



# A particle scale model for municipal solid waste and refuse-derived fuels pyrolysis



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## ABSTRACT

The solid phase decomposition during pyrolysis of municipal solid waste (MSW) and refuse-derived fuels (RDF) is modelled on particle scale accounting for heat and mass transfer. Waste pyrolysis is expressed as a linear combination of pyrolysis of its components. The novel characterization method used expresses waste composition in terms of three reference species. The selected species are a mixture of cellulose and hemicellulose, a mixture of polystyrene and polyethylene terephthalate, and a mixture of polyethylene and polypropylene. The pyrolysis kinetics models for these components are taken from the literature. The fractions of the components in the mixtures are optimized to fit the model to non-isothermal mass loss curves from selected experimental reports. The particle scale model has been evaluated against experimental transient temperature profiles at the centre of a large waste pellet during pyrolysis. The model is able to predict the main trend, but shows a more fluctuating temperature curve.

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## 1. Introduction

The production of municipal solid waste (MSW) has been continuously increasing as a result of higher product demand and increasing wealth and standard of living over the whole world, mainly due to globalization and population increase (LONDO, 2013). Therefore, it is of utmost importance that MSW is treated in a sustainable way. A first option is to simply reduce the amount of waste by smart design of more sustainable products, such as natural, highly biodegradable or long lifetime products. Another option is recycling; a lot of useful material can be found in MSW that can be reused to make new products, hence reducing the required raw material resources. Composting is yet another option, which comprises collection of the organic part of the waste and its storage under conditions, which are optimal for its natural break down by microorganisms. The residue can be used as a fertilizer. It is also possible to recover energy (heat, electricity, or in the form of gaseous and/or liquid fuel) from the non-recyclable part of the waste. The most important processes used are anaerobic digestion, landfill gas recovery, incineration, gasification and pyrolysis (United States Environmental Protection Agency, 2015). Most

of them require a form of pre-processing of the MSW to recover recycled elements such as metals and glass, which usually do not take part in the reactions. This processed MSW is referred to as refuse-derived fuel (RDF).

The present study concerns MSW pyrolysis. In comparison to incineration, the main advantages of pyrolysis are the production of syngas and useable solid residue, lower NO<sub>x</sub> and SO<sub>2</sub> emissions and the flexible capacity. The disadvantages are the variable MSW composition, which complicates the design of a pyrolysis facility, and the need for pre-processing to remove recyclable solids and moisture. Furthermore, the research done on MSW pyrolysis technology is limited and the environmental impact is still largely unknown.

In order for pyrolysis process design, waste pyrolysis models are needed to describe the reaction kinetics (solid phase decomposition, reactions in the gas phase and between the gases and the solid phase), product distribution and heat and mass transfer rates on the particle and reactor scale. Accurate modelling of these phenomena will help understanding the role and importance of the influencing parameters, such as temperature, pressure, heating rate, particle size, and waste composition. The main objective of this study is to develop a new kinetic model that predicts the loss of mass of MSW and RDF during pyrolysis. This is done via modelling of the individual decomposition of several of its components. Mass and energy balance equations have been coupled to the kinetic model to describe the particle scale transport phenomena. The full

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**List of symbols**

MSW	Municipal solid waste
RDF	Refuse-derived fuel
TG	Thermogravimetric
TGA	Thermogravimetric analysis
Bi	Biot number (/)
Py	Pyrolysis number (/)
$h$	Convective heat transfer coefficient (W/m <sup>2</sup> K)
$L$	Characteristic length (m)
$\lambda$	Thermal conductivity (W/mK)
$k$	Reaction rate (1/s)
$\rho$	Density (kg/m <sup>3</sup> )
$c_p$	Specific heat capacity (J/kgK)
$X$	Conversion (/)
$A$	Pre-exponential factor (1/s)
$E$	Activation energy (J/mol)
$R$	Universal gas constant (J/Kmol)
$n$	Reaction order (/)
$W$	Mass (kg)
$W_\infty$	Mass at the end of reaction (kg)
$W_C$	Mass of cellulosic fraction (kg)
$W_{NC}$	Mass of non-cellulosic fraction (kg)
$k_{1000K}$	Reaction rate at a temperature of 1000 K (1/s)
$k_C$	Reaction rate of cellulosic fraction (1/s)
$k_{NC}$	Reaction rate of non-cellulosic fraction (1/s)
$c_i$	Weight factor for component $i$ (/)
$m_i$	Mass of component $i$ (kg)
$y_{RDF}$	Weighted sum of the mass of the components of RDF (kg)
$m_{RDF}$	Mass of RDF (kg)
$F$	Objective function
$a$	Heating rate (K/min)
DAEM	Distributed activation energy model
PE	Polyethylene
LDPE	Low-density polyethylene
HDPE	High-density polyethylene
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
PET	Polyethylene terephthalate
PA	Polyamide
PC	Polycarbonate
$k_j$	Reaction rate for reaction $j$ (1/s)
$A_j$	Pre-exponential factor for reaction $j$ (1/s)
$E_j$	Activation energy for reaction $j$ (J/mol)
$M_i$	Molar mass of component $i$ (g/mol)
$x_i$	Fraction of mixture $i$
$\varepsilon$	Porosity (/)
$\varepsilon_0$	Initial porosity (/)
$V$	Velocity (m/s)
$r$	Radius (m)
$t$	Time (s)
$T$	Temperature (K)
$B$	Permeability (m <sup>2</sup> )
$B_s$	Permeability of the solid (m <sup>2</sup> )
$B_c$	Permeability of the char (m <sup>2</sup> )
$\mu$	Viscosity (kg/sm)
$P$	Pressure (Pa)
$\eta$	Degree of pyrolysis (/)
$Q$	Reaction heat (J/m <sup>3</sup> s)
$\lambda_s$	Thermal conductivity of the solid (W/Km)
$\lambda_c$	Thermal conductivity of the char (W/Km)
$\lambda_v$	Thermal conductivity of the volatiles (W/Km)

$e$	Emissivity (/)
$e_s$	Surface emissivity (/)
$r$	Radius (m)
$N_i$	Amount of reactions involving component $i$ (/)
$S$	Amount of solid components (/)
$d$	Pore size (m)
$T_f$	Furnace temperature (K)

particle scale model has been evaluated against experimental transient temperature profiles at the centre of a large waste pellet during pyrolysis.

## 2. Waste characterization

Following the novel method developed for biomass by Ranzi et al. (2014), the waste is described as a mixture of three reference species by only using its elemental analysis. Waste pyrolysis is then modelled as a linear combination of the pyrolysis of the species separately, assuming that they react independently. A species can either be a single component or a mixture of several components. The composition in terms of the species is calculated by solving the system of atomic mass balances for carbon, hydrogen and oxygen, together with a constraint that defines all fractions to be positive. This is shown mathematically in Eq. (1), with  $S_1$ ,  $S_2$  and  $S_3$  being the reference species and  $a$ ,  $b$  and  $c$  being the composition of the waste in terms of the reference species.

$$\begin{cases} C_{waste} = a \cdot C_{S1} + b \cdot C_{S2} + c \cdot C_{S3} & (a) \\ H_{waste} = a \cdot H_{S1} + b \cdot H_{S2} + c \cdot H_{S3} & (b) \\ O_{waste} = a \cdot O_{S1} + b \cdot O_{S2} + c \cdot O_{S3} & (c) \end{cases} \quad (1)$$

$$a \geq 0, \quad b \geq 0, \quad c \geq 0$$

Graphically, the data point of the waste sample in a C–H diagram must fall inside the triangle formed by connecting the points of the three reference species. This will be shown in following figures.

### 2.1. Waste reference components

MSW mainly consists of organic material and plastics. Naturally, both groups must be represented by at least one of the three chosen reference species. The most reasonable options are discussed here and finally several reference species (pure components or a mixture) are proposed.

#### 2.1.1. Biomass components

Biomass consists mainly of cellulose, hemicellulose and lignin, so these can be used here as reference components. Cellulose must be included in the model since it accounts for the biggest mass fraction. Following the same logic, lignin can only be included if hemicellulose is also included. Based on the composition in terms of carbon (C) and hydrogen (H) reported in Table 1, it can be seen that the values for cellulose and hemicellulose are very similar. Using cellulose and hemicellulose as two separate reference species would lead to a triangle in the C–H diagram (see Section 2.2) with a very small surface area, which would limit the applicability of the model. Therefore, only cellulose is chosen as a separate reference species. There are two possibilities when using only one reference species to model the organic part of the waste: (a) defining it as a mixture of cellulose and hemicellulose, or (b) as a mixture of all three biomass components. When defining two reference species,

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