energy of the solids in sensible form, i.e. increasing its temperature. Only Brown et al. (9) measured heat transfer coefficients in a microencapsulated phase-change material fluidized bed (octadecane encapsulated in a gelatin shell with size range of 300-600  $\mu\text{m}$ ), observing heat transfer enhancements about 30% larger than the single-phase values.

The objective of this work is to experimentally study the problem of the heat transfer from a surface to particles in a fluidized bed filled with a granular PCM that changes its phase (solid-liquid transition) at a certain temperature  $T_{pc}$ . In the following the experimental set-up and the properties of the granular PCM are described. Then, the main experimental results are presented and discussed, and finally the last section summarizes the main conclusions of the work.

## EXPRIMENTAL SET-UP AND GRANULAR PCM

Figure 1 shows a scheme of the experimental facility where the experiments were carried out. The cylindrical bed consists of a main cylinder of 0.2 m of internal diameter and a height of 0.5 m. The external surface of this part of the bed is thermally insulated in order to reduce the heat losses to the surroundings. Around the perimeter of the bed there are multiple ports, which permit to introduce thermocouples at different heights from the distributor. In the same ports the heat transfer probe can be introduced. It consists of a cylindrical resistance of 400 W with three thermocouples distributed around the surface of the resistance (see Figure 2). This probe is similar to the one used by Masoumifard et al. (7). The mean temperature measured by the three thermocouples is assumed as the mean temperature of the resistance surface  $T_s$ . The bed temperature  $T_\infty$  is the mean temperature of the different thermocouples introduced in the bed. For the experiments shown in this paper the heat transfer probe was located at 12.5 cm over the distributor and the bed temperature was measured in the center of the bed at 2.5, 7.5 and 17.5 cm over the distributor. The

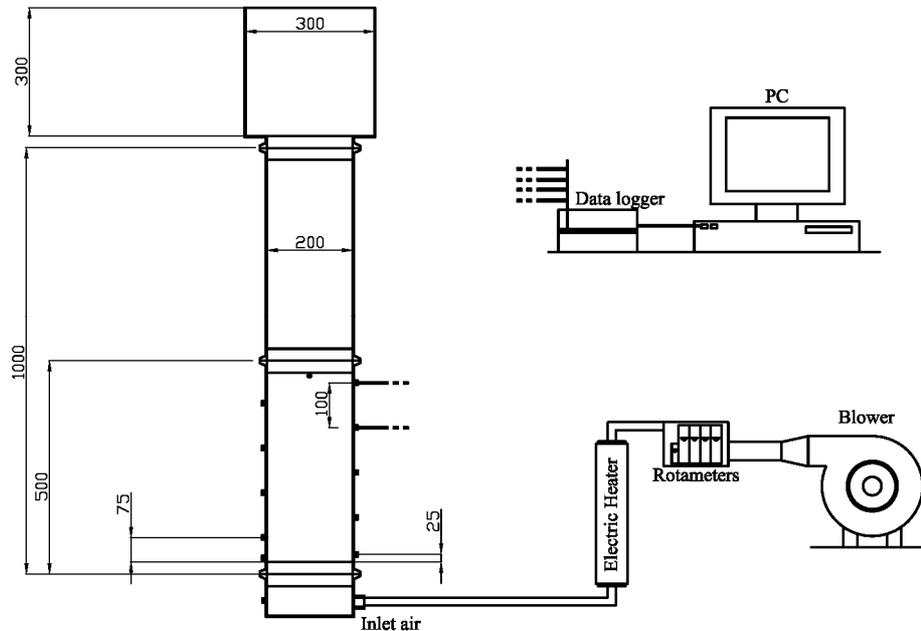


Figure 1: Schematic of the experimental set-up. Dimensions are in mm.

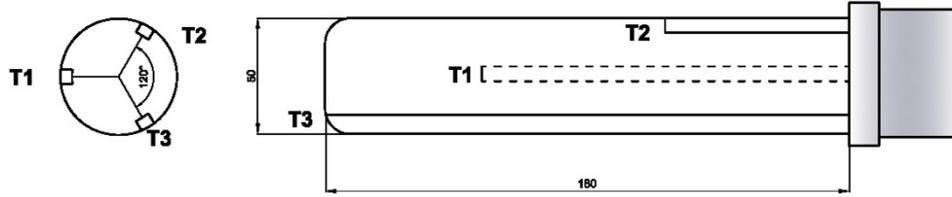


Figure 2: Schematic of the probe for measuring the heat transfer coefficient. Dimensions are in mm.

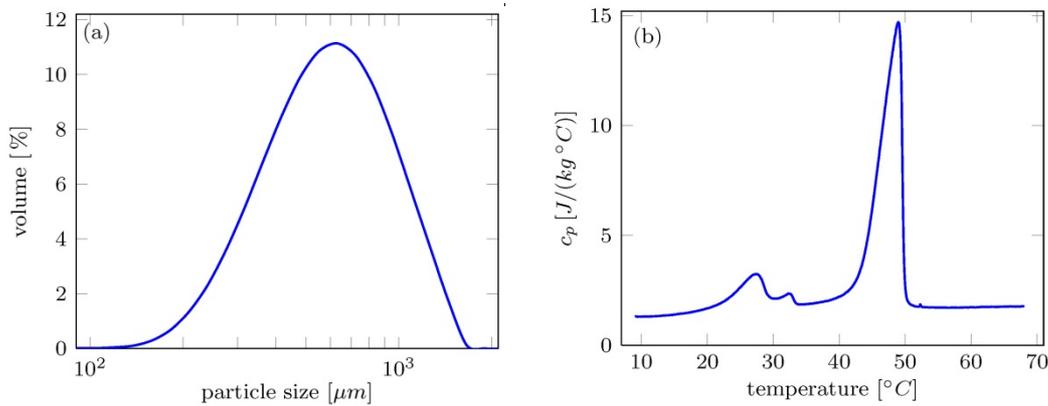


Figure 3: Particle size distribution (a) and specific heat capacity (b) of the granular PCM

$\rho_p$ [ $kg/m^3$ ]	$k_p$ [ $W/(m K)$ ]	$d_p$ [ $mm$ ]	$\sigma_{d_p}$ [ $mm$ ]
1550.5	0.2	0.642	0.0184

Table 1: Properties of the granular PCM

bed was filled with 5 kg of granular PCM, which results in a fixed bed height of approximately  $H = d = 0.2$  m. The air, previously heated by an electrical resistance to the desired temperature, was introduced into the bed through a perforate plate distributor (3 % of open area), with a pressure drop high enough to assure a correct flow distribution in the bed.

The granular PCM used in the experiments is the commercial material GR50 (10). This granular material consists of particles of silica filled with paraffin. The transition temperature of the PCM, according to the manufacturer specifications is around  $T_{pc} = 50^\circ C$ . Figure 3(a) shows the particle size distribution of the granular PCM measured with a mastersizer 2000. The mean particle size is  $d_p = 642$  mm. In Figure 3(b) the heat capacity of the PCM as function of temperature is represented. The curve is the typical obtained for a PCM, where the heat capacity increases around the phase change temperature. Table 1 summarizes the main properties of the particles.

## EXPERIMENTAL RESULTS

### Experiments with the bed at steady temperature

During the experiments, the air supplied to the bed was preheated by an electrical resistance to the desired temperature. Once the bed temperature reached a steady value, the electrical resistance of the heat transfer probe was heated with a power output that maintained a surface temperature around 20°C over the temperature in the bed. Under these conditions, the bed temperature  $T_\infty$  and the temperature of the resistance surface  $T_s$  were measured during one minute with a frequency of 1 Hz.

This measurement was repeated two more times rotating the heat transfer probe 120° in order to obtain a total of nine temperature measurements of the resistance surface. In this way we are taking into account possible variations of the local heat transfer coefficient with the tangential angle (11). The temperature  $T_s$  was obtained as the average value of these nine measurements. This process was repeated for different superficial gas velocities.

Figure (4) shows the evolution of the heat transfer coefficient  $h_w$  with the excess of air over minimum fluidization conditions for three different temperatures: with a bed temperature under the phase change temperature of the material  $T_\infty \approx 35^\circ\text{C} < T_{pc} = 50^\circ\text{C}$ , a bed temperature around the transition temperature ( $T_\infty \approx 50^\circ\text{C} = T_{pc}$ ) and finally with a temperature at which the PCM is in liquid state, i.e.  $T_\infty \approx 65^\circ\text{C} > T_{pc} = 50^\circ\text{C}$ . The heat transfer coefficients are higher for the tests in which the bed temperature is maintained below the melting point of the material, because the particles near the surface of the heated probe are able to change phase. This result was also observed by Brown et al (9). However, for bed temperatures higher than the phase change temperature, the material is always melted. In this work the heat transfer enhancement observed was much higher than in the study of Brown et al. (9), probably due to the lower thermal resistance

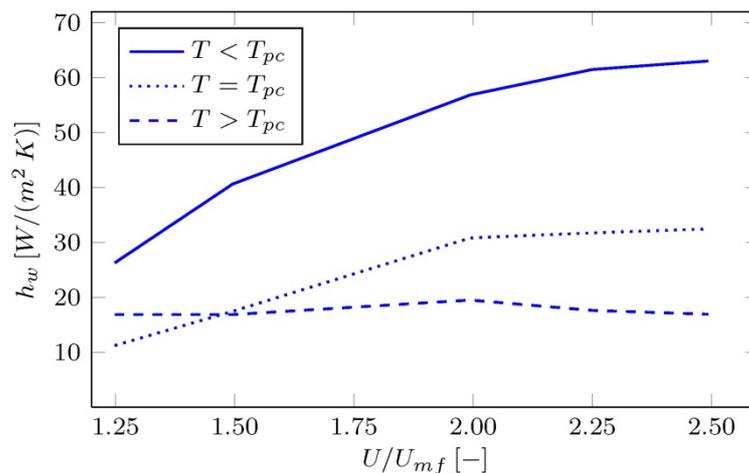


Figure 4: Convective heat transfer coefficient evolution with the superficial gas velocities for different bed temperatures.

of the shell in the present work. For the tests with bed temperature under or around the phase change temperature, the heat transfer coefficients increase with the superficial gas velocity.

### Measurements during the heating and the cooling process

The variations of the heat transfer coefficient during the whole process of phase change are not properly observed in the previous results, because the data are obtained with a constant temperature of the bed. In order to properly interpret the differences observed in  $h_w$  with the bed temperature, the heat transfer coefficient was measured during the heating of the bed from ambient temperature to a maximum temperature over  $T_{pc}$  and during the corresponding cooling period.

Although the heat transfer coefficient was measured under transient conditions, the characteristic time  $t$  of replacement of the particles that are touching the surface (see Equation (2)) is of order  $t \sim (1 - \delta_b)/f \sim 1 \text{ s}$  (8), being  $f$  the bubble frequency at the heat transfer surface, while the data of the heat transfer coefficient are averaged over one minute. During this time, the bed temperature does not vary appreciably, so the measurements were obtained under quasi-steady state conditions.

In Figure (5) it is represented the evolution of two temperatures: the temperature of the bed and the temperature of the supplied air, during a charging-discharging process in the fluidized bed, together with the variation of the heat transfer coefficient. During the charging process the values observed of the heat transfer coefficient are lower than the ones measured during the discharging process. When the granular PCM is in liquid state during the heating period, a constant value of  $h_w \approx 30 \text{ W}/(\text{m}^2\text{K})$  is observed. In contrast, during the cooling process, once the material has reduced its temperature under  $T_{pc}$  and it is in solid form, the heat transfer coefficient is more than two times higher ( $h_w \approx 75 \text{ W}/(\text{m}^2\text{K})$ ).

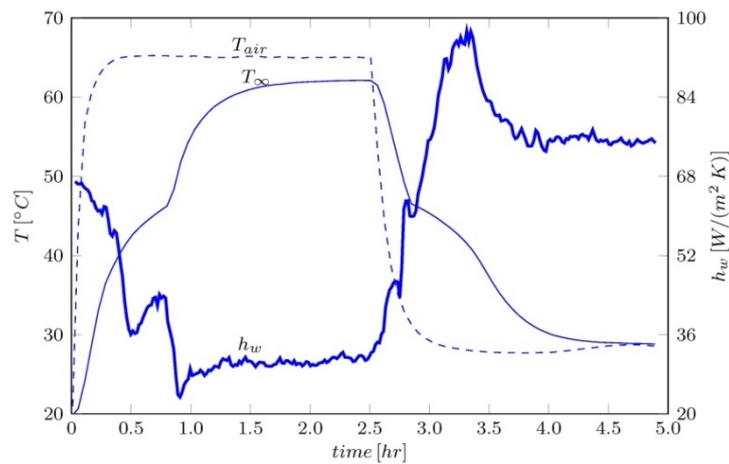


Figure 5: Evolution of the air supply temperature, bed temperature and heat transfer coefficient during a charging-discharging process with  $U/U_{mf} = 2$ .

This result corroborates the higher capacity of the granular PCM for interchanging heat with a surface due to its capacity of absorbing high amount of energy at constant temperature during the phase change process. The continuous renewal of the particle touching the surface assures the steady and high value of the heat transfer coefficient during the discharging process.

## CONCLUSIONS

The experimental results obtained in this work show that the steady heat transfer coefficient between a heated surface and a bubbling bed filled with a granular PCM is higher when the PCM is in solid form than when it is in liquid state. The difference increases with the superficial gas velocity. For example, for  $U/U_{mf} = 2.5$ , the heat transfer coefficient when the bed temperature is over the transition one is  $h_w = 18 \text{ W}/(\text{m}^2 \text{ K})$ . When this temperature is reduced under  $T_{pc}$  this value increases up to  $h_w = 62 \text{ W}/(\text{m}^2 \text{ K})$ .

Two main reasons explain this behaviour: the capacity of the granular PCM of changing its phase when is in solid phase and it is being heated, and the continuous renovation of the materials touching the heated surface.

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## NOTATION

$c$	Specific heat of the emulsion phase [ $\text{J}/(\text{kg } ^\circ\text{C})$ ]
$c_p$	Specific heat of the granular PCM [ $\text{J}/(\text{kg } ^\circ\text{C})$ ]
$c_{pg}$	Specific heat of the gas [ $\text{J}/(\text{kg } ^\circ\text{C})$ ]
$d$	Bed diameter [ $\text{m}$ ]
$d_p$	Mean particle size [ $\text{m}$ ]
$f$	Bubble frequency [ $\text{Hz}$ ]
$H$	Fixed bed height [ $\text{m}$ ]
$h_w$	Convective heat transfer coefficient defined by Equation (1) [ $\text{W}/(\text{m}^2 \text{ K})$ ]
$k_{ew}^0$	Thermal conductivity of the region adjacent to the wall [ $\text{W}/(\text{m } ^\circ\text{C})$ ]
$k$	Thermal conductivity of the emulsion phase [ $\text{W}/(\text{m } ^\circ\text{C})$ ]
$k_g$	Thermal conductivity of the gas [ $\text{W}/(\text{m } ^\circ\text{C})$ ]
$k_p$	Thermal conductivity of the granular PCM [ $\text{W}/(\text{m } ^\circ\text{C})$ ]
$\dot{q}$	Heat transfer rate [ $\text{W}/\text{m}^2$ ]
$R_{d_p/2}$	Resistance of the high voidage region adjacent to the wall defined by

	Equation (3) [ $^{\circ}\text{C m}^2/W$ ]
$R_g$	Resistance of the gas film between the surface and the particles, defines by Equation (2) [ $^{\circ}\text{C m}^2/W$ ]
$T_{air}$	Temperature of the air supply in the bed [ $^{\circ}\text{C}$ ]
$T_{pc}$	Phase change temperature of the granular PCM [ $^{\circ}\text{C}$ ]
$T_s$	Temperature of the surface [ $^{\circ}\text{C}$ ]
$T_{\infty}$	Temperature of the bed [ $^{\circ}\text{C}$ ]
$U$	Superficial gas velocity [ $m/s$ ]
$U_{mf}$	Superficial gas velocity at minimum fluidization conditions [ $m/s$ ]
$\alpha_w$	Constant defined in Equation (4)
$\delta$	Thickness of the gas film between the surface and the particles [ $m$ ]
$\delta_b$	Fraction of bubbles in the bed [-]
$\sigma_{d_p}$	Standard deviation of the particle size distribution [ $m$ ]
$\rho$	Density of the emulsion phase [ $kg/m^3$ ]
$\rho_g$	Density of the gas [ $kg/m^3$ ]
$\rho_p$	Particle density of the granular PCM [ $kg/m^3$ ]

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