IMPACT OF USING THERMOCOUPLES TO MEASURE CHAR PARTICLE TEMPERATURE IN A FLUIDIZED BED COMBUSTOR

J. Salinero[1], A. Gómez-Barea[1*], D. Fuentes-Cano[1], J.J. Leahy[2], B. Leckner[3]

[1]*Chemical and Environmental Engineering Department, University of Seville, Seville, 41092, Spain*

[2]*Carbolea Research Group, Department of Chemical and Environmental Sciences, University of Limerick, Ireland*

[3]*Department of Energy and Environment. Chalmers University of Technology, Göteborg, S412 96, Sweden*

**+34 954 487 223, agomezbarea@us.es*

Abstract – Circulating fluidized bed can be applied in several methods of CO_2 capture. In oxy-combustion the fuel particle temperature can peak in the regions near the entrance with high oxygen concentration, being a critical factor. To study this aspect, techniques to measure fuel particle temperature have been developed mainly based of thermocouples, where it is usually assumed that the thermocouple does not affect the movement of the fuel particle, although there is no rigorous evidence. In the present paper this aspect is studied by comparing the temperature of char particles with and without an embedded thermocouple (with 0.25 and 0.5 mm sheath diameters). Char particles (10 mm) are burnt in a laboratory fluidized bed made in quartz, allowing visual observation of the particles. The surface temperature is measured by pyrometry coupled to a digital camera at the same time as the particle's temperature is recorded by a thermocouple. The temperature of a char particle fluidized with an embedded thermocouple is shown to be higher than that of a freely fluidized char particle, and its burnout time is shorter. This is because the fluidization with a thermocouple makes the char particle sink in the bed, increasing its residence time in the bubble phase compared to the freely fluidized particle. Besides, this work shows how the pyrometry technique is able to track the size and movement of a particle and its surface temperature gradients during conversion, improving the data collected with this method as compared to other measurement techniques.

INTRODUCTION

It is necessary to reduce the CO_2 emissions to the atmosphere, and among other measures, to develop the combustion technologies in this respect (Nejat et al., 2015). Oxy-combustion in a circulating fluidized bed reactor stands out as favorable among all proposed technologies for CO_2 capture (Günther et al., 2013; Saastamoinen et al., 2006). One of the main challenges of this technology is to control the combustion temperature because of the high concentration of O_2 in the gas added to the boiler furnace could produce unacceptable temperature levels both globally in the furnace and locally in a fuel particle (Leckner and Gómez-Barea, 2014).

Due to the importance of the char temperature for the development and control of combustion in a fluidized bed (FB), there are many techniques dealing with temperature measurement (Stubington, 1985). One of the most widespread techniques is to embed a thermocouple inside the particle. By throwing it into the FB, the combustion temperature is recorded until the particle is detached. The use of this technique is based on the main assumption that the combustion temperature of the char particle fluidized with an embedded thermocouple (with sheath diameters between 0.2-1 mm) is similar to the freely fluidized one (Basu, 1977; Parmar et al., 2002; Hayhurst et al., 2002; Scala and Chirone, 2009; Bu et al., 2014, 2015, 2016). However, several reviews dealing with the use of thermocouple in FB have given evidence about the effects on the char conversion and combustion temperature of using thermocouples: (i) the restriction of the particles movement (Collier et al., 2004; Linjewile et al., 1995), (ii) the minimum size of a particle whose temperature can be measured (3 mm) (Komatina et al., 2006), and (iii) a decrease on the burnout time because of the use of an embedded thermocouple (Hayhurst et al., 1998).

In the present work, a comprehensive analysis is presented of the effects of thermocouples on the combustion of char from sub-bituminous coal in FB. These effects are shown by comparison of char surface temperatures using embedded thermocouple (restricted fluidized particle) and freely moving particle. The analysis is extended by a recently developed pyrometry technique with a digital camera (Salinero et al., 2016) to record the surface temperatures of the char particles.

EXPERIMENTAL AND METHODOLOGY

MEASUREMENT OF THE SUFACE TEMPERATURE AND SIZE OF A CHAR PARTICLE

The surface temperature measurement by pyrometry using a digital camera is based on the capture of the thermal radiation from the char by the camera lens and its interpretation by the digital sensor (Lu et al., 2009). Modeling the thermal radiation from the surface of the char particle, by information from the camera and by previous calibration of the digital device, the surface temperature can be measured (Salinero et al., 2016). The measurement of the temperature needs the emissivity of the char and the bed as inputs. The conversion of char from sub-bituminous coal does not form an ash layer, following a shrinking particle behavior, so its emissivity is that of the char: 0.9. The bed's emissivity is assumed to be unity (black body).

The size of a char particle can be determined from the images obtained from the tests. To do so, the number of pixels (px) occupied by the initial diameter of the char particle in the images is related to its initial size (mm). This relation (mm/px) determines the changing size of the char during combustion.

EXPERIMENTAL SET-UP

Irregular particles from sub-bituminous coal are heated in an inert atmosphere from room temperature to 800 ºC with a low heating rate (8 ºC/min). The char particles generated are then shaped to a spherical shape with a diameter of 10 mm and their mass is fit to 0.56 g. The proximate analysis of the sub-bituminous coal yields: volatiles 35.6; fixed carbon 59.2; ash 5.1; % on coal as delivered, analyzed according to ASTM. A hole is made by drilling the particles from their surface to their center (0.2 mm diameter and 5 mm deep). A thin and flexible type K thermocouple is embedded into the particle, and fixed by a high-temperature resistant sealant. Two sheath diameter of the thermocouples are used: 0.25 and 0.5 mm, all being 100 cm long.

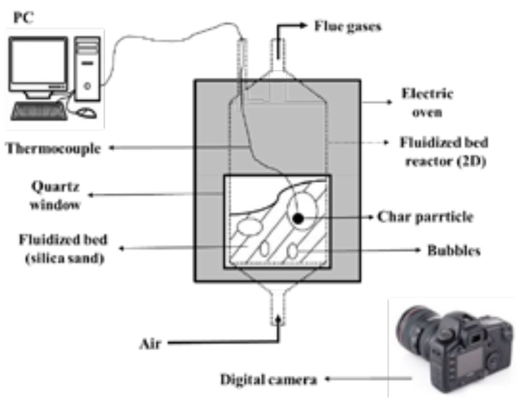

Fig. 1. Experimental set-up with the rectangular quartz, two-dimensional fluidized bed reactor: FBC 2D.

Fig. 1 shows the sketch of the experimental set-up (FBC 2D) used to analyze the effect of measuring the combustion temperature by thermocouple(s) during the conversion of a char particle. It comprises an electric oven with dimensions 50 x 70 x 30 cm. The oven has a quartz window (20 x 20 cm), which allows to see the bed and to make optical measurements. The FB reactor is made in quartz in the zone of the bed and the freeboard. A black surface (a metal box located in between the internal walls of the oven and the FB reactor) makes the thermal radiation from the electric resistances (11 kW) uniform. The reactor is placed in the center of the oven, whose geometry is approximately two-dimensional (18 x 1.8 x 50 cm) in order to get as many images of the char particle as possible. The bed temperature is controlled by a thin flexible type K thermocouple (0.15 cm sheath diameter and 100 cm long) immersed into the bed. Pre-heated air is used as fluidization agent (U_f/U_{mf} = 2 and 3). All combustion tests are carried out in a dark-room in order to only allow radiation from the char and from the background to reach the sensor. The device used to capture and interpret the thermal radiation from the char surface is a digital camera, JVC Everio HD, placed 100 cm from the FB with a field of view of 24º. Table 1 collects the main characteristics of the experimental set-up and the related tests and their goals.

Table 1: Tests and description of measurements carried out in the FBC 2D experimental set-up.

Devices	Test	Measurement
Electric oven - 11 kW - 50 x 70 x 30 cm - Window: 19.5 x 19.5 cm Fluidized bed reactor - 18 x 50 x 1.8 cm - Made of quartz Digital camera JVC Everio HD, 2 Megapixels	- Char particles from sub-bituminous coal - $d_{p,o} \sim 10$ mm - Fluidization with a thermocouple and without it (0.25; 0.5 mm sheath diameter) - U_f/U_{mf}, = 2; 3 - T_{bed} = 800 ºC	- Combustion time percentage where the char particle is in emulsion phase, bubble phase, and splash zone - Combustion surface temperature of char particles by pyrometry

PROCEDURE

All the tests are carried out with one single particle. Every operation condition is repeated three times to assess the repeatability. The results presented in one given condition are the average of the three tests conducted. The tests are carried out with and without an embedded thermocouple (0.25 and 0.5 mm sheath diameters) long enough to allow the char particle to sink and move in the bed. All tests are recorded by the digital camera. The image analyses from the videos (25 frames per second, evaluated by Adobe Premier Pro CS6 program) allow to (i) determine the size and location of the char particles in the FB, and to (ii) compare their surface temperature.

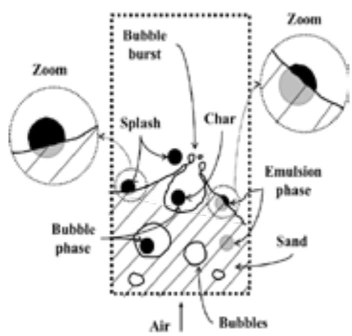

Fig. 2. Definition of the position of the char in the bubbling fluidized bed reactor.

This image classification is carried out manually by the definitions shown in Fig. 2, where the locations of the different char particles and their associated phases are represented. Frames from the last 10 s of all minutes in each test are chosen and classified. From the selected images, the percentage of the combustion time (θ_i) when the char particle is in the different phases is derived as

$$\theta_i = 100\left(1 - \frac{\sum_{j=1}^{m} N_{ph.i}^{j}}{250\,m}\right) \tag{1}$$

where $N^j_{ph,i}$ is the number of images where the particle is in emulsion phase ($i = e$), or bubble phase ($i = b$), or splash zone ($i = s$) within the 250 frames from the 10 s associated to the *j-th* minute, and *m* is the number of minutes of each test. This percentage of time concerns the time when the char particle and the thermocouple are attached. During most of the tests, the attachment time ends when the char particle's size is around 3 mm, so also for the freely fluidized char particle the test time is counted from the beginning of the combustion until the particle reaches that size.

RESULTS

THE EFFECT OF THE THERMOCOUPLE ON THE FREE MOVEMENT AND POSITION OF A CHAR PARTICLE IN THE BED

The classification of char particles seen on the video images according to their positions in the bubbling FB (see Fig. 2) allows estimation of the percentage of the combustion time (θ_i, Eq. 1), during which the char is in the emulsion phase, bubble phase, or splash zone. By doing this for all tests, the effect of the thermocouple can be evaluated for different fluidization velocities and sheath diameters of the thermocouple. Table 2 shows the locations in the bed of char particles from sub-bituminous coal when they are fluidized with (*w th*) and without (*w/o th*) an embedded thermocouple with different sheath diameters (d_{th}) at the fluidization velocities, U_f/U_{mf} = 2 and 3.

Table 2: Percentages of the combustion time (θ_i^*, Eq. 1) when the char particle is in the emulsion phase, bubble phase, or splash zone. The particle is fluidized with (w th) or without (w/o th) an embedded thermocouple of different sheath diameters (d_{th})

θ_i (%)	$U_f/U_{mf} = 2$			$U_f/U_{mf} = 3$	
	w/o th	**w th**		**w/o th**	**w th**
d_{th} (mm)	-	0.25	0.5	-	0.25
Splash zone	9	7	0	9	8
Bubble phase	9	13	15	10	15
Emulsion phase	82	80	85	81	77

* Deviation of three tests ±1%; - Without thermocouple

As seen in Table 2, a freely fluidized char particle (Table 2, U_f/U_{mf} = 2 and 3, *w/o th*) is not always in the emulsion phase, but also in the bubble phase (longer than 8 % of the time). At higher fluidization velocity the bed porosity increases and its density is lower. The reduction of the bed density should enhance the sinking tendency of the char in the bed and so, the increase of the fraction of time the char is in the bed and also in the bubble phase. Table 2 shows just a 1% increase in the residence time in the bubbles, while a corresponding reduction occurs in the emulsion, but keeping the time in the splash zone. A larger change was expected, but the drag force of the bed could have a mitigating effect: most likely the drag of the bed material dominates the movement of the char particle as a result of the upward motion of the bubbles, keeping it longer in the emulsion than in the bubble phase.

Fluidization with a thermocouple (Table 2, U_f/U_{mf} = 2 and 3, *w th*, d_{th} = 0.25 and 0.5 mm) makes the char particle sink in the bed, increasing its presence in the bubble phase by more than 40 % compared to the freely fluidized particle. The use of thicker thermocouple sheath is seen to keep the particle longer time inside the bed, even being able to avoid its presence in the splash zone. The longer time inside the bed results in a longer time in the bubble phase.

These results show that the thermocouple resists the drag of sand of the bed on the particle. The effect of this resistance on the movement of the particles is shown in Fig. 3, where the char particle is reached by the bubble burst at the bed's surface. The distance traveled by the char particle, fluidized with an embedded thermocouple, is shorter (Fig. 3b), and obviously the thermocouple resists the impact of the bubble burst, forcing the particle to move against the push of the bed, related to the collapse of the bubble.

One of the main hypotheses in theoretical models of a bubbling FB assumes that the active particle always resides in the emulsion phase, but our measurements show that this assumption is questionable, particularly if the char particle is fluidized with an embedded thermocouple. The location of char in the bubble phase has been observed before (Prins et al., 1989; Linjewile et al., 1994).

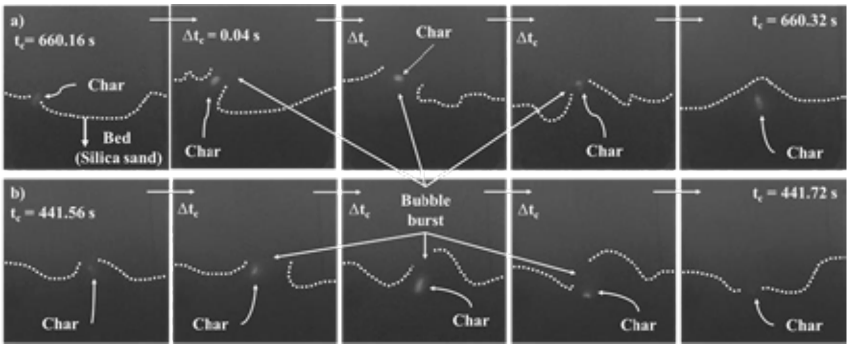

Fig. 3. The effect of the thermocouple on the movement of the particle during 0.16 s: Images (grey scale) from sub-bituminous char particle combustion fluidized without (a) and with (b) an embedded thermocouple of 0.25 mm sheath diameter (the dashed line is drawn to mark the bed's surface and the bubbles).

THE EFFECT OF THE THERMOCOUPLE ON THE CHAR PARTICLE'S SURFACE TMPERATURE

The effect of the thermocouple on the movement of the char particle and the increase of its presence in the bubble phase, where the combustion temperatures are higher (Linjewile et al., 1994), are expected to have consequences on the rate of char conversion. To study this effect, sub-bituminous char particles (~10 mm, 0.56 g) are burnt with (*w th*) and without (*w/o th*) a thermocouple of 0.25 sheath diameter. The result is shown in Fig. 4, where the temperature measured by thermocouple (T_{th}), is compared with the maximum (*max*), average (*avg*), and minimum (*min*) surface temperatures measured by pyrometry (T_P). Moreover, the burn-out time is shown, associated with the last images when the char disappears (the last image where the char is seen).

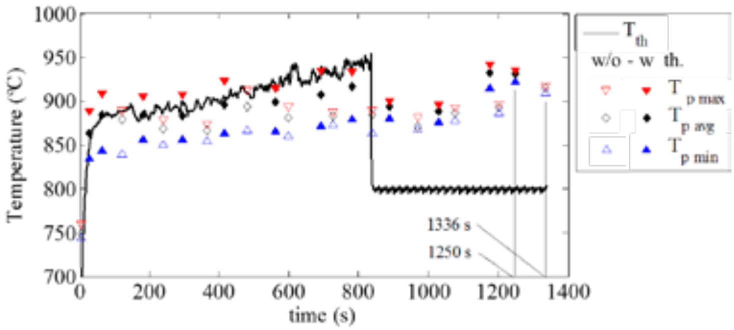

Fig. 4. Temperature of sub-bituminous char measured by thermocouple (T_{th}) and surface temperature by pyrometry (T_p): maximum (*max*), average (*avg*), and minimum (*min*) with (filled symbols) and without (empty symbols) an embedded thermocouple of 0.25 mm sheath diameter (T_{bed} = 800 ºC, U_f/U_{mf} = 2). The two times indicated at the right-hand side of the horizontal axis are the burn-out times of char (the last image when the char disappears) with (1250 s) and without thermocouple (1336 s).

Fig. 4 reveals one of the main problems associated with a contact technique: the detachment of the char particle from the thermocouple. The thermocouple reads the end of combustion at 840 s when the recorded temperature becomes equal to the bed temperature ($T_{th} = T_{bed}$ = 800 ºC). However, in this case the char combustion is far from finished, as shown by the surface temperature recorded by pyrometry. Fig. 4 shows the differences between the surface temperatures measured by pyrometry in the two cases when a thermocouple is mounted or not ($T_{p\ w\ th}$ vs. $T_{p\ w/o\ th}$). The temperature measured with the pyrometer is always higher when a thermocouple is embedded than without it. The difference between the two cases is more pronounced when the thermocouple is attached (t_c < 840 s). This is due to the longer time the char particle with a thermocouple spends in the bubble phase where the combustion temperature is higher because of the higher mass transfer (Prins et al., 1985). Once the detachment char particle - thermocouple has occurred (t_c > 840 s), the difference between the surface temperatures of the char with and without a thermocouple is reduced, because the fluid-dynamic effect of the bed (quenching) is similar on both particles. But, the surface temperature of the char particle, which had a thermocouple, remains higher than that without a thermocouple, and also, the end of the combustion is reached earlier: at 1250 vs.1336 s. This is a reduction of more than 5 % in burn-out time. The char particle with a thermocouple attached has a higher temperature than that without thermocouple, because its size is smaller due to the higher surface temperature during the time when the thermocouple was attached. This is shown in Table 3, where the size of both char particles is measured just after the detachment and at the end of both combustion processes (in the last image where the char particle is seen).

Table 3. Size of the char particle fluidized with (w th) and without (w/o th) an embedded thermocouple of 0.25 mm sheath diameter at detachment time (15 min), and at the end of both combustion events (20 and 22 min).

d_p*,mm	15 min	20 min	22 min
w th	4.5	1.8	detached
w/o th	5.2	2.8	1.7

*Sizing method's uncertainty ±0.3 mm.

The gradient of the temperature field on the surface of the particle (ranging between $T_{p\,max}$ and $T_{p\,min}$) of Fig. 4 is larger when the char particle is attached to the thermocouple (t_c < 840 s) than on the freely fluidized char particles: 50-80 ºC vs. 20-50 ºC, respectively. Once the detachment has taken place (t_c > 840 s) this difference is reduced, and the gradients have the same range on all particles. This result is due to the higher surface temperatures caused by the longer time in the bubble phase.

The thermocouple with thicker sheath diameter results in a longer time in the bubble (Table 2), and so, the combustion temperature is expected to be higher. This is confirmed in Fig. 5, where the combustion temperature histories of the char particles fluidized with an embedded thermocouple of 0.25 and 0.5 mm sheath diameter are displayed. Note that in the case of the thicker thermocouple (0.5 mm), the particle was attached to the thermocouple longer. However, comparing with Fig. 4 this total time is shorter than that of the smaller thermocouple and, of course, of the freely fluidized particle.

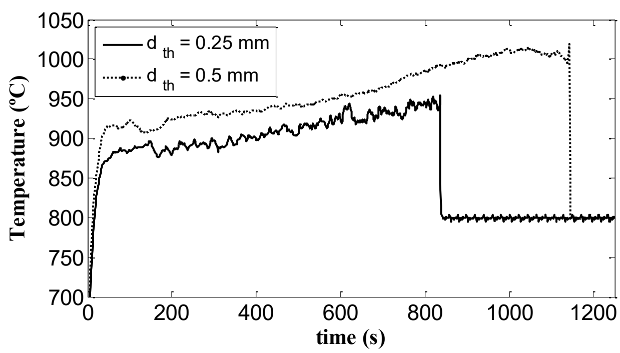

Fig. 5. Temperature evolution of sub-bituminous char measured by an embedded thermocouple of 0.25 mm and 0.5 mm sheath diameter (d_{th}) during their combustion at T_{bed} = 800 ºC and U_f/U_{mf} = 2.

CONCLUSIONS

In spite of the restriction on the free movement of the char particle in the fluidized bed, the use of thermocouple(s) to measure the combustion temperature is justified, assuming that the temperature of the char fluidized with an embedded thermocouple is similar to that fluidized freely. However, little attention has been paid in the literature to show the validity of this assumption. In the present work this is done by assessing the effect of the thermocouple on the surface temperature of the char particle by comparing with recordings by a digital camera: tests were made using thermocouples with two sheath diameters and the results were compared with those from tests with char particles fluidized freely.

The combustion of char particles (10 mm) from sub-bituminous coal in bubbling conditions was carried out in a 2D fluidized bed reactor made in quartz with rectangular cross-section. By analyzing the images of these combustion tests recorded by the video camera, the percentages of the combustion time were determined when a char particle is in the emulsion phase, bubble phase, and splash zone. The modification when the particle is fluidized with an embedded thermocouple (0.25 or 0.5 mm sheath diameter) was compared to the case without it. The surface temperature of the char particles measured by pyrometry was compared with the char temperature, measured by thermocouple.

The analysis of the images of the burning char shows that a freely fluidized char particle is not always in the emulsion phase, an observation that questions one of the main assumptions in modeling of bubbling FB. It is also concluded that the thermocouple resists the drag of the bed, increasing the time that the char particle is in the bubble phase compared to the case without a thermocouple. This increase is higher as the sheath thermocouple is thicker: more than 40 % and 60 % for 0.25, and 0.5 mm sheath diameter, respectively. The longer time in the bubble phase results in higher combustion temperatures, reducing the char burn-out time around 5 % for a thermocouple of 0.25 mm sheath diameter attached.

The results discussed make the use of thermocouples questionable, at least if accurate measurements are necessary, since the surface temperature and consumption are affected. However, the method can be used, keeping in mind the deviations pointed out. Pyrometry with a digital camera is shown to be a better option to avoid disturbing the combustion process. Besides, this method allows analysis of particle shrinkage, temperature surface gradients, and further conversion details. These results have been obtained using an embedded thermocouple with different sheath diameters and air as fluidization gas. It should be noticed that these thermocouple effects could be affected if more than one thermocouple is used, or a thicker sheath diameter, and/or a fluidization gas flux with higher oxygen concentration like that in oxy-combustion. The thermocouple effect on the conversion of a char particle could explain the differences between theoretical models and experimental measurement found in the literature (Mathekga et al., 2016.).

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NOTATION

d_{th}	Sheath diameter of the thermocouple
$N^{j}_{ph,i}$	Total frame number ($i = t$) from the combustion test, or number of frames where the char particle is in the emulsion phase ($i = e$), bubble phase ($i = b$), or splash zone ($i = s$) at the minute "j"
T_{bed}	Bed temperature
t_c	Combustion time
T_j	Char particle's temperature by pyrometry ($j = p$) or by thermocouple ($j = th$)
Ø	Diameter
θ_i	Percentages of combustion time during which the char particle is in the emulsion phase (i = e), bubble phase (i = b), or splash zone (i = s)

<u>*Abbreviations*</u>

avg	Average
FBC 2D	Experimental set-up with a rectangular fluidized bed reactor (18 x 1.8 x 50 cm)
FOV	Field of View of the digital camera
max	Maximum
min	Minimum
th	Thermocouple
P	Pyrometry

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