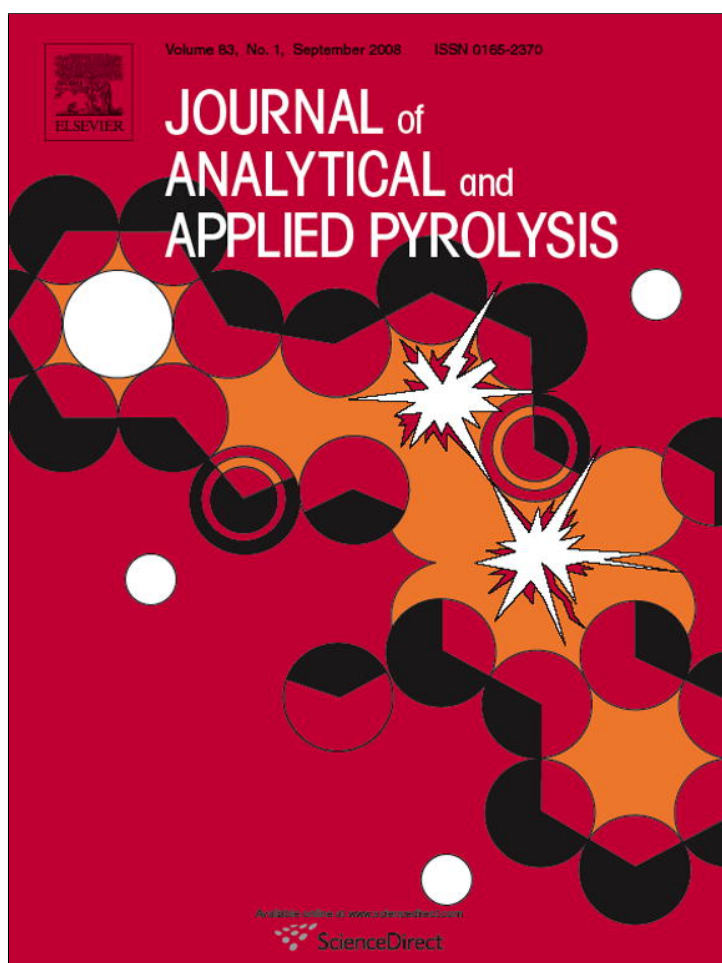


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Influence of temperature and particle size on the fixed bed pyrolysis of orange peel residues

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ABSTRACT

Orange peel is a residue from the production of juice. Its energetic valorisation could be interesting in areas where a different use, such as animal feed, is not possible. In order to investigate the viability of energy recovery, the pyrolysis of orange peel residues was studied in a fixed bed reactor, as an initial assessment of this process. The influence of pyrolysis temperature (300–600 °C) and particle size ($d_p < 300 \mu\text{m}$ and $d_p > 800 \mu\text{m}$) on product distribution, gas composition and char heating value has been investigated using a factorial design of experiments. Gas, char and water are the main products obtained; tar is only about 6 wt.% of the initial residue. Temperature was found to be the parameter which exerts a more important influence on the results than particle size.

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1. Introduction

Food processing industries, and especially the fruit processing ones, generate important amounts of residue, which must be managed properly, by recycling, incineration or landfilling. Landfilling involves fuel consumption for transportation and can cause environmental pollution.

When oranges are processed to obtain juice, a large amount of residue is produced. In 2006 19.8–33 million tons of oranges were processed worldwide [1], to produce approximately 2.2 million tons of juice and generating between 8 and 20 million tons of residues. This residue is used as an additive in the animal feed production or directly as animal feed (as is or pelletized), thus it must be transported to the end user, causing important corrosion damage on the transport trailers. As, for example, in the Pinar del Río Province, in Cuba, where an important juice production industry is located but the cattle industry is not very significant, therefore the residue that is produced must be landfilled, thus wasting what could be a significant source of energy for the area.

Currently, very limited information can be found on other treatments for this residue. Some processes that already have been studied are anaerobic digestion [2–4], and alcoholic fermentation [5,6].

A different approach could be the energetic valorisation of this residue. Few published papers can be found on this subject; to our knowledge only Li et al. [7] have studied the pyrolysis of this residue in a rotary kiln and Márquez-Montesinos et al. [8] have studied its behaviour under gasification conditions.

In this work, the thermal decomposition of orange peel has been studied in a fixed bed, as an initial step to evaluate if the pyrolysis process could be a worthy method for the exploitation of the energy contained in this residue.

2. Experimental

2.1. Feedstock

Orange residue was supplied by the company Citrus Internacional, S.A., which is located in the Pinar del Río Province, Cuba. This company manufactures juice, concentrated juice and essential oil from the fruits of the nearby plantations. The raw material received is mainly composed by orange peel and seeds, which was oven dried and crushed.

Table 1 shows proximate and ultimate analysis of the dried orange peel, as well as the higher heating value measured.

2.2. Installation and operational procedure

2.2.1. Thermogravimetry

Before studying the fixed bed pyrolysis, the decomposition of this waste sample was observed in a thermobalance, heating a

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Table 1
Properties of the waste sample

Proximate analysis	
Total moisture (wt.%)	7.05
Ash (wt.%)	4.55
Volatile matter (wt.%)	77.11
Fixed carbon (wt.%)	18.73
Ultimate analysis	
C (wt.%)	46.40
H (wt.%)	5.70
N (wt.%)	1.52
S (wt.%)	0.05
O (wt.%) (by difference)	46.33
Heating value	
HHV (kJ kg ⁻¹)	18,350

small sample of 10 mg of residue at 10 °C/min from room temperature to 900 °C. The weight evolution is shown in Fig. 1. As can be observed, most of the decomposition happens between 200 °C (when the orange peel starts losing weight) and 500 °C, thus the temperature range chosen for this study was 300 °C, where the decomposition is noticeable, and 600 °C, where the main part of the decomposition process is completed.

2.2.2. Fixed bed Installation

The pyrolysis runs were performed in a bench scale plant, shown in Fig. 2, consisting of a fixed bed reactor of 90 mm in diameter and 320 mm in length, discontinuous for the solid. Computer software provides a continuous record of carrier gas flowrate, time, temperature of the furnace and temperature of up to six thermocouples placed into the sample.

A steel basket with a radius of 28.3 mm and a height of 41 mm containing a sample weight of 40 g is placed in the reactor prior to the experiment, and hung at a depth of between 201 and 245 mm from the top of the reactor. The temperature profiles inside the sample were monitored placing the thermocouples in 8 different possible positions (T1 to T8), at two radii: 0 and 27 mm, and 4 heights: 1, 8, 15 and 22 mm from the bottom of the basket. Fig. 3 shows a scheme of the basket and the position of the thermo-

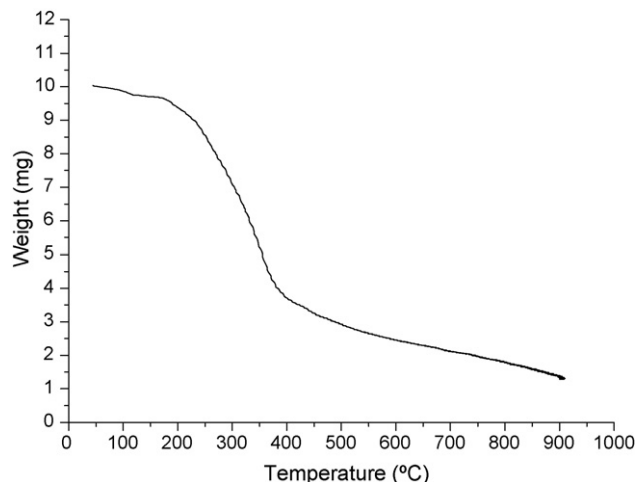


Fig. 1. Thermogravimetric decomposition of orange peel waste sample. Heating rate, 10 °C/min; *d_p*, 450 μm.

couples. Oven temperature is controlled by means of a thermocouple located externally to the sample but close to it, at 1 cm over the sample basket and at the center of the reactor.

Once the reactor is closed, a nitrogen flow of 13 cm³ NTP/s (NTP: normal temperature and pressure, 0 °C and 1 atm) is set by means of a mass flow controller. After 30 min under nitrogen flow, when the air is purged from the reactor, heating of the sample starts at the selected heating rate (10 °C/min) from 30 °C until the final pyrolysis temperature is reached. From previous works [9] with MBM, the nitrogen flow and heating rate have been selected, as they do not exert a significant influence on the results. The temperature of the reactor is then kept constant for 90 min to make sure that the pyrolysis process is complete, and gas is not evolved from the sample, which can be observed in the gas composition.

The exit gas passes through a tar condensation system which consists of two glass condenser vessels cooled with a mixture of ice and water and an electrostatic precipitator. The clean gas is analyzed by GC-TCD, by an on-line micro gas chromatograph

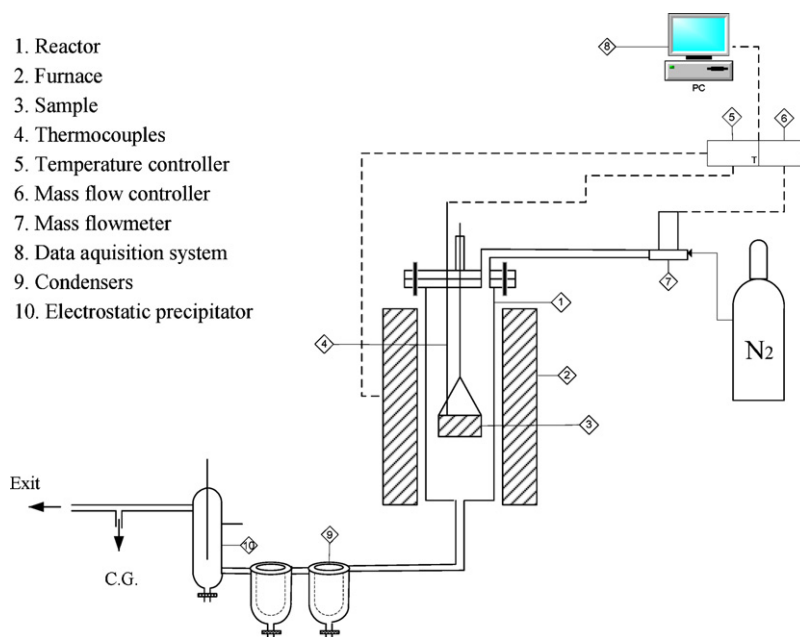


Fig. 2. Experimental system.

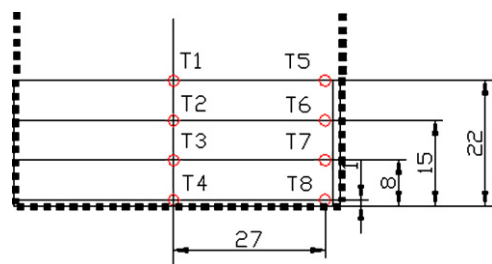


Fig. 3. Scheme of basket and position of thermocouples inside the sample. Measures in mm.

Agilent 3000A. The compounds analyzed are H_2 , N_2 , CH_4 , CO , CO_2 , C_2H_6 , C_2H_4 , C_2H_2 and H_2S . Once the experiment is finished and the system is cooled down to room temperature, the char is removed from the basket and weighed. The tar collected by the tar condenser system is also weighed and subsequently extracted with 2-propanol. Water content is analyzed by Karl-Fischer titration.

From one experiment the weight of char and tar are measured, as well as the gas composition. From these data, the following responses were considered:

- Product distribution, as the weight percentage of each fraction: char (Y_{char}), gas (Y_{gas}), tar (Y_{tar}) and water (Y_{water}).
- Average gas composition and lower heating value of the gas, LHV_g .
- Higher heating value of the char (HHV_c). This value was estimated using the method proposed in Ref. [10] from data of volatile matter and fixed carbon. These data were determined for each char obtained using the methods proposed in standards UNE 32-004-84 for ash, ISO 562-1974(F) for volatile matter. Fixed carbon was calculated by difference.

2.3. Factorial design

The only two varied factors are final pyrolysis temperature and the average particle size of the orange peel used. As it has been explained in a previous paragraph, the temperature range chosen for this study was 300–600 °C, whereas two particle diameter ranges were used, the fractions smaller than 300 μm and bigger than 800 μm . An experimental design setup of two factors and two levels for each factor were used (namely 2^k), adding a central point for the temperature (450 °C).

The central point was replicated 4 times, which leads to 10 experiments, and the whole experimental design was replicated in order to gather information on the temperature profiles inside the sample. For each design four thermocouples were placed at the center of the sample ($R = 0$ mm) at different heights (1, 8, 15, and 22 mm), and in the second, they were placed at $R = 27$ mm and the same four heights. Thus, 20 experiments were carried out, which are shown in Table 2, the order in which the experiments was carried randomly in order to avoid the effect of external or uncontrolled factors.

Analysis of variance (ANOVA) was used to study the influence of temperature, particle size, and their possible interaction on the results obtained. The ANOVA method was developed as a way to interpret results from experiments where different factors were varied. In this method, the variance observed in the results is decomposed in different fractions that can be assigned to the influence on those results (gas composition, production, etc.) of the different factors studied (temperature and particle size). Thus, the information from all the experiments is used in the analysis of the results, making ANOVA a more powerful tool than varying only one

Table 2

Experiments performed

Exp. no.	Temperature (°C)	Particle size (μm)	Thermocouples position, radius, R (mm)
1	300	<300	0
2	300	<300	27
3	600	<300	0
4	600	<300	27
5	300	>800	0
6	300	>800	27
7	600	>800	0
8	600	>800	27
9	450	<300	0
10	450	>800	0
11	450	<300	0
12	450	>800	0
13	450	<300	0
14	450	>800	0
15	450	<300	27
16	450	>800	27
17	450	<300	27
18	450	>800	27
19	450	<300	27
20	450	>800	27

factor at a time. By repeating the experiments, the influence of non-controlled factors (such as the effect of ambient conditions), can also be determined as the error of the results. A detailed explanation of the ANOVA method can be found elsewhere [13,14]. The statistical analysis was carried out using the Design-Expert[®] Version 7 Software from Stat-Ease, Inc. To consider a given significant effect (to reject the null hypothesis that changing the factor has no effect on the observed response), a confidence level of 95% for the F -distribution was selected.

3. Results and discussion

3.1. Temperature profiles in the sample

In Fig. 4 the temperature profiles measured for an experiment carried out at the final pyrolysis temperature of 450 °C with a particle size bigger than 800 μm is shown; temperature profiles for the rest of experiments are similar and are not shown, in order to avoid repetition. As can be observed during the heating up period before the final temperature is reached, the axial temperature profile at the center of the sample ($R = 0$ mm, Fig. 4(a)) is more pronounced than at the exterior part of it ($R = 27$ mm, Fig. 4(c)). In Fig. 4(b) and (d) temperature differences of each thermocouple inside the sample and the control thermocouple are shown, it can be observed that at $R = 0$ mm the maximum difference is about 200 °C during the heating up period, whereas at $R = 27$ mm, it is less than 100 °C. This could be due to the fact that the heating flow from the furnace to the sample is lateral.

With regard to the axial profiles, it can be observed at both radii that during the heating up the sample is at lower temperature than the control thermocouple (which is located close to the sample upper part but not touching it), the upper part of the sample (T1 at $R = 0$ mm, T5 at $R = 27$ mm) being hotter than the bottom part (T4 at $R = 0$ mm, T8 at $R = 27$ mm). However, at a temperature close to 400 °C, a profile inversion is observed and the hottest part of the sample is the bottom. This phenomenon of temperature inversion has also been observed in pyrolysis studies of sawdust and cellulose [11] and Meat and Bone Meal [9]. According to some works performed with wood particles [12], conduction could be considered as the main mechanism of heat transmission inside a bed of solids, and when the sample has a low thermal conductivity,

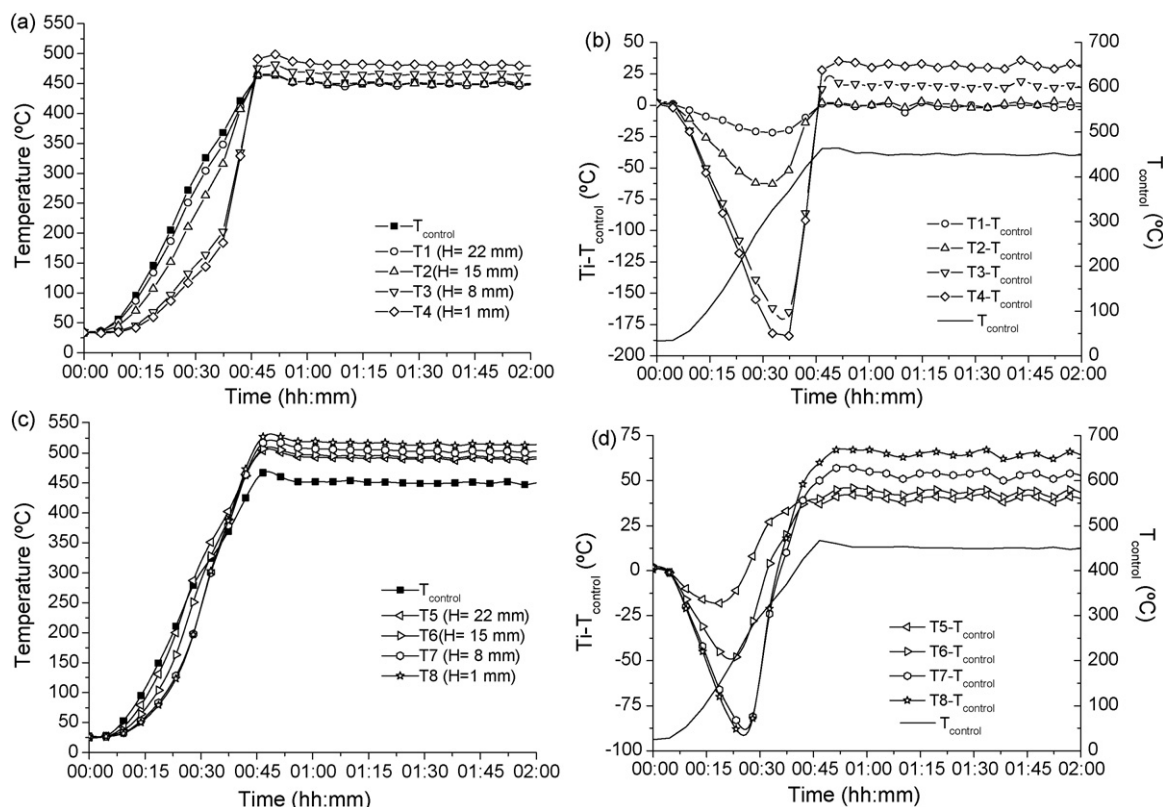


Fig. 4. Temperature profiles in the sample. Final pyrolysis temperature: 450 °C; d_p : >800 μm . (a and b) $R = 0$ mm; (c and d) $R = 27$ mm.

high temperature profiles are created inside the particle. Furthermore, it must be considered that pyrolysis reactions are mainly endothermic and, as was observed in the pyrolysis experiment carried out in a thermobalance, Fig. 3, most decomposition reactions take place between 200 and 500 °C. Thus, when decomposition is occurring, the heat transfer rate into the bed could be slower than the heat rate consumption due to the pyrolysis reactions. When pyrolysis is almost complete, energy is only used to heat up the sample, and the heat transfer rate is sufficient to minimize the temperature gap between T_{control} and the sample.

3.2. Effect of pyrolysis temperature and particle size on the pyrolysis process

Results obtained in the experiments performed are shown in Table 3.

3.2.1. Product distribution

The char yield obtained under the different conditions is shown in Fig. 5. In Table 4 the relative influence of each factor (temperature and particle size) is shown, as the result of the ANOVA analysis. On this table the following data are shown for

Table 3
Product distribution (char, gas, tar and water), and gas and char heating values

Exp. no.	T (°C)	d_p (μm)	Y_{char} (%)	Y_{gas} (%)	Y_{tar} (%)	Y_{water} (%)	LHV _g (kJ/m ³ NTP)	HHV _c (kJ/kg)
1	300	<300	35.85	27.98	6.40	29.75	15,690	25,290
2	300	<300	35.13	26.58	6.70	31.60	4,000	24,840
3	300	>800	36.83	26.68	5.23	31.27	16,430	24,960
4	300	>800	35.75	28.88	7.08	28.30	14,530	26,440
5	450	<300	27.10	31.87	9.49	31.54	13,870	27,240
6	450	<300	28.10	32.00	5.59	34.31	7,760	27,230
7	450	<300	27.68	31.70	6.40	34.22	10,360	27,140
8	450	<300	27.50	34.25	7.60	30.65	18,680	27,250
9	450	<300	27.03	30.65	6.38	35.95	12,150	27,340
10	450	<300	26.98	31.95	6.71	34.36	12,300	27,150
11	450	>800	28.90	31.15	6.02	33.93	15,980	28,230
12	450	>800	28.00	32.13	7.38	30.65	12,230	28,100
13	450	>800	28.33	31.15	8.56	31.97	15,950	28,136
14	450	>800	28.15	31.40	6.38	34.07	12,640	28,320
15	450	>800	28.13	31.08	9.65	31.15	9,770	28,060
16	450	>800	27.63	34.15	6.23	32.00	11,540	28,144
17	600	<300	24.53	34.37	6.35	34.45	13,450	28,160
18	600	<300	24.63	36.16	7.12	32.13	11,550	28,360
19	600	>800	26.48	31.08	6.66	35.79	15,550	29,000
20	600	>800	25.60	35.65	7.20	31.55	9,320	29,130

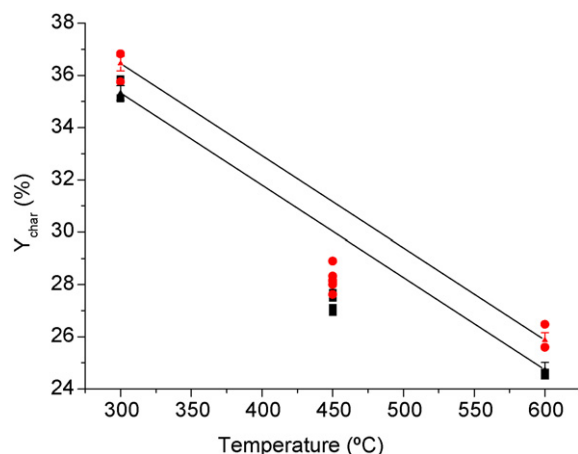


Fig. 5. Char yield. ■, $d_p < 300 \mu\text{m}$; ●, $d_p > 800 \mu\text{m}$.

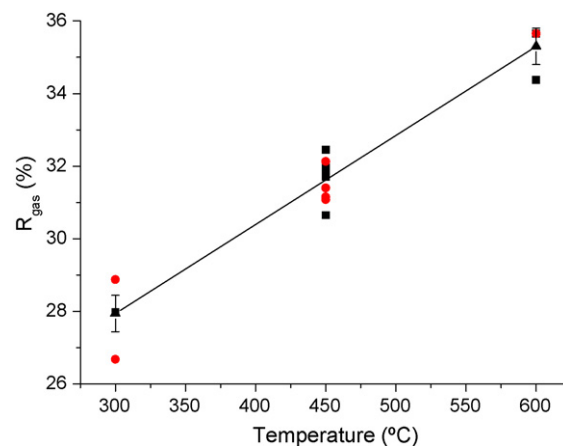


Fig. 6. Gas yield. ■, $d_p < 300 \mu\text{m}$; ●, $d_p > 800 \mu\text{m}$.

Table 4
Relative influence of the temperature and particle size on the product distribution

	Average	Temperature	Particle size	Curvature
Char (%)	30.6 ± 0.29	-5.3 ± 0.29	0.6 ± 0.29	**
Gas (%)	31.6 ± 0.60	3.7 ± 0.61	*	*
Tar (%)	6.6 ± 0.59	*	*	*
Water (%)	31.6 ± 1.55	1.9 ± 1.54	*	*

*, not significant; **, significant.

each studied response: average (%) which is the average of the whole set of results obtained, temperature (%) is the effect which has to change the temperature on the studied response (char, gas, etc.), particle size (%) is the same applied to the change of waste sample particle size, curvature is the measure if, in the experimental range of each factor, the change of a response is linear or not (for example only the char yield is not linear, which is also observed in Fig. 5). This influence is calculated with the coded levels of each factor, which are -1 for the low level (300 °C for the temperature and $d_p < 300 \mu\text{m}$) and +1 for the high level (600 °C for the temperature and $d_p > 800 \mu\text{m}$). This way it is easier to compare the influence of one factor in the studied range in comparison with the other factors. The ANOVA of the results show (Table 4) that char yield diminishes as temperature increases and also as particle size of the waste sample decreases, although its effect is smaller than that of temperature, there is not a significant interaction of temperature and particle size, which means that increasing the temperature leads to the same decrease in char yield for both particle sizes used in the study. As can be observed in Fig. 5, the decrease in the char yield is greater in the 300–450 °C range (-38.6%) than in the 450–600 °C one (-7.5%), which means that it is not a linear dependence of the char yield with temperature; in the ANOVA analysis it can be observed as a significant curvature, which is calculated from the difference between the average of the results obtained at 300 and 600 °C (shown in Table 4) and the central point (450 °C). Similar tendencies have been observed in the fixed bed pyrolysis of other biomass residues as Meat and Bone Meal [11], hazelnut, walnut, almond and sunflower seed shells [15], sawdust, bagasse and macadamia nut shell [16], olive husk, corncob, tea waste [17], ligning from the pulping process [18], pistachio shell [19], Cynara Cardunculus [20], and rice husk [21]. The effect of particle size on the char yield was also observed in different pyrolysis works, as in Ref. [22] for hazelnut shell, olive husk, corncob, tea waste [17], and rice husk [23]. This effect could be explained by the fact that small particles have a bigger surface area to interact with the pyrolysis medium and form volatile

products that leave the biomass matrix without undergoing secondary cracking reactions [22]. In the case of larger particle sizes, this phenomenon could be dominant, leading to additional char formation. On the other hand, mass and heat limitations are more significant in the case of larger particles [22].

The gas yield, Y_{gas} , is shown in Fig. 6, the ANOVA analysis shows that the particle size of the residue does not have a significant influence, only the temperature, for which a linear influence cannot be dismissed, as the curvature of the data is not significant. This tendency was also observed in the previously cited works with different types of biomass. In what concerns the influence of the particle size, it could be expected that a bigger particle diameter would cause a more important temperature gradient inside a particle, leading to a higher char yield, which was observed, as previously discussed, and to a lower gas or tar production, but from our data this result cannot be asserted. For example Encinar et al. [24] did not observe either the influence of the particle size in the pyrolysis of olive and grape bagasse working in a particle size range of 0.40–0.63 mm to 1.60–2.00 mm for any of the pyrolysis products. The reason for this lack of tendency can be ascribed to the accuracy of the experimental system. The relative influence of temperature on the gas yield on the average result is shown in Table 4.

As explained in Section 2, the condensibles recovered in the condensation system were analyzed by Karl-Fischer titration, which is the recommended method for analysing water in pyrolysis liquids [25]. As the variability on the tar determined in the experiments performed is similar to the one caused by changing temperature or particle size, it is not possible to observe any influence of temperature or particle size on the tar yield, thus from the statistical point of view the 20 experiments carried out are similar and the average tar production can be calculated with 19 degrees of freedom, which is $6.6\% \pm 0.59$. On the other hand, most of the condensed matter is water (28–35% of the weight of the orange peel fed into the reactor), as shown in Fig. 7. For this yield only the pyrolysis temperature affects significantly, as can be observed in Table 4, increasing the water yield when temperature is increased.

The lack of effect of pyrolysis temperature on the tar production was studied with further experiments. In order to know at what temperature it is produced, a series of experiments were carried out under similar conditions, but in these experiments a single sample of orange peel ($d_p < 300 \mu\text{m}$) was heated at 10 °C/min up to final pyrolysis temperatures of 200–600 °C with 50 °C steps, keeping the sample at each final temperature (200, 250, 300, ..., 600 °C) for 1 h, to assure total decomposition of the sample.

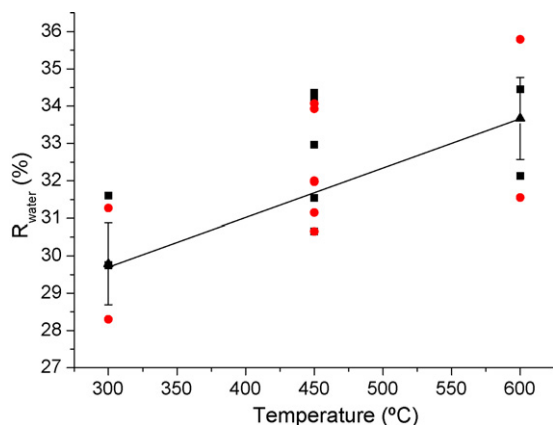


Fig. 7. Water yield. ■, $d_p < 300 \mu\text{m}$; ●, $d_p > 800 \mu\text{m}$.

This way for the first experiment the product distribution was measured for a pyrolysis temperature of 200 °C, in the second one the product distribution for the 200–250 °C range, and so on up to 600 °C. The cumulative product (char, gas, tar and water) distribution obtained is shown in Fig. 8, as only one experiment was carried out for each condition, the data are shown without confidence intervals. As can be observed, the char yield diminishes as temperature increases, gas and water both increase noticeably, but the increase in the tar yield is very small (4.9% at 300 °C and 6.1% at 600 °C). As this increase is small compared to the experimental deviation observed in the data, it is logical that we could not observe a statistically significant influence of pyrolysis temperature in the tar production.

On the other hand, the fact that most of the organics in the condensable matter are produced at low temperature could be related to the chemical composition of orange peel, whose main components are [26–28]: cellulose (10–15%), hemicellulose (2–6%), lignin (2–3%), pectin (25–30%), proteins (8–12%), lipids (2–3%) and ash (2–3%). It is well known, as pointed out by the review of Mohan et al. [29], that under a slow heating regime, decomposition of cellulose is complete under around 360 °C, hemicellulose decomposes between 200 and 260 °C, most of the decomposition happens under 180 °C, and lignin between 280 and 500 °C, which is the compound that produces the higher amount of char and tar of the three. Less information of the pyrolytic behaviour can be found on the other compounds, but in the work of Sharma et al. [30], decomposition of citrus pectin is also complete under 400 °C.

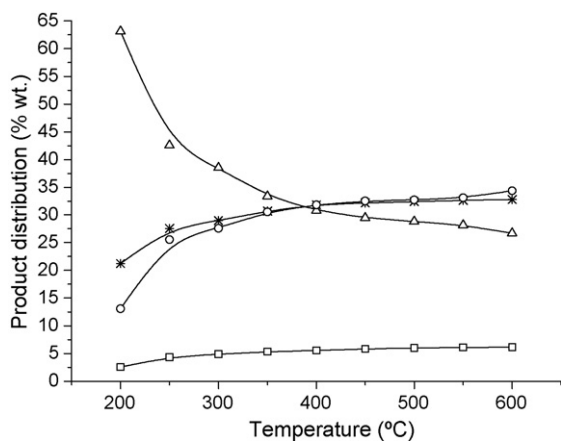


Fig. 8. Evolution of the accumulated product distribution with temperature. △, char; □, tar; *, water; ○, gas.

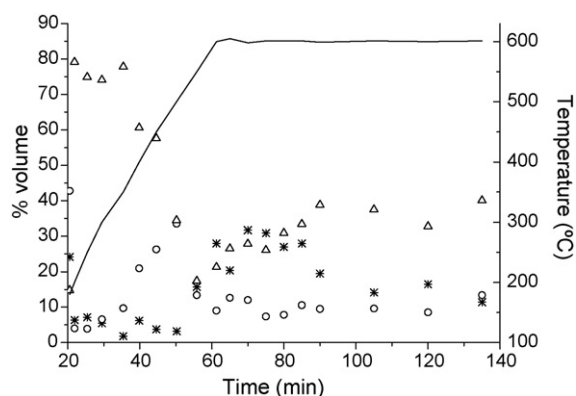


Fig. 9. Evolution of the gas composition with time. *, H_2 ; ○, CO; △, CO_2 ; —, temperature.

3.2.2. Gas composition

The pyrolysis experiments carried out in this work are discontinuous for the solid, thus the composition and flow rate of the gas evolving from the sample change as the pyrolysis takes place. The gas composition, in a nitrogen free base, is shown in Figs. 9 and 10, for an experiment carried out at a final pyrolysis of 600 °C and with a $d_p > 800 \mu\text{m}$. It can be observed that CO_2 is the main gas component up to around 450 °C being about 80% by volume, once the isothermal period is reached it is again the most important gas with a 35% volume. The composition of average gas volume obtained at this temperature is: H_2 15.6%, CO 12.1%, CO_2 40.7%, CH_4 9.8%, C_2H_2 17.3%, C_2H_4 4.0% and C_2H_6 0.4%.

The ANOVA of the average gas composition obtained in the different experiments is shown in Table 5. It can be observed that, by volume, CO_2 is the main gas component (about 50% by volume), followed by CO (15%) and H_2 (10%). CH_4 and C_2H_2 each account for about 9% by volume of the average gas. The effect of changing pyrolysis temperature and particle diameter is hardly noticeable in the average gas composition. Only hydrogen is both affected by pyrolysis temperature and residue particle diameter. Thus, both increasing the final pyrolysis temperature and the particle diameter lead to higher hydrogen content, while the effect of temperature is more important than the particle diameter, as can be observed in Table 5. On the other hand, CH_4 and CO_2 are only affected by particle diameter and not by pyrolysis temperature. CH_4 percentage in the gas increases while CO_2 decreases when the particle diameter is increased. The rest of the gas components are not affected by either pyrolysis temperature or particle diameter in the range studied. In pyrolysis studies of other materials as plastic

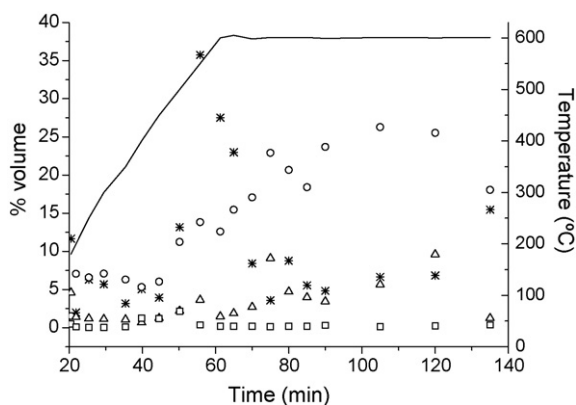


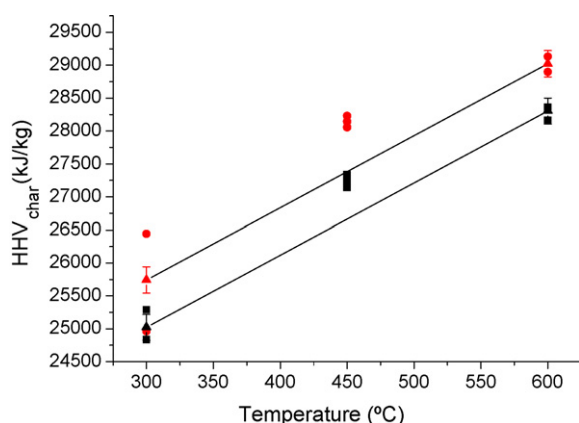
Fig. 10. Evolution of the gas composition with time. *, CH_4 ; ○, C_2H_2 ; △, C_2H_4 ; □, C_2H_6 ; —, temperature.

Table 5

Relative influence of the temperature and particle size on the mean gas composition and char heating value

	Average	Temperature	Particle size	Curvature
H ₂ (%)	10.3 ± 1.66	4.5 ± 1.66	1.9 ± 1.66	**
CO (%)	15.1 ± 3.40	*	*	*
CH ₄ (%)	8.5 ± 1.91	*	2.2 ± 1.91	*
CO ₂ (%)	53.9 ± 5.13	*	-6.71 ± 5.13	*
C ₂ H ₄ (%)	2.2 ± 0.71	*	*	*
C ₂ H ₆ (%)	1.1 ± 0.55	*	*	*
C ₂ H ₂ (%)	8.7 ± 3.83	*	*	*
HHV _c (kJ/kg)	27,020 ± 210	1640 ± 210	360 ± 210	**

*, not significant; **, significant.

**Fig. 11.** Char higher heating value. ■, $d_p < 300 \mu\text{m}$; ●, $d_p > 800 \mu\text{m}$.

waste [31] and tyres [32] it was found that H₂ and CH₄ are favoured by high temperatures, whereas the lower temperature leads to a gas richer in heavier hydrocarbons.

Gas heating value does not show either any influence of the experimental conditions, an average value of $12,900 \pm 2200 \text{ kJ/Nm}^3$ was obtained for the 20 experiments performed.

3.2.3. Char heating value

As mentioned in Section 2, char higher heating value (HHV_c) was estimated using the method proposed in Ref. [9], which reached the following equation:

$$\text{HHV}_c = 354.3 \text{ FC} + 170.8 \text{ VM}$$

where HHV_c is the higher heating value (kJ/kg in a dry basis), and FC and VM are the fixed carbon and volatile matter contents, both in weight percent on a dry basis.

In Fig. 11 the effect of varying temperatures and particle sizes is shown and as can be observed the char heating value increases by increasing both temperature and particle size. The effect of temperature is about four times more important than that of particle size, as can be observed in Table 5 where the ANOVA results are shown. The same effects of temperature [20,33] and particle size [5] were observed for other biomasses.

4. Conclusions

In the experimental range tested (temperature, 300–600 °C; particle size, $d_p < 300 \mu\text{m}$, $d_p > 800 \mu\text{m}$), pyrolysis temperature exerts a more significant effect than particle size in the parameters analyzed.

An increase of the temperature diminishes the char yield (about 10% from 300 to 600 °C) but increases its heating value (in about 3000 kJ/kg in this temperature range). An increase of particle size (from particles smaller than 300 μm to bigger than 800 μm) of the residue favours both parameters, only 1% in the case of char yield and 700 kJ/kg the HHV_c.

The gas yield is only affected by temperature, increasing about 7% in the temperature range studied. Gas composition does not show clear trends, only the hydrogen percentage is affected by both temperature and particle size; increasing with both parameters (about 9% with temperature and 4% with particle size), CH₄ increases when the particle size is increased (4%) and CO₂ decreases (13% when particle size is increased). The rest of the gas components does not show any influence of either temperature or particle size.

Most of the condensable product consists of water, only 6.6% of the residue is organic (tar), and it is formed below 300 °C, so no influence of temperature was observed, nor of particle size in its production either.

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