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Thermogravimetric analysis and kinetic study on pyrolysis of representative medical waste composition

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Abstract

To obtain detailed information on the pyrolysis characteristics, a thermogravimetric study on the pyrolysis of 14 typical medical waste compositions was carried out in thermogravimetric analysis (TGA) equipment using dynamic techniques in a stream of N₂. An index representing pyrolysis reactivity of waste was presented. Kinetic parameters were obtained by Coats–Redfern method and used to model the TG curve. The results showed that: (a) Plastic, protein, cellulosic material, synthetic fibre, and rubber entered pyrolysis process in succession. (b) There was one decomposition stage in the pyrolysis of one-off medical glove, operating glove, cellulosic waste, absorbable catgut suture and adhesive plaster, while other components had two obvious weight loss stages. (c) The obtained apparent activation energy for second stage pyrolysis was comparably higher than that for first stage. (d) Each stage was controlled by only one kinetic mechanism, in which kinetic parameters were constant. (e) The degradation kinetics of medical waste may be affected by special physical and chemical treatment in the product manufacturing process. (f) Among 13 waste samples, the pyrolysis index of cellulosic matter was the highest, which indicated cellulosic matter had strong pyrolysis reactivity. (g) With increasing heating rate, TG curve and DTG peak shifted to high temperatures and main reaction interval of the sample became longer.

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1. Introduction

The problem of solid waste disposal including medical wastes and other toxic hazardous wastes is growing throughout the world, as a direct result of rapid industrialization and population growth. Especially, the disposal of hospital waste has been a serious environmental problem because the wastes also contain infectious wastes and will pose a great health risk to the public if they are not properly disposed of. For example, diseases like diarrhea, leptospirosis, typhoid and cholera can be transmitted through mismanagement of wastes. Moreover, because of the recent acquired immune deficiency syndrome (AIDS) dilemma, Severe acute respiratory syndrome (SARS) epidemic, Avian influenza and those posed by other communicable diseases such as hepatitis B, the public is increasingly concerned over the handling of medical waste.

Environmental Protection Agency (EPA) research data and industry operating experience indicate that incineration has historically been the most widely used treatment technology for the disposal of medical waste (Lee and Huffman, 1996). There are many other technologies such as autoclaving, gas sterilization, and chemical disinfection, but many unavoidable disadvantages exist in each method, such as tail gas pollution and exhaust of dioxins to the environment in waste incineration. Now a novel pyrolysis technology for the treatment of medical waste is coming into use (Zhang et al., 2003), which could reduce waste mass, make it innocuous, and finally convert it into fuel; the technology has been proposed for the treatment of municipal solid waste (MSW) and biomass by many scientists (Sørum et al., 2001; Font and Williams, 1995; García et al., 1995). In China, high-temperature pyrolysis technology has been designated in centralized treatment technology.
criterion of medical waste issued Dec 2003 by the government. So it is important to have knowledge on the characterization of medical waste related to pyrolysis.

Characterization of the quantities and composition of medical waste has to some extent been reported in previous work (Lee and Huffman, 1996); however, proximate and ultimate analysis, especially the pyrolysis studies including thermogravimetric analysis and kinetic modeling of single and mixed medical waste composition, had hardly been seen. The lack of data on the characteristics and kinetics of pyrolysis has motivated this work.

In order to understand the pyrolysis mechanism of medical waste and provide basic first-hand information for industrial application, the study turns to thermogravimetric analysis, which is one of the techniques for studying the primary reaction in the decomposition of solids, and has been widely used to study the mechanism and kinetics of the thermal decomposition of biomass, tires, solid waste and other materials (Sørum et al., 2001; Cooley and Antal, 1988; Williams et al., 1990; Cárdenas and Bartulin, 1982; Hirschler, 1986; Wu et al., 1994; Cho et al., 1998; Williams and Besler, 1995). The interpretation of the experimental data can provide information on the composition of the matter studied, order of the reaction, number of different processes taking place in the reaction, and the corresponding kinetic constants (Swaminathan and Madhavan, 1979; Sørensen, 1979; Dharwadkar et al., 1978).

In the present work, the thermal decomposition of medical waste in DTG equipment has been studied. The following objectives have been proposed:

1. To obtain detailed information about the process of medical waste decomposition.
2. To propose an index presenting matter reactivity, viz., pyrolysis ability.
3. To obtain kinetic parameters of the main reaction of pyrolysis for medical waste decomposition, and simulate the pyrolysis process.
4. To investigate the influence of heating rates on behavior of medical waste treated by pyrolysis.

2. Experimental

2.1. Materials

Medical waste refers to any waste generated from the healthcare industry such as hospitals and medical laboratories. The overriding characteristic of medical waste is its heterogeneity. Medical waste includes paper, plastics, pathological wastes, animal carcasses, blood soaked-bandages, intravenous bags and many other types of materials. There is a large variation in the composition of medical waste. These variations have a dramatic impact on the performance of medical waste treatment equipment. Those representative components that are commonly present in medical waste were chosen for this work. The samples studied in this work contained 14 materials, which are tubes for transfusion, sample collector for urine, one-off medical glove, operating glove, catheter, cotton swabs, toilet paper, gauze, absorbent cotton, absorbable catgut suture, muscle of white rat, filling of dressing, adhesive plaster and dressing, which were supplied by Tianjin General Hospital. The main constituent and ultimate analysis of the samples are listed in Table 1. Ultimate analysis for multi-material was not done because it is a heterogeneous material.

To meet medical application, medical wastes were dealt with special physical and chemical treatment in the manufacturing process, for example, disinfection of all medical products, addition of kinds of medicine to adhesive plaster and dressing, and chemical modification such as additives of plasticizer, stabilizer, intensifier, flame retardant and so on. The special technological process in production of a medical product may affect its degradation behavior and kinetics, which has been observed in later research.

2.2. Apparatus and procedure

The equipment used to carry out the pyrolysis of medical waste was a SHIMADZU DTG-60H thermobalance. The simultaneous TGA-DTA instrument is based on a dual-beam horizontal design in which each ceramic beam (arm) functions as one-half of a DTA thermocouple pair, as well as part of a horizontal null-type balance. One arm accommodates the reference and the other accommodates the sample and measures its changes in property. The temperature was controlled and measured by the thermocouple placed at the bottom of the crucible, close to the sample. The crucible was pyro-ceramic material and the reference substance was an appropriate amount of inert material, Al₂O₃ (aluminum oxide) powder.

The dynamic (non-isothermal) runs were performed in an atmosphere of N₂ at 20 °C/min for all medical samples. Firstly, high purity N₂ was purged for 40 min at a flow rate of 75 ml/min, before starting the heating of the samples, to be sure of an atmosphere free of oxygen. The nitrogen used in obtaining the results was at a flow rate of 20 ml/min. All samples were heated up to the desired temperature (600, 800 or 1000 °C) at the pre-selected heating rate of 20 °C/min. Besides, the experiments of tube for transfusion were performed at different heating rates, 5, 10, 20, 30, 50 °C/min to investigate the influence of heating rate on pyrolysis characteristics of the sample.

The mass of sample spread in the crucible varied from 2 to 9 mg, because the specific gravity of materials differs greatly from each other. The samples were cut into very small pieces, about 0.5 mm in diameter, and distributed all over the surface of the crucible, forming a layer with a thickness less than 2 mm, to ensure a representative sample from the different materials and a reaction situation mainly controlled by chemical kinetics, free of heat transfer and mass transfer.

A check of the repeatability of experiments was performed for all samples. The results showed the TG and
the DTG curves were almost identical, consequently giving very low standard deviations (less than 1.5%) on the obtained calculated kinetic parameters. The results presented here are a set of ones among those experiments which meet the above-mentioned conditions.

3. Results and discussion

3.1. Pyrolysis of medical waste

It is obvious that the samples contain the following fractions, as shown in Table 1: plastic fraction (tube for transfusion, sample collector for urine, one-off medical glove), rubber fraction (operating glove, catheter), cellulosic fraction (cotton swabs, toilet paper, gauze, absorbent cotton), protein fraction (absorbable catgut suture, muscle of white rat), synthetic fibre fraction (filling of dressing) and multi-material fraction (adhesive plaster, dressing). The thermal analyses data of all test samples at a heating rate of 20 °C/min are presented. Among the fractions, cellulose and protein are a natural macromolecule compound, while the others are a synthetic macromolecule. Therefore, pyrolysis of medical waste could be regarded as pyrolysis of high macromolecule compound to some degree.

The TG and DTG curves of all the analyzed samples at heating rate of 20 °C/min are shown in Figs. 1 and 2, respectively. The percentage weight loss, based on the initial weight, is reported as the ordinate in Fig. 1. The rates of weight loss obtained by differentiation of weight loss curves expressed in milligrams are shown in Fig. 2.

It can be observed that the initial and final temperatures of the decomposition of all samples are different. This is attributed to the difference in pyrolysis characteristics of experimental materials. Below 150 °C, the cellulosic fraction, protein fraction and synthetic fiber fraction show slight weight loss due to water evaporation, while between 200 and 290 °C, all samples enter a strong weight loss process successively, which denotes that pyrolysis is taking place; up to 600 °C, most compositions slow or nearly finish the procedure except catheter, whose visible weight loss still occurs between 680 and 780 °C; up to 800 °C. Fourteen samples finally end their pyrolysis. However, for existence of subordinate reaction, there was no absolute plain tailing section even in end of the TG curve for most test samples. Taking into account the information described above, the hearth temperature of the pyrolytic reactor should be

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Table 1

| Sorts           | Samples                     | Major constituent | wt.%       |
|-----------------|-----------------------------|-------------------|------------|
|                 |                             |                   | C    | H    | O*  | N    | S    | Cl   | Si   |
| Plastic         | Tube for transfusion        | PVC               | 50.87| 7.06 | 7.56| n.a. | 0.46 | 34.05| –    |
|                 | Sample collector for urine  | PVC               | 42.81| 5.95 | 3.12| n.a. | 0.73 | 47.39| –    |
|                 | One-off medical glove       | LDPE              | 86.19| 13.41| 0.40| n.a. | n.a. | –    | –    |
| Rubber          | Operating glove             | Natural rubber    | 86.06| 10.27| 2.04| 0.42 | 0.42 | 1.04 | 0.17 |
|                 | Catheter                    | Natural rubber, CaCO₃ | 43.86| 5.79 | 48.45| 0.35 | 1.23 | 0.32 |
| Cellulosic      | Cotton swabs                | Cellulose, hemicellulose, lignin | 46.26| 6.43 | 47.09| n.a. | 0.22 | –    | –    |
|                 | Toilet paper                |                   | 41.63| 5.71 | 52.35| n.a. | 0.31 | –    | –    |
|                 | Gauze                       |                   | 42.51| 6.35 | 51.01| n.a. | 0.13 | –    | –    |
|                 | Absorbent cotton            |                   | 42.90| 6.69 | 50.19| n.a. | 0.22 | –    | –    |
| Protein         | Absorbable catgut suture    | Collagen          | 43.16| 7.60 | 34.85| 13.59| 0.80 | –    | –    |
|                 | Muscle of white rat         | Actin, myosin     | 50.08| 7.36 | 28.44| 12.81| 1.31 | –    | –    |
| Synthetic fibre | Filling of dressing         | PVA               | 54.50| 5.18 | 40.16| n.a. | 0.16 | –    | –    |
| Multi-material  | Adhesive plaster            | Rubber, textile, Chinese traditional medicine, pot clay | –    |     |     |     |     |     |     |
|                 | Dressing                    | Paper, fiber, cotton yarn, hemostat | –    |     |     |     |     |     |     |

—: not tested.
n.a.: tested but not available.
O*: obtained by mass balance, containing impurity content.
PVC = polyvinyl chloride; LDPE = low-density polyethylene; PVA = polyvinyl alcohol.
800 °C or higher in engineering design, to ensure the farthest reaction.

Many medical waste compositions show one major weight loss stage. However, for other components, like tube for transfusion, sample collector for urine, catheter, filling of dressing and dressing, there appear two stair stepping stages (see Fig. 1), which are clearly expressed with two prominent peaks in Fig. 2. This is caused by the individual physical and chemical composition of each test material, playing a fundamental role in pyrolytic behavior. For example, tube for transfusion mainly consists of PVC (polyvinyl chloride), presenting two-stage degradation behavior. The first stage is the de-hydrochlorination of the polymer and the formation of a proportion of volatile organic compounds; during the second stage, the evolution of toluene together with a small quantity of other alkyl aromatics takes place, yielding a residual char (Marcilla and Beltran, 1995). In the case of dressing, the multi-material containing paper, synthetic fibre and gauze, such three physical ingredients control the pyrolytic behavior together, presenting two-stage weight loss.

Table 2 shows the key temperature points of the TG and DTG curve of every test specimen, containing temperature interval ΔT, extrapolated onset temperature T_onset, extrapolated endset temperature T_endset and temperature at the peak maximum T_max of every stage weight loss of decomposition. Thus, it is observed that the obvious weight loss of plastic matter occur at 200–580 °C, with two-stage decomposition for tube for transfusion, sample collector for urine and one-stage decomposition for one-off medical glove. The degradation of rubber matter take place in 250–500 °C, connected to the pyrolysis of natural rubber, with maximum rate of weight loss at 396 °C. But there is still second stage weight loss for catheter as stated above. The decomposition of cellulosic and protein matter appear in 200–420 °C and 230–480 °C, respectively, with the T_max at 382 °C and 350 °C, respectively. For the synthetic fibre fraction (filling of dressing), two stages of weight loss in 270–390 °C and 390–510 °C can be observed. The last fraction, multi-material, containing paper, synthetic fibre and gauze, such three physical ingredients control the pyrolytic behavior together, presenting two-stage weight loss.

The weight loss caused by the evaporation of moisture from the sample is also reported in Table 2, with protein matter having the highest moisture content.
The weight loss of test samples is up to 95% at 800 °C, except 85% for catheter and 90% for protein matter, which proves that pyrolysis technology can remarkably reduce the mass of waste, and provides data for the deslagging design of the pyrolytic boiler.

The most active reaction step is the research focus on thermogravimetric analysis, reflecting strong pyrolysis behavior, which can be briefly represented by the point, maximum rate of weight loss \( \frac{d\alpha}{dT}_{\text{max}} \), with corresponding temperature at \( T_{\text{max}} \). As shown in Table 2, all \( T_{\text{max}} \) locate within the temperature range of 310–450 °C (comparatively higher \( \frac{d\alpha}{dT}_{\text{max}} \) was chosen in two-stage weight loss). Thereby, it was of consideration to extend the residence time of the feedstock in the above time interval, to ensure reaction to the maximum extent.

3.2. Pyrolysis index

It is learned that from the DTG peaks of samples differing in position and height, the information on sample reactivity may be deduced. Then, considering an expression using the proper value obtained by the DTG curve may reflect the pyrolytic ability of matter. Ghetti et al. (1996) used traditional 100(\( \frac{d\alpha}{dT} \))_{\text{max}}/T_{\text{max}} and Li et al. (1999) proposed their opinion with \( I_r = \frac{d\alpha}{dT}_{\text{max}}/(T_{\text{max}} \cdot \Delta T) \) to describe pyrolysis characteristics of biomass or MSW. Ghetti et al. did not consider unscattered degree of decomposition and Li et al. ignored the temperature of the beginning and ending of the procedure. Especially, the conversion fraction of which material could pyrolyze, a very important value describing the pyrolytic ability of matter, escaped their attention.

The pyrolysis index is presented here, expressed as follows:

\[
I_r = \left( \frac{d\alpha}{dT} \right)_{\text{max}} \cdot \frac{\Delta T}{(T_{\text{max}} \cdot T_{\text{onset}} \cdot T_{\text{endset}})}
\]

Hereinto, \( \left( \frac{d\alpha}{dT} \right)_{\text{max}} \) and \( \Delta T \) are directly proportional to the reactivity, while the temperature \( T_{\text{onset}}, T_{\text{endset}} \) and \( T_{\text{max}} \) are inversely proportional to that. Thus \( I_r \) was calculated for each peak of every material, and then the weighted mean value for those which had two weight loss peaks was obtained. The results at a heating rate of 20 °C/min are reported in Table 2. Of course, \( I_r \) is still related to particle size, property of feedstock and influenced by heat transfer and mass transfer of the procedure. Comparing the results, it is clear that the cellulosic fraction (a bit lower for cotton swabs) and operating glove have the highest value of \( I_r \), plastic matter, with cotton swabs and adhesive plaster in the next place; the lowest is the value for catheter, protein fraction, filling of dressing and dressing. So, in view of pyrolytic reactivity, samples may be ranked in the same decreasing order. The lower the value of \( I_r \), the poorer the ability to pyrolyze. This is in agreement with the visual experimental results.

3.3. Influence of heating rates on pyrolysis behavior

Fig. 3 show TG and DTG curves of tube for transfusion (TFT) decomposition at different heating rates of 5, 10, 20, 30, and 50 °C/min. The shift of the peak to high temperatures and the spread of the main reaction section can be observed when the heating rate is increased. This is because when the heat transfer rate is not high, temperature differences and temperature gradients increase in combination with a serious effect of thermal lag, between test point and specimen, outer layer and inside of specimen. A lower heating rate helps to reduce the phenomena.

3.4. Kinetic model

The large variety in medical waste composition and various additives including plasticizer, stabilizer, fire retardant for every compositions results in remarkable distinction in thermal degradation behavior. However, they have the same property. That is, the decomposition procedure of every stage is essentially dominated by a leading reaction, meanwhile, coupled with a series of subordinate competing reactions. According to this, assuming every stage pyrolysis was only controlled by one major reaction mechanism, the kinetic parameters in this stage were invariable with temperature increasing. In this case, a model of single reaction can describe the overall decomposition by stages.

Applying the Coats–Redfern method (Coats and Redfern, 1964), an integrative approach with low deviation, to every temperature stage as shown in Table 2, the kinetic parameter was then calculated. The method benefiting from not using data of the DTG curve is based on the following general equation:

\[
\frac{dz}{dt} = A \exp \left( -\frac{E}{RT} \right) (1 - \alpha)^n
\]

where \( \alpha \) is the degree of conversion, defined in each decomposition stage as \( \alpha = \frac{W_t - W_f}{W_0 - W_f} \). The meaning of notations refers to the list of symbols in the Appendix. Expressing time by temperature and heating rate, Eq. (1) can be written as

\[
\frac{dz}{dT} = \frac{A}{\beta} \exp \left( -\frac{E}{RT} \right) (1 - \alpha)^n
\]
Thus, integrating this equation and taking logarithms, the following expression can be obtained:

\[
\begin{align*}
\text{when } n &\neq 1, \quad \ln \left[ \frac{1 - (1 - \alpha)^{1-n}}{T^2(1 - n)} \right] = \ln \left[ \frac{AR}{\beta E} \left( 1 - \frac{2RT}{E} \right) \right] - \frac{E}{RT} \\
\text{when } n &\neq 1, \quad \ln \left[ \frac{-(1 - \alpha)^{1-n}}{T^2} \right] = \ln \left[ \frac{AR}{\beta E} \left( 1 - \frac{2RT}{E} \right) \right] - \frac{E}{RT}
\end{align*}
\]

For usual reaction at possible temperature, \( \frac{E}{RT} \gg 1, (1 - \frac{2RT}{E}) \approx 1 \). Hence, the first part of the right hand of Eqs. (3) and (4) is regarded as constant. So a line with slope \( -\frac{E}{RT} \) and intercept \( \ln \left[ \frac{AR}{\beta E} \right] \), can be obtained by plotting the left hand of Eqs. (3) and (4) vs. \( \frac{1}{T} \), with \( n \) correctly selected. In this way, a set of kinetic parameters can be obtained, as reported in Table 3.

\[\text{Table 3} \]

| Samples                      | E (kJ/mol) | A (min\(^{-1}\)) | n   | r  |
|------------------------------|------------|-------------------|-----|----|
| Tube for transfusion         | 110.42     | 3.28 \(\times\) 10\(^9\) | 1   | 0.998 |
|                              | 246.94     | 9.87 \(\times\) 10\(^{16}\) | 1   | 0.982 |
| Sample collector for urine   | 130.62     | 2.09 \(\times\) 10\(^7\) | 1   | 0.975 |
|                              | 208.27     | 2.19 \(\times\) 10\(^{14}\) | 1   | 0.982 |
| One-off medical glove        | 181.36     | 2.15 \(\times\) 10\(^{12}\) | 0   | 0.999 |
| Operating glove              | 148.81     | 1.74 \(\times\) 10\(^{11}\) | 1   | 0.993 |
| Catheter                     | 117.61     | 5.70 \(\times\) 10\(^9\)   | 1   | 0.992 |
|                              | 412.92     | 1.35 \(\times\) 10\(^{11}\) | 1   | 0.999 |
| Cotton swabs                 | 84.45      | 4.07 \(\times\) 10\(^9\)   | 1   | 0.993 |
| Toilet paper                 | 170.11     | 6.91 \(\times\) 10\(^3\)   | 1   | 0.992 |
| Gauze                        | 185.85     | 7.62 \(\times\) 10\(^{14}\) | 1   | 0.998 |
| Absorbent cotton             | 198.23     | 7.70 \(\times\) 10\(^{15}\) | 1   | 0.999 |
| Absorbable catgut suture     | 85.47      | 6.02 \(\times\) 10\(^6\)   | 1.5 | 0.993 |
| Muscle of white rat          | 80.62      | 2.09 \(\times\) 10\(^9\)   | 1.5 | 0.992 |
| Filling of dressing          | 147.90     | 1.69 \(\times\) 10\(^{12}\) | 1   | 0.998 |
|                              | 228.12     | 2.02 \(\times\) 10\(^{16}\) | 1   | 0.999 |
| Adhesive plaster             | 128.60     | 9.45 \(\times\) 10\(^9\)   | 1   | 0.994 |
| Dressing                     | 135.98     | 1.14 \(\times\) 10\(^{11}\) | 1   | 0.994 |
|                              | 285.31     | 3.94 \(\times\) 10\(^{21}\) | 1.5 | 0.992 |

Few data on kinetic parameters for the degradation of medical waste has been published in the literature, while there was much information for similar materials, i.e., with similar physical and chemical compositions.

3.5. Comparison with kinetic parameters obtained by other authors

For the second stage, the values obtained in this paper for tube for transfusion and sample collector for urine were 239.1 kJ/mol for \( A \), and 4.70 \(\times\) 10\(^{16}\) min\(^{-1}\) and 1.62 for \( n \).
3.5.2. One-off medical glove

As listed in Table 3, the activation energy of 181.36 kJ/mol, pre-exponential factor of $2.15 \times 10^{12}$ min$^{-1}$ and reaction order of 0 were presented for one-off medical glove, which had LDPE as its main ingredient, separating from PVC plastics by having one-stage degradation behavior. Cho et al. (1998) reported activation energy 146.8 kJ/mol by Kissinger equation. In the literature, an activation energy of 194–246 kJ/mol (Marcilla and Beltran, 1995; Wu et al., 1992, 1993) was found for LDPE. The researchers gave fluctuations of 146–246 kJ/mol for $E$. The results presented in this paper were in the middle area.

3.5.3. Operating glove and catheter

Natural rubber (NR) was a leading ingredient of operating glove and catheter. It is obvious that the weight loss at 260–500 °C for the two samples was caused by NR decomposition. The kinetic parameters obtained were 148.81 and 117.61 kJ/mol for the $E$, $1.74 \times 10^{11}$ and $5.70 \times 10^{8}$ min$^{-1}$ for $A$, and 1 for $n$, respectively. The values of 199.9 kJ/mol for $E$, $1.2 \times 10^{14}$ s$^{-1}$ for $A$ have reported in the literature (Williams and Besler, 1995).

In addition, the catheter sample showed a degradation stage at 685–776 °C, which was due to the additive CaCO$_3$. The activation energy was 412.9 kJ/mol, pre-exponential
factor was $1.35 \times 10^{21} \text{min}^{-1}$, and reaction order was 1 (Table 3). There were values applying the Arrhenius differential method for CaCO$_3$ degradation in the literature (Dollimore et al., 1996): 391 kJ/mol for $E$, $2.74 \times 10^{18} \text{min}^{-1}$ for $A$. The data are very close to those reported here.

### 3.5.4. Cotton swabs/toilet paper/gauze/absorbent cotton

All the four samples are biomass material. The kinetic parameters obtained were 84.45, 170.11, 185.85 and 3.5.4.3. For primary and heterogeneous secondary reaction were as their main components. So the kinetic parameters for the latter three materials are very close.

Reina et al. (1998) reported kinetic parameters for waste wood (furniture, forest and pallet) obtained by dynamic experiment (2 °C/min) at the same conversion (0.75). The results were 127.61–136.18 kJ/mol for $E$; 4.07 $\times 10^6$, 6.91 $\times 10^3$, 7.62 $\times 10^4$ and 7.70 $\times 10^15 \text{min}^{-1}$ for $A$; and 1 for $n$, respectively. Among them, cotton swabs separated from the others by having the cellulose, hemicellulose and lignin; while, toilet paper, gauze and absorbent cotton contained only cellulose as their main components. The data are very close to those reported here.

### 3.5.6. Filling of dressing

Filling of dressing mainly consists of PVA; however, very little data about the degradation of PVA was found in the literature, so there is no comparison with other authors. To compensate, more experiments (5, 10, 20, 30, and 50 °C/min for filling of dressing) were conducted here to provide kinetic data. The Kissinger model was applied for the kinetic data to calculate the kinetic parameters. $E$ of 143.34 and 159.50 kJ/mol, and $A$ of $5.46 \times 10^8$ and $1.97 \times 10^8$ for two-stage degradation of filling of dressing were obtained. The activation energies of the two methods were much at one for the first stage, with some deviation for the second stage.

### 3.5.7. Others

As multi-materials, adhesive plaster and dressing links kinetic behavior with its physical ingredients. The kinetic data is not discussed here; further work will be done.

As can be seen from the comparison with kinetic parameters obtained by other authors, some results are very close to each other, others show an acceptable dispersion. Differences can be attributed to the effect of experimental conditions, to the kinetic model used, and especially to the special physical and chemical treatment of medical wastes. The catalytic effect caused by kinds of additives such as plasticizer, in the case of tube for transfusion and sample collector for urine, may enhance the reactivity and lower the activation energy of de-chlorination in PVC degradation.

### 4. Conclusions

From the study on thermogravimetric analysis of medical waste composition, the following conclusions can be deduced:

1. Because characteristic physical and chemical composition of medical waste compositions play a fundamental role in pyrolytic behavior, many of them show one major weight loss stage, but others appear in two stage-stepping stages. The activation energy of secondary stage pyrolysis is quite higher than that of the first stage and that of only one stage.

2. The maximum of rate of weight loss highly centralizes within 310–450 °C.

3. The weight loss of the absolute majority of test samples is up to 95% at 800 °C, which proves that the pyrolysis technology can remarkably reduce the mass of waste.

4. When the heating rate increases, the TG curve and DTG peak shift to high temperatures and the main reaction interval of the sample becomes longer.

5. It is advisable that assuming that every stage pyrolysis of medical waste components was only controlled by one major reaction mechanism; the kinetic parameters in this stage were invariable with temperature increasing.

6. It is observed that, roughly, the results show a comparatively good agreement between calculated and experimental curves, proving that the model of single reaction mechanism dominating each decomposition stage is adaptable.

7. From the comparison with kinetic parameters obtained by other authors, some results are very close, others show an acceptable dispersion. Differences can be attrib-
uted to the effect of experimental conditions, to the kinetic model used, and especially to the special physical and chemical treatment of medical wastes in the manufacturing process for meeting medical application.

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Appendix A

List of symbols

- $A$: pre-exponential factor, min$^{-1}$
- $E$: apparent activation energy, kJ/mol
- $I_r$: pyrolysis index
- $k$: reaction rate constant, s$^{-1}$
- $M$: weight loss caused by moisture evaporating from sample, wt.%
- $n$: reaction order
- $R$: universal gas constant, 8.3145 J/(mol K)
- $r$: correlation coefficient
- $\Delta T$: temperature interval corresponding to each stage
- $T_{onset}$: value of extrapolated onset temperature for beginning of decomposition, °C
- $T_{endset}$: value of extrapolated endset temperature for end of decomposition, °C
- $T_{max}$: value of temperature at the peak maximum for the decomposition procedure, °C
- $W_0$: initial sample weight, mg
- $W_{\infty}$: final sample weight, mg
- $W$: sample weight at time $t$, mg
- $\alpha$: conversion fraction of sample, %
- $\eta$: weight loss of sample of every stage, %
- $\beta$: heating rate, °C/min

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