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Product distribution and kinetic scheme for the fixed bed thermal decomposition of sewage sludge

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ABSTRACT

In this paper, a new kinetic model for the thermal decomposition of dry sewage sludge was determined. In order to achieve this main objective, various experiments were carried out to collect enough information for the estimation of the different numerical parameters of the model. These experiments include both results from a fixed bed pyrolysis installation and a thermogravimetric analysis device. The experiments allowed for the detailed monitoring of the dynamical evolution of the mass of the sample under investigation, together with the cumulative amounts of tars and permanent gases produced during thermal decomposition of sewage sludge at low heating rates (5–20 °C/min). Solid mass loss during the pyrolysis shows two regions, between 150 °C and 600 °C, where most of the tar is depleted from the solid and non-condensible gases are formed, and a second one between 600 °C and 900 °C where mainly only non-condensible gases are produced. The solid fraction accounted for about 50% of the initial weight, tar around 30% and gases the remaining 20%.

Regarding the formation of non-condensible gases from low temperature, a new kinetic scheme was proposed involving an initial decomposition step of the sludge yielding tar and gases as gas phase products and a solid intermediate compound which decomposes at higher temperatures, giving the char fraction and more non-condensible gases. The comparison between the numerical prediction and the experimental results was excellent.

1. Introduction

One of the main drawbacks of wastewater treatment processes (either urban or industrial) is the by-production of sludge. As an example, a European production of 8.3 Mt of sludge (expressed in dry matter) was estimated for 2005 [1]. Up to now, landfills have played a major role in the disposal of these wastes. However, because of the public awareness of environmental issues as well as European regulation, other treatments have to be used for their processing. Among these processes, one way is to heat the sludge so that it undergoes thermo chemical transformation able to make the sludge non-pathogenic but also to enable it to recover the potential energy that it holds because of its organic content. Among these processes, pyrolysis is expected to play a major role in the context of sustainable heat and power generation. However, the route to industrial process requires a better understanding of the physics and chemistry of this thermal degradation.

This knowledge requires as a first step the determination of the chemical pathway and the kinetic route of this thermal decomposition. This is not a trivial task and a huge amount of work has been performed for this specific topic either for biomass (see for example the recent review work of Di Blasi [2]), municipal solid wastes [3], sludge [4–15] or for complex solid fuels [16]. When dealing with sludge, the different kinetic routes that have been proposed can be split into three groups.

In the first one, the sludge is supposed to be composed into several organic fractions (dead bacteria, other biodegradable materials or not. . .), each of them being decomposed into volatiles and char on a parallel mode. This kind of model has been widely studied [4,6,7,10,11]. However this description suffers from the lack of physical significance of the numerical parameters obtained by the fitting to experiments procedure (minimization of the least squares). Indeed, high order of reactions can be obtained what could be unrealistic.

The second group of models falls into the category of distributed activation energy models (DAEM). Basically this theory

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Abbreviations: DAEM, distribution activation energy models; DSC, differential scanning calorimetry; DTG, differential thermogravimetry; HHV, higher heating value; STA, simultaneous thermal analysis; TG, thermogravimetry; TGA, thermogravimetry analysis.

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Nomenclature

A_i	pre-exponential factor of reaction i (min^{-1})
$E_{a,i}$	activation energy of reaction i ($\mathrm{J\,mol}^{-1}$)
k_i	kinetic rate constant of reaction i (min^{-1})
n_k	reaction order for species k
X_k	ratio of actual mass of component k to initial mass sample

Subscripts

C	Char
G	Gas
I	Intermediate
S	Sludge
T	Tar

Table 1
Properties of the dried sludge

	Sludge
Proximate analysis	
Total moisture (wt% (ar))	6.46
Ash (wt% (db))	44.14
Volatile matter (wt% (db))	50.13
Volatile matter (daf) (wt% (daf))	89.74
Fixed carbon (wt% (db))	5.73
Ultimate analysis	
C (wt% (daf))	53.28
H (wt% (daf))	7.02
N (wt% (daf))	7.55
S (wt% (daf))	1.45
O (wt% (daf)) (by difference)	30.70
Heating value	
LHV ($\mathrm{MJ\,kg}^{-1}$ (ar))	11.95

assumes that the material under investigation is composed of several fractions, each of them being characterized by first order decomposition reaction for which the activation energy is a continuous distribution function [13,16–18]. This method is known to perfectly fit the experimental results obtained in a TGA. However, as noted by Scott et al. [16], the use of this method can be difficult to complete a model where mass and energy transfer have also to be accounted for.

The last kind of model considers that the chemical pathway of the thermal degradation of sludge can be described by a set of competitive and successive reactions, assuming that the original solid material firstly decomposes into volatile material and a solid intermediate, which in turns decomposes into volatile material and char [5,9,14,15]. It is precisely this scheme which in this study focuses. More precisely, it is shown that it is well suited to represent the decomposition of wastewater sludge at low (5 °C/min) to moderate (20 °C/min) heating rates and an evolution of this scheme based on the differentiation between permanent and condensable volatiles is provided.

In this work a fixed bed pyrolysis plant has been used to study the pyrolysis of sewage sludge. Data obtained have also been compared with TG data using the same sludge and similar conditions. Solid weight loss has been obtained in both experimental systems, whereas tar and gas evolution has been followed from the fixed bed data. These data have been used to modify a previously published kinetic scheme in order to fit the observed trends, thus getting a model that represents better the pyrolysis of the sludge used.

2. Experimental

2.1. Materials

The sewage sludge used in the study was obtained as a dried, granulate product from an urban waste-water treatment plant. The sludge came from an anaerobic digestion and thermal drying process. Proximate and ultimate analyses of the received sewage sludge are shown in Table 1. As can be seen, the sludge is mainly composed of volatile matter (89.74 wt% on a dry, ash free basis) and ash (44.14 wt% on a dry basis). As a general characteristic of sludge issued from an urban water treatment process, there is also a high content of nitrogen (7.55 wt% on a dry, ash free basis). The higher heating value (HHV) has also been determined using a calorimeter IKA A-2000 (standard procedure: ISO-1928-89). The value obtained for HHV is 11.4 MJ/kg. Before the pyrolysis, the sludge sample was pre-dried at 109 °C until constant mass, grounded and then screened to give the fractions of diameter between 250 μm and 500 μm.

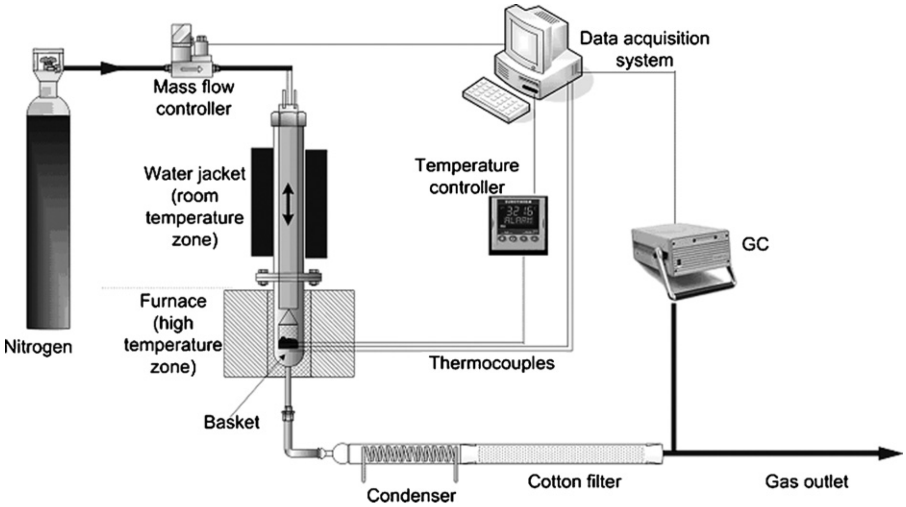

Fig. 1. Fixed bed reactor used for experiments.

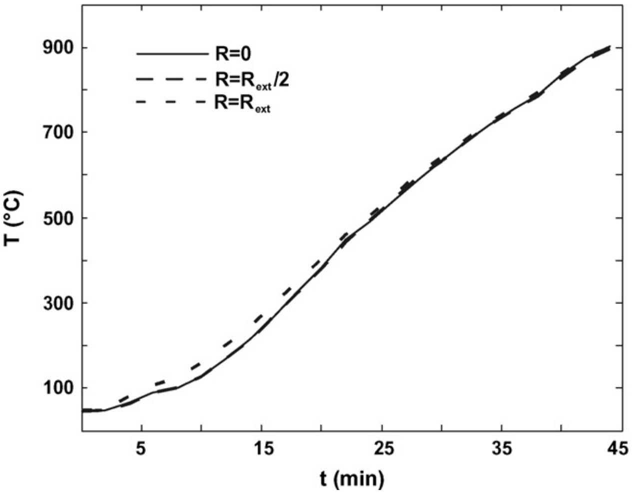

Fig. 2. Temperature profile inside the basket at a heating rate of 20 °C/min.

2.2. Fixed bed reactor

A set of experiments was performed in a fixed-bed reactor. This facility is shown in Fig. 1. Basically it is made up of a steel basket with a radius of 10 mm and a height of 21 mm that can hold up to 3 g of sample. This basket is placed in a cylindrical steel reactor with a diameter of 50 mm and a height of 320 mm. The basket is hung at a depth of 25 mm from the bottom of the reactor, which is heated externally by an electrical furnace. A moving head of the reactor allows the sample to be quickly removed from the hot zone of the furnace while keeping the system gas-tight. Computer software provides continuous records of carrier gas flow rate (N_2), time, temperature of the reactor and temperature of up to four thermocouples located in the sample.

During our experiments, the basket was loaded with 2.5 g of sludge. Due to this small sample size, isothermal conditions within the sample under investigation are guaranteed, as could be measured by the system (Fig. 2 illustrates the temperature profile inside the basket for the worst heating rate of 20 °C/min). Then, once the reactor was closed, a nitrogen flow of 125 mL/min was fed into the reactor. The reactor is set free of air after 30 min under nitrogen flow, then, heating of the sample starts at the desired heating rate from 30 °C to the final pyrolysis temperature. The exhaust gas passes through a tar condensation system which consists of a water-cooled coil and a cotton filter. The gas was then analyzed by GC-TCD (model Agilent 3000A), taking a gas sample every 5 min. The compounds that were tracked were $H_2, N_2, O_2, CH_4, CO, CO_2, C_2H_6, C_2H_4, C_2H_2$ and H_2S. Once the experiment was finished and the system cooled down to room temperature, the pyrolysis solid residue was removed from the basket and weighed. The tar collected by the tar condenser system was also weighed.

The experiments performed in this device were divided into two groups. In the first one, the main interest was to determine the transient composition and yield of the gases leaving the reactor. These experiments were performed according to three heating rates (5 °C/min, 10 °C/min and 20 °C/min) up to 900 °C. The second group of experiments was used to determine the transient evolution of the tars produced during the pyrolysis reaction. To do so, the sample was heated at 10 °C/min, but, from 150 °C to 900 °C, every 60 °C, the sample was quickly cooled (“frozen”) to room temperature by rising it from the heated zone to a cool zone in the upper part of the reactor. The sample was then weighed and so was the tar collection system.

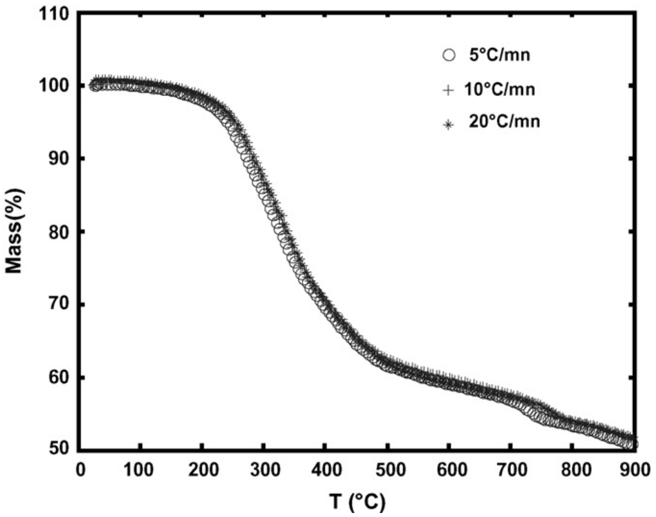

Fig. 3. TG curves for the sludge under study at three heating rates: (○) 5 °C/min, (+) 10 °C/min, and (✱) 20 °C/min.

2.3. Thermogravimetric analysis

The experiments were carried out in Netzsch STA 409C (Simultaneous Thermal Analysis) in the TGA/DSC configuration. The sample, approximately 30 mg, was linearly heated at three heating rate (5 °C/min, 10 °C/min and 20 °C/min) to 900 °C. It was then held at this temperature for 10 min. The atmosphere used was nitrogen with a flow rate of 12 mL/min. This flow was chosen in order to have the same conditions as the ones prevailing within the fixed bed experiments.

3. Results

The evolution of the different compounds (solid, tar, gas) was followed by experiments carried out in the fixed bed reactor because this system was equipped with a gas analyser on line, and it also allowed the measurement of tars mass due to the significant amount of sludge treated, compared with the thermobalance. However, in this device the sample mass could not be recorded continuously; successive cooling, withdrawing and “re-heating” steps were necessary to establish the transient profiles of the different compounds. Consequently, it seemed important to perform, on the same sludge, TGA tests (continuous mass recording) in order to compare at least the transient profile of the solid matter, and thus validate our fixed bed results. Moreover, the continuous recording in TGA tests enables to plot the DTG curves and give some more information.

3.1. Thermogravimetric analysis

Figs. 3 and 4 show respectively the mass loss and the rate of this loss at three heating rates. They exhibit two different regions. The first one (between 150 °C and 600 °C) which corresponds to the maximal loss (−40.2% for 5 °C/min; −39.8% for 10 °C/min;−40.7% for 20 °C/min) is associated with the thermal degradation of organic material. The information brought with the study of the DTG curve, where several peaks appear, is that this thermal decomposition implies several reactions. The loss mass of sludge above 600 °C is 8% on average (−8.4% for 5 °C/min; −8.4% for 10 °C/min; −7.4% for 20 °C/min); it can be attributed to the decomposition of inorganic material [13]. Similar weight loss percentages have been observed for other sludge in TG pyrolysis [19].

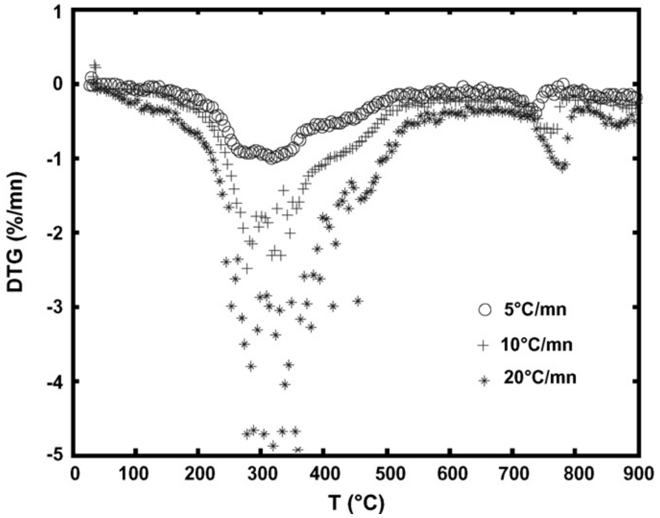

Fig. 4. DTG curves for the sludge under study at three heating rates: (◯) 5 °C/min, (+) 10 °C/min, and (✱) 20 °C/min.

3.2. Fixed bed reactor

Experiments carried out in the fixed bed reactor exhibit little discrepancies in the overall mass balances. More precisely, at 5 °C/min, 10 °C/min and 20 °C/min, only 71.9%, 95.4%, and 85.9% of the initial mass sample were, respectively, recovered. Such discrepancies were incompatibles with our numerical purposes. This is the reason why it has been chosen to fit the experimental results so that the overall mass balance was satisfied. Indeed, because the error associated with the measurement of the solid yield was expected to be small with respect to the measurements of both the gas and the tar yields, only the tar and gas yield were adjusted to fulfil the overall mass balances. Table 2 sums up the experimental and corrected products yields (in terms of solid residue (char), species collected in the tar condenser (tar), and permanent gases sampled in the GC (gas)). The char yield does not vary with the heating rate, whereas tar and gas yield exhibit a significant dependence on this criterion. Indeed, the gas production seems to decrease when the heating rate is increased whereas the opposite trend drives the production of tar. This phenomenon could be attributed to the fact that the higher the heating rate, fewer products of thermal decomposition stay within the solid matrix, and the less these heavier compounds undergo secondary cracking.

Figs. 5 and 6 show the cumulative and instantaneous gas yield associated with the decomposition of the sludge under investigation at three heating rates. It can be seen that at low and medium heating rates, the production of permanent gas is quite similar. Indeed, the peaks in the production occur at the same temperatures, even though the importance of the peaks is not the same. Also, the figures show that the main release of permanent gas occurs at two main steps (approximately 300 °C and 800 °C for 5 °C/min and 10 °C/min; 500 °C and 800 °C for 20 °C/min). This observation has leaded to the proposition of a modification to known sludge decomposition scheme (see paragraph 4). In Fig. 7, the composition of H_2 (a), CO (b), CH_4 (c), CO_2 (d) and $C_{2's}$ (e) is shown for the three heating rates. It can be observed that the behaviour of each component analyzed is very similar in spite of the heating rate.

Table 2
Products yields (experimental and corrected) in the fixed bed reactor at three heating rates

	Yield %					
	5 °C/min[a]		10 °C/min[a]		20 °C/min[a]	
	Exp.	Corrected	Exp.	Corrected	Exp.	Corrected
Char	50.17	50.17	51.80	51.80	50.50	50.50
Tar	10.56	31.66	31.68	35.10	27.24	37.79
Gas	11.22	18.17	11.88	13.08	8.31	11.71

[a] Heating rate.

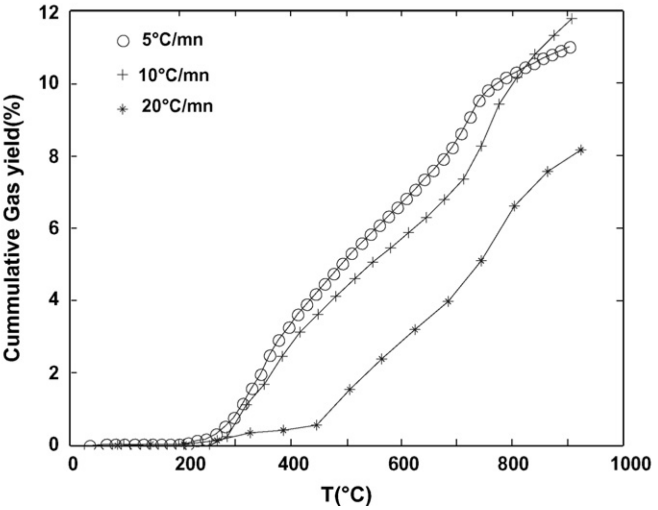

Fig. 5. Cumulative permanent gas yield of the sludge under study at three heating rates: (◯) 5 °C/min, (+) 10 °C/min, and (✱) 20 °C/min.

Hydrogen starts to increase significantly when the sample reaches 400 °C, being the most important component of the gas in volume at the temperature range 600–700 °C, after that its concentration decreases, reaching a plateau (near 60% at 5 °C, about 40% for the heating rates of 10 °C/min and 20 °C/min). CO starts to increase at 250 °C, reaching a local maximum at about 400 °C and a second and more important maximum at about 750–900 °C. Light hydrocarbons (CH_4 and $C_{2's}$), show a similar trend, appearing in the gas in significant amounts between 350 °C and 600 °C, with a maximum composition at about 500 °C where methane is more important. This temperature range matches the one at which the weight loss is more important, as observed by in the TGA experiments and most of the liquid fraction is produced.

Of the $C_{2's}$, ethane is the most important, as can be observed in Fig. 8, where the concentration of C_2H_2, C_2H_4, and C_2H_6 for the

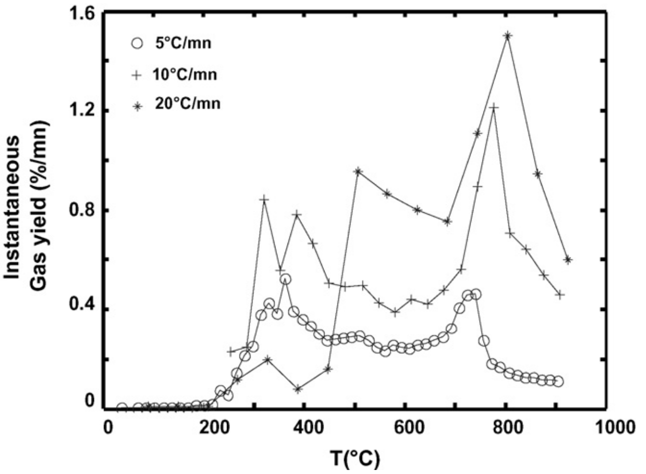

Fig. 6. Instantaneous permanent gas yield of the sludge under study at three heating rates: (◯) 5 °C/min, (+) 10 °C/min, and (✱) 20 °C/min.

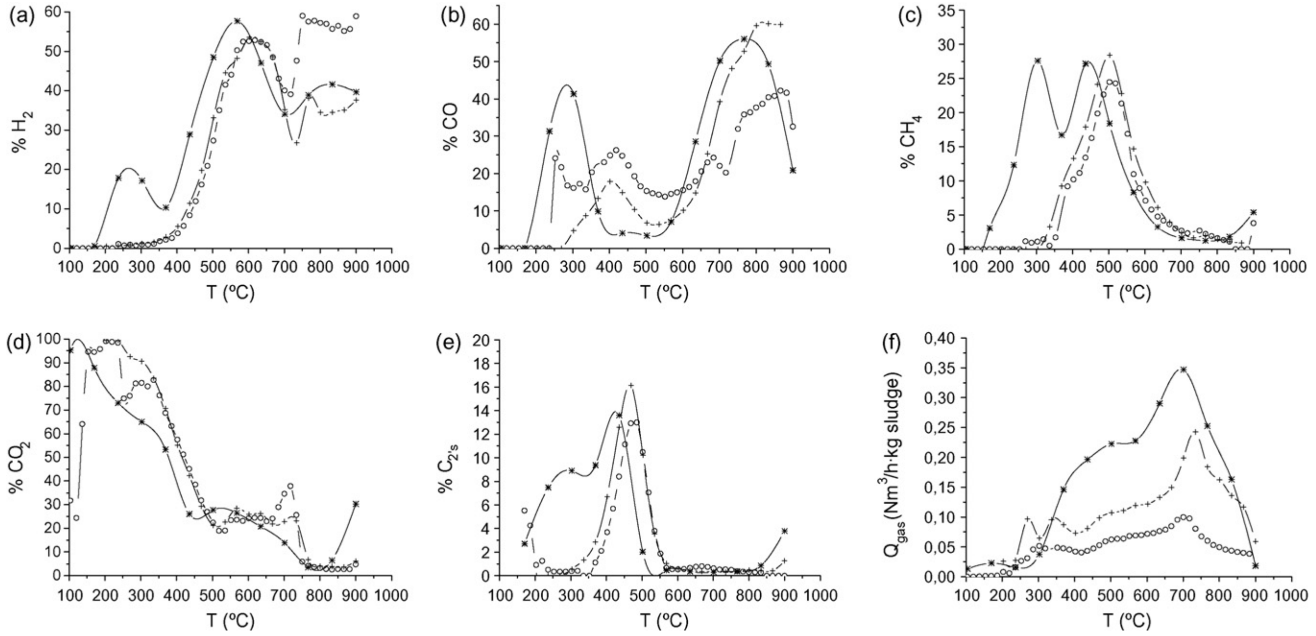

Fig. 7. Dry gas composition and flowrate, (a) H_2, (b) CO, (c) CH_4, (d) CO_2 and (e) $C_{2's}$, (f) flowrate (○) 5 °C/min, (+) 10 °C/min, and (✱) 20 °C/min.

experiment carried out at 10 °C/min are shown, the same trend was observed in [20] for C_2H_6 and C_2H_4, although in that work C_2H_2 was not analyzed.

CO_2, on the other hand, shows a different trend, being the main gas component at low temperatures and decreasing to reach a concentration plateau of about 25% of the gas, which lasts from 500 °C to 750 °C and then falls to less than 5%.

Similar trends and temperature ranges have been found by Inguanzo et al. [20] in the fixed bed pyrolysis of an anaerobically digested sludge, although in their work CO_2 is the main product by volume which also decreases when temperature increases and H_2 does not show two maximums (peaks) but a continuous increase with temperature.

Specific gas flow rate produced (Nm^3/h kg sludge) is shown in Fig. 7f). The volumetric flow rate increases up to 700 °C and then falls as the pyrolysis of the sludge is close to its end and most of the volatiles have already been depleted for the solid.

In Fig. 9 the mean gas composition obtained at each heating rate is shown. Only small differences can be observed, H_2 and CO_2 are the main components by volume, with a slight trend to decrease as the heating rate increases, where as CO tend to increase. The same tendency was observed in Meat and Bone Meal fixed bed pyrolysis [21].

Fig. 10 shows the transient evolution of the char, tar, and gas yield, obtained by thermal decomposition of the sludge under study in the fixed bed reactor at 10 °C/min. Compared to Fig. 3 (mass loss of the sample in the case of TG analysis) it can be seen that the transient evolution of the solid yield is very similar in both cases. Indeed, the main mass loss occurs between 150 °C and 600 °C and the final char yield is very similar. Dealing with the transient tar yield, one can conclude that the successive cooling and heating of the sludge (necessary to obtain these transient profiles in the case of the fixed bed reactor) does not modify too significantly the final

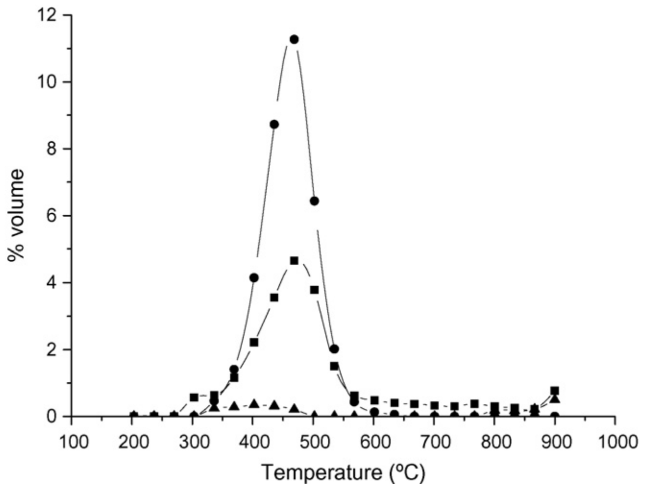

Fig. 8. % of $C_{2's}$. Experiment at 10 °C/min (●) C_2H_4, (■) C_2H_6, and (▲) C_2H_2.

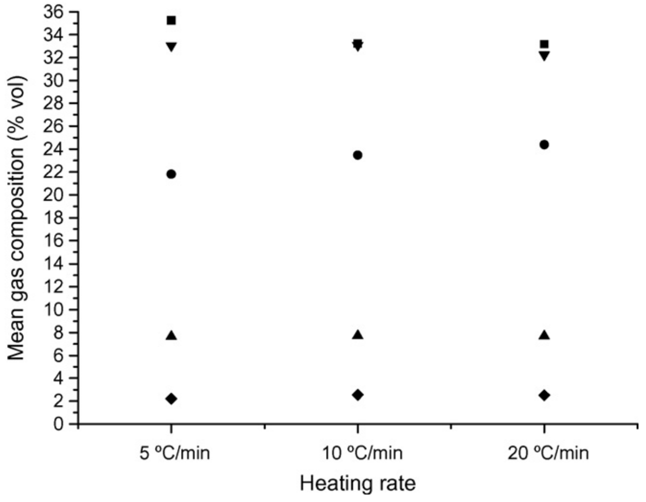

Fig. 9. Mean gas composition (●) H_2, (■) CO, (▲) CH_4, (▼) CO_2, and (♦) $C_{2's}$.

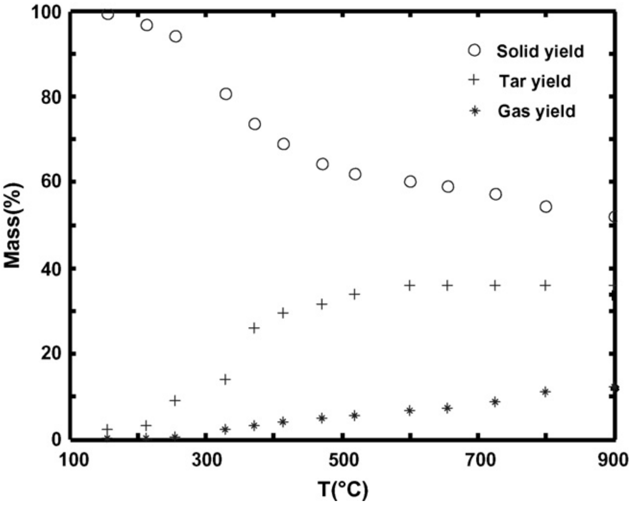

Fig. 10. Transient evolution of the char, permanent gas and tar yields in the fixed bed reactor at 10 °C/min (○) char yield, (+) tar yield, and (✱) gas yield.

tar yield (35% in the continuous fixed bed operation, 31% in the fractional mode of operation). Thus the profile depicted on Fig. 10 will be used in the following paragraphs.

4. Pyrolysis model

A kinetic model has to be used to describe the behaviour of sludge under pyrolysis. As mentioned in Section 1, different categories of kinetic schemes were already presented in the literature. In order to propose a realistic scheme, but not too complex (to be easily used in complete description where mass and energy transfer are taken into account), we will consider that the decomposition of sludge leads to the parallel formation of an intermediate species and tar and that this intermediate secondly decomposes into permanent gas and char (Fig. 11).

This scheme, initially proposed by Dumplemann et al. [5], assumed that the reaction orders were $n_1 = n_2 = 2$ and $n_3 = n_4 = 4$, respectively. It was later used by Chen and Jeyaseelan [9] but with different reaction orders, all assumed to be equal to one. Given this scheme, one is able to derive the following equations to compute the transient profiles of the different compounds:

$$\frac{\mathrm{d}X_\mathrm{S}}{\mathrm{d}t} = -k_1 X_\mathrm{S}^{n_1} - k_2 X_\mathrm{S}^{n_2}$$

$$\frac{\mathrm{d}X_\mathrm{I}}{\mathrm{d}t} = k_2 X_\mathrm{S}^{n_2} - k_3 X_\mathrm{I}^{n_3} - k_4 X_\mathrm{I}^{n_4}$$

$$\frac{\mathrm{d}X_\mathrm{T}}{\mathrm{d}t} = k_1 X_\mathrm{S}^{n_1}$$

$$\frac{\mathrm{d}X_\mathrm{G}}{\mathrm{d}t} = k_3 X_\mathrm{I}^{n_3}$$

$$\frac{\mathrm{d}X_\mathrm{C}}{\mathrm{d}t} = k_4 X_\mathrm{I}^{n_4}$$

Assuming Arrhenius law for the computation of the kinetic rate constants k_i ($k_i = A_i \exp(-E_{a,i}/\mathrm{RT})$), 8 parameters (4 pre-exponential factors and 4 activation energy) have to be estimated in order to have the complete description of the whole kinetic of pyrolysis. Computations have been carried out, for both sets of n_i values, to evaluate the set of 8 parameters which enables the best fit between the experimental data and the chosen kinetic scheme. Optimisation software (Easy fit), which minimizes the least square errors between the experimental results and the numerical predictions, was used for this task. The model which considers a first order for every reaction gave the best results. Table 3 sums up the set of parameters which gave the best fitting of experimental results and a comparison between predicted and experimental data is presented on Fig. 12. This comparison was performed at a heating rate of 10 °C/min because this configuration gave the best overall mass balance. As can be seen, even if the complete model gives a good prediction for the tar yield it seems to over predict the char yield and under predict the permanent gas yield, which starts evolving from the sample at a lower temperature than the one predicted by the model. This is the reason why we think that the proposed scheme is not accurate enough to represent the phenomenon occurring during the thermal decomposition of our sludge. In our opinion, the first decomposition of the sludge does not lead only to the production of intermediate and tar, but also to the formation of permanent gases (Fig. 13).

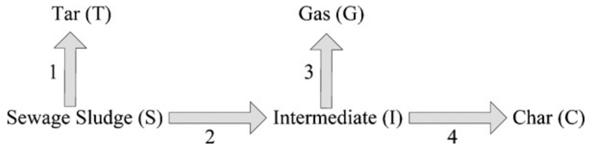

Fig. 11. First scheme for the thermal decomposition of sludge.

Table 3
Best (least mean squares) set of parameters for the model of Chen and Jeyaseelan [9]

Reaction no.	A_i (min^{-1})	$E_{a,i}$ (kJ mol^{-1})
1	13.23	31.5
2	7.42×10^5	84.8
3	3.37×10^{12}	149.1
4	1.50×10^7	69.4

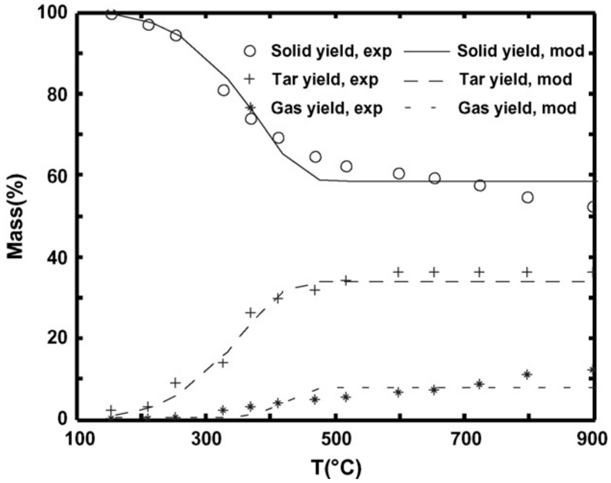

Fig. 12. Transient evolution of the char, permanent gas and tar yields in the fixed bed reactor at 10 °C/min. Comparison with Chen and Jeyaseelan model [9] (Experimental values: (○) char yield, (+) tar yield, (✱) gas yield; theoretical values: — char yield, – – tar yield, - - gas yield).

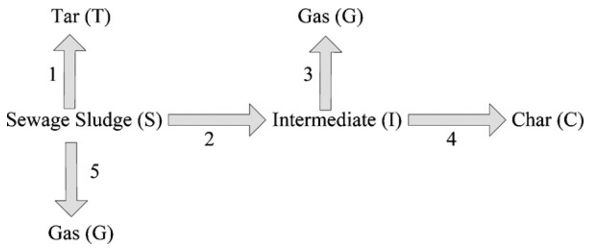

Fig. 13. Modified scheme for the thermal decomposition of sludge.

Table 4
Best (least mean squares) set of parameters for the model we propose in this work

Reaction no.	A_i (min^{-1})	$E_{a,i}$ (kJ mol^{-1})
1	16.91	31.03
2	2.25	19.00
3	5.50	57.68
4	2.45×10^{11}	252.00
5	19.52	41.64

Assuming a first order for every reaction, the transient profiles of the different compounds can be computed according to the following set of equations:

$$\frac{dX_S}{dt} = -(k_1 + k_2 + k_5)X_S$$

$$\frac{dX_I}{dt} = k_2X_S - (k_3 + k_4)X_I$$

$$\frac{dX_T}{dt} = k_1X_S$$

$$\frac{dX_G}{dt} = k_3X_I + k_5X_S$$

$$\frac{dX_C}{dt} = k_4X_I$$

The set of parameters which best fit the experimental data was estimated using the same procedure as the one presented previously. This set of parameters is reported in Table 4 and the comparison between experimental data and the model, at 10 °C/min, is shown on Fig. 14. As it can be seen, the main drawback of the first model (under prediction of the gas yield) seems to be corrected. Moreover, the new model leads to a better estimation of the final char yield.

The values resulting from our computation procedure are compared to the ones of Dumplemann et al. [5], and to the ones of Chen and Jeyaseelan [9] in Table 5.

Also, Figs. 15 and 16 show the comparison between the prediction of the present model (for which values have been computed by fitting the data at 10 °C/min) with experimental results obtained at 5 °C/min and 10 °C/min. It has to be noticed here, that because the transient evolution of the tars and char yield were available only at

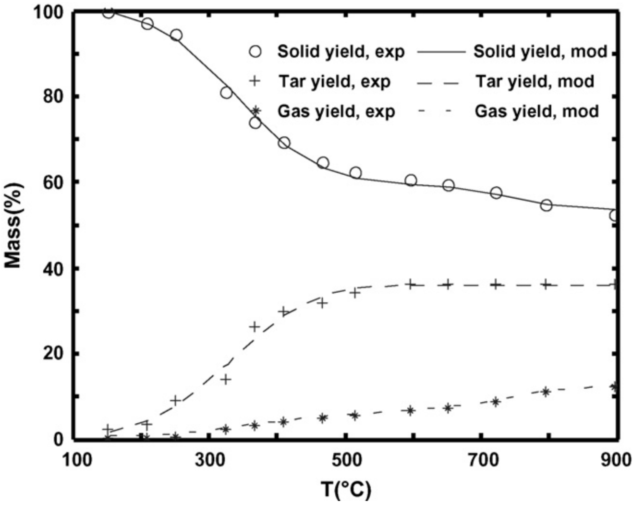

Fig. 14. Transient evolution of the char, permanent gas and tar yields in the fixed bed reactor at 10 °C/min. Comparison with the model proposed in this work. (Experimental values: (○) char yield, (+) tar yield, (✱) gas yield; theoretical values: — char yield, – – tar yield, - - gas yield).

Table 5
Comparison of the values of the parameters of our model with values from similar work in the literature.

No. of reactions	Reaction order					Pre-exponential factor (min^{-1})					Energy of activation (kJ mol^{-1})					Ref.
	n_1	n_2	n_3	n_4	n_5	A_1	A_2	A_3	A_4	A_5	E_{a1}	E_{a2}	E_{a3}	E_{a4}	E_{a5}	
4 (Fig. 11)	2	2	4	4	–	1.49×10^2	2.73×10^4	6.89×10^{12}	2.60×10^3	–	169.0	160.0	315.0	269.0	–	[5]
4 (Fig. 11)	1	1	1	1	–	2.33×10^{10}	1.39×10^9	2.78×10^{13}	7.22×10^{10}	–	52.7	73.2	205.2	78.5	–	[9]
5 (Fig. 13)	1	1	1	1	1	1.69×10^1	2.25	5.50	2.45×10^{11}	1.95×10^1	31.0	19.0	57.7	252.0	41.6	This work

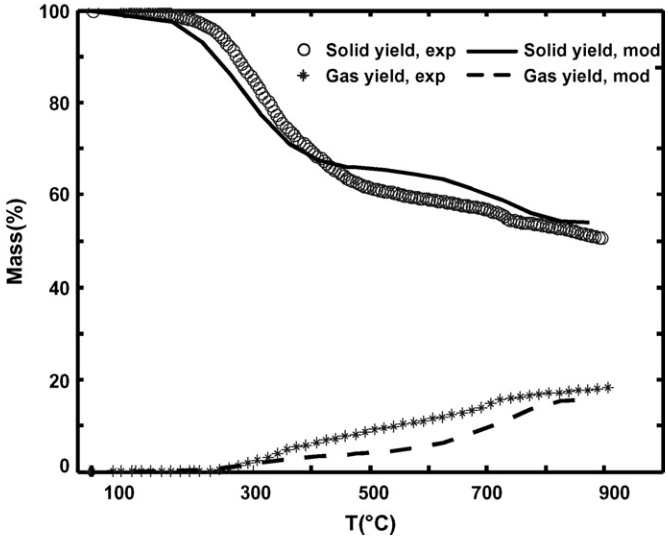

Fig. 15. Transient evolution of the char, permanent gas and tar yields in the fixed bed reactor at 5 °C/min. Comparison with the model proposed in this work. (Experimental values: (○) char yield, (✱) gas yield; theoretical values: — char yield, – – gas yield).

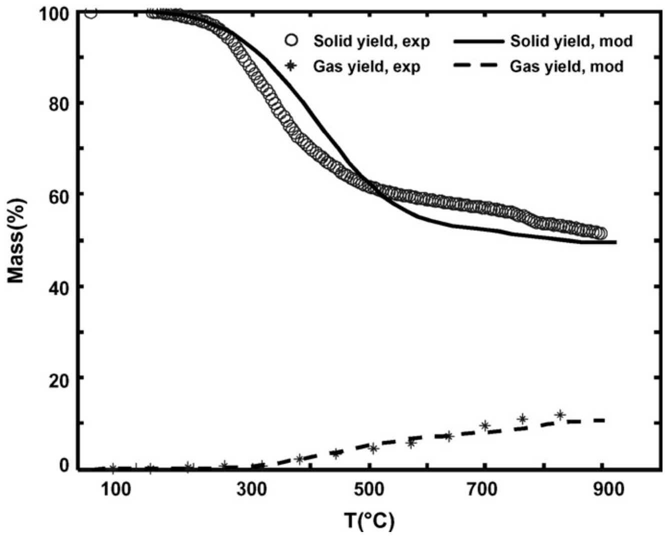

Fig. 16. Transient evolution of the char, permanent gas and tar yields in the fixed bed reactor at 20 °C/min. Comparison with the model proposed in this work. (Experimental values: (○) char yield, (✱) gas yield; theoretical values: — char yield, – – gas yield).

10 °C/min, results from TGA analysis were used in Figs. 15 and 16 to estimate the char yield. As it can be seen; the present prediction is quite correct.

5. Conclusion

This work deals with the pyrolysis of sewage sludge. Its main goal is to derive a mathematical model able to represent the complex phenomenon involved in the thermal degradation of this material. This work contains both experimental and numerical investigation. Results from TG analysis were used in order to gather information about the temperatures at which the decomposition occurs. The fixed bed device was used in order to get insights into the process of gas production and also to give insights into the transient evolution of tar yield. This specific trend is very important because it allows for a better understanding of the phenomenon involved. Also, it gives several points for the estimation of the parameters of the mathematical model that was checked in this work. Dealing with this mathematical formulation, different kinetic schemes published in the literature were firstly studied to fit our experimental data. The one considering the formation of an intermediate compound seemed the most appropriate. However, with the sludge used in this study, this kinetic scheme was not able to accurately predict the char and gas yield. Consequently, it was partially modified by assuming a third parallel step in the first decomposition of sludge. The use of the new model, with the adapted set of parameters, gave a very good description of the experimental results and can be recommended for further works.

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